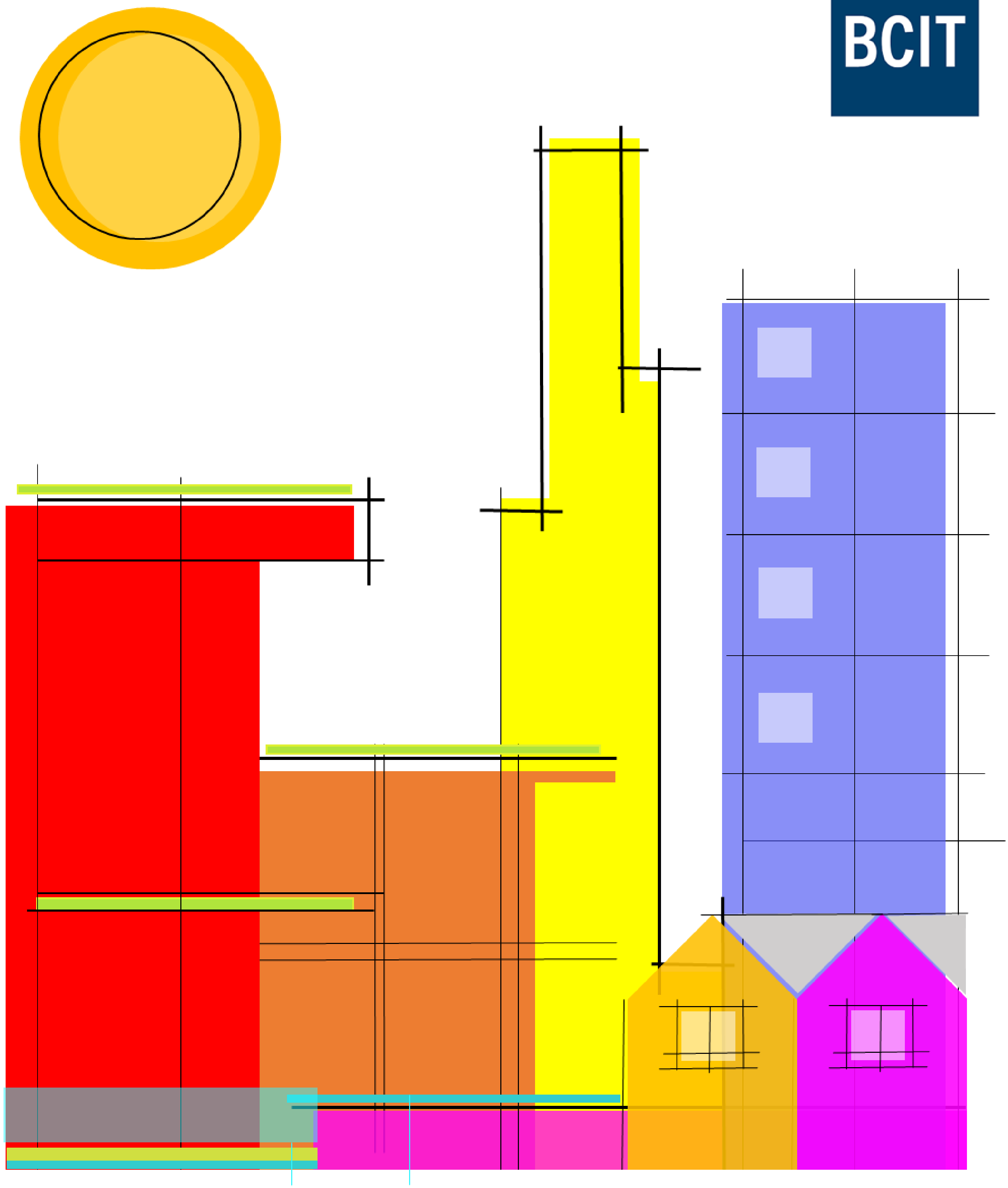

Ventilation Effectiveness for Satisfactory Indoor Air Quality in Multi-Unit Residential Buildings

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EXECUTIVE SUMMARY

This report presents a holistic approach to address indoor air quality and ventilation in multiunit residential buildings (MURBs). The overarching goal is to propose a more methodic treatment of the subject to help design healthy and resilient indoor environments while minimizing the use of energy and resources at the same time. The report is organized as follows:

Chapter 1. Introduction – Lays out the motivation, main concepts, and main challenges underlying this study, as well as its objectives and scope.

Chapter 2. Building airflow principles – Synthesizes the well-known airflow principles in buildings, with a focus on multiunit residential buildings.

Chapter 3. Residential indoor air pollutants – Describes the main residential indoor air pollutants from the literature. Outlines priority indoor air pollutants, and briefly introduces health effects.

Chapter 4. **Residential ventilation principles and practice** – This is a core chapter of this report because it introduces a set of principles that drive the design of ventilation systems in general, and synthesizes residential ventilation practices that guide discussions in subsequent chapters.

Chapter 5. Boundary conditions – Introduces outdoor environmental conditions affecting ventilation and indoor air quality, and perhaps most importantly, indoor human factors that are often overlooked in the design of ventilation systems, and surprisingly remain not evaluated during post-occupancy.

Chapter 6. Ventilation regulations – Describes relevant residential ventilation standards, and makes the case that fire and smoke control regulations are overarching, particularly in multiunit residential buildings, and therefore may limit any ventilation proposals that risk decompartmentalizing the building.

Chapter 7. **Generic ventilation performance requirements** – Lays out for the first time a set of generic requirements for optimum ventilation systems to guide designs of these systems. These requirements include resilience requirements. It is acknowledged that even though these requirements could optimize ventilation systems, many cannot be achieved in the context of MURBs for practical reasons.

Chapter 8. **MURB systems** – Synthesizes an integrated view of MURB systems as they affect airflows and pollutant transport, and as they synergize or interfere with ventilation and indoor air quality requirements.

Chapter 9. Performance-based ventilation design for satisfactory indoor air quality (IAQ) – Proposes a modeling-based methodology to support performance-based ventilation design for acceptable IAQ. The methodology intends to enable the optimization of ventilation systems to achieve satisfactory indoor air quality, while minimizing health risks for the dwellers.

Chapter 10. Case studies on ventilation and IAQ modeling – Case studies are presented to demonstrate that multi-zone airflow modeling can be used as a viable tool to explore ventilation alternatives and support ventilation design for satisfactory IAQ and indoor environmental and health resilience. These case studies provide valuable insights to design that are not available otherwise, except through field monitoring and post-occupancy studies.

Chapters 11 and 12. **Discussion, conclusions, and further work** – Reflects on the lessons learned from the study, and emphasize that post-occupancy field data is necessary to provide evidence of performance as well as data to support and validate the performance-based design methodology. Laboratory and field-testing data on systems and components are also necessary to support the modeling and design of ventilation systems for satisfactory indoor air quality

The main contributions and lessons learned from this study are the following:

- The study presents a holistic approach to ventilation and indoor air quality. This approach is grounded in building science and engineering principles, and considers humans as receivers and enablers of indoor environmental quality.
- The study presents a set of generic ventilation performance requirements and proposes a ranking method for ventilation systems according to these requirements. The study acknowledges that many of these requirements cannot be achieved in MURBs for practical reasons. However, the set of requirements can still set optimum performance targets, and be used to compare ventilation systems.
- Similar to building energy modeling, which is used to support the performance-based energy targets, a proposed performance-based ventilation-IAQ approach is intended to be used to support design of ventilation systems for indoor air quality and health. However, ventilation and IAQ performance measurement and verification protocols are required, similar to those developed to track and validate energy performance targets.
- The study incorporates indoor environmental resilience as a performance target, proposes a set of building system measures to maximize dwellers' livability during wildfires, and uses simulations in Chapter 10 to demonstrate the effectiveness of these measures.
- The study exposes the complexity of human factors that need to be considered to optimize the design of residential ventilation systems in new and existing buildings. It also proposes using dweller archetypes to guide the design of these systems. However, the development of dweller archetypes requires a proper characterization of dwellers based on field campaign data tailored to the dwellers in relation to the building.
- The simulation case studies in Chapter 10 provide the following lessons:
    - Ventilation responsiveness and resilience – In-suite, decentralized, HRV/ERV systems provide better responsiveness to pollutant loads in the suites while centralized systems provide better resilience to outdoor environmental pollutants such as smoke from wildfires. However, modern centralized systems offer the advantages of both centralized and in-suite levels of airflow control by having a pair of terminal supply/return airflow regulator dampers set to suite-level demand-controlled ventilation.
    - Wildfire smoke penetration resilience – Regardless of the type of building, enhanced ventilation filtration, MERV16 + activated carbon, and building pressurization are the most effective measures to minimize the penetration of airborne pollutants from wildfires into the building. Building envelope airtightness and compartmentalization are also important measures, because controlling airflows and pressures is much more effective in airtight and compartmentalized buildings. As demonstrated in the case studies, for small and medium-size MURBs, centralized enhanced filtration combined with slight mechanical pressurization can counter the stack effect during short, typically about one-week-long, wildfire periods. For larger/taller MURBs, high compartmentalization and mechanical zoning alternatives can be analyzed using the performance-based modeling approach proposed in this document. Furthermore, the proposed approach can be used to develop building compartmentalization-airtightness-fan flow/pressure curves to help size air handlers and specify compartments to achieve the required levels of building pressurization.
    - Balanced ventilation and building compartmentalization – In both new and existing buildings, enhanced building compartmentalization along with maintaining balanced ventilation are the top measures to minimize the migration of pollutants between suites. Simulations on a passive house building demonstrate how a combination of balanced ventilation and increased airtightness and compartmentalization results in well-controlled pressures and airflows across the building.

- Ventilation of existing buildings – Simulations on existing buildings demonstrate that unbalanced ventilation on leaky and uncompartmentalized existing buildings lead to highly variable and inconsistent building pressures and airflows that are difficult to control. Unbalanced airflows in uncompartmentalized buildings lead to unpredictable pollutant migrations across the building. For example, a retrofit case study demonstrates that suites close to poorly compartmentalized staircases or shafts attract second-hand tobacco smoke from adjacent suites. A ventilation retrofit case study demonstrates the complexity of dealing with existing buildings. The simulations provided multiple insights to improve the ventilation of the case study building, while saving energy. However, the case study concluded that ventilation retrofits need to be addressed on a case-by-case basis.
- Uncompensated cook-stove exhausts – These exhausts are not acceptable in MURBs because they unbalance building airflows, draw pollutants/odours across suites, and waste energy. Providing makeup air for cooking exhausts is still the most effective solution. Boosting the HRV during cooking operation does not seem to be effective in removing cooking pollutants. A proposed solution for in-suite, decentralized, systems switches the HRV exhaust fan off during cooking, while exhausting the same amount of air from the cookstove hood. For centralized systems, the return airflow regulator damper of the suite can be closed during cooking. A PM2.5 sensor can inform the cooking mode operation, as demonstrated by previous studies. The solution has the drawback that it disables the heat recovery while cooking. A preheater before the HRV could compensate for the lack of heat recovery. However, it is acknowledged that this solution requires more energy and therefore may not be viable. Research on the effectiveness of cookstove recirculation fans/filters is still in progress.
- Ventilation system optimization- Suite-level simulations uncover many issues affecting the effectiveness of the room air distribution and the circulation between rooms, including interactions with the room heating system. Multi-zone airflow (MZ-AF) and computational fluid dynamic (CFD) simulations can be used to optimize the suite- and room-level design of ventilation systems to satisfy the elements of ventilation described in section 4.4 of this document.

This research is a first step to address the ventilation of MURBs holistically. Even though the modeling demonstrates the application of the proposed method to support and optimize ventilation designs, with promising results, the research reported in this document is work in progress. The most important next step is to develop a measurement and verification protocol to evaluate the ventilation and air quality of MURBs, followed by a measurement campaign that systematically collects field data on dwellers' archetypes, ventilation system air flows and pressures, indoor air quality monitoring, and field and laboratory data on airtightness of systems and components. Standard measurement and verification protocols are also necessary for ventilation and indoor air quality. Parallel efforts need to be undertaken to raise awareness and educate dwellers about the impacts of poor air quality on health, and their role in maintaining acceptable indoor air quality in dwellings, without compromising energy targets. Implementing smart ventilation in MURBs can also enable the implementation of a data-driven statistical and stochastic modeling approach to increase confidence in modeling outcomes. Last but not least, collecting systematic feedback from occupants, perhaps as part of embedded smart ventilation systems, is necessary to improve the designs of these systems and optimize their operation.

This report intends to serve as a foundation to foster a more systematic treatment of the topic of ventilation and air quality in MURBs, and to frame further studies on this subject. It is also hoped that the document will serve as a catalyst to generate discussion and industry feedback, including more in-depth case studies, and be used as a learning tool for students in building science.

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"Ventilation is the intentional introduction of outside air into a space"

"acceptable indoor air quality: air toward which a substantial majority of occupants express no dissatisfaction with respect to odor and sensory irritation and in which there are not likely to be contaminants at concentrations that are known to pose a health risk."

[ASHRAE Standard 62.2-2022]

1 INTRODUCTION

This study follows a first-principles approach to help understand the challenges of air quality and ventilation in multi-unit residential buildings (MURBs), and uses simulation case studies to demonstrate alternative approaches to achieve reliable ventilation in MURBs. COVID-19 raised awareness of the importance of ventilation, as well as concerns among MURB occupants and landlords about the shared indoor spaces in MURBs. However, as explained in this document, the potential exposure to air pollutants is higher near the source in spaces with reduced ventilation where people spend more time. People spend more time in MURBs at their suites, and particularly in their bedrooms. Furthermore, partly due to pandemics more people are also spending a large amount of time working from home at a home office or room. Amenities in MURBs such as gyms, community rooms and recreation centres, and swimming pools have their own self-contained ventilation requirements as per ASHRAE Standard 62.1. Lobbies, corridors, staircases, and elevators provide minimal mechanical ventilation. However, this is not a cause for concern since these are transient spaces where people are expected to spend only a few minutes. Furthermore, being transient circulation spaces, thoses spaces are continuously exhanging air with each other and with the outdoors, and any exposure to air pollutants in those spaces is expected to be minimal. Therefore, this documents focuses on how to achieve effective ventilation in MURB suites, and how it can be affected by the whole MURB ventilation.

In this document, the terms **contaminant** and **pollutant** often used interchangeably. However, it is important to make a distinction between these two terms in the context of indoor air quality. The term "contaminant" is commonly used in the field of indoor air quality to describe unwanted constituents that may or may not be associated with adverse human health effects. The term "pollutant" is used to refer to outdoor contaminants that are known to cause illness. The distinction assumes that buildings are designed to provide acceptable indoor air quality, and the indoor air is therefore not intended to include any contaminant known to cause illness, or any pollutant reaching concentrations beyond acceptable values (quality design).

1.1 STUDY SIGNIFICANCE

Humans have become an indoor species (Ott 1988). Over generations, we have been gradually increasing our time spent indoors, and therefore, increasing our exposure to potentially adverse indoor environmental conditions (Samet and Spengler 2003). Over the years, many studies have provided evidence of the presence of numerous indoor air contaminants adversely affecting human health at home (e.g. Logue et al. 2012). Nowadays, it is a well-known fact that humans spend about 80% to 90% of their time indoors. A study by Klepeis et al. (2001) found that people in the U.S. spend 86.9% of their time indoors, and 68.7% of their time in a residence, of which 30% we are at sleep. Similar studies around the world show the same indoor occupancy patterns, which are similar across age and gender groups. Surveys by Leech et al. (2002) indicate that the overall mean time spent at home by Canadians is 15.8 h/day, and by Americans 15.6 h/day, which is consistent with earlier German studies in Europe according to Brasche and Bischof (2005). According to a Canadian General Social Survey in 2015, seniors, men and women, over 65 years old spend about 16 h/day at home, and about 9 h/day sleeping. Studies also show that children's lives have become more home-centred (Brinkman 1999). Furthermore, on the one hand, vulnerable individuals in Europe (the elderly, young children, and people with compromised health) may spend an even larger proportion of their time at home (Vardoulakis et al. 2015). On the other hand, the prevalence of social media and home entertainment technologies is increasing the time people spend indoors, and this increase is more predominant in children and young people (Gottschalk 2019).

Over the years, the requirement for air cleanliness has been increasing by virtue of the heightened awareness of indoor air quality and health. Furthermore, the building industry has realized that due to the increased amount of time people spend at home and the diversity of occupancy compared to other types of buildings (babies, children, elder, pregnant, etc.), occupants' exposure to airborne contaminants at home deserves more attention. It is often argued that overheating risk due to climate change is a major health concern. However, outdoor and indoor air pollution pose greater risks to health than any other environmental hazard (Rajagopalan et al. 2018). Furthermore, while humans react in many ways to thermal discomfort (Nicol et al. 2012), poor air quality is easily undetected because our nose is not a reliable air quality sensor, and we adapt to whatever odour or smells our nose senses. For example, a study shows that adaptation to tobacco smoke caused acceptability to increase (Gunnarsen and Fanger 1992). Therefore, it can be stated that because the air is almost invisible to our senses, we take the air we breathe for granted!

Researchers have suggested that climate change will lead to people spending more time indoors (Bluyssen, 2009; Samet, 2009). There is growing evidence that projected climate change has the potential to have significant effect on public health. In the province of British Columbia, much of this impact is likely to amplify existing risks related to rising temperatures and extreme heat, poor ambient air quality, wild fires, and flooding (BC-MECCS 2020). All these risks will have effects on the indoor environment and health of building occupants. On the one hand, due to rising temperatures, people will want to spend more time indoors in mechanically cooled spaces, which will increase people's reliance on air conditioning, and decrease their tolerance to temperature variations, i.e. thermal adaptation (Roaf et al. 2009). According to the Climate Projections of Metro Vancouver (Metro Vancouver 2016), cooling demand will increase to nearly 6 times what is currently required. On the other hand, poor outdoor air quality will force people to spend more time in "clean air" indoor environments, particularly those that are more at risk. In both cases, the reliance on outdoor air for natural cooling or building ventilation will be questioned, and ventilation will likely be minimized or even completely disabled. In most developed countries, building ventilation typically assumes that outdoor air is clean. Outdoor air filtration has traditionally been used in HVAC systems to protect equipment from degradation. However, over the years this view has been shifting due to growing concerns with increased urban air pollution. The health effects of increased urban air pollution due to traffic and factories are being amplified due to increased urban heat island and climate change (IPCC 2014).

Despite the above, currently, the main government initiatives and economic, net-zero energy, and low-carbon targets do not include indoor human health and well-being targets. In general, it is assumed that high-performance buildings are more comfortable and healthier because they are more effective at managing temperatures and fresh air throughout the building (BC Energy Step Code 2020). This is in part achieved with the use of standards that promote the use of reliable building systems and enforce stringent quality assurance protocols from design, construction, and commissioning, and throughout service life of buildings (Passive House Standard 2020). However, air quality is particularly difficult to quantify because even though it is well known that there are countless of contaminants present in both in the indoor and outdoor air, we cannot know the concentrations of each contaminants in the air, and we do not know how the air carrying contaminants circulates in our dwellings. Most importantly, we cannot know how any of those contaminants affect our health.

1.2 MOTIVATION

What does it mean to ventilate right? A simple answer is: ventilating right is achieved by designing ventilation systems according to the requirements of the local ventilation codes and standards. However, there are significant gaps in ventilation codes and standards on how much to ventilate, as well as on how to ventilate. Furthermore, the definition of "good" indoor air quality, and the most effective, energy efficient methods for delivering it are still subjects of research and debate (Borsboom et al. 2016).

How much to ventilate? A lack of sufficient information on indoor sources and health impacts of indoor pollutants has resulted in ventilation standards relying heavily on engineering judgement (Rudd and Bergey 2014, Borsboom et al. 2016). There are no scientific, widely accepted criteria for ventilation rates (Kurtinski et al. 2021). Are there sound health criteria to rely on when defining appropriate ventilation rates? As summarized by Persily (2005), referring to ASHRAE Standard 62.1 (2004), ventilation rates have been recommended based on control of body odour, perception of pollutant sources by un-adapted individuals, and associations between ventilation rates and sick building syndrome in offices. These ventilation rates have ranged over the years from 15 L/s/person to 7.5 L/s/person, satisfy the substantial majority (at least 80%) of un-adapted persons. In general, 10 L/s, per person is internationally considered as acceptable ventilation rate. However, higher ventilation rates up to 10-20 L /s per person can be justified considering the impact ventilation has on occupants, such as productivity and sick-building-syndrome symptoms (Kurtinski et al. 2021). However, due to energy concerns, standards changed the approach, from recommending ventilation rates to prescribing minimum rates, i.e. ventilation rates are minimal, not optimal. The ventilation rates have therefore been reduced significantly to satisfy a substantial majority of adapted persons. A relevant question concerning the adequacy of ventilation and energy efficiency is the following: how can ventilation rates be optimized to avoid the energy consumption problems of over-ventilation, as well as the air quality and moisture control problems of under-ventilation? A related more fundamental question yet to be answered is the following. Can we adequately assess indoor air exposures to any contaminant; such that we may confidently reduce outdoor air ventilation rates to save energy reduce unnecessary exposure to outdoor pollutants and save energy, without compromising health?

How to ventilate? There is a significant gap in the research of air distribution in residential buildings regarding whether ventilation systems actually perform as intended by codes to maintain satisfactory indoor air quality (IAQ) in dwellings (Rudd and Bergey 2014). Residential ventilation systems are characterized by being low-flow systems, intended to supply a minimum amount of ventilation air as prescribed by codes. Two critical questions are the following: is low-flow ventilation capable of reaching the occupants' breathing zone under diverse design and operation conditions? Are the code-required ventilation rates sufficient to maintain satisfactory IAQ in all rooms for the comfort and health of the dwellers? Observations of ventilation and air quality in low-flow systems in monitored houses (Tran 2016), as well as laboratory experiments with smoke visualization (Bhalla 2020), have shown that low-flow systems are prone to supply-air short-circuiting and poor air distribution, particularly when supply and return ventilation outlets are not located properly in spaces.

Furthermore, the are significant challenges in achieving proper ventilation in dwellings versus in offices or other types of buildings. People spend more time at home than at work and school. At home dwellers are "in control" over their environment, and have more freedom than anywhere else to conduct themselves in manners that can either improve or deteriorate the indoor environment. Regardless of the ventilation system in place, our presence, choices, home-maintenance, and actions at home have the biggest impacts on its indoor air quality. So how can residential ventilation systems respond effectively to the prevailing and inherently dynamic human factors affecting indoor air quality?

Below are some complexities identified in designing and implementing reliable ventilation systems in MURBs:

1. **Increased densification of dwelling and occupants in MURBs** – Concentrating more people in smaller suites and facilities increases the production of human-generated contaminants per unit area, the number of occupant interactions with the building, the human circulations in the building, and the possibility of crowding common areas and shared facilities. As a result, if the ventilation is not adequate, the probability of occupants' exposure to indoor building contaminants increases, as well as the possibility of human-to-human pathogen transmission.
2. **Augmented effects of occupants' behaviours** – Multiple occupancy increases the recurrent opening of entry doors, the use of elevators, and the often untimely and dissimilar patterns of opening windows, which have a major impact on building airtightness and infiltration (Proskiw and Phillips 2008).
3. **Building size and height** – High-rise buildings are more susceptible to the effects of the environmental thermal and wind forces driving uncontrolled infiltration airflows, which are typically stronger at the top and at the base of the building. As a result, maintaining proper mechanical pressure differentials to control airflows becomes more challenging, and makes the effectiveness of ventilation systems in high-rise buildings more dependent on the quality of the constructions. High-rise buildings also face tight space constraints for the layout of suites and rooms, and ventilation duct systems.
4. **Inherently compartmentalized, yet interconnected** – Multifamily buildings are inherently compartmentalized into "semi self-contained" suites/units that are intended to operate almost in isolation for safety, privacy, and well-being of the dwellers. However, they require shafts and corridors for circulation that continuously open the compartments and allow airflows. Air infiltration is increased by an enhanced height/stack-effect, and by the presence of elevator, mechanical, and electrical shafts, and staircases that channel infiltration airflows and may carry contaminants between floors. Pressure differences between suites, caused by the use of kitchen and bathroom fans and by window opening, further promote the migration of contaminants between suites, and between common areas and suites. Furthermore, having multiple compartments means that the probability for unintended airflow paths between compartments is increased.
5. **Fire and smoke control** – Fire safety, smoke migration control, and the provision of clear routes of egress for people in cause of a fire, are particularly critical constraints in high-rise buildings, and impose tight constraints on the selection and layout of ventilation systems, as well as the measures (such as compartmentalization) to contain fire and smoke at the source, and minimize the risk of fire propagation and smoke migration into the building.
6. **Constraints multiplied by the number of suites** – Any decision affecting the ventilation system design has repercussions that are multiplied by the number of suites in the building. For example, compared to centralized ventilation systems, the number of operation and maintenance issues in decentralized/in-suite systems are multiplied by the number of suites. Similarly, decentralized systems require more envelope penetration for air intakes and exhausts than centralized systems. Therefore, implementing smart/responsive ventilation at the suite level is challenged by the increased costs and constraints in system/control installation, reliable operation, and maintenance.

Emerging issues such as climate change and its effects, overpopulation, and pandemics, have further raised concerns over ventilation and human health, which are compounded by the specific MURB complexities outlined above. So much so that nowadays, building resilience has become a trendy research topic involving all aspects of building performance, including of course ventilation. The COVID-19 pandemic, begs to raise the question again: is the ventilation in our buildings adequate to improve the hygiene of the indoor environment and by connection promote our health and protect us from diseases? (Seppänen 2021). Paradoxically, under COVID-19 the "ventilate right" motto has become of common use even by top health authorities. Again, what does ventilate right mean? The increase in the recurrence and intensity of wildfire events is also forcing the building industry to rethink ventilation and filtration and question the meaning of "ventilate right" under these events.

1.3 WHAT'S IN THE AIR? GENERAL CLASSIFICATION OF INDOOR AIR POLLUTANTS

The indoor air contains contaminants that originate from outdoor and indoor sources (sections 2.1.1 and 2.2.1). Numerous outdoor pollutants penetrate through cracks, gaps, and leakages, as well as through openings and ventilation systems. The potential sources of indoor air contaminants at home are numerous, and have been documented in many studies (section 2.1.1). Aside from well-known hazards, such as carbon monoxide (CO) from incomplete combustion, the typical sources of indoor contaminants are the following. 1) Volatile synthetic chemicals present in indoor finishes, materials, and products (flooring, cabinets, and furniture). 2) Biological from microbes in our homes (e.g. mould, bacteria). 3) Human from the presence (metabolic) and activities of dwellers (e.g. cooking, smoking, cleaning). The air relative humidity is an important agent modifying biological contaminant exposures at home (Borsboom et al. 2016). A lack of sufficient information on indoor sources and health impacts of indoor contaminants has resulted in ventilation standards relying heavily on engineering judgement. As a result, the definition of "good" indoor air quality, the correct amount of ventilation, and the most effective, and energy efficient methods for delivering it are still subject of research and debate (Borsboom et al. 2017).

Table 1 (Mora 2020) provides a general classification of air contaminants in two large groups: particulate matter and gases. Air contaminants are present as a suspension of fine particles, gases, and liquid droplets in diverse concentrations, called aerosol. Aerosols include quantities of biological contaminants (bioaerosols), dust, fine particulate contaminants, and gaseous contaminants. The size of particulates (aerodynamic diameter D) affect their presence and behaviors in the air. In general, smaller particles remain airborne longer and travel farther, while larger particles tend to settle close to their source.

Table 1. General Classification of Airborne Contaminants (Mora 2020)

Class	Subtype	Characteristics
Respirable Particulate Matter (PM)	Ultrafine (UFP): $D < 0.1\ \mu m$	• Combustion, smoke, cooking (chemically active), biological (viruses) • Behave like gases: advection transport by air currents and diffusion transport in still air, chemical reactions affected by air humidity
	PM2.5: $D < 2.5\ \mu m$	• Combustion, smoke, cooking (chemically active), biological • Advection transport by air currents and diffusion transport in still air • Coagulation, agglomeration, settling and resuspension
	PM10: $D < 10\ \mu m$	• Chemically inert, biological allergens (animal, plants) • Gravity controlled, settle rapidly in still air near source, carried by air currents
Gases / Vapours	Organic: Volatile Organic Compounds (VOCs)	• VOC: volatile organic compounds, VVOC: very-volatile organic compounds, SVOC: semi-volatile organic compounds, MVOC: microbial organic compounds • Advection transport by air currents and diffusion transport in still air, chemical reactions affected by air humidity
	Inorganic	• Carbon monoxide (CO), Nitrogen oxides (NOx), Sulphur oxides (SOx) • Secondary (chemical reaction): Ozone • Ammonia, chlorine
	Radioactive	• Radon

Figure 1 (Gameiro da Silva, REHVA 2020) illustrates the particle size ranges in the indoor air. In general, all particles are inhalable, i.e. interact with the human respiratory system. However, while the larger particles (D > PM10) are typically captured in the nasal passages, the smaller ones (D < PM10) are typically respirable, i.e. they can penetrate into the respiratory system down into the lungs. The smaller the size, the higher the probability that they can penetrate deeper into the respiratory system (ASHRAE 2021). Furthermore, the smaller particles, typically generated by processes such as fuel combustion, smoke, and cooking, are chemically active and potentially toxic, because they are formed by agglomeration of gases. Gases are chemically active and they react with other gases. The regulatory threshold limit concentration of any gas in the air depends on its toxicity. The most prevalent gases are volatile organic compounds (VOCs). VOCs are a large family of chemicals that originate from multiple natural and synthetic sources.

The excessive generation of contaminants from any of the sources above can easily overwhelm the capacity of any mechanical ventilation system. However, relatively small concentrations of harmful volatile chemicals can go easily undetected for years and cause chronic health problems to occupants. Furthermore, new chemicals appear in our buildings almost daily that are unregulated. Even chemicals that have demonstrated to harm the population are still prevalent in the residential indoor air at concentrations beyond the regulatory limits (Sherman 2013). However, it is difficult to know whether the exposure most people have with these substances pose a health risk, because the capacity of each compound to cause sickness is exceedingly hard to estimate (Ott and Roberts 1998).

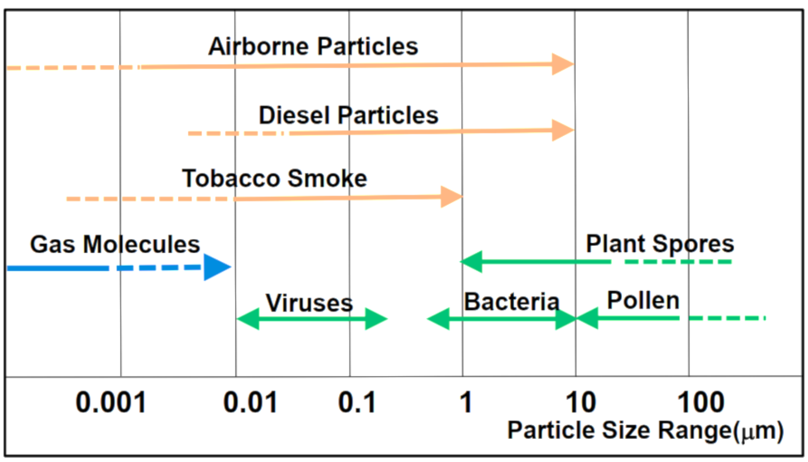


Figure 1. Particle size ranges in the indoor air (Gameiro da silva REHVA 2020)

1.4 Building Ventilation: A Risk Management Approach

Ventilation is the intentional <u>*and controlled*</u> *introduction of outdoor air into a space to dilute indoor contaminants.* Since we can never know with certainty the contaminants present in the indoor air, ventilation is considered a risk management approach to deliver outdoor ventilation air to spaces to dilute and remove any indoor air contaminants that are likely present under normal conditions, which excludes unusual contaminants. Ventilation is intended to remove and dilute indoor air contaminants likely to be present in buildings, before they can reach uncomfortable, unhealthy, and possibly harmful concentrations. However, due to the complexities explained below ventilation systems cannot guarantee safe indoor conditions under all circumstances.

Figure 2 illustrates the main factors affecting Indoor Air Quality (IAQ). The ventilation system removes and dilutes indoor contaminants through a) source control, b) airflow control, c) distribution, and d) treatment, which are ventilation principles described in strategies described in section 4.1 of this document. However, the effectiveness of the ventilation system is highly dependent on the envelope and construction systems, and the occupants (dwellers). The envelope and the construction system intervene to either impede or enhance airflows, and therefore the transport of contaminants through the building. Occupants open/close windows, and can disable, enable, or enhance mechanical airflows, and therefore the dispersion of contaminants. Occupants can also buy furniture that smell new, thus releasing a range of airborne chemicals, as well as pollutants from smoking, burning candles, and even hobbies and other activities, without caring for properly venting these out. The control of building airflows is central to the control of the contaminant transport and removal in buildings.

The proper control of building airflows is a necessary requirement to achieving effective ventilation in buildings.

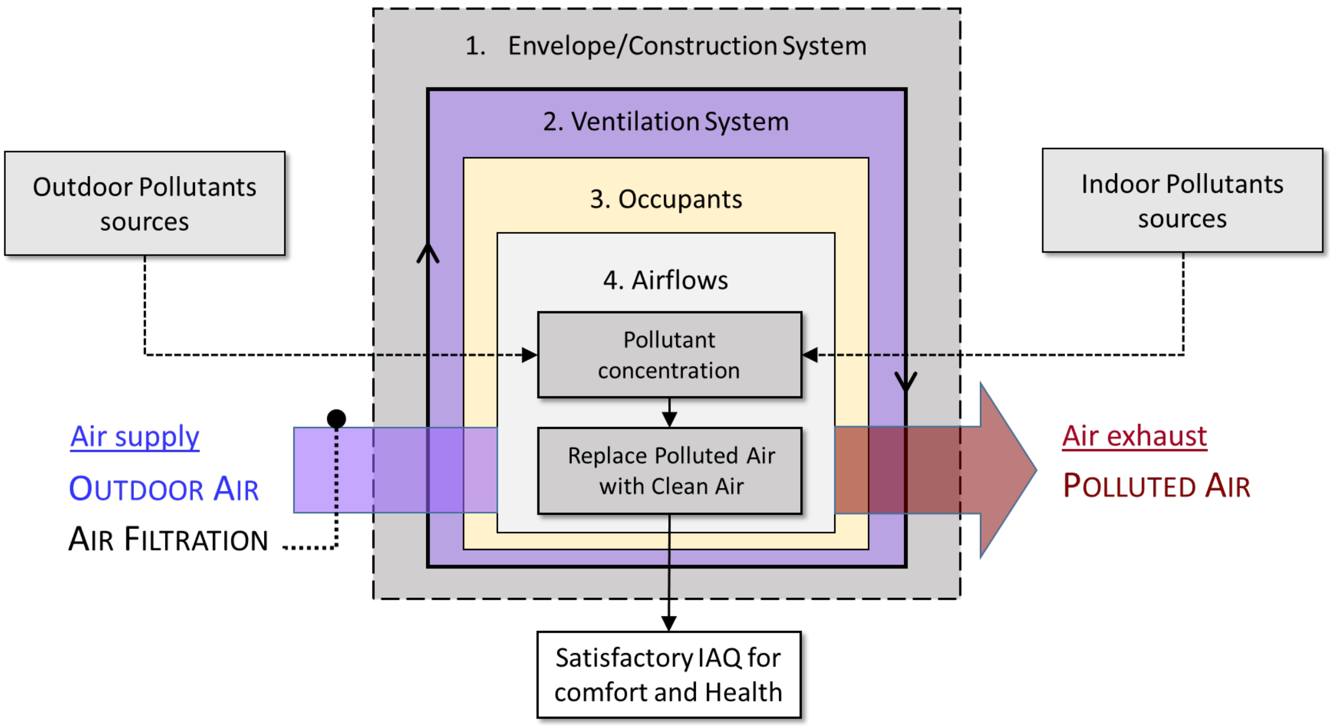


Figure 2. Ventilation and Indoor Air Quality in Buildings

Table 2 shows three groups of factors affecting indoor air quality in residential buildings. The combination of the factors shown in Table 2 creates unique complexities for the selection, design and operation of ventilation systems in residential buildings.

Table 2. Factors affecting indoor air quality

Design & Operation factors	• Minimum ventilation, outdoor airflow, rate • Enhanced ventilation versus energy efficiency trade-off • Ventilation reaching the occupants' breathing zone in all rooms
Environmental factors	• Ambient temperature: window operation • Ambient temperature: stack effect driving infiltration • Ambient pollution: window operation • Ambient pollution: pollutant penetration through air infiltration
Building characteristics	• Building age • Ventilation system type and operation • Heating and cooling system • Construction system air-tightness • Construction system compartmentalization • Indoor air temperature • Thermal bridges prone to condensation • Indoor contaminants in the building
Human factors	• Socioeconomic and cultural factors • Owned versus rented • Human generated contaminants: presence and activities • Family habits: moisture generation, cooking, smoking, personal care • House cleaning and maintenance habits, garbage handling • Changes in environmental and human hygiene due to aging, reduced physical and psychological capacity to operate environmental controls, including windows, changing filters, etc., reduced capacity/desire for personal hygiene, washing of bedding, towels, bathrooms, kitchens etc. • Presence of pets and pests • Use and storage of chemical products such as pesticides

1.5 BUILD TIGHT, VENTILATE RIGHT

The influence of the construction system on building airflows and on the effectiveness of ventilation is reflected in the well-known ventilation motto *"Build Tight, Ventilate Right"*. Modern residential ventilation systems no longer rely on uncontrolled infiltration airflows through constructions to maintain satisfactory indoor air quality. It is a fact that infiltration (air leakage) wastes energy. It is also a fact that leakage-based ventilation is unreliable. Less obvious it the fact that infiltration negatively interferes with the ventilation effectiveness of controlled mechanical ventilation systems.

Several studies have confirmed that improved indoor air quality is maintained in airtight low-energy homes with well-controlled mechanical ventilation (Koffi 2009, Boulanger et al. 2012, Laverge and Janssens 2013, VHS 2015). The idea that increased building airtightness can be detrimental to indoor air quality originates from either a) studies on envelope retrofits including air-tightening, on buildings ventilated through infiltration, leakage-based ventilation (Milner et al. 2015), or b) studies on passive houses with poorly designed, poorly installed, or poorly operated mechanical ventilation systems (Hasselaar 2008, Sharpe et al. 2015). Expertise in the design, as well as the implementation of proper installation, and commissioning procedures have been demonstrated to be indispensable for the successful operation of systems with heat recovery ventilators (van der Pluijm 2010). However, a question is still unanswered: how can buildings guarantee adequate ventilation for occupants at all times? What does ventilate right mean? Local codes typically prescribe minimum ventilation rates for energy efficiency and comfort. However, can we guarantee that airtight homes with well-controlled mechanical ventilation will keep us safe? Can we know with certainty what is in the air at all times? Can we know with certainty what the right amount of outdoor air is? Can we know with certainty that the ventilation air will reach the occupants?

1.6 VENTILATION AND ENERGY EFFICIENCY TRADE-OFFS

The trade-off between energy efficiency and ventilation is well known by building practitioners and facility managers. Ventilation draws untreated outdoor air into the building that is mechanically treated before it is delivered to the indoor spaces. Therefore, mechanical ventilation typically carries an energy penalty. This is why codes prescribe minimal, not optimal, ventilation rates to achieve acceptable indoor air quality, and green building standards promote enhanced ventilation for health. Heat Recovery Ventilators (HRV) and Energy Recovery Ventilators (ERV) are now prescribed by codes to reduce ventilation energy waste. For details on these devices and their application in MURBs, see BC Housing (2015) and CMHC (2015) guides.

1.7 HUMAN FACTORS: VENTILATION CHALLENGES AT HOME

The main factor affecting indoor air quality at home are the occupants' behaviors: activities and habits (IOM 2011). Unlike in any other building, occupants at home have the freedom to behave at will. Occupants' behaviors affect the production and persistence of contaminants, including bathing, cooking, smoking, not/cleaning, using chemicals such as fragrances and insecticides, etc. Behaviors also include interactions with he building that may inhibit or enhance contaminant presence, such as room air venting from contaminant producing activities, opening/closing windows, tampering with equipment, etc. ventilation systems are not designed to remove excessive concentrations of air contaminants generated from occupants' activities, or operate reliably when improperly handled. The venting and air polluting habits of dwellers depend on the country, the city and its climate, and on demographics of the dwellers: cultural and socioeconomic factors. In cold climates, a prevailing factor causing respiratory health effects is the excessive production of moisture by occupants that promotes biological growth and causes building deterioration (Fisk et al. 2007, Hagerhed-Engman et al. 2009). Crowding, cluttering, and lack of care compound to these effects. In Western countries, chemical emissions from interior finishes, cabinets, and furniture are also major risk factors for respiratory deceases (Mendell 2007). Unvented cooking-related contaminants (from fuel and cooking products) and the cooking moisture generated are also of concern (Parrott et al. 2003, Buonnano et al. 2009). Under COVID-19 the issue of the effect of human behaviours on virus transmission has become more apparent, so much so that under such a pandemic the motto *"behave tight, ventilate right"* would be more appropriate.

1.8 THE BUILDING VENTILATION SYSTEM

Controlling building airflows is central to building ventilation to enable achieving satisfactory indoor air quality (Figure 2). As discussed in the previous section and in the following chapters, the ventilation of buildings is central to the management and control of airflows in buildings, which are also dependent on the performance of other building systems. Adequate amounts of clean ventilation air are required for the health and comfort of the occupants in buildings. However, aside from pollutants, the air also carries moisture and energy, and therefore, controlling air flows is essential to the durability and energy efficiency of buildings. Therefore, a whole-system approach to ventilation is necessary, not limited to introducing outdoor air, including a more encompassing definition of the building ventilation system.

The Ventilation System *is an air management system that balances the introduction and treatment of outdoor air in buildings to remove indoor air contaminants, with the indoor and outdoor air quality requirements and conditions, and the control of identified pollutants at the source. Important considerations for the design and operation of ventilation systems are the following:*

1) *Operate reliably under varying weather conditions and human interactions with the building*
2) *Synergize with other systems and consider the effects of building constructions*
3) *Be integral to any indoor moisture control strategy,*
4) *Be energy efficient in controlling airflows, and*
5) *Be robust to deviations from the design assumptions and conditions*

1.9 Objectives and Scope

The overarching goal of this study is the systematic analysis of ventilation systems and strategies in multi-unit residential buildings (MURBs). To support this approach, the detailed objectives are the following:

1) To raise awareness on the complexity of maintaining satisfactory indoor air quality in at home, and in particular in MURBs, due to the multiple factors involved and their associated uncertainties.
2) To raise awareness on the range of contaminants and pollutants that people can be exposed to at home, and characterize their sources and behaviors.
3) To review and synthesize the literature on the main building and ventilation design and operation factors that interfere with the performance of ventilation systems.
4) To use models to compare ventilation systems' performance through a sensitivity analysis that exposes the main factors affecting performance, and evaluate alternatives to improve systems effectiveness.
5) To compare the ventilation performance of modern ventilation systems at the suite and whole-building levels. In particular the following questions are explored:
   - Q1. What are the metrics of effective ventilation?
   - Q2. What are the strengths and weaknesses of centralized versus decentralized systems?
   - Q3. How does MURB compartmentalization affect suite ventilation effectiveness?
   - Q4. What are the factors affecting the ventilation effectiveness of suite low-flow air distribution?
   - Q5. How to design ventilation systems that are reliable and resilient to maintain satisfactory indoor air quality and occupants' health during emerging climate and population related threats such as pandemics, episodic forest fires?

Assumptions and inputs used in the modeling are based on data from a few case studies available on MURB buildings. The main limitation of this study is the lack of actual field data to validate the models used for ventilation systems comparison. Unfortunately, it was not possible to get access to a case study building to validate the findings and models of this work. This study intends to raise awareness on the importance of this topic, and increase the local efforts and collaborations between the local industry and the local academic institutions to conduct comprehensive field studies and strengthen the local capacity to better design, model, and measure the performance of ventilation systems and air quality in MURBs.

2 BUILDING AIRFLOW PRINCIPLES

As illustrated in Figure 3, and reflected in the more encompassing definition of ventilation provided in section 1.8, the control of building airflows is intrinsic to the control of the contaminant transport and removal in buildings. In general, building airflows are controlled by both the construction system and by the ventilation system, with occupants acting as airflow modifiers. There are many good documents available describing the physics of building airflows (Straube 2007, ASHRAE 2021), as well as the airflows in multi-unit residential buildings, including the fundamental governing equations, and measures to mitigate uncontrolled construction-related building airflows (RDH 2013, Ricketts 2014, CMHC 2017). Readers interested in studying these details are encouraged to read the documents above. This section focuses on the interactions between air-tightness and compartmentalization as main contributing factors to uncontrolled airflows in multi-unit residential buildings.

Airflows in buildings result from a combination, sometimes conflicting and sometimes reinforcing, natural wind and thermal forces, and mechanical forces. The relative strengths of these forces is dependent on the size and height of the building, and on the internal interconnectivity between floors and between individual suites and common areas.

Figure 3 illustrates from first principles how a combination of driving forces leads to airflows. Natural (stack effect and wind), and mechanical (fans) forces drive airflows through multiple paths. Differential pressures develop across paths with magnitude depending on the relative strengths of the driving forces at both sides of the path, and on the size and shape of the path itself. These pressure differentials (ΔP) in turn drive airflows through the paths; i.e. large paths generate smaller differential pressures across, and drive more air through, and vice versa, and small paths generate larger differential pressures across, and drive less air through.

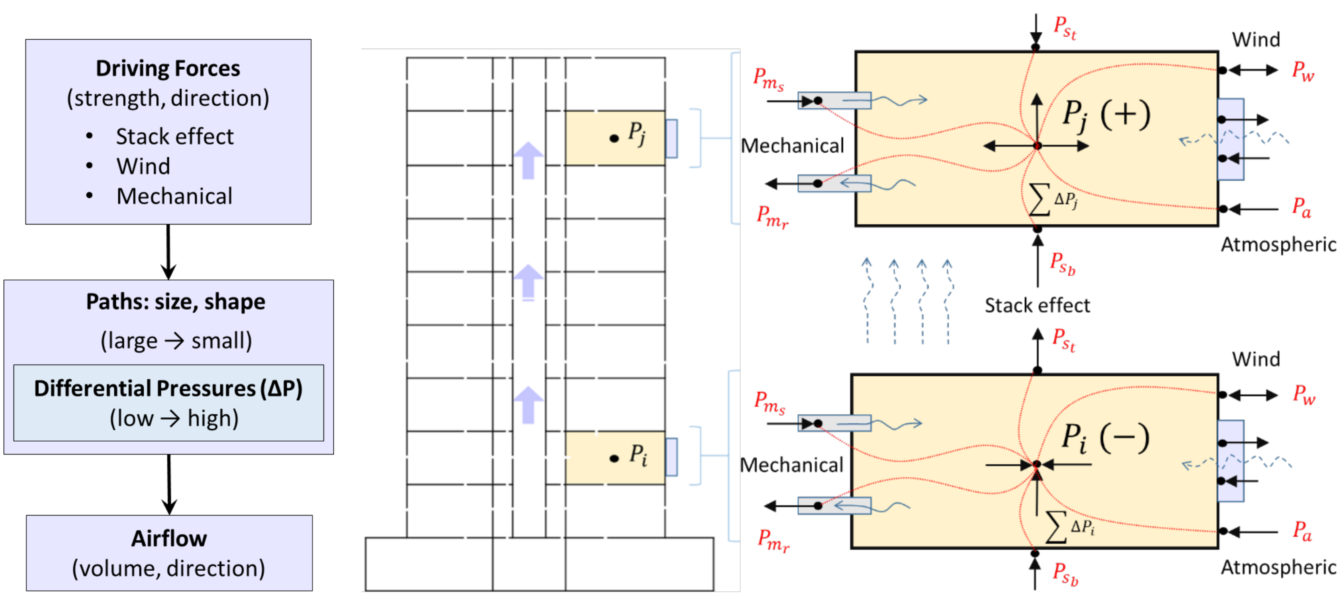


Figure 3. Building airflow principles: a) factors involved, b) driving forces on tall buildings in cold climates

Law of conservation of mass applied to building ventilation *- The mass of air entering a room or a building must equal the mass of air leaving the building. This means that on average, at any given time, if fresh (new) ventilation air is entering the building, then an equal amount of used (old) air must be leaving.*

The relationship between external driving forces/pressures and the resulting suite internal pressures is illustrated with dotted red curves in Figure 3.b. Building pressures are dynamic, owing to the dynamic nature of the driving forces. In any apartment suite, the combination of external forces leads to air motion inside the suite, which depends on the configuration of the suite and its openings, as well as its location and orientation, and is also affected by the suite's internal sources. At any given moment, the combination of external pressures/flows results in a whole-suite internal pressure, so that each suite becomes either pressurized, depressurized, or neutral/balanced, with respect to its neighbouring spaces and the atmosphere. Therefore, controlling airflows in buildings involves maintaining controlled/stable air pressures in all the enclosed spaces inside a building, which requires air-tightening the enclosed spaces as much as possible to minimize the impacts of natural forces on a space flows and pressures, while maintaining controlled/stable mechanical airflows in and out of each space. However, in tall buildings, as the natural forces grow stronger their effects become more difficult to control by mechanical forces. Furthermore, strong natural forces may lead to mechanical air unbalances that compound to the instability of interior air pressures and flows.

2.1 STACK EFFECT

Stack effect is a thermal force that is caused by warm air being less dense than cold air. Stack effect and air buoyancy are tightly coupled phenomena, but they are not the same. The stack effect is caused by the bulk air inside the building being at a different temperature from the outside air. In winter, the air outside is cooler and denser, which makes it heavier at the ground; this causes the outdoor air pressure to be higher than the indoor air pressure at the ground level, thus pushing outdoor air into the building at its base and at its lower floors. By the law of conservation of mass, an equal amount of indoor air must leave the building at the upper floors of the building where the direction of the indoor-outdoor pressure differentials is reversed. This differential-pressure reversal occurs because the outdoor air pressure decreases faster with height than the indoor air pressure due to the indoor air being less dense. Buoyancy, which is caused by the expansion of warm air, enhances the stack effect. Buoyancy occurs everywhere (e.g. air rising around the human body), however, its effect is more pronounced in large heated spaces because buoyancy develops with height. In MURBs, the effect of air buoyancy can be reduced because thermostats-heating in suites maintain more-or-less the same temperature across the building, and interior compartments obstruct continuous vertical buoyant airflows. Figure 4 illustrates air movement between two compartments driven by both stack effect and buoyancy forces. As illustrated in Figure 4, as lighter warm air rises, it displaces air at the top and makes room for heavier cold air to enter at the bottom.

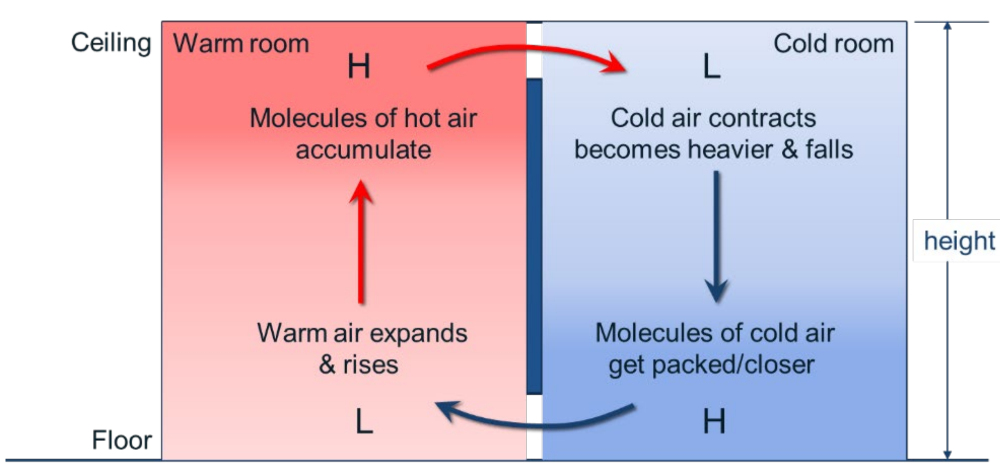


Figure 4. Stack effect principle

The strength of the stack effect is a function of the temperature difference between the two rooms, and on the height of the rooms (the stack). Therefore, the taller the building, the stronger the stack effect is. In the warm room, as warm air rises it produces a low pressure region at the base (L), and as air accumulates at the top, it creates a high pressure region at the top (H). In the cold room, a high pressure region is created at the base (H) and a low pressure region is created at the top (L). The differences between high and low pressures drive airflows between the two rooms.

In Figure 5, the principle of stack effect is applied to a multi unit residential building in cold/heating season. The cold room is the cold atmosphere and the warm room is the building. In cold/heating season, cold air enters the building through the lower floors and leaves through the upper floors. Differential pressures (ΔP) drive airflows across consttructions. The right-hand side of Figure 5 shows that the differential pressures are higher at the base and at the top of the building, and decrease towards the middle of the building. Figure 5 illustrates the importance of controlling the differential pressures at the base of the building, in particular those between the outdoors and the shafts, and the outdoors and the core. At some middle height, called the neautral pressure plane, the indoor and outdoor pressures nearly equalize and the resulting ariflows through the envelope driven by stack effect are therefore minimal. For air quality safety and fire safety reasons, the air from the parking garage needs to be decoupled from air in the rest of the building (Chapter 4).

Two general types of paths can be identified: horizontal paths and vertical paths. Stack effect uses both. Therefore, to control the stack effect, these paths should be sealed at the envelope (airtightness) and inside the building (compartmentalization). Vertical paths are due to shafts (staircases, elevators, duct risers) and slab penetrations. Horizontal paths are due to envelope leaks and gaps, and leaks and gaps in interior walls and doors.

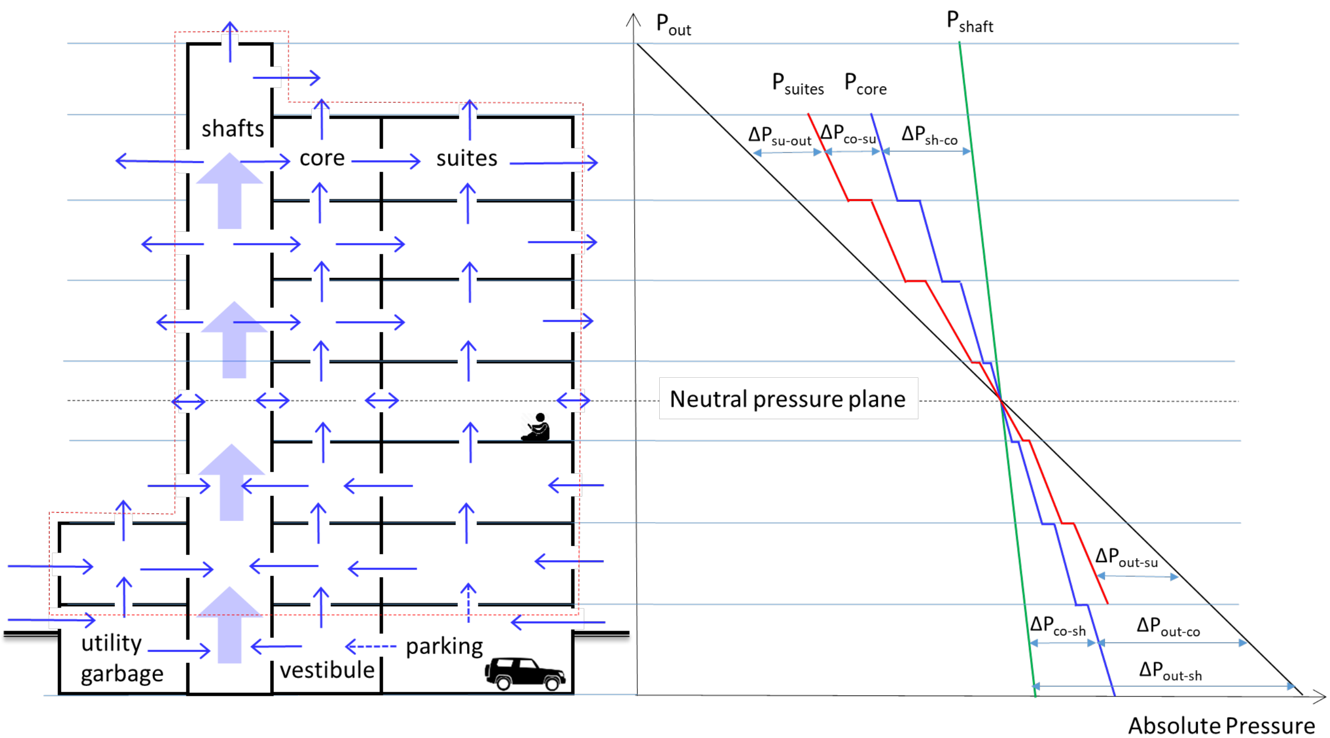


Figure 5. Stack effect in a MURB in cold/heating season

Airtightness *– "In general, the approach taken to control air flow is to attempt to seal all openings at one plane in the building enclosure. This primary plane of airtightness is called the air barrier system. The word system is used since airflow control is not provided by a material, but by an assemblage of materials, which includes every joint, seam, and penetration." (Straube 2007).*

Compartmentalization *– Is the sealing of all openings and gaps in the interior walls, in the floor slabs, and around doors to create independent air compartments. Compartmentalization is a passive fire and smoke protection measure recognized in fire codes (Klote et al. 2012, section 2.2.2). For airflow control in MURBs, each suite can be treated as a separate compartment, as well as each floor. For safety reasons, the underground parkade is also treated as a separate compartment that is isolated from the rest of the building.*

Compartmentalization reduces stack-effect pressures at the enclosure, that drive airflows in and out of the building, by reducing the stack height possibly down to the height of each compartment. Vertical service shafts, staircases, and elevators can still generate major driving forces for stack effect and carry air pollutants across floors. Therefore, air sealing their access doors when not in use, and all penetrations is a priority. Airtight vestibules at the entry of lobbies and staircase/elevator shafts help maintain airtightness and compartmentalization when people enter or leave those spaces. Furthermore, building compartmentalization is the only strategy that would permit opening windows in suites without affecting the whole-building building pressure control, and generating unintended airflows across the building.

Taking a closer look at the pressure gradients at the right-hand side of Figure 5, the relative magnitude of these pressure gradients are affected by the sizes of the paths. The following hypothetical scenarios can be help explain the nature of the interactions between paths, pressures, and flows:

- **Scenario 1 (Figure 6a)** – The envelope is airtight and the interior is not compartmentalized (e.g. all interior doors, including the staircase door, are open). This scenario will cause the largest pressure differentials across the envelope ($\Delta P_{suite\text{-}out}$), particularly towards the top and the bottom of the building. By contrast, the internal pressure differentials between spaces are small, internal airflows are almost unrestricted. Rising warm air accumulates at the top, generating large pressures across the envelope at the top floors ($\Delta P_{suite\text{-}out}$), while at the same time large pressure differentials are also generated at the base ($\Delta P_{out\text{-}suite}$) caused by the room left by the rising air. This is reflected in Figure 6a by the suites and core pressure lines being pushed towards the shaft.
- **Scenario 2 (Figure 6b)** – The envelope is leaky and the interior is well compartmentalized (doors closed, proper sealing of holes and gaps). In this case, the largest pressure gradients will be at the interior between compartments. This scenario will significantly reduce the stack effect because its strength will be limited by the height of each individual compartment. Airflows between compartments will be significantly reduced. This is reflected in Figure 6b by the suites core, and shaft pressure lines being pushed towards the outdoors.

In Figures 5 and 6, it is clear that the shaft is the single most important element that controls, channels, the stack airflows. The shaft is the tallest compartment, and controls the pressure gradients with all other compartments: core and suites. Therefore, in MURBs, the "warm room" is the shaft, not the suites or the core (Figure 4). Figure 6, illustrates the importance of properly compartmentalizing the building, in particular at its base where the higher differential pressures are developed.

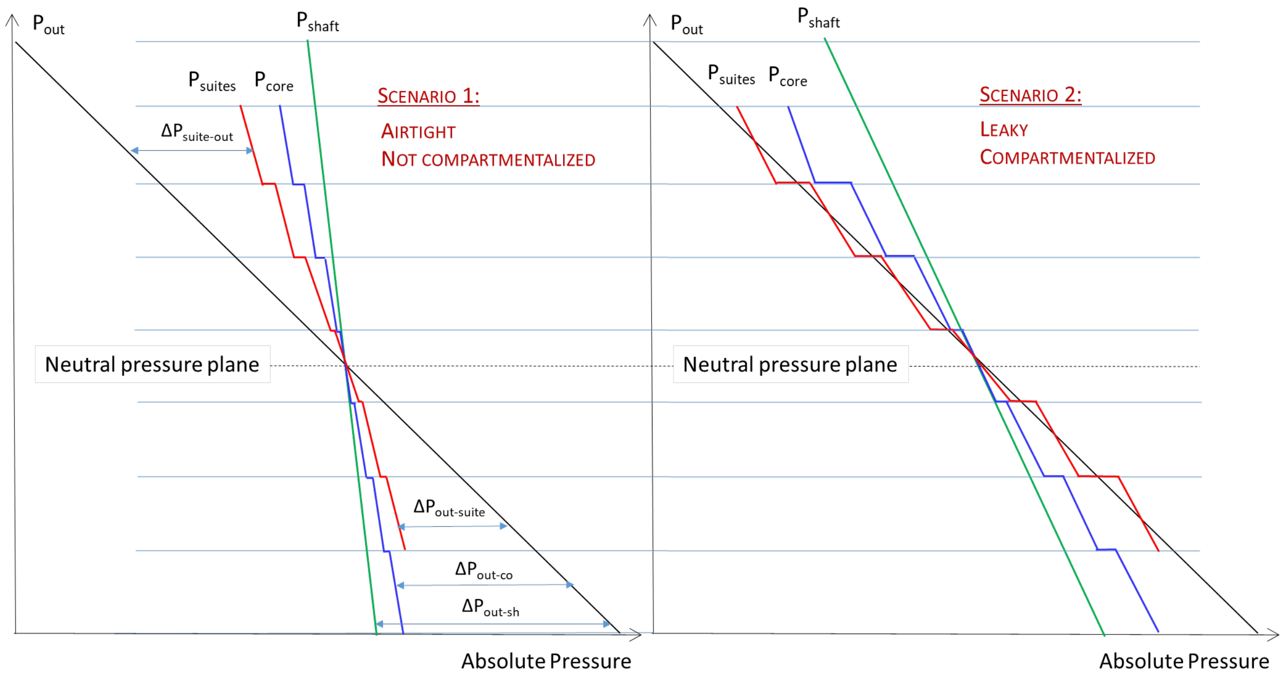


Figure 6. a) Scenario 1: airtight envelope, not compartmentalized, b) Scenario 2: leaky envelope, compartmentalized

The strength of the stack effect is dependent on the temperature difference between the shaft and the outdoors (Klote et al. 2012).

Figure 7, shows airflows from stack effect at two floors, below the NPP (Figure 7a), an above the NPP (Figure 7b), cold air enters through bottom floors, is channeled through shafts, and exists through top floors.

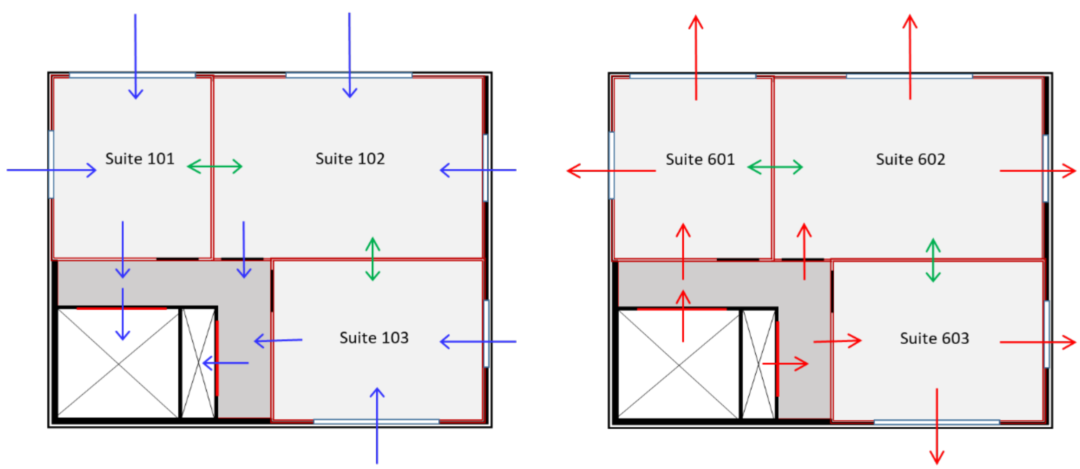


Figure 7. Airflows a) at the bottom floor (below the NPP) and b) at the top floor (above the NPP)

The green arrows between the suites indicate that airflows can be in either direction depending on other airflow driving forces present (wind and mechanical), and on the occupants. For example, the occupants in one suite may use a stove range/exhaust fan to vent cooking contaminants, which reduces the air pressure in the suite. Opening windows relieves the envelope pressure in the suite.

2.2 WIND

Wind is a less predictable force than stack effect because it is unsteady and changes its speed and direction every second. Wind gustiness and turbulence cause fluctuating flows. Due to its highly fluctuating nature, in a matter of seconds a strong gusting wind pumps air into a suite and increases its internal pressure beyond the outdoor pressure. Seconds after, wind recedes causing the excess suite pressure to produce an outward airflow from the suite. However, prevailing steady winds that are properly channeled in and out of rooms, can produce more steady flows of air. Thus, the importance of proper design for prevailing winds. Wind pressures are stronger in upper floors in high-rise buildings.

2.3 MECHANICAL

Residential ventilation airflows are relatively small and can be easily overpowered by the natural forces, particularly in tall, leaky, and not-compartmentalized buildings. This is unlike in hospitals and laboratories where the mechanical ventilation airflows are high, buildings are airtight, and hospital wards are carefully compartmentalized to help control the transport of pathogens across spaces. Therefore, the airflows in those buildings are highly controlled (Lim et al. 2011). A good degree of airflow control in MURBs can only be achieved by exercising the same level of care as in hospitals, in air tightening and compartmentalizing the building, which is demonstrated in Section 10 of this document. Figure 6, illustrates that compartmentalization is the most effective measure to control airflows in MURBs.

In tall buildings in particular, as the natural forces grow stronger with height their effects become more difficult to control by mechanical forces. Furthermore, strong natural forces may lead to mechanical air/pressure unbalances that compound to the instability of interior air pressures and flows. In Figure 3.b for example, the stack effect depressurizes the lower suite, while pressurizing the upper suite. The depressurized lower suite (P_i) “pulls” more supply air (P_{m_s}) from the mechanical system, while reducing the amount of return air (P_{m_r}) to the system. The opposite effect takes place in the upper suite where the pressurized suite-air (P_j) restricts the supply air from the mechanical system, while increasing the amount of return air to the system. As a result, the mechanical air system is unbalanced, i.e. it supplies more air in the lower floors and less air in the upper floors. Modern constant airflow regulators can now be specified to be used in duct systems to maintain controlled supply and return air flows, independent of changes in the natural pressures. The technologies consist of a modulating damper that has been calibrated to open or close to maintain constant flow in response to changes in pressures.

Open windows, as illustrated in Figure 3.b, act as “pressure-relief valves” that turn the enclosed suite/space to almost unenclosed (depending on the size of the window), making the suite pressures more subject to the dynamic wind and stack forces. Under such conditions, mechanical constant airflow regulators can maintain the mechanical flows constant, unaffected by the room dynamic pressure variations. However, maintaining constant mechanical flows does not necessarily produce controlled suite flows and pressures, unless these natural pressures are maintained relatively small through proper building airtightness and compartmentalization.

3 RESIDENTIAL INDOOR AIR POLLUTANTS

No home should expose its occupants to well-identified indoor environmental hazards, which may originate from malfunctioning combustion cook stoves or heating equipment, phased-out materials such as lead and asbestos, radon from the ground, and biohazards such as mycotoxins from toxic molds and endotoxins from bacteria. Ventilation systems are not designed to mitigate these hazards, if present. Instead, these should be treated or removed at their source.

Chapter 11 of the ASHRAE Handbook of Fundamentals (ASHRAE 2021) provides a comprehensive characterization of indoor air contaminants in buildings. this section synthesizes the literature residential indoor air contaminants. In general, indoor air quality is affected either by single events and sources, or more commonly by a number of synergistic concurrent conditions.

3.1 SOURCES, EMISSIONS, AND BEHAVIOURS

Hundreds of pollutants have been measured in the indoor residential environment (Borsboom et al. 2016). There is an extensive scientific literature on the sources of indoor pollution including a number of summaries and reviews (Health Canada 1989, WHO 2010, Borsboom et al. 2016, Vardoulakis et al. 2020, ASHRAE 2021). A review on indoor air quality in Passivehause dwellings by Moreno-Rangel et al. (2020) indicate that most available residential IAQ field studies are short-term (one- or two-weeks induration), and indicate the need for more long-term and homogenous monitoring and reporting methods for IAQ studies. They further indicate that very few studies link occupants' health and well-being to IAQ perceptions, and concentrations of indoor air pollutants.

Table 3 from Crump et al. (2009), adapted and expanded using the sources above, groups the major sources of residential indoor air contaminants. The most prevalent indoor pollutants are Volatile Organic Chemicals/Compounds (VOCs) from multiple sources. From the family of VOCs, formaldehyde is one of the most prevalent contaminants in the residential environment according to multiple studies conducted in North America, Europe, and Asia (Offermann 2009, Abadie et al. 2017). Formaldehyde can be emitted from various materials and products, including: particle board, press-wood paneling, some carpeting and backing, some furniture and dyed materials, etc. (ASHRAE 2021).

The sources of outdoor air pollutants are also numerous. These are monitored by Environment and Natural Resources Canada (2020), and their human exposure and health risks are tracked using the Air Quality Health Index (AQHI). As part of this monitoring system, Metro Vancouver monitors outdoor air quality using a network of ambient stations along the so-called Lower Frazer Valley Airshed (Metro Vancouver 2020). Metro Vancouver publishes yearly Caring for the Air reports describing prevalent air pollutants and their sources. From the ambient monitoring reports, it is noted that smoke from wild fires is becoming an increasing major source of air pollution in the urban environment in the Frazer Valley. The variety of pollutants released by wild fires include carbon dioxide, methane, nitrogen dioxide, carbon monoxide, and fine and coarse particulate matter (Urbanski et al. 2009).

Cooking and operating stoves (particularly gas appliances) emit a mix of chemicals and compounds. Indoors, these pollutants are less diluted than they are outdoors, and in the absence of proper venting, they remain are trapped inside (Seltenrich 2014). In general, cooking pollutants originate from three possible sources: 1) the heating source fuel/appliance (gas, electric), 2) the type of cooking type/media (oil, steam), and 3) the food.

Table 3. Sources of residential indoor air contaminants (adapted from Crump et al. 2009)

Source	Main contaminants
Outdoor air	Sulphur oxides (SOx), Nitrogen oxides (NOx), VOCs (e.g. benzene), Carbon monoxide (CO), particulate matter (UFP, PM2.5), Ozone (O_3), ammonia used in farms, black carbon (diesel)
Fuel combustion	Nitrogen oxides (NOx), VOCs (acrolein), Carbon monoxide (CO), particulate matter
Mechanical system	Dirt, excessive moisture (e.g. cooling pans, leaks), microbes
Tobacco smoke	VOCs (benzenes, formaldehyde, acrolein), Carbon monoxide (CO), particulate matter, PM2.5
People	CO_2, moisture, metabolic VOCs (acetone, methane, ammonia)
Washing/cleaning	VOCs, chlorine, ammonia, alcohols, course particles (cleaning activities)
Cooking / cooking oils	VOCs (e.g. acrolein from cooking oils), particulates (UFP, PM2.5), vapors, gas stoves: CO, NO_2
Building materials	VOCs (formaldehyde, styrene, acetaldehyde, α-pinene, etc.), new furniture
Furnishings, Fire retardants	VOCs (formaldehyde, terpenes, α-pinene, etc.), EDCs (endocrine disruptive chemicals)
Paints, glues, solvents	VOCs (benzene, toluene, xylene)
Consumer products	VOCs (acetone, ethanol), insecticides/pesticides (SVOCs), fragrances (SVOCs)
Biological (Bioaerosols)	Bacteria: biological particulates, endotoxins Virus: biological particulates Fungi/Molds: microbial VOCs (MVOCs), fungal fragments, spores, mycotoxins
Animals	Allergens, course particles
Attached garage	Particulate matter, NO_2, CO, VOCs
Ground	Radon
Household dust	SVOCs, UFP, PM2.5, biological, allergens

Air contaminants can be either localized (garbage, cooking) or distributed (people, interior finishes). Their presence and behaviors depend on the nature of the sources (source strength, and its spatial and temporal variability). Table 4 characterizes the presence of air contaminants in three groups: continuous, periodic, and episodic. The presence of contaminants in the indoor air indicates its prevalence and the duration of human exposure, which is a function of time and frequency of exposure. The presence and behaviors of contaminants in the air provides information on how these can be handled by ventilation. Notice that outdoor pollutants can be periodic (daily traffic during rush hours), and episodic (smoke from wild fires).

As an example of emission rate variability, consider the evaporation rate of moisture from building materials. It depends on the amount of water in the material, the water concentration at its surface, the water concentration (relative humidity) in the surrounding air, and the air speed at the surface of the material. Similarly, VOC emission rates depend on the properties of the VOCs (e.g. volatility), the surface properties (e.g. sealed), the amount of VOcs in the material, its internal diffusion rate, the temperature of the material and of the air, the VOC concentration in the surrounding air, and the air speed at the surface of the material. Just like with moisture evaporation, high temperatures increase VOC emissions. Furthermore, VOC emissions depend on whether the material is newly applied like a paint, newly installed like caulking, directly exposed, or sandwiched as part of an assembly.

Pollutants from pesticides, fragrances and other consumer products are semivolatile (SVOCs), they remain adsorbed at surfaces for long periods and become volatile when the conditions are appropriate. They are also easily adsorbed by household dust. Threfore, they either need to be cleaned from surfaces, or require much higher ventilation rates to evaporate and be removed by the air (Xu and Zhang 2011).

Table 4. Presence and behaviors of air contaminants at home

Presence	Behaviors	Examples
Continuous (increasing or decreasing)	Long exponential decay	• VOC building new materials, finishes, and furniture
	Long exponential growth (growing hazard)	• Mold, bacteria • Deterioration/decay from water leak
Periodic (Intermittent & regular)	Constant during use	• Cooking • Cooking gas appliances
	Daily cycles	• Outdoor pollutants (traffic) • Heating gas appliances
Episodic (Intermittent & irregular)	Quick decay	• Outdoor pollutants (smoke wild fires) • Renovation work • Carpet cleaning

Source Strength *– Also called emission rate, is the rate (mass per unit time) at which contaminants are produced by a product or process and become part of the room air. If there is no contaminant removal system in place, the contaminant source strength is said to be uncontrolled. Depending on the type and nature of the source, some emissions rates are constant (combustion, people), while others depend on the ventilation rate, the temperature and the relative humidity in the air, and the temperature, relative humidity and the airflow at the surface of the source (VOCs, bioaerosols).*

3.2 Units of Measurement and Human Exposure Limiting Values (ELVs)

The presence of contaminants in the indoor air is measured in concentration units as indicated in Table 5. Exposure limiting values (ELVs) are established by cognizant health agencies on pollutant concentrations, to determine the human exposure limits to individual contaminants in the air.

Exposure limits and guidelines are given as a function of exposure time. The exposure limiting time depends on the degree of toxicity of the chemical and the health risks, with a long-term exposure time relating to chronic health risks, and a short-term exposure time relating to acute health risks. The limits are determined based on animal experiments and epidemioloigcal studies on human populations.

Table 5. Concentration units of measurement for indoor air contaminants

Contaminant type	Units of measurement	Units of measurement
Particulate matter	Mass of pariculates in a sample volume of air	mg/m^3
	Particulate counts in a sample volume of air for a given range of particulate diameter	$\#/m^3$
Bioaerosol particles	Particulate counts in a sample volume of air (viable plus non viable)	$\#/m^3$
	Colony-forming units (CFU) per unit sample volume (viable)	CFU/m^3
Gases	Mass of contaminant per unit volume of air	$\mu g/m^3$
	Parts of contaminant by volume: $\frac{ml_c}{m^3_{air}}$	Parts per million: ppm_v Parts per billion: ppb_v
	Parts of contaminant by mass: $\frac{mg_c}{kg_{air}}$	Parts per million: ppm_m Parts per billion: ppb_m

There are two types of ELVs: toxicity reference values (TRVs) or thresold limiting values (TLVs), and reference guideline values (RGVs).

- TRV/TLV – Are typically used as occupational exposure limits. WorkSafe BC Occupational Health and Safety Regulation (OHS) prescribes two of these limits:
  - "8-hour TWA limit" means the **Time Weighted Average (TWA)** concentration of a substance in air which may not be exceeded over a normal 8 hour work period.
  - **Short-term Exposure Limit (STEL)** means the time weighted average (TWA) concentration of a substance in air which may not be exceeded over any 15 minute period, limited to no more than 4 such periods in an 8 hour work shift with at least one hour between any 2 successive 15 minute excursion periods.
- RGV – Are applicable in all indoor environments (not only at work) and were determined from the epidemiological studies associating health symptoms observed in populations of individuals exposed to pollutants indoors. RGVs are available only for a limited number of compounds. Health Canada identified Indoor Air Reference Levels (IARLs) for 25 different volatile organic compounds (VOCs) commonly found in indoor air (Health Canada 2022).

Table 6 summarizes Healh Canada recommended exposure limits for selected contaminants from its residential air quality guidelines (Health Canada 2022). These limits include:

- **Long-term exposure limits:** for health problems that can occur from continuous or repeated exposure over several months or years.
- **Short-term exposure limits:** for health problems that can occur immediately after a brief exposure.

Table 6. Health Canada recommended exposure limits (Health Canada 2022)

Contaminant	Long-term exposure limit	Short-term exposure limit
Acetaldehyde	24 hours: 280 µg/m3 (157 ppb)	1 hour: 1420 µg/m3 (795 ppb)
Acrolein	24 hours: 0.44 µg/m3	1 hour: 38 µg/m3
Benzene	Keep indoor levels of benzene as low as possible	
Carbon dioxide	24 hours: 1800 mg/m3 (1000 ppm)	
Carbon monoxide	(24 hours): 11.5 mg/m3 (10 ppm)	(1 hour): 28.6 mg/m3 (25 ppm)
Formaldehyde	(8 hours): 50 µg/m3 (40 ppb)	(1 hour): 123 µg/m3 (100 ppb)
Fine particulate matter (PM2.5)	Keep indoor levels of PM2.5 as low as possible Use stovetop fan (exhaust outdoors) while cooking, do not allow smoking indoors	
Mold	Address any water damage within 48 hours to prevent mold growth Address any visible or concealed mould growing in residential buildings	
Naphtalene	(24 hours): 10 µg/m3 (1.9 ppb)	
Nitrogen dioxide	(24 hours): 20 µg/m3 (11 ppb)	(1 hour): 170 µg/m3 (90 ppb)
Ozone	(8 hours): 40 µg/m3 (20 ppb)	
radon	exposure limit 200 Bq/m3	
Toluene	(24 hours): 2.3 mg/m3 (0.6 ppm)	(8 hours): 15 mg/m3 (4.0 ppm)

Notice in Table 6 that there are no exposure limit values for mold, and for bioaerosols in general, as well as for PM2.5. There is no regulation concerning the evaluation of the presence or the growth of bacteria & moulds indoors, and their exposure limits, because bioaerosol dose to human response relationships are not easy to characterize. Even if it were possible to precisely measure the biomass of existent microbial damage, it would be very difficult to determine the exact risk and toxicological significance (Pluschke and Schleibinger 2018).

3.3 Priority Pollutants

Based on a review of measured pollutants at homes, and their potential chronic and acute health effects on occupants, Table 7 (Borsboom et al. 2016) presents the priority pollutants in the indoor residential environment for consideration in making ventilation standards. Notice that mould/moisture is included in this list; this is because The World Health Organization (WHO 2009, WHO 2011) and the European report on indoor air pollution and health study identified mould/moisture as significant chronic health burden in the indoor environment. Furthermore, according to WHO (2011), a considerable proportion of childhood asthma cases is attributable to exposure to indoor dampness and mould. Therefore, categorizing moisture as a pollutant relates to the phenomena caused by moisture-damage of the building construction and emissions therefrom. As discussed by Wolkoff (2018), synergistic effects may also occur between low RH and air pollutants. However, the effects of indoor humidity itself, at the breathing zone, on indoor air quality and health are not apparent. In this respect, evidence suggests that higher RH is favoured for health reasons over dry air. In particular, studies have reported negative effects of dry air on the airways, impairing the nasal cavity function and causing greater penetration of particles into the lungs. However, more information is needed to understand how humidity influences human health and performance (Wolkoff 2018). Furthermore, Wolkoff (2018) reports that it is important to distinguish indoor humidity directly affecting the breathing and ocular zone of humans, versus humidity related to moisture damage of the building construction and emissions therefrom.

Table 7. Priority residential air pollutants for ventilation standards (Borsboon et al. 2016)

Priority Pollutants for Chronic Exposure (Ranked by Population Impact)	Potential Acute Exposure Concerns
• Particulate matter • Formaldehyde • Acrolein • Mould/moisture	• Acrolein • Chloroform • Carbon Monoxide • Formaldehyde • NO2 • PM2.5

The EBC-IEA ANNEX 68 project: Indoor Air Quality Design and Control in Low Energy Residential Buildings (Abadie et al. 2017) collected and summarized data from multiple studies that measured contaminant concentrations in the residential building stock. The study further selected the main pollutants of concern based on health considerations. Table 8 shows pollutants considered to be relevant in the context of the objectives of Annex 68 i.e. definition of pollutants present in residential low-energy buildings, to which exposure potentially creates the health risk.

Table 8 also shows the Exposure Limiting Values (ELVs) for the selected pollutants of concern. The pathogens and allergens are not considered in the present report and are not mentioned in Table 8 although they do create the health risk. Carbon dioxide is not a pollutant as well, although listed in Table 8. It is included in the list as a surrogate for the adequacy of ventilation in relation to human occupation (Abadie et al. 2017).

In the list in Table 8, the vast majority of the pollutants are VOCs. The exceptions are NO_2 (from incomplete combustion), PM10, PM2.5, Radon, Mould, and CO2 (which is not a pollutant). The studies do not report the possible sources of VOCs. Indoor air is a complex mixture with typically more than 200-300 pollutants (Abadie et al. 2017). Multiple different products can possibly emit same VOCs, because some of their chemical compounds are the same. Therefore, identifying the sources of these pollutants in field studies is a challenging task.

Table 8. List of selected target pollutants for Annex 68 with their respective exposure limits (Abadie et al. 2017)

	Long-term Exposure			Short-term Exposure		
	ELV*	Averaging period	Source	ELV*	Averaging period	Source
Acetaldehyde	48	1 year	Japan	-	-	-
Acrolein	0.35	1 year	USA-California	6.9	1 h	France
α-Pinene	200	1 year	Germany	-	-	-
Benzene	0.2	whole life (carcinogenic risk level: 10^{-6})	France	-	-	-
Formaldehyde	9	1 year	USA-California	123	1 h	Canada
Naphthalene	2	1 year	Germany	-	-	-
Nitrogen dioxide	20	1 year	France	470	1 h	USA-California
PM10	20	1 year	WHO	50	24 h	WHO
PM2.5	10	1 year	WHO	25	24 h	WHO
Radon	200	1 year	Austria, Canada	400	8 h	Austria, China, Portugal
Styrene	30	1 year	Germany	-	-	-
Toluene	250	1 year	Portugal	-	-	-
Trichloroethylene	2	whole life (carcinogenic risk level: 10^{-6})	France	-	-	-
TVOC	-	-		400	8 h	Japan, Korea
Mold	200	1 year	EU	-	-	-
Carbon dioxide	-	-	-	*1000*	*8 h*	*Hong-Kong, Korea*

* ELV concentration in µg/m³ except for carbon dioxide in ppm, radon in Bq/m³ and mold in CFU/m³

3.4 Cooking pollutants

Cooking releases a suspension of particles, gases, vapors and droplets in a high-temperature aerosol (pollutant mix) that elevates as a buoyant plum and disperses upwards and horizontally at the ceiling level. Furthermore, these pollutants may undergo physicochemical interactions that may form other pollutants or condense and agglomerate into larger particles, all of which may eventually condense and be absorbed by surfaces or accumulate as sticky dust. These pollutants originate from three possible sources. (1) The heating source/fuel (gas, electric), gas appliances release CO and NOx as by-products of incomplete combustion. (2) The cooking method/media, cooking with oil and particularly frying produces VOCs, including Aldehydes such as Acrolein, Formaldehyde, and Polycyclic aromatic hydrocarbons (PAH), as well as UFP, and PM2.5. Frying produces the highest emissions of UFP and PM2.5. Boiling produces large amounts of moisture. (3) The food and cooking style. Emissions from food depends on the food mix and ingredients, as well as on the cooking style and temperature. Fatty foods produce large amounts of VOCs, UFP, and PM2.5, as well as organic carbon (OC) and elemental carbon (EC). Emissions increase when fat content increases, when grilling and specially when deep frying. This is due to the oil, and fat particles that vaporize in the flame or from the hot surface. Vegetables have a significant reduction in particle number concentration during grilling and frying. The higher the temperature the more pollutants are produced, particularly when the temperature exceeds the smoke point of oil (where the oil breaks down and releases harmful chemicals) or when the food is overcooked. O'Leary et al. (2019) show that report that frying in a stainless-steel pan had an immediately obvious effect on the emission rates, with the mean emission rate increasing by 940%, and argue that the higher emission rates may be a function of the thermal conductivity of the pans, their surface temperatures, and the adhesion between the food and the pan. This suggests that using a non-stick pan can minimize PM2.5 emission during frying.

Acrolein is a prevalent cooking pollutant, particularly when overheating animal or vegetable fats or oils. Food frying is a major source of acrolein. Acrolein is a highly toxic material in air and water, and can enter in human body by inhalation, ingestion, and dermal exposure. Chronic exposure can lead to cardiac arrest (Henning et al. 2017). However, other sources include tobacco smoke, glues, paints, varnishes, and cleaning products. The Health Canada exposure limits to acrolein are presented in table 9 below.

Table 9. Recommended Exposure Limits for Acrolein (source Health Canada)

Country/State	Concentration $(\mu g/m^3)$	
	Short-term	Long-term
Health Canada	38 (1-h), eye irritation	0.44 (24-h), respiratory lesions
France	6.9	0.8
California	2.5	0.35
United States	70	0.2

The cooking pollutant emission rates cannot be measured directly. These are calculated using a mass balance model. If the average mass concentration of a selected pollutant is measured before and during cooking, the emission rate can be calculated with steady state mass balance equation. Multiple studies have been conducted to assess cooking pollutant emission rates under controlled conditions. Many of these studies report that emission from cooking is highly variable, even for the same cooking method with the same ingredients (e.g. Thiébaud et al. 1995, O'Leary et al. 2019). Cooking pollutant emissions are also affected by the room boundary conditions such as the air speed and humidity around the cooker, which may reduce or enhance emissions. High relative humidity (RH) has been linked to the hygroscopic growth of particles (O'Leary et al. 2019). Pollutant concentrations and decay in a room, although dependent on their properties, are highly dependent on the type of ventilation and the ventilation rate. The literature review below is not exhaustive. It uses PM2.5 and acrolein to demonstrate the wide variability of emissions and concentrations of cooking pollutants.

Particle matter concentrations are particularly high indoors during cooking periods, substantially higher than outdoor concentrations (Fortmann et al. 2001). Indoor pollutant concentrations spike for short periods by orders of magnitude above the outdoor level during indoor source-induced events like cooking (Shrestha et al. 2019). Using a test house, Fortmann et al. (2001) obtained PM2.5 emission rate of 2.92 mg/min for stir-frying using the gas burner, and 2.45 mg/min using the oven and cooktop while cooking a complete meal. However, over an hour, the mean PM2.5 emission rates from multiple experiments varied between 1.5 mg/h and 617 mg/h (0.025 mg/m to 10 mg/min). the tests involved cooling with electric and gas ranges, and microwave oven. O'Leary et al. (2019) reported PM2.5 emissions with gas cooking of four types of meals between 0.54 mg/min and 3.2 mg/min. A study by Dacunto et al. (2013) revealed the PM2.5 emission rate of 0.4 mg/min for a stir-fried meal with vegetable, chicken and soy sauce using an electric hot plate and an aluminium frying pan. Furthermore, pan-fried chicken drumsticks for 19-28 minutes increased the emission rate to 2.5±0.9 mg/min, while the pan-fried chicken with olive oil emission increased to 15.2 mg/min. He et al. (2004) reported PM2.5 emission rates from various types of foods that were measured from 15 kitchens for a period of 48-hour sampling. The general cooking events got a median emission rate of 0.11mg/minute (σ=0.99 mg/min), frying 2.68 mg/min (σ= 2.18 mg/min) and stove cooking with 0.24mg/min (σ= 1.29 mg/min). Hu et al. (2012) compiled emissions rates from cooking different types of food in various types of oil from the literature, ranging between about 0.4 mg/min to 5.3 mg/min. Fortmann et al. (2001) reported PM2.5 concentrations from cooking over $1000\ \mu g/m^3$ during stovetop stir-frying, frying of tortillas in oil on the range top burner, and baking lasagna in the gas oven. Similarly O'Leary et al. (2019), reported PM2.5 concentrations ranging from about $100\ \mu g/m^3$ to over $1000\ \mu g/m^3$ depending on the type of meal, the type of ventilation, and the ventilation rate.

Figure 8 (O'Leary et al. 2019) shows PM2.5 concentrations and emission rates cooking with a gas stove in a test chamber during and after the cooking of four types of meals. Each meal experiment was repeated 6 times, as shown in each Figure. The result clearly shows the variability of pollutant concentrations and emissions for a given meal when the experiment is repeated using the same amount of ingredients and under the same conditions. The experiments were conducted under a low ventilation scenario with an airflow rate of 21 L/s (75 m3/h), the minimum required in domestic kitchens by the Netherlands Building Regulations. The results were later repeated using range (cooker) hood, which resulted in reductions higher than 90% in emissions into the test chamber.

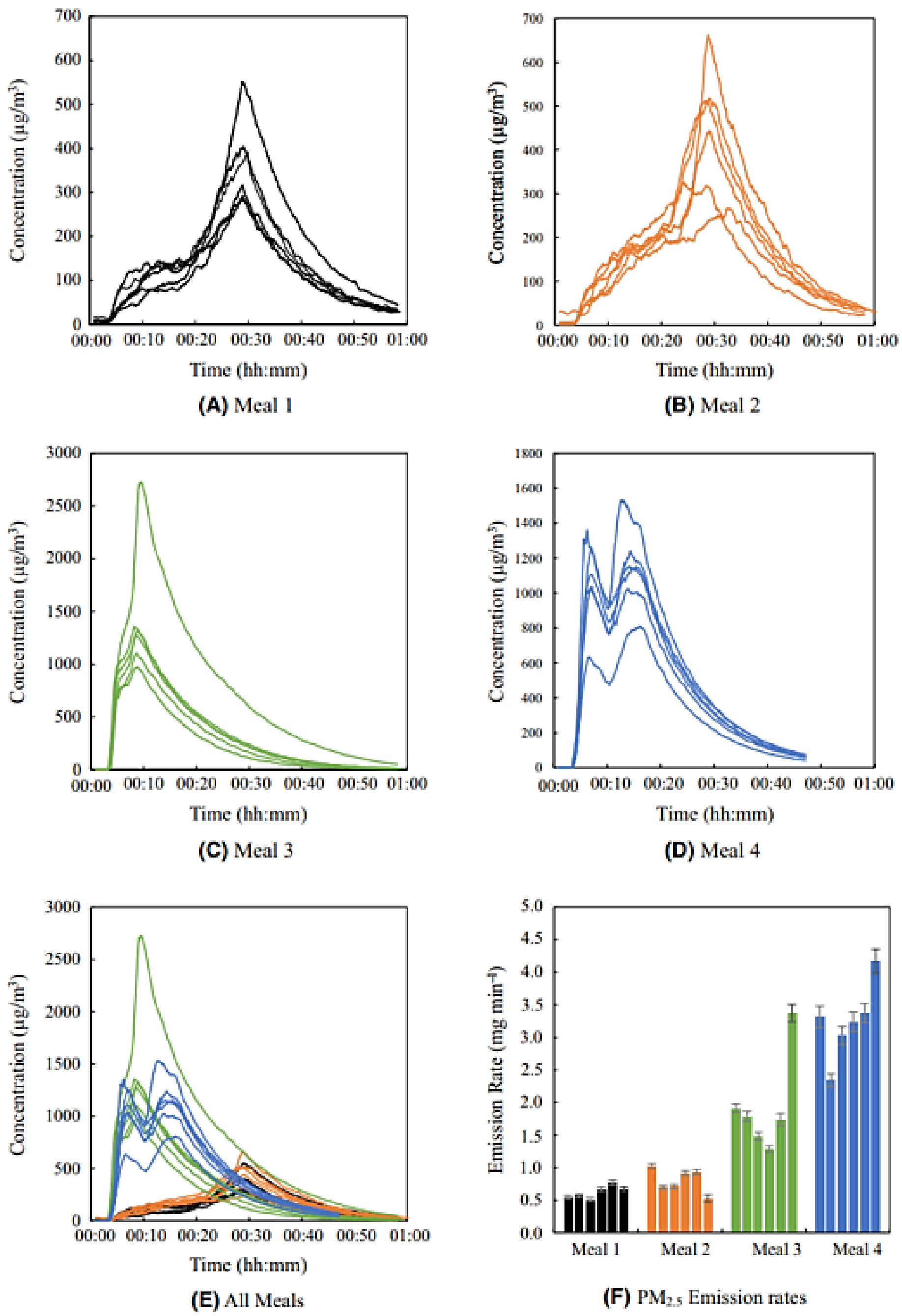


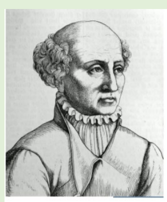
Figure 8. PM2.5 Concentrations and emission rates for four test meals (O'Leary et al. 2019)

Similarly, Acrolein emission rates vary greatly. Seaman et al. (2007, 2009) reported acrolein emission rates ranging from 0.31 mg/h to 1.46 mg/h during cooking, with concentrations varying between 2.1 $\mu g/m^3$ and 12.2 $\mu g/m^3$ under air exchange values varying from 0.12 to 2.23 ACH. In another study, Seaman et al. (2009) reported emission rates of acrolein from canola ($52.6 \pm 2.4\ mg\ h^{-1}L^{-1}$),extra-virgin olive ($9.3 \pm 1.2\ mg\ h^{-1}L^{-1}$) and olive oils ($9.6 \pm 0.9\ mg\ h^{-1}L^{-1}$) heated to 180°C, with concentrations varying between 26.4 and 64.5 $\mu g/m^3$, under a very low air change rate ($0.063 \pm 0.011\ ACH$).

3.5 HEALTH EFFECTS

Numerous studies have reported associations between different kinds of indoor air pollutants and human health effects, including exposures to VOCs from materials and furnishings, dampness and mould, and cooking pollutants among others. It is out of the scope of this document to review all these sources.

If knowing the source strength of all contaminants at home is difficult, knowing cause-effect: exposure to health is even more difficult. Given the wide range of variability of contaminant emission rates and the susceptibility of individuals to contaminant exposures (occupant responses), it is not possible to know the indoor air exposure limiting values (ELVs), concentrations, of all contaminants in the indoor air, under normal conditions to meet the indoor health and comfort ventilation goals. Only ELVs for the most hazardous, known, pollutants have been established by cognizant authorities. Figure 9 illustrates the complexity of the relation between pollutant emission and the effect on an individual. Due to our limited understanding of contaminant source emissions and behaviors in the air, as well as the effects on people, ventilation criteria (i.e. ventilation rates) is used to meet indoor air quality goals in buildings.



"All things are poison, and nothing is without poison; the dosage alone makes it so a thing is not a poison." (Wikipedia: The dose makes the poison)

Paracelsus, 1493-1541

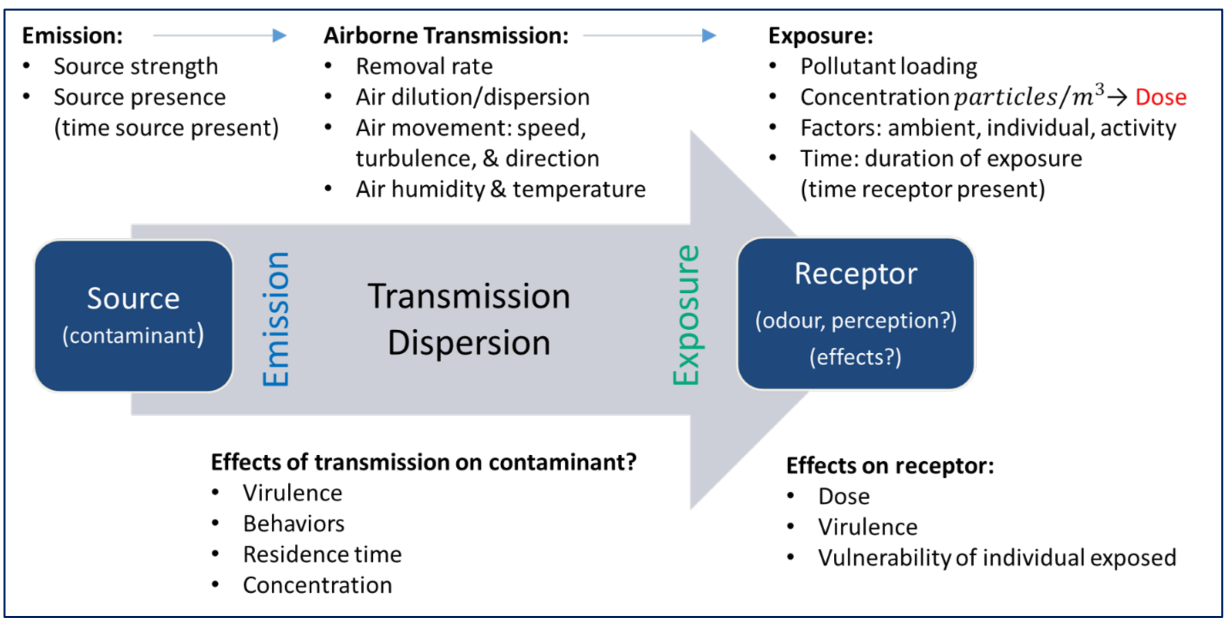


Figure 9. Relation pollutant emission and effect of individual

As illustrated in Figure 9, from a ventilation perspective, reducing human exposure to a pollutant requires eliminating the source or reducing its source strength, and reducing its concentration to "safe" levels through dilution. The contaminant effects on people can range depending on the contaminant virulence (e.g. toxicity) and its dose, the time of exposure, and the susceptibility of the person exposed:

- Sensory detection: discomfort due to odours
- Sensory irritation: mild or chronic (e.g. allergies, asthma)
- Toxicity: acute (rapid, sudden, severe) or chronic (long lasting, persistent)
- Cancer toxicity: from products such as radon and asbestos
- Endocrine disruptive: plasticisers, flame retardants, pesticides, etc.

Two factors complicate associating exposures to health (Rodea-Palomares et al. 2015):

- **Latency from exposure**: time lag between the time of exposure and the manifestation of the disorder (can be many years).
  Mixture effects: when multiple environmental pollutants are present in the air, the effect on humans may be either independent, additive, or synergistic (possible chemical reactions and combined effects is larger than those from each individual chemical).

Exposure to pollutants accounts for both the concentration of a substance and the amount of time the occupant is present with the substance. This circumstance was recognized by Ott (1985) who proposed a simple sum model for exposure to air polluting substances.

$$E_i = \sum_{j=1}^{n}(C_j \cdot t_{ij}) \quad \text{(Equation 1)}$$

Where, E_i describes the total exposure of an individual i, C_j the air concentration of a pollutant at location j, and $t_{i.j}$ the proportion of the day which is spent by individual i in location j.

The impacts of pollutants on health are more difficult to predict. The disability-adjusted life year (DALY) index has been proposed recently (Figure 10). Logue et al. (2012), estimated the chronic heath impact, using the DALY index, due to inhalation of indoor air pollutants (IAP) in U.S. residences. Particulate matter ≤ 2.5 µm in aerodynamic diameter (PM2.5), acrolein, and formaldehyde accounted for the vast majority of DALY losses caused by IAPs considered in this analysis, with impacts on par or greater than estimates for second hand tobacco smoke (SHS) and radon (Logue et al. 2012).

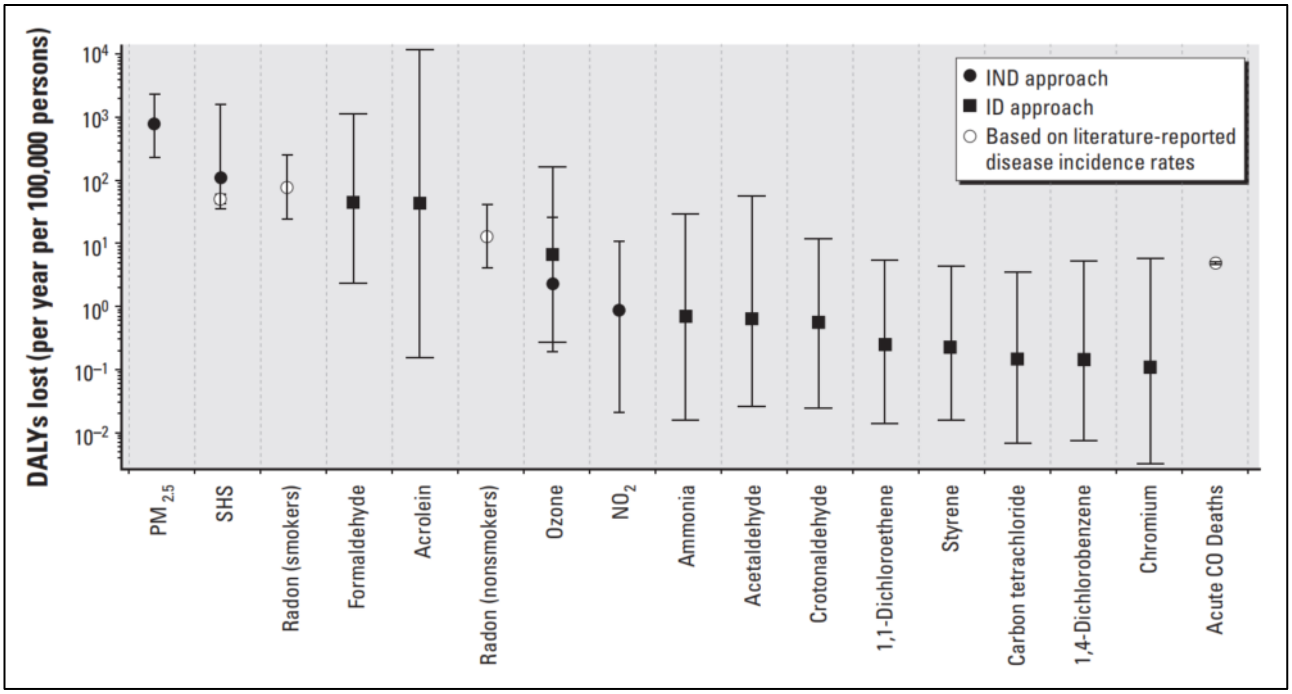


Figure 10. Estimated the chronic heath impact, in disability-adjusted life-years (DALYs) lost, due to inhalation of indoor air pollutants in U.S. residences (Logue et al. 2012)

3.6 CO2 AS AN INDICATOR OF INDOOR AIR QUALITY

CO_2 is a natural gas in the air. Research has demonstrated that the majority of the air pollutants inside our buildings are produced by people due to their presence and their activities. Because CO2 is exhaled by humans, it is conveniently used as a surrogate measure of indoor air pollutants emitted by humans: high CO2 concentrations indicate the probability of other human-related indoor air pollutants being present (e.g. viruses) and reaching high concentrations. Consequently, as an indicator of human presence in a space, CO2 is also an indicator of probable human exposure to human-generated indoor air pollutants that may be present in the air.

Because ventilation dilutes CO2 with outdoor air, indoor CO2 concentrations are a scientifically accepted method of measuring how efficient a ventilation system is in removing human-generated pollutants. In other words, indoor CO2 concentrations indicate the adequacy of outdoor air ventilation relative to indoor occupant density and metabolic activity (human CO2 production is proportional to the activity level). For example, high indoor CO2 concentrations are indicative of overcrowding in spaces such as classrooms and offices contributring to unhealthy indoor air.

However, CO_2 cannot be used as a comprehensive indoor air quality indicator because the presence of many indoor pollutants (Table 3) is not dependent on human presence (e.g. building materials) or not strongly correlated to CO_2 concentrations (e.g. cooking, smoking, bathing, cleaning) or moisture generation at home.

CO_2 is not harmful or toxic, and depite the many research efforts, there is no conclusive evidence of effects of CO2 concentrations on perceived air quality, health, or performance (Fitsk et al. 2019). Despite not being a comprehensive indoor air quality indicator, interior CO_2 concentrations are used as a scientifically accepted method of measuring how efficient a ventilation system is at maintaining the ventilation rate required to refresh the air (Handel REHVA Journal 2017). As such, indoor CO2 concentrations indicate the adequacy of outdoor air ventilation relative to indoor occupant density and metabolic activity (human CO_2 production is proportional to the activity level). In residential buildings, CO_2 is representative of occupant density and overcrowding in bedrooms, family rooms, living rooms, dining rooms, and kitchens. Indoor residential monitoring studies (including studies by the author) have consistently measured the highest CO_2 concentrations in bedrooms (Handel REHVA Journal 2017). Table 10 (adapted from Passive House 2021) shows ventilation airflow rates per person, according to the European Standard EN 13779 (EN 13779 2007), to maintain CO2 concentrations within prescribed limits, and depending on the activity level of the occupant.

Table 10. Ventilation airflow rates per person for indoor air quality (adapted from Passive House 2021)

SIZING AIRFLOW RATES FOR AIR QUALITY / person (m^3/h)				
European Standard EN 13779 Class	Max CO2, ppm (outdoor ~ 400 ppm)	CO2 per Activity Level		
		Asleep (12 L/h CO2)	Typical (18 L/h CO2)	Working (23 L/h CO2)
IDA 1 (High IAQ)	800	30	45	58
IDA 2 (Medium IAQ)	1000	20	30	38
IDA 3 (Moderate IAQ)	1400	12	18	23
IDA 4 (Low IAQ)	> 1400	10	15	19

The data used to produce this table uses a simple steady-state air and CO2 mass balance model. For example, A sedentary person typically breathes at a rate of 8 L/min (0.3 L/min = 18 L/h CO2 production). The concentration in the incoming air is 400 ppm (0.04 percent). It is desired to hold the concentration in the room below 1000 ppm (0.1 percent). Assuming that the air in the room is perfectly mixed, the ventilation rate required to maintain indoor CO2 below 1000 ppm is obtain as follows:

$$Q = \frac{E}{(C_r - C_o)} = \frac{0.30\ L/min}{(0.001 - 0.0004)(60s/min)} = 8.3\ L/s = 17.6\ cfm \approx 30\ m^3/h/person$$

Note that there is no universal standard set of ranges to qualify the indoor air based on CO_2 Concentrations. The ranges above are therefore approximate and vary between countries. In fact, the above is true for almost every air contaminant. However, these ranges are even more flexible for CO_2, because CO_2 is not an air a contaminant. Furthermore, the accuracy of the CO_2 sensors is witihn ± 50 ppm.

Numerous studies have shown that CO_2 concentrations at home are highest at the bedrooms, indicating lower ventilation for the occupancy. However, studies by the author demonstrate increasingly elevated CO_2 levels in home offices. Based on a simple transient room CO_2 mass balance model, Figure 11 simulates how the CO_2 concentration increases in a master bedroom when two occupants go to sleep, until it reaches steady state. The simulation assumes a background (outdoor) concentration of 400 ppm. In the morning, when the occupants leave the room, the CO_2 concentration decreases back to its background level. The simulation is run for four different standard ventilation rates. The results demonstrate the different levels of satisfactory indoor air quality determined by different residential ventilation standards. In Figure 11, according to the CO_2 level in the master bedroom the indoor air quality is acceptable by BCBC 9.32 (BCBC 2018), but not optimal.

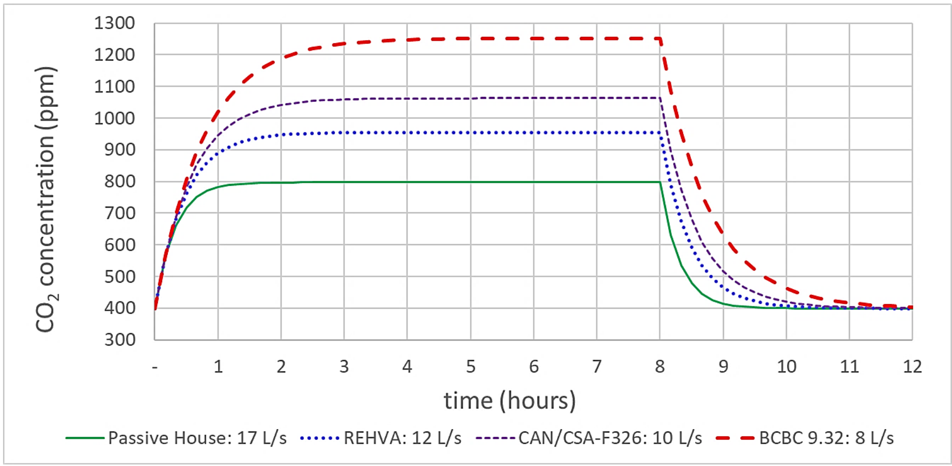


Figure 11. Simulation of CO2 concentration in a master bedroom (2 people) while sleeping

3.7 POLLUTANT DISPERSION AND EXPOSURE IN BUILDINGS

Pollutants disperse in the air driven by airflow currents in rooms and across rooms. However, as pollutants disperse, they are diluted by mixing air currents, removed by cracks and filters, and undergo physical and chemical processes that either remove them from the air or transform them into other pollutants. In some situations, such as cooking, hot cooking pollutant plumes drive pollutant-laden air currents in spaces and between spaces. Air and pollutant dispersion control in MURBs is complex due to the amplification of the natural driving forces with height (Chapter 2), the multiplication of unintended and airflow paths, and the continuous movement of people throughout the building. Controlled mechanical airflows can generate pressures that overpower natural airflows in enclosed and compartmentalized buildings. However, the amplification of the natural forces in leaky and uncompartmentalized MURBs creates conflicting pressure differentials across the envelope and across spaces whose magnitude depend on the relative magnitudes of the driving forces. Pollutants of concern can migrate from enclosed underground parking, storage spaces, indoor swimming pools, mechanical rooms, and outdoor sources into suites and indoor amenities under favorable pressure conditions. However, common complaints in MURBs from occupants about unwanted cooking and tobacco smoke migrating from other suites and common areas indicate that pollutants regularly migrate between suites in the same floor and at different floors. McKeen and Liao (2022) used multi-zone airflow simulations to demonstrate that stack effect affects the uniform distribution of ventilation in the suites throughout the building, and lead to suite door-undercut airflow reversals, which confirms field study results by Ricketts and Straube (2014). Building compartmentalization (Section 8.3) is regarded as the most effective means to address uncontrolled airflows in buildings and enable reliable controlled ventilation (CMHC 2003, Lstiburek 2005). However, achieving proper compartmentalization in existing buildings is challenging. Therefore, Section 8.3 of this document provides some guideline on how to prioritize the existing building compartmentalization efforts. A literature review in this subject is out of the scope of this document. For a review of papers on inter-zonal airflow and pollutant dispersion in multi-unit residential buildings please refer to Luzinski and Touchie (2021).

To guide the control indoor pollutant dispersion, Chapter 4, Table 11, breaks-down a MURB into generic functional compartments with order-of-magnitude exposure durations and ventilation considerations; and sections 8.2, 8.3, and 8.4 characterize the air leakage paths in MURBs in an attempt to prioritize their treatment and control.

4 RESIDENTIAL VENTILATION PRINCIPLES AND PRACTICE

A centralized ventilation system that has been used in MURBs for many years is the **corridor pressurization system**, which uses the corridors, as "leaky ducts", to supply "fresh" outdoor air to each suite under the suite's main door (i.e. door undercut). When the outdoor air is cold, it is heated, typically using a gas-fired boiler, to supply warm air to the corridors. Numerous studies have demonstrated the unreliability of this system in delivering fresh air to the suites (Wray et al. 1998, CMHC 2003, Ricketts and Straube 2014). Two main ventilation and air quality concerns in MURBs are following:

- The reliability/robustness of the ventilation system to supply adequate ventilation to each suite.
- The control of the migration of contaminants between suites, and between common areas and suites.

As explained by Ueno et al. (2012), corridor pressurization systems over-ventilate some portions of the building, resulting in poor energy performance, while simultaneously under-ventilating other portions, resulting in diminishing indoor air quality and moisture problems. CMHC (2003) also underlines a fundamental flaw of corridor pressurization systems, which is that these systems intentionally couple corridor air with air in the suites, thereby creating potential conduits for unintended smoke transport across the building during fire emergencies.

4.1 PRIORITY MEASURES TO CONTROL AIRFLOWS AND CONTAMINANT MIGRATION IN BUILDINGS

From a functional compartmentalization point of view, ventilation systems in MURBs can be grouped in three categories:

1) **General ventilation for common areas (CA)** – Considers ventilation air for the common areas of the building including lobbies, corridors, amenities, and underground parking. For fire, smoke, and air-quality safety reasons, parking ventilation is isolated from the rest of the building. The common areas can be divided in three subgroups: 1) amenity areas (AA), 2) service areas (SA), and 3) transient/circulation areas (CI). The ventilation of amenities (AA) are designed to be self-contained according to ASHRAE Standard 62.1 with little interference with/from the building ventilation. The ventilation of service areas (SA) is typically induction-based (i.e. exhaust) source-control. By contrast, the ventilation of transient/circulation areas (CI), such as corridors and elevators, is less concerned with pollutant exposure control, because those areas are transient and therefore the duration of exposure is limited, and focuses more on the control of air pressures throughout the CI and the building, as well as the control of air pollutants' dispersion throughout the building.
2) **Enclosed Parking Area (PA).** An important area that is convenient to differentiate from all the rest is the enclosed PA because it is a main source of high-risk pollutants that could migrate into the building, from car engines and potentially car-related fires.
3) **Dwelling unit (DU), suite ventilation** – Considers ventilation air to the individual suites. Compared to common areas, the exposure time of occupants to indoor air pollutants can be much longer, up to eight hours in bedrooms, and even more in home-offices.

Dwelling Unit (DU) *– A single unit providing complete, independent living facilities for one or more persons, including permanent provisions for living, sleeping, eating, cooking, and sanitation (ASHRAE 62.1-2019).*

The generic ventilation and exposure characteristics of each of these types of spaces or compartments are described in Table 11 below.

Table 11. Ventilation and exposure characteristics of generic MURB compartments

Space type		Purpose	Occupancy time (exposure time)	Examples	Ventilation	Important considerations
PA		Parking	Minutes	Enclosed parkades	Induction - exhaust	Due to high risk of toxic pollutant propagation, requires decoupling from the rest of the building
CA	**CI**	Circulation Transient	Seconds – minutes	Lobbies, corridors, elevators	Slightly pressurized ASHRAE Standard 62.1	Fire propagation, evacuation, pollutant migration between spaces
	AA	Amenities Leisure	Minutes – hours	Gym, recreation, community	ASHRAE Standard 62.1	Self-contained, independent from the rest of the building
	SA	Services Mechanical Electrical Laundry Garbage	Minutes - hours	Storage, cleaning, laundry, mechanical rooms, service shafts, garbage rooms	Source-control, induction-based exhaust ventilation	Risk of chemicals stored, migration into the building
DU		Dwellings	Hours – days	Suites	Balanced: BCBC 9.32	Self-contained

Ideally, these generic ventilation compartments should be isolated from each other. However, due to the challenges discussed in Chapters 1 and 2 of this document, these compartments often interfere negatively with each other. The interactions between these compartments is discussed in Chapters 7 and 8. Achieving adequate ventilation for satisfactory indoor air quality in MURBs requires a whole-building approach that considers the possible interactions between these two levels under dynamically varying boundary conditions.

Figure 12 (a) illustrates three building-system measures for the effective control of indoor air contaminants in DUs, while Figure 12 (b) illustrates four building-system based measures for the effective control of indoor air contaminants in MURB DUs. These four measures are 1) building airtightness, 2) building compartmentalization, 3) building pressure control, and 4) mechanical ventilation-filtration in DUs. As a complementary measure, room air cleaning is increasingly being considered. However, the effectiveness of room air cleaning is also dependent on the system-based measures above. In Figure 12, it is acknowledged that heating and cooling affect ventilation, and vice versa. Last but not least, the dwellers are not simply considered as passive receivers of ventilation, but also as potential polluters as well as enablers/disablers of ventilation in buildings as discussed in sections 4.3.7, 4.3.8, and 5.2 of this document.

Indoor airflows are difficult to predict and control in leaky buildings. Furthermore, leakage air bypasses any mechanical filtration and heat recovery rendering these useless. In theory, if only mechanically balanced ventilation controls the airflow in a suite, it can maintain a zero (neutral) pressure differential across the envelope, which ideally allows no infiltration to take place. However, natural wind and thermal forces, as well as uncompensated kitchen fan operation affect the pressure balance causing positive and negative pressure differentials whose magnitude depend on the relative magnitudes of the driving forces. The magnitudes and directions of the airflows in and out of suites will vary, depending on the relative strengths of the forces (supply fan, bathroom/kitchen exhaust, stack effect) acting at each suite. Air follows the least effort path therefore if the mechanical system is overpowered in some rooms, air will come into the suites through the envelope or through other internal unintended paths.

In general, the air-tighter a building is, the more controlled the indoor pressures/airflows can be by the mechanical system, and the less influential natural, stack-effect and wind, forces will be on the indoor airflows. In high-rise buildings, enhanced compartmentalization adds a necessary increased level of control of natural pressures/airflows, which in-turn enables better mechanical ventilation and filtration control across the building.

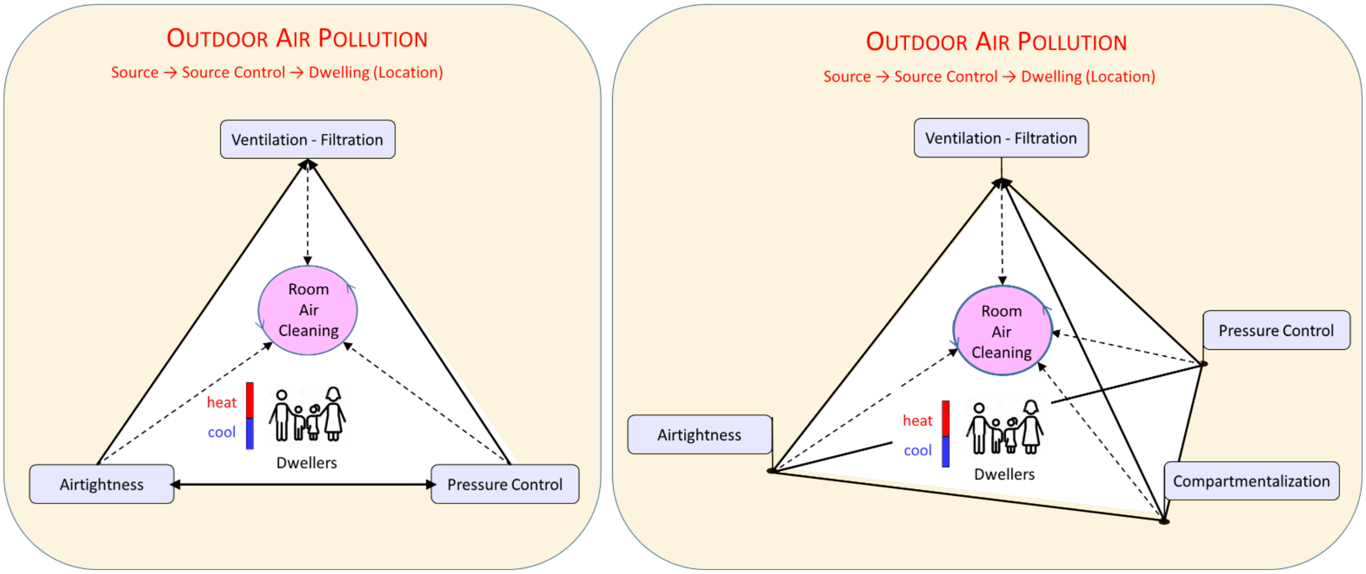


Figure 12. Contaminant control strategies in a) individual DU, and b) MURBs: suite and whole

4.2 VENTILATION AND BUILDING ENERGY EFFICIENCY

It has been argued that airtight, more energy efficient buildings are detrimental to indoor air quality due their to reduced natural uncontrolled air changes through air leakages. However, from first principles, this can only happen if 1) there is no provision in these buildings for adequate controlled ventilation, and/or 2) there is no provision for adequate source control (section 4.3) of certain pollutants in these buildings.

A comprehensive indoor air quality comparison of non-low-energy and low-energy residential buildings was conducted within the scope of the EBC-IEA ANNEX 68 project: Indoor Air Quality Design and Control in Low Energy Residential Buildings (Abadie et al. 2017). The study compared non-low-energy and low-energy residential buildings based on data form Australia, Belgium, China, France, Japan, and USA. The study is based on data from six studies on about 3000 low-energy residential buildings, which was compared with data from about 5000 non-low-energy residential buildings. The study found a variety of VOCs with a large variation in concentrations of each individual VOC between studies, which reflects the variation in indoor sources, outdoor sources, ventilation systems, and ventilation rates. As a general conclusion, the studies found lower contaminant concentrations for most pollutants in low-energy buildings. However, for a few VOCs, such as formaldehyde, heptane, α-pinene, d-limonene, hexanal, styrene, toluene, ethylbenzene, trichloroethylene and 1,3 dimethylbenzene, concentrations were higher in low-energy buildings. The authors point out that because low-energy buildings are more recently constructed, the emissions from newer products are higher, and new pollutants may be present.

A study on envelope retrofits in Ireland (Coggins et al. 2017) measured increased contaminant concentration levels of a group of contaminants, including formaldehyde, PM2.5, and CO_2 after the retrofit. The results indicate that the new products used to increase envelope thermal performance and airtightness increase the release of chemicals to the interior of the houses. Therefore, it is recommended to design integrated home retrofits that combine envelope energy efficiency retrofits and ventilation system retrofits.

Ng et al. (2017) calibrated airflow-contaminant simulation models with data from an experimental NetZero energy house. The study found that even though proper mechanical ventilation can be effective in controlling formaldehyde and acetaldehyde concentrations, the need for source control is critical, particularly in houses with relatively airtight envelopes. In the study, the combination of source control and proper ventilation led to concentrations roughly four times less than in other new homes.

Using data from 18,971 Canadian households, Sims et al. (2021) concluded that radon concentrations have been steadily increasing in newer homes since the mid 1990s. Furthermore, these homes are occupied by significantly younger people experiencing greater radiation dose rates from radon. The authors report that these trends are likely explained because *"first time home-seekers (i.e. ages 24–44) have more limited financial resources that preclude buying or renting the typically more expensive residential properties in older and "more established" neighbourhoods, and/or are preferring newer properties with more modern design trends that are also smart-home ready and/or energy efficient."* However, the authors do not report any information regarding radon control measures, if any, from the houses in the data set, which raises the particular concern that radon control has not been a priority the construction of new houses in Canada over the past 20 years. Similarly, Khan et al. (2021) conducted a large study on long term radon tests on thousands of buildings in Canada and Sweden, and compared their evolution of radon levels in parallel with energy efficiency improvements since 1945 up to the present. The observed that the radon levels were comparable in buildings in these two countries in the past, but have diverged over the years rising in Canada and falling in Sweden. They further observed that the introduction of energy efficiency measures, including heat recovery ventilation, within each nation's building codes are independent of the radon fluctuations over time. These studies demonstrate that more airtight houses, even those provided with adequate outdoor mechanical ventilation air, also require the careful consideration of the control of particularly hazardous pollutants at the source. Also, as discussed in Section 6.1.1. (Figure 39) high-performance airtight buildings are required to maintain mechanically-balanced differential pressures across the envelope, in order to avoid excessively high envelope pressure differentials that can easily developed as the air leakage flow paths become smaller as illustrated in Figure 3.

4.3 Ventilation principles

The design of ventilation systems in buildings is guided by the five principles below to maintain the balance between contaminant source strength and removal rate (Figure 13).

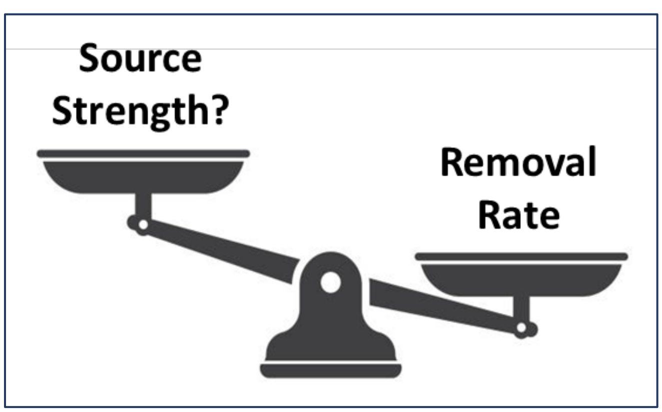


Figure 13. Ventilation: a balance between contaminant source strength and removal rate

1. **Source control** – Potential pollutant sources are identified and treated according to their type and nature. Residential buildings these sources are: kitchens (cooking), bathrooms (moisture), laundry (detergents) and utility and storage rooms (paints, pesticides, etc.), and equipment rooms.
   a. Remove – If possible, the source should be removed.
   b. Reduce – If the source cannot be removed then its source strength should be reduced.
   c. Isolate (enclose) – if the source cannot be removed or reduced, then it may need to be isolated.
   d. Exhaust – The pollutant should be exhausted directly from the source, or from the room.
2. **Dilution control** – Outdoor air is introduced at a specified ventilation rate to dilute air contaminants that may be present down to acceptable levels. ASHRAE Standard 62.1 (not for residential DUs) specifies acceptable outdoor air quality requirements. If these requirements are not met, then the standard prescribes enhanced outdoor air filtration. However, residential standards do not have such requirement.
3. **Dispersion control** – Supply and exhaust fans are laid out to implement "cascade ventilation", directing airflows from clean habitable rooms towards more transient and polluted rooms. Pressure differentials are created at the doors, gaps, and cracks between rooms, whose magnitude depends on the size of the openings and gaps.
4. **Air filtration/cleaning** – Air filtration (particulates) and cleaning (gases) has been traditionally considered to be the last ventilation measure (line of defense) when the former measures are not sufficient in maintaining indoor pollutants below comfortable and healthy levels. However, due increased concerns about high indoor concentrations of pollutants from cooking (Stratton and Singer 2014), and from outdoors (Asikainen et al. 2016, Salthammer et al. 2018), air filtration/cleaning is becoming an increasingly more important indoor pollutant control measure.
5. **Localized exposure control** – This measure is implemented under high-risk situations that cannot be handled by the measures above (e.g. COVID-19 pandemic).

The first three principles are embedded in the design of ventilation systems. Outdoor air filtration is implicit in the second principle if necessary, because in principle, outdoor air is either clean or filtered/cleaned to acceptable levels before being introduced into spaces. Principles 4 and 5 are additional measures that apply under special circumstances.

Indoor air quality and ventilation should always prioritize **source control** measures. Well-known residential pollutant sources are: cooking, laundries and cleaning, humidity and mold, and bathrooms. Other air pollutant sources are less evident: furniture, cabinetry, and interior finishes.

As discussed in Chapter 16 of the ASHRAE Handbook for Fundamentals (ASHRAE 2021), variation in pollutant source strengths, rather than variation in ventilation/removal rate, is considered the largest cause of building-to-building variation in concentrations of pollutants that are not generated by occupants. Therefore, as indicated by ASHRAE (2021), because pollutant source strengths are highly variable, maintaining, code-prescribed, minimum ventilation rates does not ensure acceptable indoor air quality in all situations.

4.4 ELEMENTS OF VENTILATION

Table 12 outlines the five elements of ventilation that are part of any ventilation system. Guidelines on each of these elements have been developed, and standards provide detailed specifications. These are out of the scope of this document.

Figure 14 illustrates the application of the five elements of ventilation. The figure uses CO_2 to illustrate the changes in air quality as "new" outdoor air is introduced into spaces, mixes in the rooms, disperses through rooms, collects contaminants and becomes "used", until finally it is exhausted back into the atmosphere.

Table 12. Elements of Ventilation

#	Description	Requirements/ Guideline	Design / Operation	Application issues
1	Outdoor air intake	Room air quality requirements	Outdoor air quality Outdoor air filtration Outdoor air flowrate Airflow boosting	ERV/HRV malfunction Air handling unit malfunction Filter clogged/bypassed Cross-contamination
2	System air distribution	System pressures System air flows Dwelling pressures	System pressure loses Duct air velocity Supply air flows Noise level	System pressure imbalances Duct system leaks Excessive noise
3	Room air distribution	Ventilation air reach the breathing zone, acceptable noise level	Room configuration Air terminal type & location Supply air flow Supply air temperature Air mixing in the room	Air "short circuiting" room Air not reaching breathing zone Stagnant-air pockets Air terminal misadjusted
4	Air circulation between rooms	Cascade: Clean to polluted Source control	Directional airflow Differential pressures between rooms Air transfer details	Supply-Exhaust flow control Source control Little air transfer between rooms
5	Heat recovery	Heat recovery Moisture recovery	Heat recovery efficiency Efficiency degradation	Frost of HRV/ERV cores Condensate accumulation Dirt accumulation

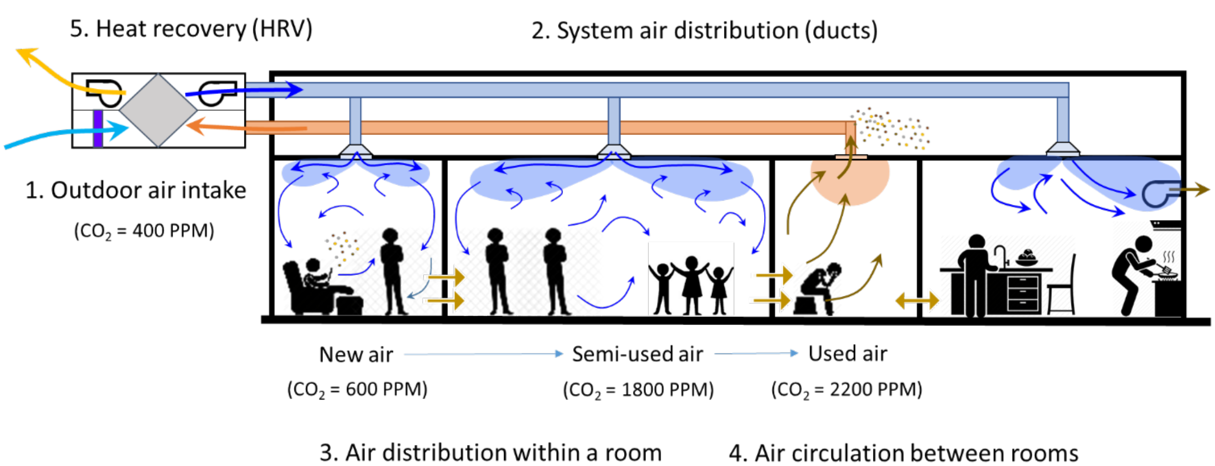


Figure 14. Elements of Ventilation

Element 1 – Outdoor air intake

A minimal amount of ventilation air intake is prescribed by codes, and is discussed in Sections 4.3.2 and 6.1.1 of this document. As discussed in section 4.4.2, ventilation rates have changed over the years, they are not “cast in stone”. A Finnish study by Säteri et al. (2019) on 8 European countries found significant differences in the prescribed ventilation rates between these countries. The study observed that in general ventilation rates are too high for small apartments, and too low for homes for elderly people, and for larger apartments.

Element 2 – System air distribution

Discussing the design and principles of air distribution through ducts is out of the scope of this document. Aside from proper design and balancing of the air distribution system, two important issues have been observed by the author in field studies: 1) for airflow and energy performance ventilation designers favor the shortest duct layouts close to the core, which often lead to having a room supply diffuser close to the door leading to a bathroom exhaust, thus bypassing the room, 2) ducts are not sealed properly for leakages thus resulting in poor supply airflows (Tran 2016).

Element 3 - Room air distribution

Proper room air distribution (element 3) assumes that **room air is well mixed**, and most importantly, that it is well distributed throughout the occupants’ breathing zone.

> ***Breathing zone*** *– the region within an occupied space between planes 3 and 72 in. (75 and 1800 mm) above the floor and more than 2 ft. (600 mm) from the walls or fixed air conditioning equipment. (ASHRAE Standard 62.1-2019)*
>
> ***Occupied zone*** *– the region normally occupied by people within a space. In the absence of known occupant locations, the occupied zone is to be between the floor and 1.8 m (6 ft.) above the floor and more than 1.0 m (3.3 ft.) from outside walls/windows or fixed heating, ventilating, or air-conditioning equipment, and 0.3 m (1 ft.) from internal walls. (ASHRAE Standard 55-2020)*

Generic room air distribution requirements apply to the volume in the room that is actually occupied (the occupied zone). The general requirements for room air distribution in the occupied zone are described below:

1. Avoid having stagnant air in the occupied zone.
2. Avoid short-circuiting between supply and return terminals.
3. Avoid short-circuiting between supply terminals and room doors.
4. Avoid directing supply air directly to the occupants, causing draft discomfort.
5. Maintain velocities between 0.1 m/s (20 fpm) and 0.25 m/s (50 fpm).
6. Ensure that the supply air mixes properly with the room air.
7. Offset cold air drafts from poorly insulated windows or walls.
8. Avoid collisions between air streams.
9. Avoid collisions between air jets and walls or ceiling protrusions
10. Achieve acceptable noise levels.

The requirements above are generic; they are not specific to residential buildings. In particular, the range of air velocities above, between 0.1 m/s and 0.25 m/s, at the occupied zone is typical of office buildings that that distribute large volumes of air primarily for heating and cooling, and supply air in rooms at air velocities higher than 1 m/s, up to 5 m/s. By contrast, residential ventilation systems supply air at velocities typically lower than 0.1 m/s, and therefore air velocities at the occupied zone are lower than 0.1 m/s, i.e. close to stagnant. This why it is very important to investigate whether low-flow air from these systems can effectively reach the breathing/occupied zone and dilute air pollutants.

Achieving proper room air distribution depends on the proper sizing and balancing of the ventilation system (Table 12: System air distribution), and is affected to some extent by the pressure relations with adjacent rooms (Table 12: Air circulation between rooms). At the room level, proper air distribution requires the proper selection of supply diffusers, and the careful layout of air supply diffusers in the room.

> ***Coanda effect*** *– is the tendency of a fluid jet to be attracted to a nearby surface. When supply air velocity is sufficiently high, a negative or low-pressure area is created between the moving air mass and the ceiling at or near the supply air outlet. This low-pressure area causes the moving air mass to cling to and flow close to the ceiling surface for a sufficient distance to allow it to reach far into the room.*

In an attempt to improve room air distribution, residential ventilation designers are now promoting the application of the "coanda" effect for the ventilation air to cling to the ceiling and reach farther into the room. This can be achieved if a ceiling diffuser supplies air at an angle of no more than 10° to 15° from the ceiling, or a wall diffuser supplies air at an angle of 10° to 15° towards the ceiling. However, a question is still unanswered: ***is the low-flow ventilation in residential buildings sufficient to achieve a "coanda" effect?***

The effectiveness of room air distribution is affected by air supply-exhaust bypassing (short-circuiting) the room. The main cause of supply air bypassing the room is the that ventilation design prioritize duct layout optimization (Element of ventilation 2) over room air distribution. Suite ventilation case studies in Chapter 10 demonstrate the effects of this room bypassing of ventilation supply air.

Figure 15 shows elevated CO_2 concentrations (Figure 15, bottom) at the study area near the envelope (Figure 15, right). The results are not surprising because the room uses a fan-coil unit for heating that recirculates room air away from the study area, and unlike the baseboard heater in this case study, there are no indoor pressure gradients inducing air into the study area. Well-calibrated CFD simulations can demonstrate this phenomenon. Yan and Mora (2016) studied the risk of moisture condensation in windows under different heating systems. In Passive House buildings with high-performance windows, the risk of condensation is minimized as demonstrated in case study SR-4 (Section 10.8). Figure 15 shows other interesting indoor environmental issues with this Passive House dorm building: the supply diffuser can be easily covered by the pillow; the artificial light is turned on in a sunny summer day because the small window does not bring enough natural light into the suite (window-to-wall area = 15.7%); the window opening is very minimal especially given that the window is recessed in the thick high-performance wall. Unfortunately, just like in most high-performance buildings that focus on zero-energy and zero-carbon targets, occupants are not prioritized and not considered in the measurement and verification protocols.

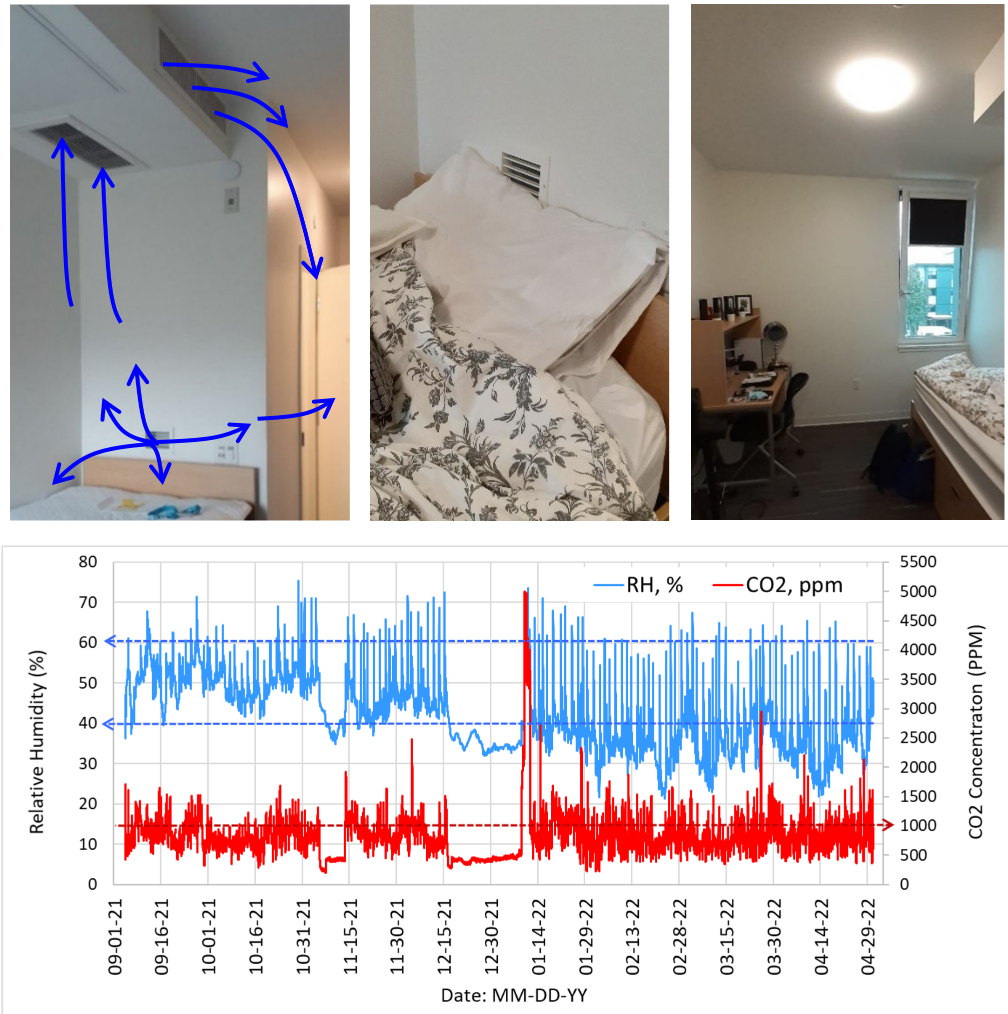


Figure 15. Relative Humidity and CO2 monitoring in a studio suite (Logger located above the desk)

<u>Element 4 - Air circulation between rooms</u>

Adequate suite ventilation aims to implement the ventilation principles outlined in Section 4.1. Air circulation in particular implements ventilation principle 3: Dispersion control or cascade ventilation, which for residential suites supplies ventilation to the rooms where dwellers spend more time, which are the bedrooms, the family room, and now the home office. The supplied air is then dispersed towards the exhausts located at the bathroom, kitchen and laundry areas where dwellers spend more time. Numerous field studies reporting monitoring IAQ of homes, including studies by the author, consistently demonstrate that bedrooms are the rooms in a dwelling in need for more ventilation, in particular the master bedroom. Depending on the dwellers' habits, the family room can also become a critical room for ventilation. Field monitoring by the author, shows that nowadays home office rooms have become even more critical rooms for ventilation. Dwellers also spend a substantial amount of time in the kitchen, however, given that the kitchen is a prime pollutant-source area, ventilation principle 1: source control prevails in the kitchen. The air circulation between rooms is also affected by the by passing of rooms by the supply air due to air distribution duct layouts that favor shortest lengths.

Element 5 - Heat Recovery Ventilation

Heat Recovery Ventilators (HRV) and Energy Recovery Ventilators (ERV) are now prescribed by codes to reduce ventilation energy waste. HRVs transfer a portion of the energy (sensible heat) in the ventilation air leaving the building to the incoming air entering the building in winter (preheating), and transferring a portion of the energy in the incoming air entering the building to the air leaving in summer (precooling). In addition to sensible heat, ERVs transfer moisture in air and its energy (latent heat) between incoming and leaving air streams. The efficiency of HRVs and ERVs in transferring energy between the incoming and leaving air, depends on the amount of ventilation air that the device supplies and exhausts, and on the outdoor-indoor air temperature and humidity differences. The use of HRVs and ERVs enables more energy-efficient ventilation, and add the possibility to increase ventilation rates, on demand, beyond the rates prescribed by code, with minimum energy penalties. For details on these devices and their application in MURBs, see BC Housing (2015) and CMHC (2017) guides.

Van der Pluijn (2010) pointed out that previous installation of heat recovery ventilators (HRVs) reporting poor indoor air quality consisted of systems suffering from low ventilation capacities and noise due to erroneous design and configuration of the systems and poor maintenance. Van der Pluijn (2010) conducted field measurements in two residences ventilate with HRVs, as well as laboratory tests simulating a typical bedroom enabling variations of system configurations and properties. He concludes that ventilation rate deviations affect the system ventilation effectiveness to a great extent. The study concludes that if quality control and qualification procedures are well regulated, HRV ventilation can be robust and effective ventilation system. According to the study, the type of supply diffuser, positioning, and flow rate must be well designed. Engelmann et al. (2013) monitored IAQ in two airtight net zero energy houses. The study used CO_2 and VOCs as indoor air quality indicators. The results reported very high CO_2 concentrations in the bedrooms due to malfunctioning of the HRV, and formaldehyde concentrations exceeding chronic 8-hour TLVs because the houses due to a large amount of interior formaldehyde-based pressed-wood products. However, the authors point out that these concentrations are still below the average concentrations found in American homes according to studies by Offermann (2009). Furthermore, the study shows that increasing the HRV ventilation rates by 0.1 air change rates (ACH) will lead to formaldehyde concentration reductions od 18% to 25%. Another study by VHS (2015) in Greenland, where envelopes are inherently airtight, and indoor moisture problems are recurring due to the cold climate, measured CO2 levels in bedrooms before a ventilation retrofit of about 4000 ppm (very poor: > 3500 ppm above outdoor levels!), and indoor relative humidity between 30% and 50%. After a ventilation retrofit with HRV, the CO2 levels in the bedrooms dropped to 1500 ppm in the bedrooms (between acceptable and poor: about 1000 ppm above outdoor levels).

4.5 VENTILATION OF MURB SUITES (DUs)

4.5.1 Generic types of residential ventilation systems

From a driving forces, paths-pressures, and airflows perspective (Figure 3), residential ventilation systems for dwelling units (houses or suites) are classified as indicated in Table 13 below. In cold climates, exhaust ventilation has traditionally been used as the main mode of ventilation for dwelling units (house and suites). However, ventilation ineffectiveness and unreliability, poor air quality, and energy waste considerations have precluded the use of this method in new homes, in favor of balanced ventilation. The British Columbia Building Code (2018) still allows exhaust ventilation with passive air inlets to be used under restricted conditions that can apply to MURB suites.

Table 13. Generic residential ventilation system classification

Ventilation system	Characteristics	Comments
Supply	Outdoor air is drawn in by a fan and distributed to the rooms using ducts. Outdoor air can be conditioned and dehumidified before being distributed to spaces	Homes become slightly pressurised by the supplied air, which forces warm-humid indoor air out through the envelope
Exhaust	Indoor air is continuously exhausted to the outdoors with one or more fans located in bathrooms. Outdoor air forces its way in to replace the exhausted air.	Homes become slightly depressurized by the exhaust air, which forces outdoor air in through the envelope or passive air inlets
Balanced	Two supply/exhaust fans deliver equal quantities of air into and out of the home. Supply air is distributed to the rooms using ducts, while an equal amount of air is exhausted through the bathrooms	Usually use heat recovery ventilators (HRV) to recover sensible heat, or enthalpy recovery ventilators (ERV) to recover sensible and moisture (latent heat). See section 1.6.

Heat Recovery Ventilators (HRV) and Energy Recovery Ventilators (ERV) are now prescribed by codes to reduce ventilation energy waste. HRVs transfer a portion of the energy (sensible heat) in the ventilation air leaving the building to the incoming air entering the building in winter (preheating), and transferring a portion of the energy in the incoming air entering the building to the air+ leaving in summer (precooling). In addition to sensible heat, ERVs transfer moisture in air and its energy (latent heat) between incoming and leaving air streams. The efficiency of HRVs and ERVs in transferring energy between the incoming and leaving air, depends on the amount of ventilation air that the device supplies and exhausts, and on the outdoor-indoor air temperature and humidity differences. The use of HRVs and ERVs enables more energy-efficient ventilation, and add the possibility to increase ventilation rates, on demand, beyond the rates prescribed by code, with minimum energy penalties. For details on these devices and their application in MURBs, see BC Housing (2015) and CMHC (2015) guides.

Table 14 and Figure 16 describe how these systems are typically implemented in practice. Table 13 presents four types of ventilation systems that are installed in residential applications. These ventilation systems apply to dwelling units (DUs) in general, not necessarily to MURB suites. For example, system S1 applies to houses, not to MURB suites. However, including all these systems enables a better understanding of the complexities and challenges in meeting all the requirements for ventilation systems in residential buildings in general.

Table 14. Generic types of ventilation systems in DUs.

System	Applications	Characteristics	Strengths	Weaknesses
S1. Forced air HVAC Air Handling Unit (AHU) Mechanical energy source: natural gas (heating), heat pump (heating & cooling)	Single family homes Designed for heating and cooling Forced heating, cooling, and ventilation air distributed to bedrooms and living areas	System air recirculating High airflows: ~(400 – 600 L/s) Ventilation air intake at the air handler return air House central exhaust fan maintains air intake	Enhanced air filtration for outdoor and recirculated indoor air Enhanced room air distribution and circulation between rooms Entire house air is well-mixed recirculated, & filtered	Ventilation subservient to heating and cooling When heating/cooling not in operation, ventilation supplied at central return (not to bedrooms and living areas) Entire house air is recirculated, filtered and well mixed
S2. HRV/ERV balanced Independent heating and cooling	Single family home and MURB DU Ventilation air distributed to bedrooms and living areas	Independent from heating and cooling Low airflows: < 100 L/s Heat/enthalpy recovery	Balanced ventilation/pressures Heat/energy recovery core Independent from heating and cooling	Low airflows, risk effective room air distribution Enhanced air filtration is limited
S3. Forced air HVAC + HRV AHU + HRV Adds heat recovery	Combines S1 and S2 In MURB DUs, HRV supplies air to ceiling mixing plenum. A FCU draws air from the plenum and distributes it to each room	Combines S1 and S2	Combines S1 and S2 Entire house air is recirculated, filtered and well mixed	When heating/cooling not in operation, ventilation supplied at central return (not to bedrooms and living areas) Entire house air is recirculated, filtered and well mixed
S4. Exhaust fan/ passive air inlets	Mild climates	Passive ventilation air inlets at the bedrooms and living areas DU central exhaust fan maintains ventilation air intake through inlets	Low cost Low maintenance No ducts	Room air distribution and air circulation highly dependent on DU architectural layout Air circulation between rooms dependent on transfer details between rooms Cold air drafts No air filtration

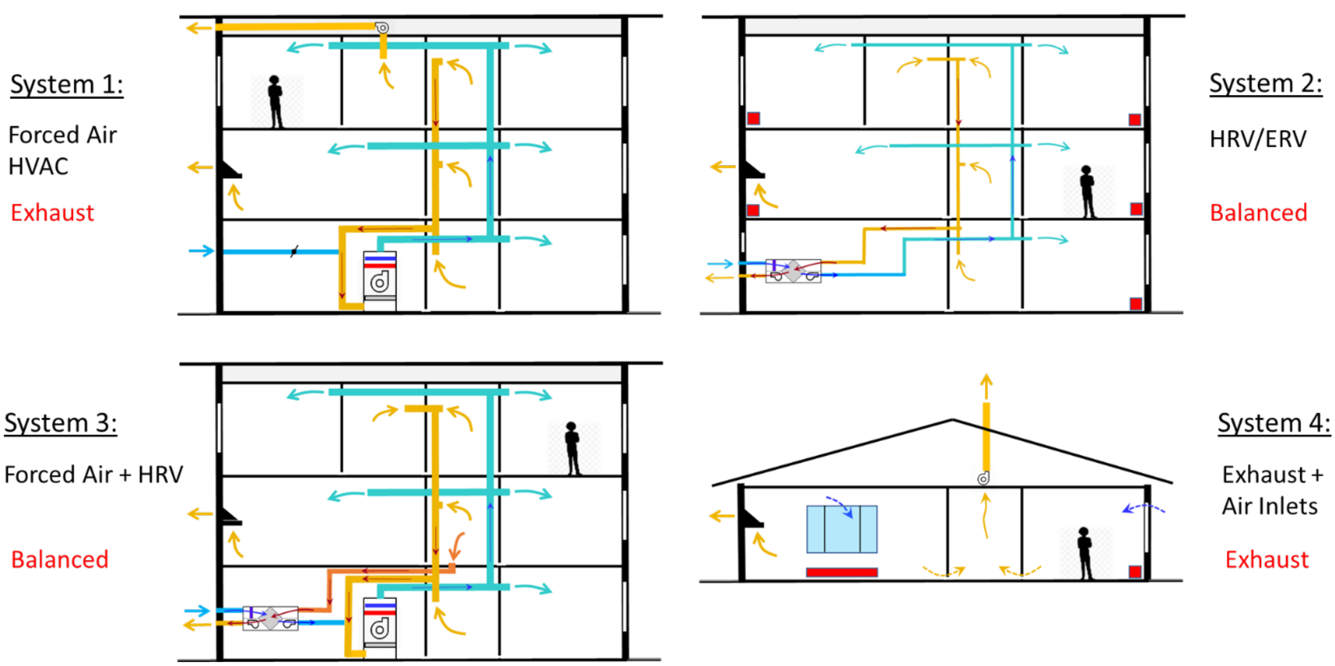


Figure 16. Generic types of ventilation systems in DUs: S1 top-left, S2: top-right, S3: bottom-left, S4: bottom-right

4.5.2 How much should we ventilate?

Ventilation is a balancing act (Figure 17). First, ventilation is a balance between the source strength of contaminants in a room and the removal rate of these air contaminants by the ventilation system (Figure 16, middle). Second, ventilation uses energy: increasing energy efficiency requires reducing the ventilation rate to minimal required by code (Figure 17, right). Third, ventilation assumes that outdoor air is fresh and unpolluted. However, urban air traffic, nearby factories, etc. pollute the outdoor air and make it unhealthy to breathe. Therefore, when the outdoor air is polluted the ventilation rate needs to be reduced or even shut down in extreme situations (Figure 17, left). Therefore, knowing with confidence how much to ventilate at any given moment is not possible in the context of residential buildings. Confidence about the effectiveness of ventilation in removing indoor air contaminants requires confidence about the emission rates (source strength) of indoor contaminants of concern (CoC), as well as confidence about the quality of the outdoor air.

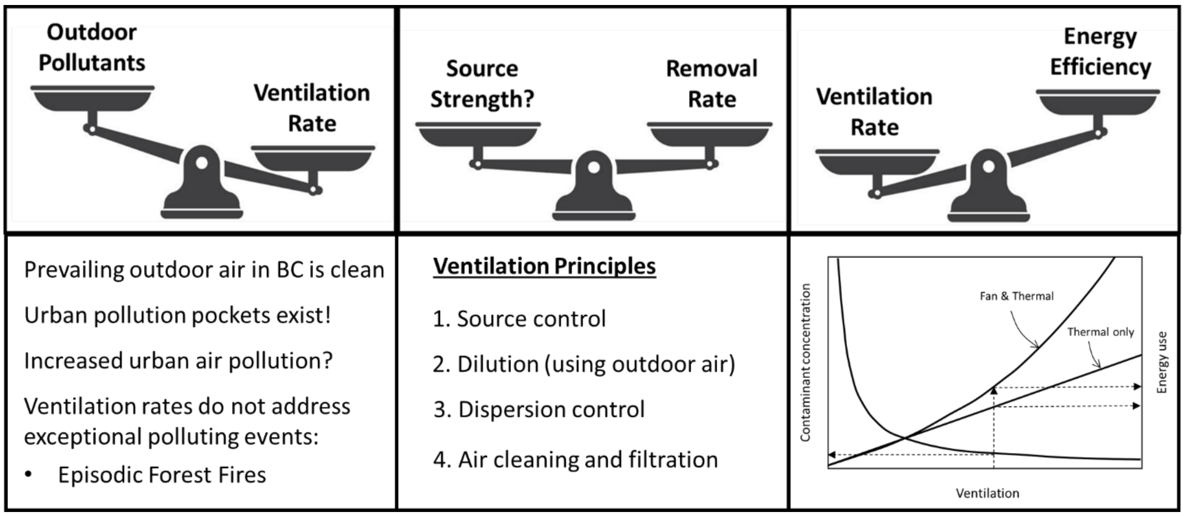


Figure 17. Ventilation is a balancing act

4.5.3 Science supporting ventilation requirements

As discussed in Chapter 1, nobody knows with certainty what is in the air, and even if we knew, it is difficult to predict actual emission rates of all possible indoor air contaminants present under normal conditions. However, not knowing the source strength of indoor contaminants implies not knowing the removal rate. Knowing the ventilation contaminant-removal rate (Figure 17, middle) involves answering the following question:

Can we adequately assess indoor air exposures to any contaminant, such that we may confidently reduce outdoor air ventilation rates, to reduce exposure to outdoor pollutants (Figure 17, left) and save energy (Figure 17, right), without compromising health?

Historically, building ventilation rates have been determined on a **per-person basis**. As summarized by Persily (2005), using environmental chamber studies and buildings, ventilation rates have been recommended based on control of body odour, perception of pollutant sources by un-adapted individuals, and associations between ventilation rates and sick building syndrome in offices. These ventilation rates have ranged over the years from 15 L/s/person to 7.5 L/s/person and even lower depending on the type of space, satisfy the substantial majority (at least 80%) of **un-adapted persons**. However, due to energy concerns, standards changed the approach, from recommending ventilation rates to prescribing minimum rates, i.e. ventilation rates are minimal, not optimal. The ventilation rates have therefore been reduced significantly to satisfy a substantial majority of **adapted persons**.

Therefore, awareness of limitations in the determination of ventilation rates is important in making design decisions following ventilation codes and standards. In general, standard ventilation requirements do not account for the following factors and events:

- Ventilation rates are based on the average response of a large number of individuals, and do not address those who are more sensitive or vulnerable, e.g. having weak immune system, or suffering from asthma or allergies.
- Differences among individual buildings, their occupants and the indoor materials.
- Occupants' behaviors affecting ventilation rates and emissions.
- High-polluting sources and episodic occupant-controlled events, such as painting, cleaning, and smoking.
- The presence of a high number of occupants.

Increased ventilation rates need to be considered when there are concerns about the prevalence or recurrence of any of the factors above.

4.5.4 Ventilation and moisture control

A large number of studies have found associations between indoor dampness (excessive moisture) and respiratory health effects, as well as other effects such as tiredness and headache (Koskinen et al. 1999, Sundell 2004, Bornehag et al. 2004, Fung and Hughson 2003, Fisk et al. 2007). The WHO (2009) illustrates the paths linking moisture sources of dampness and health effects. Under extreme dampness, mycotoxins from toxic moulds can produce more serious health effects in buildings with undetected severe moisture problems (Brewer et al. 2014), with low ventilation rates observed in most of these studies (Hagerhed-Engman 2009). In cold climates in particular, ventilation is minimized to save energy and avoid cold-air drafts. As a result, high indoor humidity levels can prevail, which enhance microbial growth, particularly in cold and concealed envelope surfaces. Optis et al. (2012) characterized mold as a health risk in First Nations reserves in Canada and concluded that unhealthy moisture conditions resulted from deficiencies in housing conditions, structural damage to the building envelope, overcrowding, and insufficient use of ventilation systems.

Figure 18a shows the relation between daily average indoor moisture production rates by occupants and their activities, ventilation (air change rates), room relative humidity, envelope surface temperatures, and envelope surface relative humidity. Figure 17 was derived using a steady-state moisture mass balance calculation (excluding moisture buffering effects through indoor furniture and finishes, and moisture diffusion through the envelope). The shaded areas illustrate room and surface relative humidity levels that are potentially unhealthy because they enhance microbial development and growth. From the literature, reasonable moisture production levels are between 6 kg/day in apartment suites and 10 kg/day in houses. In particular, human respiration and showering have been found critical moisture production sources (Johansson et al. 2010). Figure 18b, shows that over ventilating can lead to very low indoor relative humidity levels that could trigger negative respiratory health effects or dry air discomfort. This is particularly valid in the coldest regions as indicated in the boundary conditions.

From a ventilation system point of view, moisture can be controlled in two ways: 1) humidity-sensitive demand-controlled ventilation (DCV), and 2) system/mechanical device humidity control. These are described in section 4.3.7, and in Chapter 8. Humidity-sensitive DCV relies on enhancing ventilation rates when moisture loads are high, e.g. in bathrooms when showering in response to a bathroom humidistat.

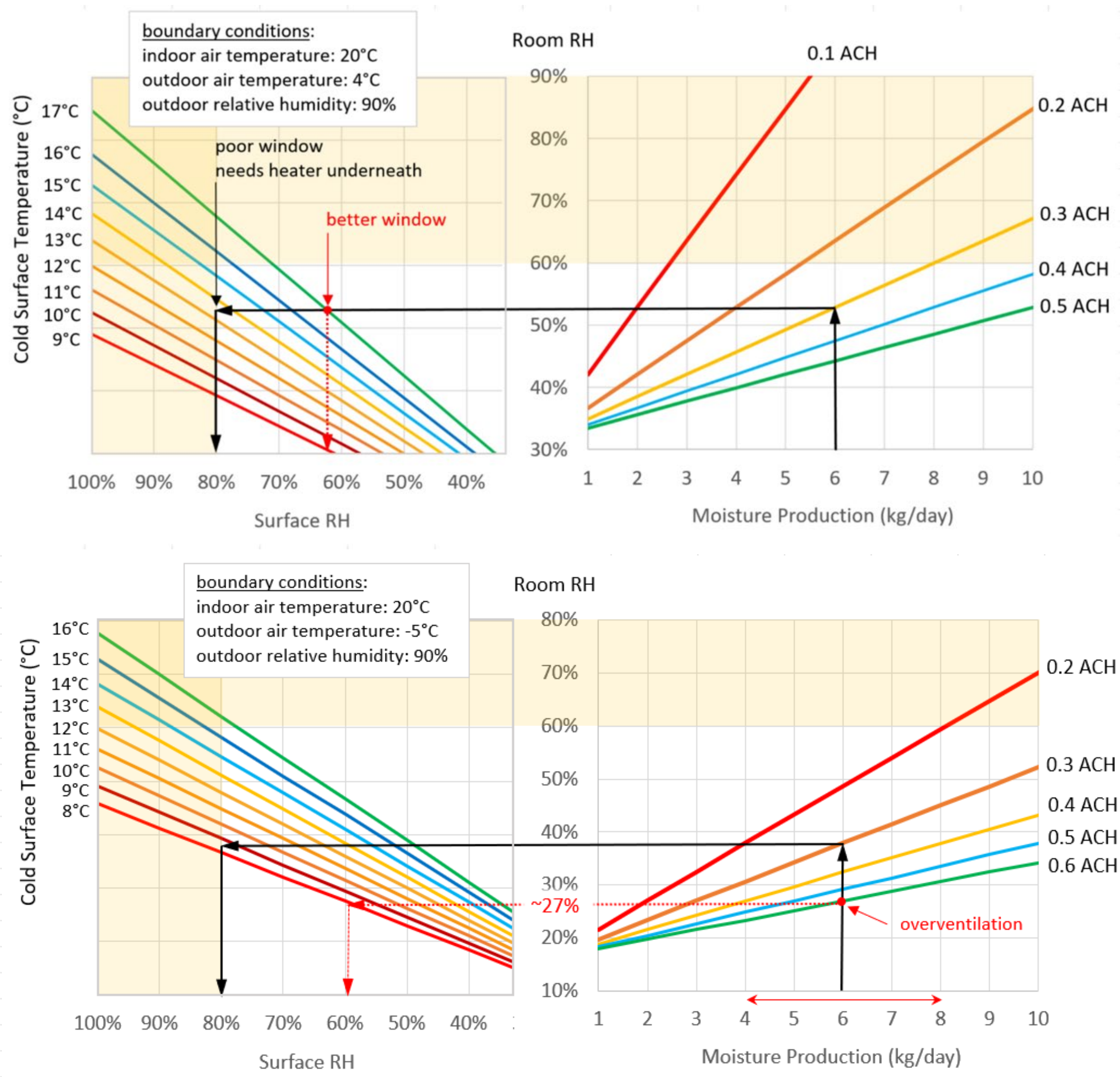


Figure 18. Steady-state ventilation and moisture balance. a) Top: condensation risk, b) Bottom: over ventilation risk.

4.5.5 Ventilation and outdoor air pollution

Well-ventilated spaces are desirable from a heath and productivity standpoint (Meadow et al. 2013). In developed countries, building ventilation typically assumes that outdoor air is fresh and clean. The stinky pond analogy (Figure 19) compares a building without ventilation to a stinky pond, and illustrates the positive effect of having a constant and "infinite" supply of fresh, outdoor air on building environmental health. However, the "water stream" seems to be getting less fresh and more polluted.

Outdoor air filtration has traditionally been used in HVAC systems to protect equipment from degradation. However, over the years this view has been shifting due to growing concerns with persistent increased urban air pollution (Aiskanen et al. 2016, Salthammer et al. 2018). ASHRAE ventilation Standard 62.1 (ASHRAE 2019) requires an investigation of outdoor air quality prior to completion of the ventilation system design, and prescribes outdoor air treatment if the outdoor air quality is unacceptable. However, ASHRAE Standard 62.1 does not apply to residential buildings.

Figure 19. Insufficient ventilation: stinky pond analogy

Outdoor air pollution is a leading cause of cardiovascular disease and global mortality (Rajagopalan et al. 2018). Furthermore, it has been demonstrated that outdoor air pollution substantially influences indoor air quality (Salthammer et al. 2018) and the risk of mortality from indoor exposure (Xiang et al. 2019). The effect of the envelope and the mechanical system have been studied (Walker and Sherman 2013), as well as the effects of filtration (Zhao et al. 2015). Outdoor air pollution can be either persistent (traffic, industry) or episodic (forest fires). Most studies focus on persistent outdoor air pollution, while only few (Kirk et al. 2018) study the indoor quality effects of forest fires. Several solutions are proposed to minimize the impact of outdoor air pollution on indoor air quality, such as the following: increasing the envelope airtightness, increasing outdoor air filtration, reducing ventilation rates, and adjusting the operation of the mechanical ventilation.

A large study spanning 26 European countries (Askainen et al. 2016) reported the largest burden of disease attributable to indoor pollutant exposures is from outdoor sources. The main type of disease being cardiovascular disease, followed by lung cancer. Aside from source control policies, the study recommends enhanced high-quality filtration, and substantial reductions of outdoor airflow rates. In the study, the mean air change rate of the 26 countries is 0.7 1/h and the mean ventilation rate per person is 17 L/s/person. The study concluded that under the context of increased air pollution these rates are high, and derived lower mean ventilation rates down to 4.4 L/s/person without filtration and 7.7 L/s/person with filtration.

4.5.6 Residential air filtration and cleaning

The effectiveness of any filtration system in removing outdoor air pollutants is greatly reduced by air infiltration through the envelope that either bypasses the system filter, or overpowers the air cleaning capacity of a portable air cleaner.

Air filtration and cleaning remove unwanted contaminants from the air. Figure 20 outlines the main air filtration mechanisms. In selecting filters, the main question to answer is the following: what are the contaminants of concern (CoC) in suite MURBs (DUs)? In Chapter 3, the CoC in residential buildings are potentially many. As discussed in section 1.4, ventilation is a risk management approach that is intended to remove and dilute indoor air contaminants likely to be present in buildings before they can reach uncomfortable, unhealthy, or possibly harmful concentrations, under normal conditions, which excludes unusual contaminants. These airborne contaminants originate from the occupants, their activities, indoor materials and products, and outdoor pollution.

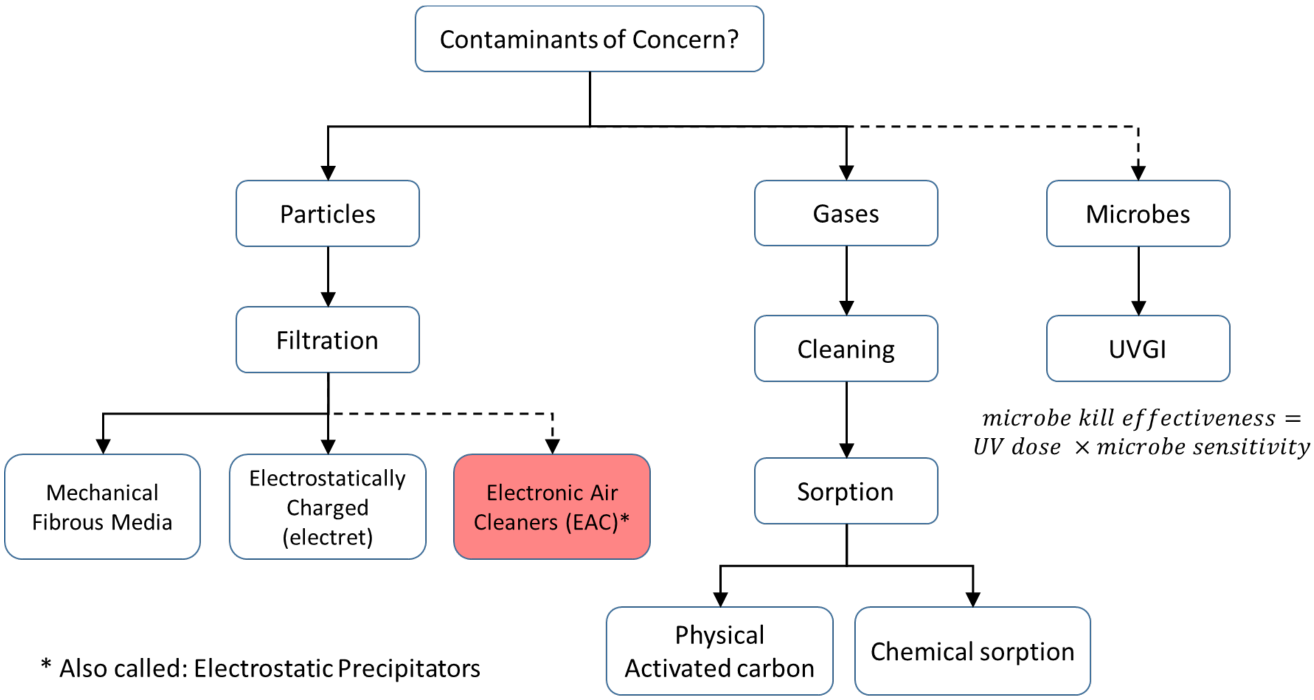


Figure 20. Air Filtration mechanisms

From Figure 20, mechanical filtration through fibrous media has been the main mechanism for particle removal in buildings. Historically, air filters have been used in HVAC systems to protect the air handling equipment, to keep fans, coils, and ducts clean & prevent any malfunctions. However, the requirement for air cleanliness has been increasing over the years by virtue of the heightened awareness of indoor air quality and health. Still, filters are considered the last line of defense for indoor air quality after source control, dilution control, and dispersion control principles have been applied.

Over the years, within the building sector, residential air filtration has received the lowest attention, being the sector with the lowest filtration requirements. Recently, the building industry has realized that due to the increased amount of time people spend at home and the diversity of occupancy compared to other types of buildings (babies, children, elder, pregnant, etc.), occupants' exposure to airborne contaminants at home deserves more attention.

The efficiency of air filters to remove air contaminants is rated using tests methods by ASHRAE Standard 52.2 (2017): Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size. The industry accepted metric for rating air filters I called **MERV (Minimum Efficiency Reporting Value)**. It classifies the types of filters according to their efficiency to capture airborne particulates based on the range of sizes. The MERV rating is obtained from extensive filter testing, under laboratory-controlled air velocity and humidity ranges (NAFA 2017).

Table 15 adapted from the National Air Filtration Association (NAFA 2020) synthesizes the MERV ratings according to filter capture efficiency of particles based on their size range, and gives examples of controlled contaminants and typical applications. For example, a MERV 13 rated filter can capture up to 75% of the particles in the size range between 0.3 microns and 1.0 microns. It means that it is more efficient in capturing the larger particles within this size range, and loses efficiency in capturing the smallest particles. Whereas a MERV 16 filter is far more efficient in capturing all the particles in this range, particularly the smallest ones. Similarly, a 99.99% performer compared to a 99.97% will remove much more of the tiniest of particles and those happen to be the most dangerous since they are too small to be captured by your nasal system and can pass directly to your lungs. These tiny particles stay suspended in the air the longest and are more likely to be breathed in. The last group of MERV filters are at the level of efficiency of the top filters found in the market, **HEPA (High Efficiency Particle Arrestance) filters**.

Table 15. Air filters and their applications (adapted from NAFA 2020)

Group	MERV	Particle size range, μm			Particle size range, μm	Typical of controlled contaminants	Applications
		3 - 10	1 - 3	0.3 - 1			
I	1	<20%	-	-	>10	Light pollen, dust mites, carpet fibers, textile fibers, hair, debris	Basic residential
	2	<20%	-	-			
	3	<20%	-	-			
	4	<20%	-	-			
II	5	20-35%	-	-	3.0 - 10	Bacteria, dust, mold spores, cat and dog allergens, hair spray, fabric protector	Better residential General commercial Industrial workspaces
	6	35-50%	-	-			
	7	50-70%	-	-			
	8	>70%	-	-			
III	9	>85%	<50%	-	1.0 – 3.0	Legionella, tobacco smoke, combustion, cat and dog allergens, mold spores	Superior residential Better commercial Larger PM2.5
	10	>85%	50-65%	-			
	11	>85%	65-80%	-			
	12	>90%	>80%	-			
IV	13	>90%	>90%	<75%	0.3 – 1.0	Bacteria, droplet nuclei (sneeze), cooking oil, most smoke and insecticide dust, combustion, smog	Superior commercial Hospitals Surgery Laboratories Smaller PM2.5
	14	>90%	>90%	75-85%			
	15	>90%	>90%	85-95%			
	16	>95%	>95%	>95%			
V	17	HEPA		≥ 99.97%	< 0.3	All the above but better, plus: virus	Hospitals protective Electronics Pharmaceutical Cleanroom
	18			≥ 99.99%			
	19			≥ 99.999%			
	20			≥ 99.9999%			

Figure 21 based on testing reported by Azimi et al. (2014) demonstrate how filter particle removal efficiency varies according to the size of the particles. This is called particle size efficiency (PSE). These filter removal performance behaviors result from the mechanical filtration mechanisms described elsewhere (NAFA 2014). Because filter removal is a strong function of particle size, the underlying size distribution of indoor particles inside the home can greatly influence the magnitude of reductions in particular matter concentrations (EPA 2018). Knowing the size of a particular contaminant of concern (CoC), helps identify the appropriate filter that has the desired PSE for the size range of the CoC.

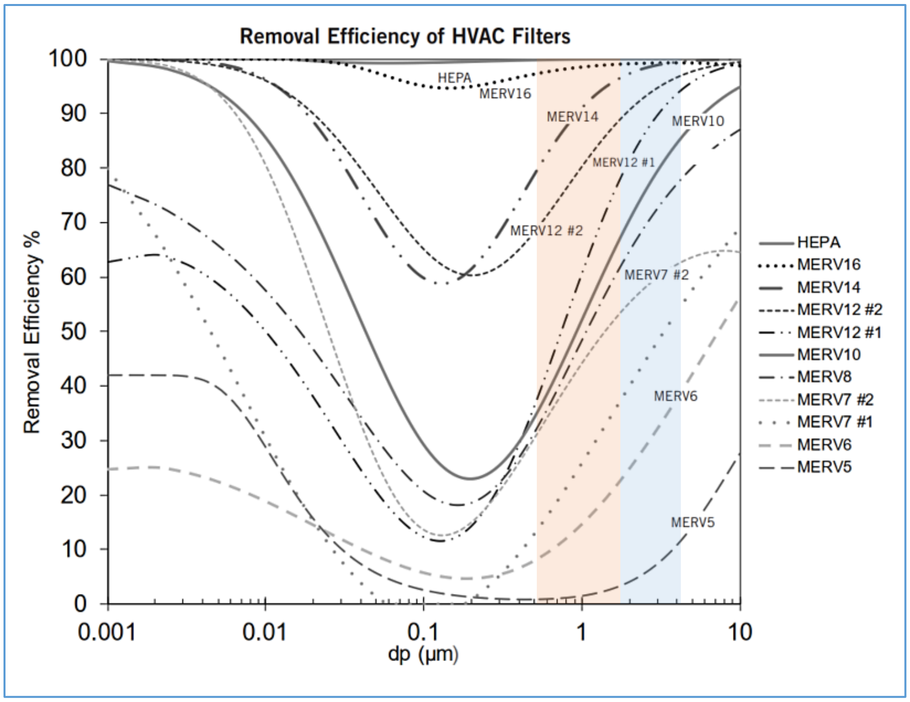


Figure 21. Typical size-resolved removal efficiency curves for new (clean) fibrous media air filters (Azimi et al. 2014)

As seen in Table 14, filters in residential applications have had the lowest rating requirements (Group I: basic residential). However, it is now common to see residential ventilation systems with rating in Group II: better residential. Most residential ERV/HRV have filters have MERV 6 to MERV 8 rated filters. Some can even be upgraded up to MERV 11 or even MERV 13. However, basic aerodynamics tells us that increasing the efficiency of filters involves having increasingly more powerful fans that can pass the filtered air through the filters. Filters obstruct airflow. In Figure 3, adding a filter involves significant reductions in the airflow path, which can only be overcome with a more powerful fan (driving force) to overcome a larger drop of pressure at the filter. The more efficient the filter, the smaller the path, and the more powerful the fan has to be. Furthermore, the high differential pressures caused by the reduced path (Figure 3) make it more critical to install and secure the filter properly to avoid the risk of being entirely bypassed, thus negating its purpose.

*The more efficient the filter, the higher the flow restriction, and the more powerful the fan needs to be. Furthermore, it the filter is not properly installed. High differential pressures caused by the increased flow restriction (**Figure 3**) make it more critical to install and secure the filter properly to avoid the risk of being entirely bypassed, thus negating its purpose.*

4.5.7 Smart ventilation

Following a human-centered approach, smart-ventilation systems are human and climate responsive in regular operation, and responsive to extreme/episodic climate events, such as wildfires. In general, implementing smart building environmental systems in buildings relies on levels of sensing of the environment that match the intended responsiveness of the system. Smart environmental systems are inherently dynamic, which means that their reliability depends on the accuracy of the sensing technologies, and the reliability and responsiveness of the controlled devices. Research from Lin et al. (2017) raised the following question: can or should residential ventilation be automated in practice to improve indoor air quality based on sensed parameters and other smart home features?

Artificial intelligence based smart systems make inferences dynamically based on limited data on a set of factors to improve system responsiveness based on given targets. For example, building environmental systems can be predictive, by anticipating an environmental parameter or an event, or use data-driven machine learning to learn from past behaviors and adjust the systems responses dynamically to maintain satisfactory air quality while minimizing energy use. Other smart systems aim to minimize the number of sensors by inferring certain parameters or events from a limited number of sensor data, for example use CO2 sensor data and room air temperature data to infer room occupancy and window operation (Atwal et al. 2013).

An ideal or comprehensive "smart" ventilation system considers the factors illustrated in Figure 22, to meet the ventilation performance requirements described in Chapter 7. Furthermore, being human-centered smart ventilation systems need to consider the factors introduced in section 5.2 of this document. Smart ventilation systems are responsive to indoor air contaminants (Chapter 3) and to outdoor air pollutants (Section 5.1). As described in section 5.2, humans are a main source of indoor pollutants by their presence and their activities. Humans are also receptors exposed to indoor and outdoor air pollutants, which is the reason to have ventilation systems in the first place. Humans are environment modifiers that may enable or disable the ventilation. Energy efficiency and ventilation/IAQ are mutually interrelated (Section 7.3). Mechanical ventilation uses energy and affects the energy balance in rooms and suites (Section 4.5.2, Section 7.3). Suite overheating, opening/closing windows, and using air-conditioning affect ventilation and indoor air quality (Section 4.5.8). Noise by the mechanical ventilation affects the dwellers' well-being and may lead to disabling the ventilation. Outdoor noise may cause occupants to close windows.

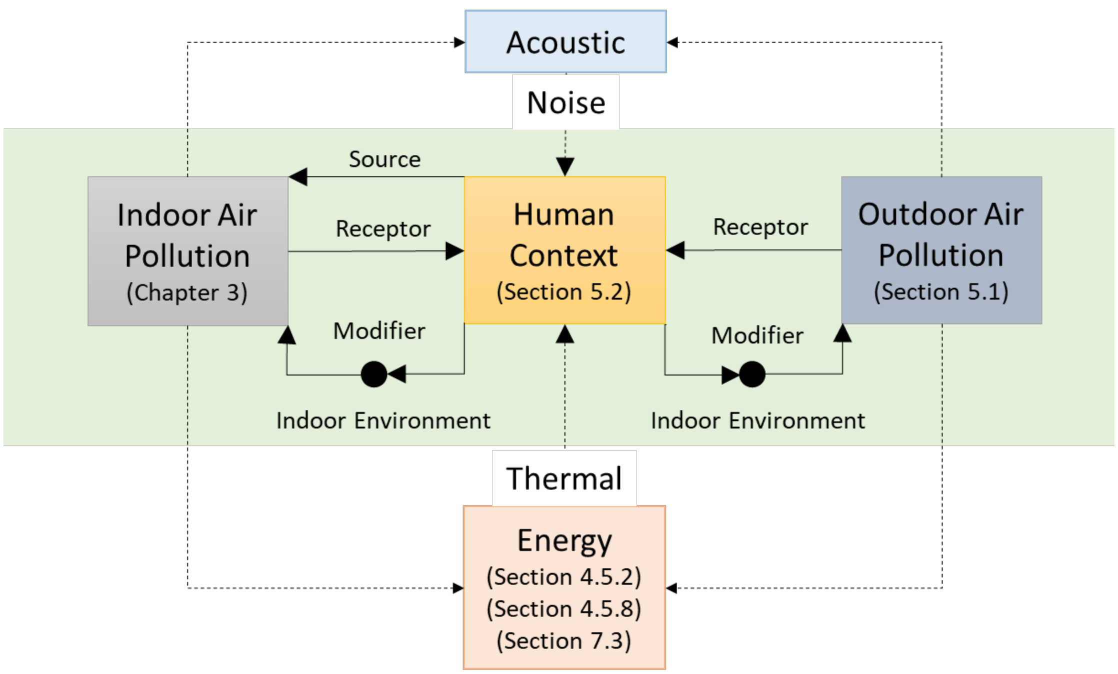


Figure 22. Factors Affecting Smart Ventilation

In Figure 22, to achieve human and climate responsiveness, as well as resilience (Section 7.6), smart ventilation requires four levels of smart sensing and monitoring:

1) Human – Human sensing and monitoring, related to factors discussed in section 5.2, refers to sensing a) the human presence in the suite and in rooms through CO2 or relative humidity sensors, b) human activities such as cooking and showering/bathing, c) human behaviors that may affect ventilation, and d) IAQ-energy

feedback to humans that may affect human behaviors: pollute less and/or ventilate more/less; for example, a two-way human-system feedback in the ventilation controls integrates human satisfaction and preference feedback to fine-tune the system response, and provides feedback to humans on the past and forecasted (predictive) consequences of their choices and actions, as well as suggestions on how to improve IAQ.

2) Indoor air quality – Considering the discussion in Chapter 3, practical IAQ sensing can be narrowed to relative humidity (RH), CO2 as a surrogate of other occupant-related pollutants, and perhaps VOCs and PM2.5 from indoor materials and cooking when commercial sensors become readily available.
3) Outdoor air quality – Outdoor Air Quality (OAQ), discussed in section 5.1, depends on the prevailing urban pollution in the city or region, the prevailing local air pollution at the site, and outdoor air pollution threats from episodic events such as wildfires.
4) Energy – Energy sensing and monitoring, refers to helping adjust ventilation based on energy considerations.

In practice however, in MURBs the level of sensing and system responsiveness is limited by affordability and economies of scale, since the first costs and maintainability of implementing sophisticated sensing technologies is multiplied by the number of suites; thus, the first costs and system maintainability are passed to the dwellers. It can be argued that smart-responsive ventilation can only implemented in decentralized, in-suite, ventilation systems in MURBs because these systems have the capacity to respond to the regular internal air pollutant loads, as opposed to the centralized systems (Chapter 8). However, centralized MURB ventilation systems can be considered more resilient/responsive to episodic wildfire smoke events, compared to decentralized systems, because they can more effectively implement the whole building predictive smart filtration/control proposed in section 7.6.1 of this document. Chapter 8 describes a proposed high-performance ventilation system that can be considered “smart” because it combines the advantages of both decentralized (best suite-based response) and centralized systems (best whole-building outdoor/ambient response).

Fully implementing the four smart ventilation levels above in residential buildings in general and in MURBs in particular is not practical. However, all levels can be partially implemented and controlled through a smart IAQ-ventilation control system including: 1) monitoring RH, CO2 and perhaps VOCs and PM2.5 in source-pollution and exposure locations, 2) using IAQ sensors as surrogates for human presence, activities, and exposures, 3) controlling the amount of ventilation based on IAQ sensors, and indoor-outdoor temperatures, and 4) maintaining an outdoor PM2.5 sensor to monitor outdoor air quality and adjust ventilation to respond to extreme episodic events. Section 7.6.1 of this document proposes a smart, predictive PM2.5-based DCV control system to be used during periods of high outdoor air pollution, such as during wildfire periods of the year. The system can optimize ventilation in response to indoor CO2 and RH, and outdoor PM2.5.

Two overlapping views of smart ventilation are described in the literature: energy-focused, and air-quality-focused. Both views rely on sensors to monitor the ventilation needs, and provide optimal temporal (when needed) and spatial (where needed) ventilation response. Beyond these two overlapping views.

- **Energy-focused Smart Ventilation** (Guyot et al. 2017, Walker et al. 2021), aims to reduce the amount of energy use attributable to ventilation in dwelling while maintaining acceptable indoor air quality. In this way, ventilation can be managed in response to the utility grid demand. Central to the concept of smart ventilation is the use of controls to ventilate more when doing so provides an energy or air quality advantage and/or a resource to the power grid, and less when it provides a disadvantage. Smart ventilation shifts enhancing ventilation for IAQ-based response from times when energy costs are high to times when energy costs are low, while always maintaining acceptable IAQ levels. Energy-based smart ventilation is predictive, i.e. it allows anticipation of future ventilation needs, and retroactive compensation for previous ventilation needs.

- **Air-Quality-Focused Smart Ventilation** (Guyot et al. 2017, Schieweck et al. 2018, Walket et al. 2021) aims to provide the “right” amount of ventilation air to each room to respond to the room pollutant concentrations and/or its occupancy. These systems also intend to save energy, because they supply only the right amounts of ventilation, thus avoiding over-ventilating, or under-ventilating. The systems can also run at minimum speed/flow when there are no occupants in the suite.

The most common energy-focused and IAQ-focused smart ventilation systems are the so-called demand-controlled ventilation (DCV) systems, a subset of smart ventilation, that supply ventilation required to each room on demand. To operate, DCV systems require a room sensor that senses typically room CO_2 or humidity. A fundamental goal of demand-controlled ventilation (DCV) systems is to improve IAQ while reducing ventilation energy. Two possible levels of complexity in the implementation of DCV can identified. *a) Temporal response* – Provides variable ventilation system flow rate (e.g. HRV variable fan speed) that reduces ventilation based on overall suite occupancy (scheduled or sensed), or increases ventilation based on a determined source such as bathroom humidity or a stove range PM2.5. *b) Spatial-Temporal response* – Provide variable differential room ventilation rates based on a room-by-room demand (DCV). The first smart-ventilation level is already implemented in Passive House HRV systems. The second level is not available for residential ventilation due to its costs and reliance on a sophisticated control system.

A common example of *temporal response* of residential ventilation is the use a bathroom humidistat (humidity-sensitive DCV system) to boost the exhaust ventilation fan when bathroom humidity exceeds a threshold. Walker et al. (2019) and Wang et al. (2020) studied low-cost PM2.5 sensors that could be integrated to residential stove ranges with a control system that operates the exhaust fan at variable speed depending on the PM2.5 concentration level, and maintains the exhaust fan in operation until PM2.5 concentrations reach acceptable levels (PM2.5-based DCV system). In both studies, the conclusion is that these sensors are still not reliable enough to be integrated in stove-range exhaust systems, because they show low or no response to ultrafine particles. A study by Singer and Delp (2018) tested consumer and research grade particulate matter monitors, and concluded that all consumer and research-grade monitors substantially under-reported or missed events for which the emitted mass was comprised of particles smaller than 0.3 µm diameter. A review conducted by Guyot et al. (2018) of smart ventilation energy and indoor air quality performance in residential buildings, identified that the vast majority of smart ventilation applications are humidity-sensitive DCV systems, with a few prototype applications on CO_2-based DCV, TVOC-based DCV, and occupancy-based DCV. In some of these systems, energy savings were observed mainly due to ventilation reductions based on occupancy.

Figure 15 in Section 4.3, illustrates a challenge in implementing CO_2-sensitive or humidity-sensitive DCV in a studio suite in a Passive House dorm. The studio suite, is served by a central ERV that supplies air just above the head of the bed (Figure 15 left, at the bottom). Heating is delivered by a recirculating fan-coil unit at the ceiling level (Figure 22 left, at the top). Figure 15-bottom shows relative humidity and CO_2 data collected in the suite from September of 2021 through April of 2022. In Figure 15 it is observed that while the CO_2 level persistently exceeds 1000 ppm, and the relative humidity levels are frequently below 40%. Implementing CO_2-sensitive DCV would increase the ventilation rate to reduce CO_2 levels, which would further decrease the suite relative humidity to low uncomfortable and unhealthy levels, while consuming more energy for heating.

A hypothetical example of level of *spatial-temporal response* in a MURB suite, consists on relying on room CO_2 sensors to increase ventilation rates in occupied rooms, and reduce ventilation rates in the empty rooms, thus not requiring more energy. When occupants are dining or in the living room, the system would supply increased ventilation to these rooms, while decreasing ventilation to the other rooms. When occupants are sleeping, the system would increase ventilation to the bedrooms and supply minimum ventilation to the other rooms.

4.5.8 Natural ventilation: for indoor air quality and natural cooling

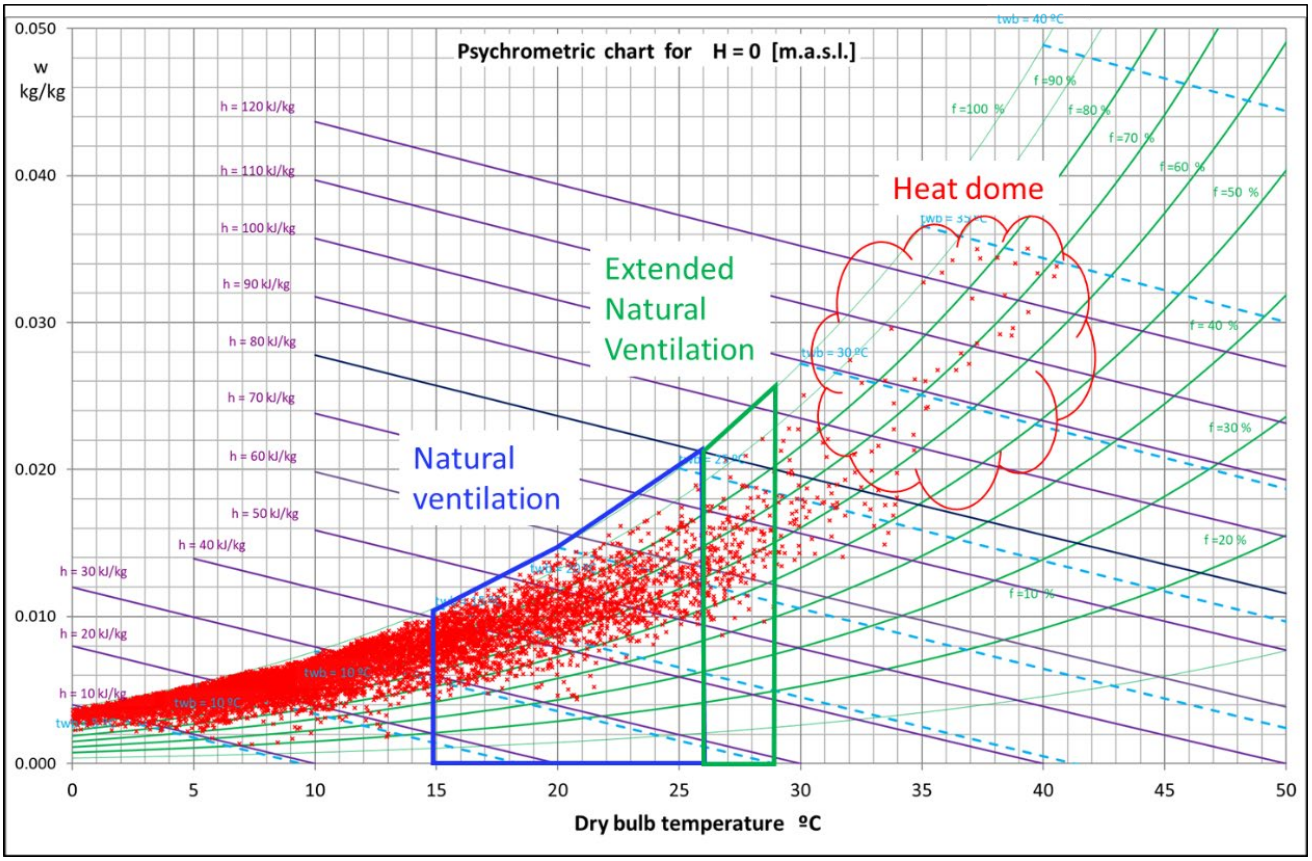
*Uncertainty is the culprit of natural ventilation design. How to design a naturally ventilated building with **robust** thermal, energy, and ventilation air quality performance?*

In cold climates, indoor air quality is a main concern in the cold seasons when buildings are fully closed to save energy. However, a warming climate is inducing building owners and occupants to maintain windows closed in warm seasons and install more ductless air conditioning systems thus substantially reducing outdoor air exchange (Gall et al. 2016). Sections 8.1.4 and 8.1.6 discuss combined ventilation and mechanical cooling strategies for MURBs. This section focuses on natural ventilation to raise awareness that efforts are still necessary to implement passive measures in building design. Furthermore, relying entirely on mechanical cooling for thermal comfort risks habituating dwellers to get used to a mechanical cooling "all-or-nothing" approach where small indoor temperature fluctuations are not tolerated anymore. The consequence of this full reliance on AC is a rebound effect where dwellers become habituated to cooler indoor temperatures in the summer, thus demanding more mechanical energy for cooling, and fostering a long-term disconnect between humans and the outdoor environment. Studies in Singapore by Sekhar (2004), and Gall et al. (2016) showed that bedrooms with ductless split air conditioners (AC) resulted in significantly higher CO_2 levels than naturally ventilated (NV) bedrooms, indicating reduced ventilation in the bedrooms with AC.

In theory, natural ventilation can be used for natural cooling and indoor air quality. However, natural ventilation is not treated with rigor in building design because of its inherent design limitations involving highly variable driving forces, and a high impact of overall building geometry and suite location on performance, as well as the uncertainties and constraints affecting its operation.

Natural ventilation and indoor air quality – The ventilation air flow rates required for indoor air quality (IAQ) are much smaller than the flow rates required for cooling. Therefore, window opening is much more effective to dilute indoor air pollutants than to cool the suite, as long as the windows are open. However, in colder months, when mechanical heating is used and windows are closed, mechanical ventilation is required. Studies on residences, by the author and others, have shown that indoor CO_2 follow annual cycles tending to gradually increase in colder months, and gradually decrease in warmer months due to natural ventilation. However, during wildfire periods, windows remain closed and therefore natural ventilation is disrupted, i.e. it can neither be used for cooling nor indoor air quality.

Natural ventilation cooling – Figure 23 shows the Psychrometric chart with hourly data from a weather station at BCIT in 2021. In Figure 23, the hours when natural ventilation can be effective for cooling (i.e. outdoor temperatures range between 15°C and 26°C) are enclosed in a blue line. The natural ventilation hours could be extended to outdoor temperatures up to 29°C (area enclosed in a green line). This extension can be achieved by the use of fans to enhance convective cooling of the human body, and other adaptive measures. Beyond 29°C, mechanical cooling is required. The table in Figure 23 shows the hours and percent of total hours and summer hours that natural ventilation can be effective for natural cooling. It is important to note that the extended natural ventilation range in Figure 23 applies only to **healthy occupants**. For suites with elders, and other dwellers that cannot physically or physiologically adapt, natural ventilation cannot be extended beyond 26°C.



Range	Hours year	%	Hours May-Sep	%
Hours of the year	8760	100%	3600	100%
Natural ventilation: 15°C – 26°C	2187	25%	2187	61%
Overheating hours > 26°C	288	3%	288	8%
Extended: 15°C – 29°C	2364	27%	2364	66%
Overheating hours > 29°C	111	1%	111	3%

Figure 23. Natural ventilation ranges and hourly data from a BCIT station in 2021

Any design for natural ventilation must begin with a thorough local climate analysis. Tools are available to assist in those analyses, such as the "*CBE Clima Tool*" developed by the Center for the Built Environment at UC Berkeley (https://clima.cbe.berkeley.edu/). The goal is to determine whether the local climate is suitable to provide satisfactory thermal comfort and ventilation. A climate analysis helps observe seasonal trends and evaluate periods of the year that are either too cold or too hot, as well as to characterize the prevailing driving forces. A local climate analysis must be combined with a study of site-specific factors and constraints such as air pollution, urban heat island effect, noise, etc. that can affect the feasibility of relying on natural ventilation for thermal comfort, ventilation, and indoor air quality.

Figure 24, illustrates the challenges in designing robust natural ventilation systems. Natural ventilation design relies on the magnitude and patterns of dynamic wind and thermal buoyancy forces to provide satisfactory thermal comfort and indoor air quality. Aside from the uncertainty of the natural forces that cannot be reduced, factors 3, 4, and 5 are difficult to consider all together, during design, when attempting to design natural ventilation as an integrated system. On the one hand, key parameters such as the building layout and the dwelling/suite layout are subjected to site and occupation density constraints, and have to be decided at the early design stages. On the other hand, later-stage decisions such as designing the opening types, sizes, and locations require complex aerodynamic airflow testing and modeling that are out of the scope of any design. This is unlike mechanical equipment that includes capacity/performance curves that are applied in the design and implementation of these systems. Due to a lack of specialized design analysis tools and expertise to support robust natural ventilation designs, natural ventilation design has become prescriptive, i.e. by specifying room dimensions and corresponding locations of openings, or based on rules-of-thumb. Considering building operation, daily concerns of dwellers distracts them from trivial tasks such as opening or closing windows. Therefore, they cannot be relied upon to optimize natural ventilation to cool spaces or access fresh air.

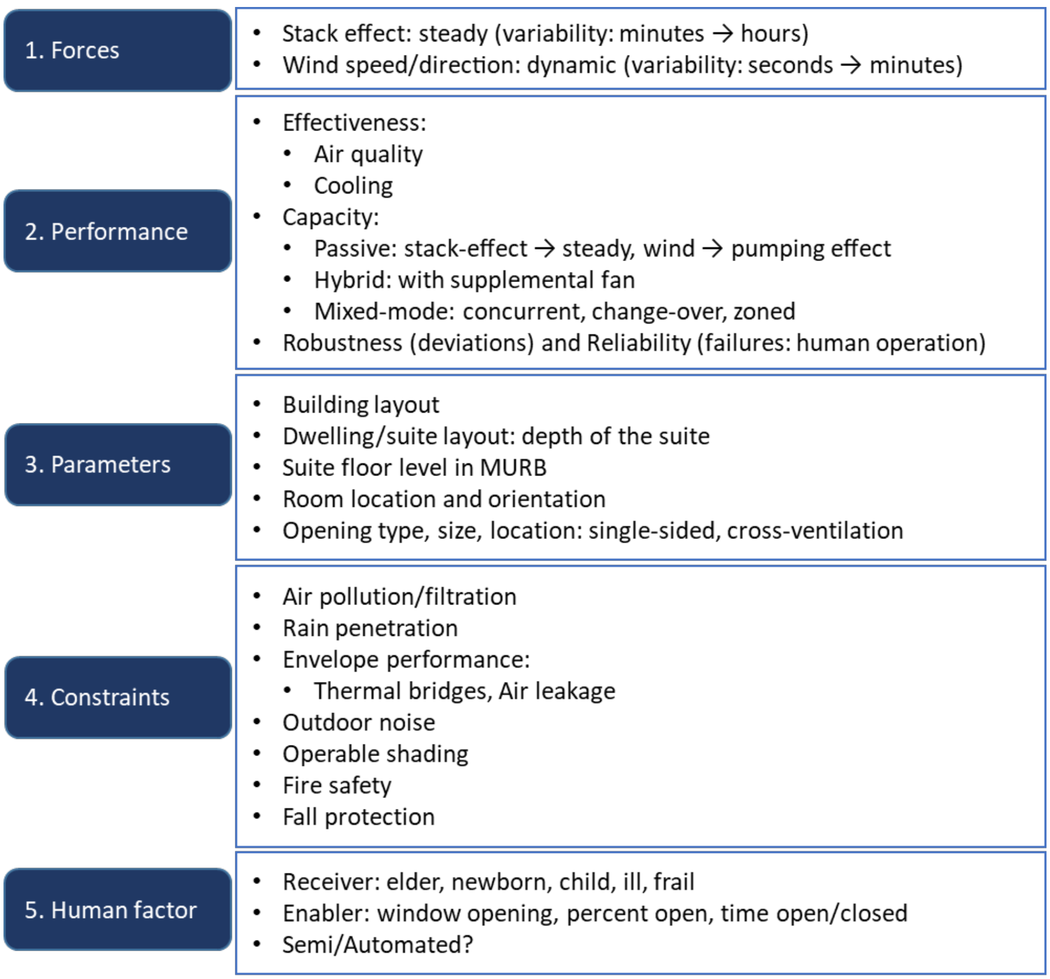


Figure 24. Factors affecting natural ventilation design and performance

The effectiveness of natural ventilation to provide satisfactory cooling for occupants in buildings is highly dependent on the shape, configuration and orientation of the building and its components, as well as on its connection to the site. The main challenge in natural ventilation design comes from the highly variable and uncertain nature of the local natural forces, and the shaping and configuration of the building and its components to reliably regulate or even enhance the effects of these forces in spaces. Another challenge is caused by the dependence of natural ventilation performance on the occupants' interactions with the building. This is in contrast to fully mechanically conditioned buildings with typically fully enclosed envelopes, where the mechanical system enables tight control over the indoor environment that overpowers any weather and occupancy "disturbances". Despite the limitations and constraints, natural ventilation can still be relied upon locally for most of the mild and warmer seasons, instead of promoting full reliance "all-or-nothing" on air-conditioning.

Residential buildings have lower internal heat gains than commercial buildings, consequently heating is required for larger portions of the year (heating dominated). Therefore, in theory achieving proper indoor cooling is less critical. However, MURBs have smaller footprints than commercial buildings and consequently, are characterized by having larger envelope areas to enclosed volume ratios. This is particularly applicable to small suites. As a consequence, heat transfer through the building envelope is relatively more important as well as its impact on occupant thermal comfort, i.e. the thermal behavior of residential buildings tends to be more skin dominated, rather than internal gain dominated. Furthermore, window temperatures and solar heat gains have a bigger impact on thermal comfort in MURBs suites. However, providing effective natural ventilation for MURB suites is particularly constrained by the layout of the building. To conserve energy in a heating dominated climate, local MURB buildings are configured with compact shape, and internal corridors. Therefore, ventilation is limited to single-sided ventilation, which is much less effective than cross-ventilation for cooling. Furthermore, for fall protection, operable windows are small and shallow in height, thus minimizing stack effect at the suite level. Wind can make a difference in taller, more wind-exposed buildings. However, wind speeds vary from one second to another as indicated in Figure 25, as well as the wind directions, thus producing the so-called "pumping effect" (i.e. pulsating flow) that creates irregular and alternating inwards/outwards air flows at the window. This effect is highly dynamic and difficult to model and predict.

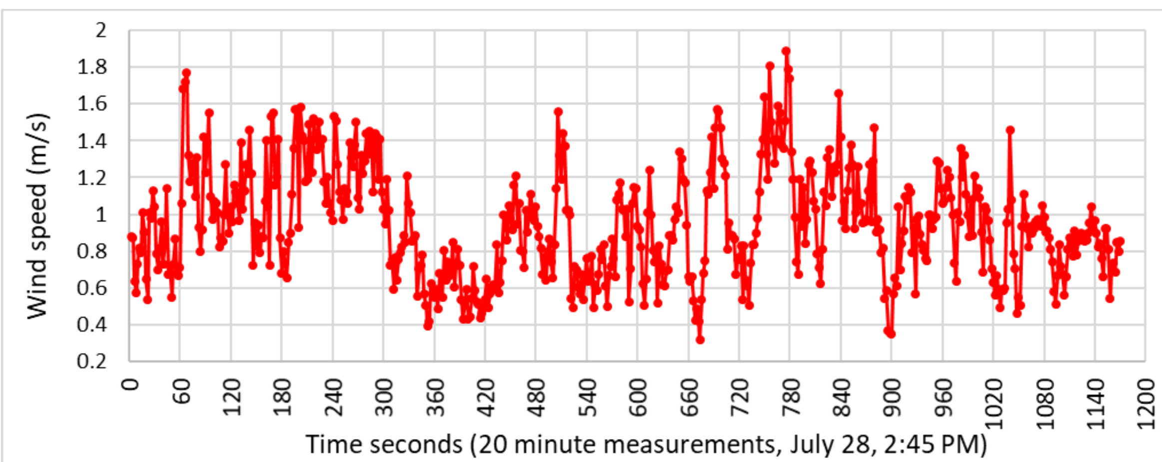


Figure 25. Wind speed variability

Furthermore, designing vertical stacks with solar chimneys at the building core could help enhance the stack effect if connected via ducts to the suites. However, these stacks raise fire concerns because they decrease the building compartmentalization and may promote the spread of smoke and fire. As mentioned before, despite the limitations, natural cooling can reduce reliance on mechanical cooling to only the short periods of the year where peak temperatures occur. Maximizing the effectiveness of single-sided ventilation requires designing operable windows that are tall and narrow, as opposed to short and wide. Research has shown that designing two tall operable windows at opposite sides of the envelope enhances wind induced natural ventilation (Zhong et al. 2022). An alternative is to design four smaller operable windows located at the four corners of the envelope wall.

However, effective natural ventilation can only be achieved if sufficient amounts of air enter though the windows. Figure 26 shows outdoor air temperatures during three summer days in 2021. In theory, natural ventilation could be used during these three days because the maximum temperature of the day is about 29°C. However, at warmer temperatures, the stack effect is minimal. Therefore, wind becomes the main natural ventilation force. During the night, however, the outdoor temperature drops, enabling natural ventilation to cool the suite and the building thermal mass. Figure 26 clearly shows that natural nigh-cooling is a feasible mechanism to cool the suite to enable a good nighttime sleep, and prepare its thermal mass for the following warm day. However, a large WWR will cause the thermal mass to gain heat rapidly during the day, because windows have virtually no thermal mass and their temperature fluctuates rapidly with the outdoor temperature and almost instantly when under the sun.

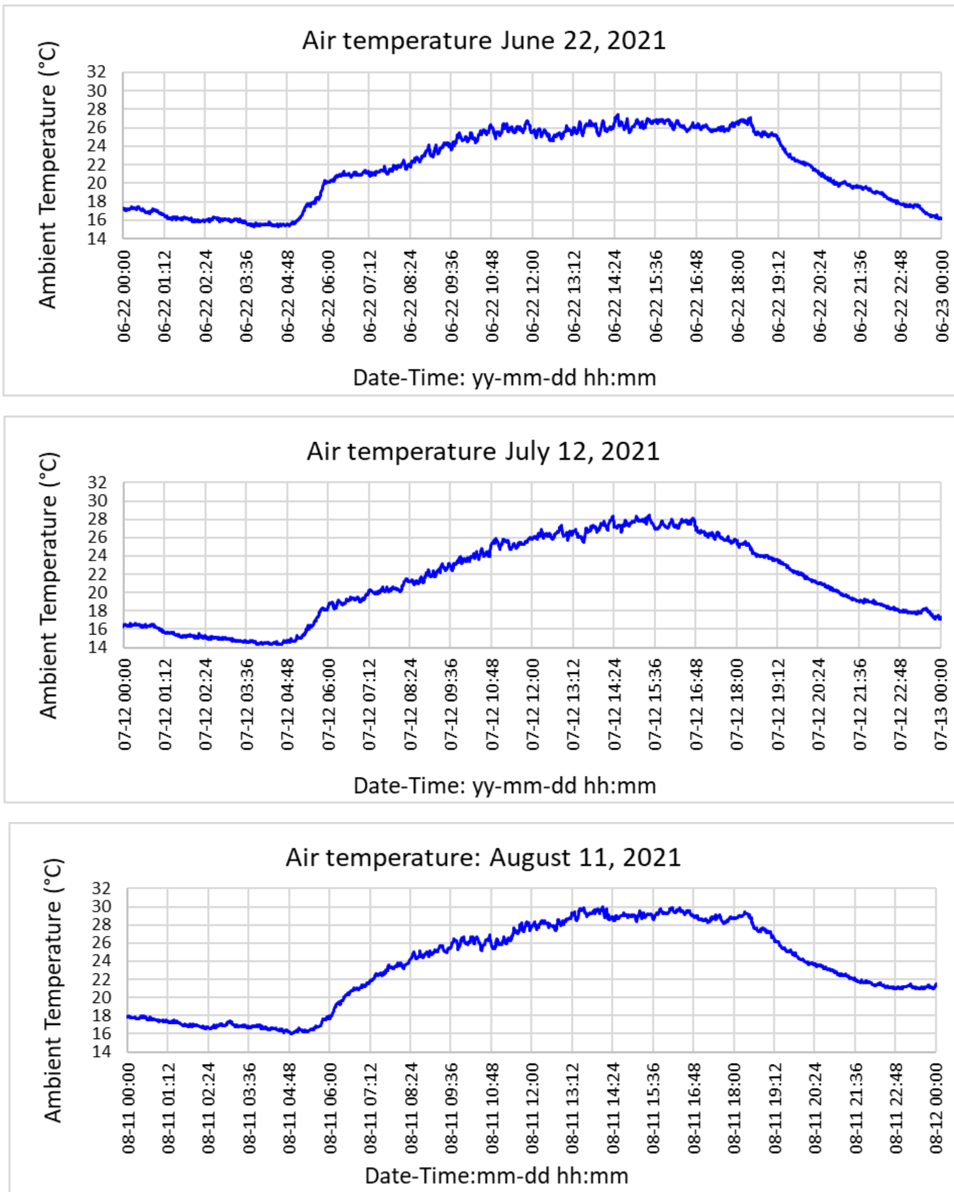


Figure 26. Outdoor temperatures in summer days in 2021

Wind, is highly dynamic as can be seen in Figure 27, where the wind speed and direction vary significantly during a day. Furthermore, Figure 27 shows hourly data, whereas in Figure 25, where the measurement interval is 2 seconds, the wind speed varies every second. Studies demonstrate that wind and stack effects may reinforce or oppose each other (Alloca et al. 2003).

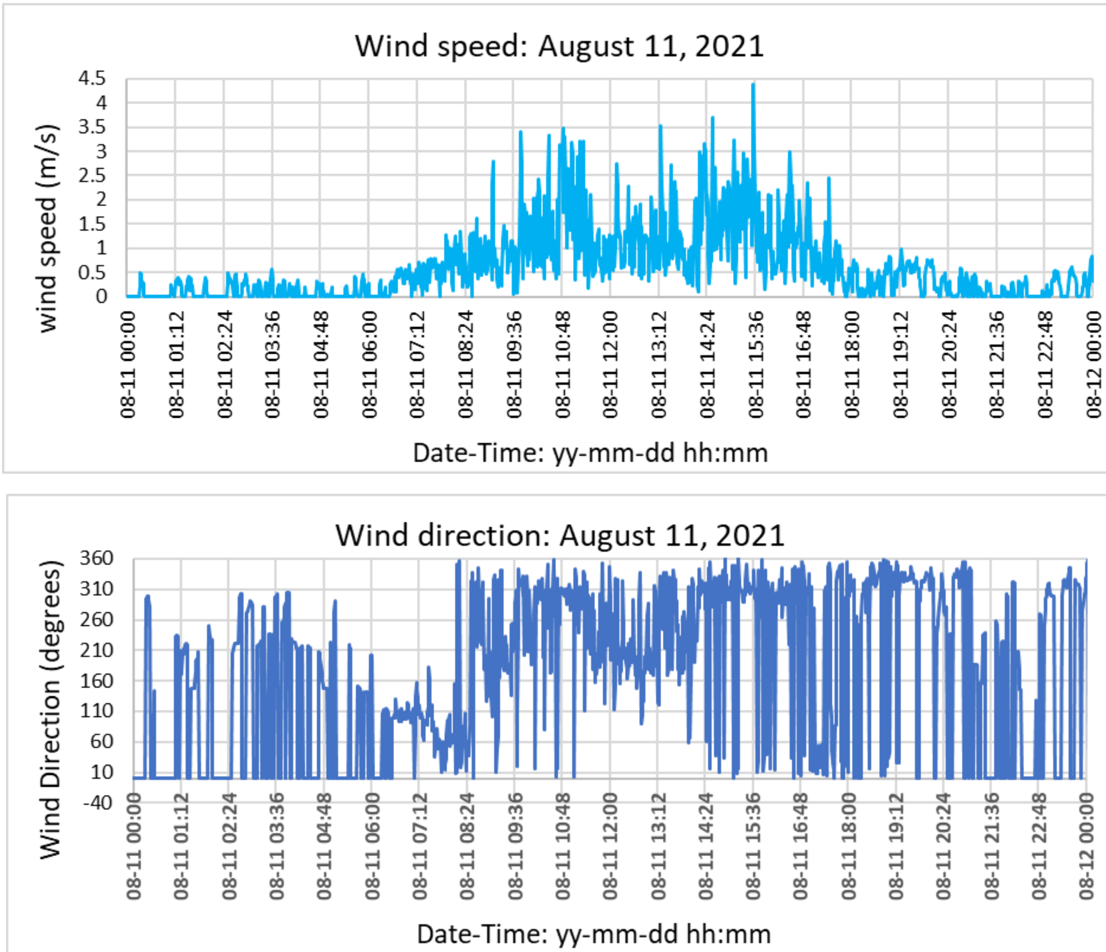


Figure 27. Wind speed and direction variability in August 11 of 2021

When natural ventilation is not strong enough, room fans can compensate to enhanced convective body cooling if the indoor temperature is not warmer than the outdoor temperature. Figures 28, 29, and 30 illustrate a comfort study using the CBETool (https://comfort.cbe.berkeley.edu/) developed by the Center for the Built Environment in UC Berkeley. The Figures show thermal comfort bands using the adaptive thermal comfort model (Mora and Bean 2018, Mora 2019) that is applicable when occupants are able to adapt to the weather conditions by changing clothing, using a fan, drinking cold/hot drinks, moving to a cooler area, opening/closing windows, etc. Figure 28 shows that natural ventilation can be used for natural cooling up to 29°C, as long as the indoor operative temperature is not higher than the outdoor air temperature. In Figure 28, natural ventilation typically produces indoor air speeds of 0.3 m/s according to adaptive comfort field studies in buildings. A room fan can produce indoor air speeds of 0.6 m/s or higher around occupants, which extends the comfort zone as illustrated in Figure 29.

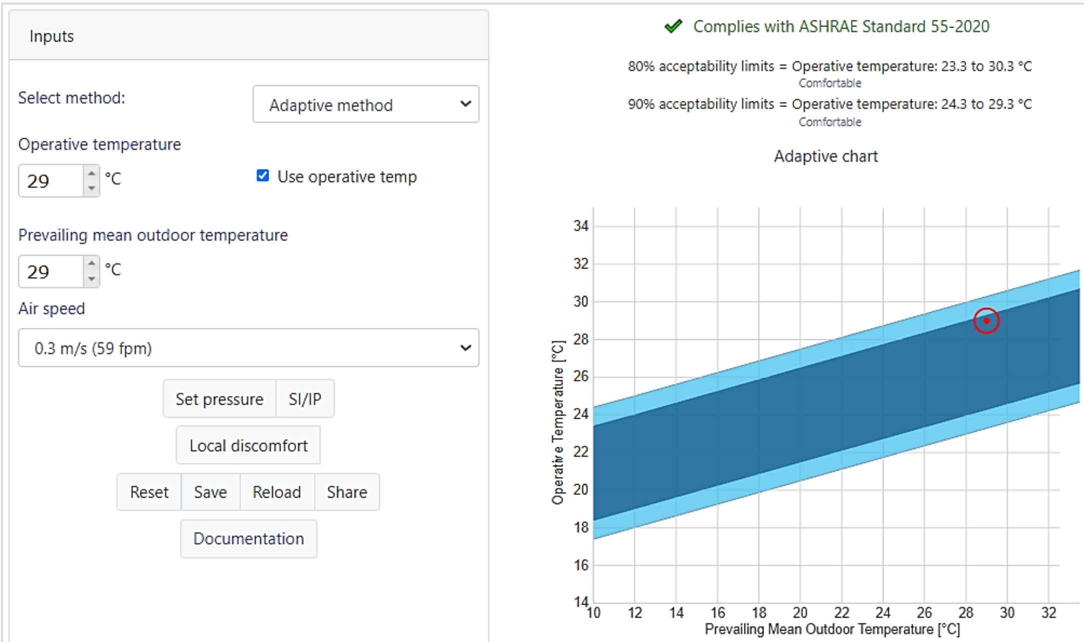


Figure 28. An indoor operative temperature of 29°C is acceptable if occupants can adapt thermally

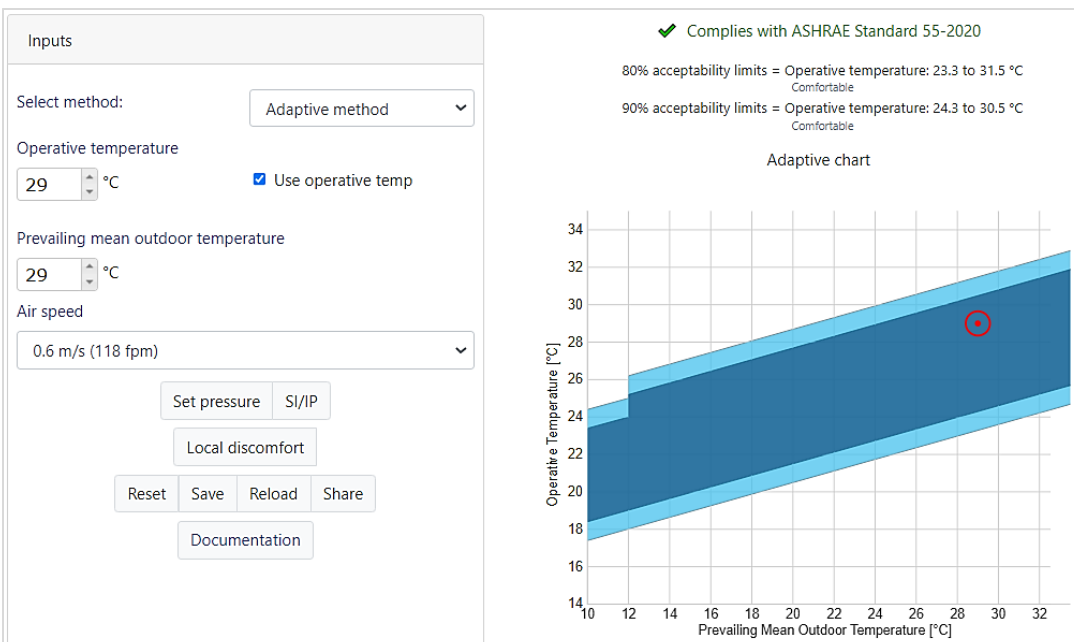


Figure 29. Increasing the air speed to 0.6 m/s using a fan can further extend the thermal comfort bands

However, Figure 30 shows that natural ventilation is ineffective, even with an increased air speed of 0.6 m/s, when the indoor operative temperature is higher than the outdoor temperature, in which case the suite will overheat. This occurs when solar gain increases the temperature of the interior window surface, as well as the temperature of the irradiated indoor surfaces. Therefore, we can assume that Figures 28 and 29 apply to north-facing windows, while Figure 30 applies to other windows directly facing the sun, without any effective shading to control direct solar gain.

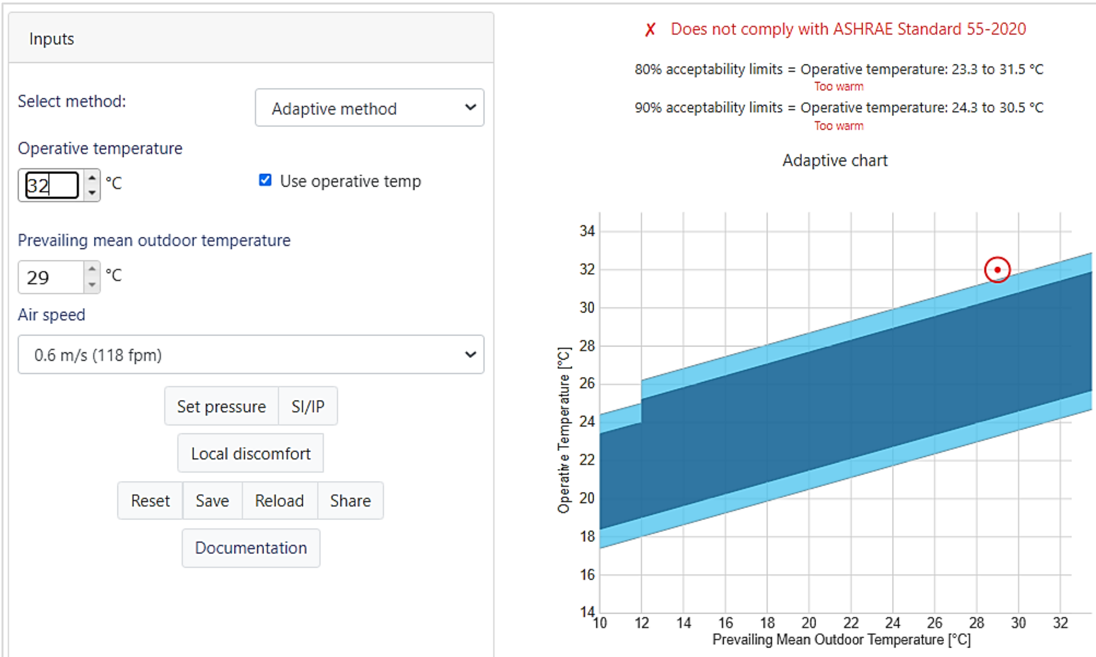


Figure 30. Hot surfaces under the sun can increase the indoor MRT and result in thermal discomfort

Figure 31 shows that even increasing fan speed up to 1.2 m/s, at the occupant level, adaptive thermal comfort cannot be achieved under such high solar gain conditions. In this conditions, external shading is the only solution.

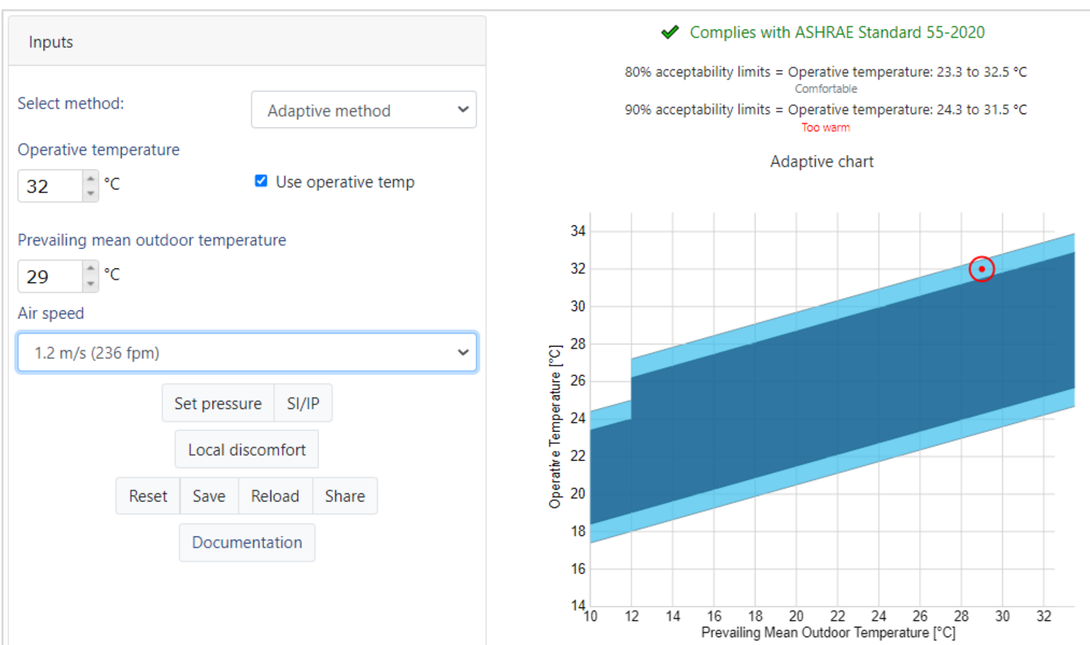


Figure 31. Even increasing the fan speed to 1.2 m/s is ineffective under high radiant thermal conditions

As discussed earlier, extending the natural ventilation range, by assuming human adaptive behaviors, is only applicable to healthy and abled occupants. For occupants that are physically or mentally impaired, or occupants that are vulnerable to warmer conditions, or occupants that have little tolerance for higher temperatures the human thermal balance, PMV model is applicable (Mora and Bean 2018). Figure 32 shows that under warm conditions with a typical room air speed of 0.1 m/s occupants' thermal comfort is barely achieved (Case a). Natural ventilation increases air speeds to about 0.3 m/s according to field studies (Case b), which clearly achieves comfort conditions for the occupants. However, if solar gain increases the interior surfaces temperatures, the room radiant temperature could reach 29°C (Case c), which can be compensated by increased air speeds around the occupants of about 0.6 m/s, using a room fan.

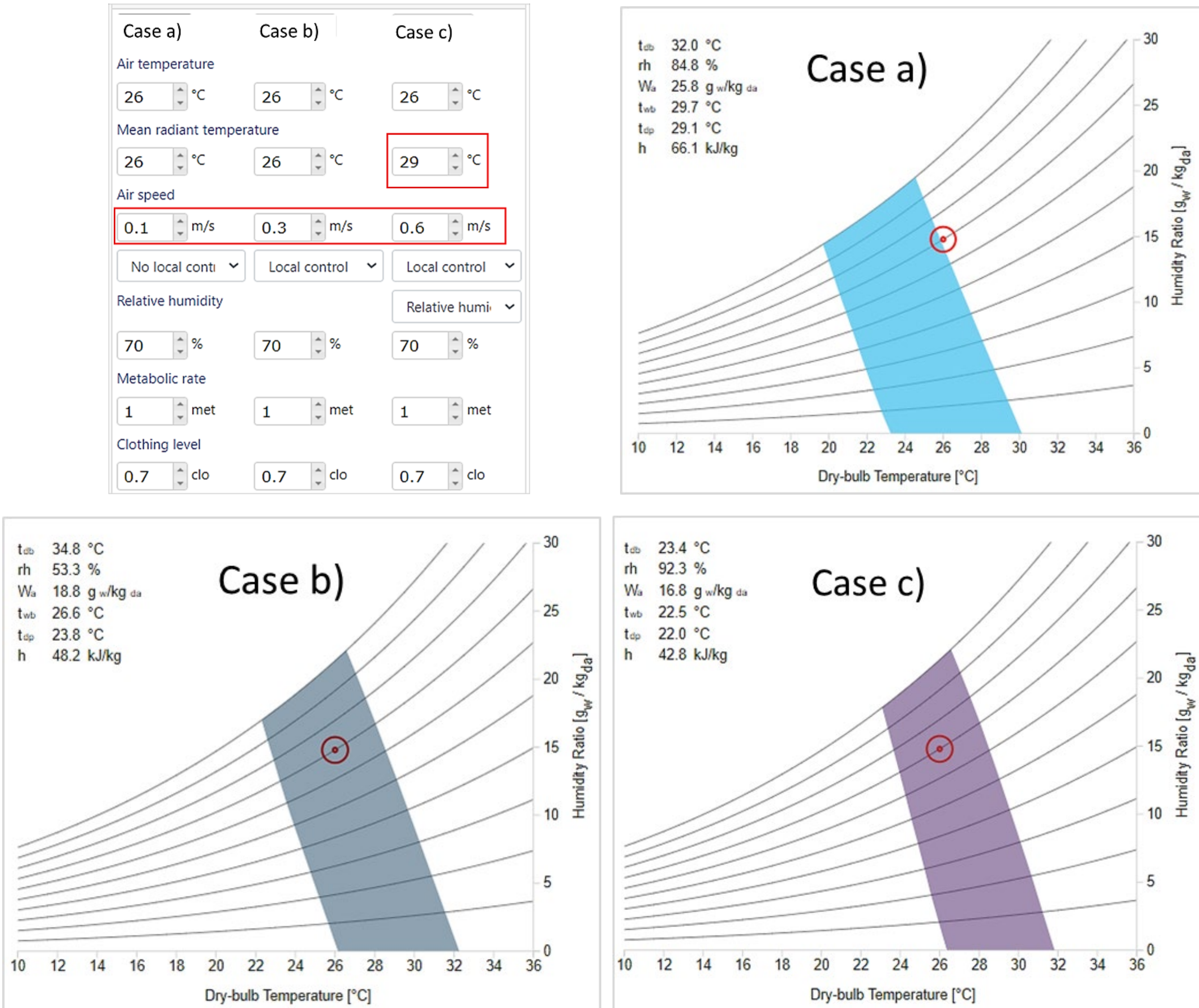


Figure 32. The effect of radiant temperature and air speed on thermal comfort using the PMV model

The analyses above are steady-state and assume indoor air, radiant temperatures, and airflows. More detailed analyses would require dynamic simulations to be conducted. These can use dynamic thermal models of archetype suites. To be useful for thermal comfort analyses, these models should enable calculating hourly indoor air temperatures and radiant temperatures, while considering window solar gains, window operation, natural ventilation, and the suite thermal mass. The key factors to be considered by such models are illustrated in the Figure 33 below. From the factors indicated in Figure 33, the ones that are more difficult to predict are the human factors, and the ventilation airflows. Unlike with mechanical cooling or heating, where the impact of humans on heating and cooling is limited to a thermostat set point, natural ventilation provides humans with a higher level of control over its operation, which also depends on their level of tolerance and adaptability for higher temperature fluctuations. Furthermore, the effectiveness of natural ventilation also depends on the proactive adaptive behaviors of occupants to close blinds when solar radiation is more intense, ventilate at night to maximize natural night cooling, use fans to enhance convective cooling, and remain hydrated.

As demonstrated with the PMV and adaptive thermal comfort analyses, fans can increase air speeds at the occupant level to up to 1.2 m/s, to help extend the thermal comfort bands. A study by Malik et al. (2022) in Australia's demonstrates that indoor fans can raise the temperature threshold of heat discomfort that is the predominant driver of air conditioner use. Furthermore, the authors demonstrate that the widespread adoption of fans to elevate the temperature at which air conditioner units are turned on has the potential to reduce energy demand and emissions attributable to air conditioner use by up to 70–75%.

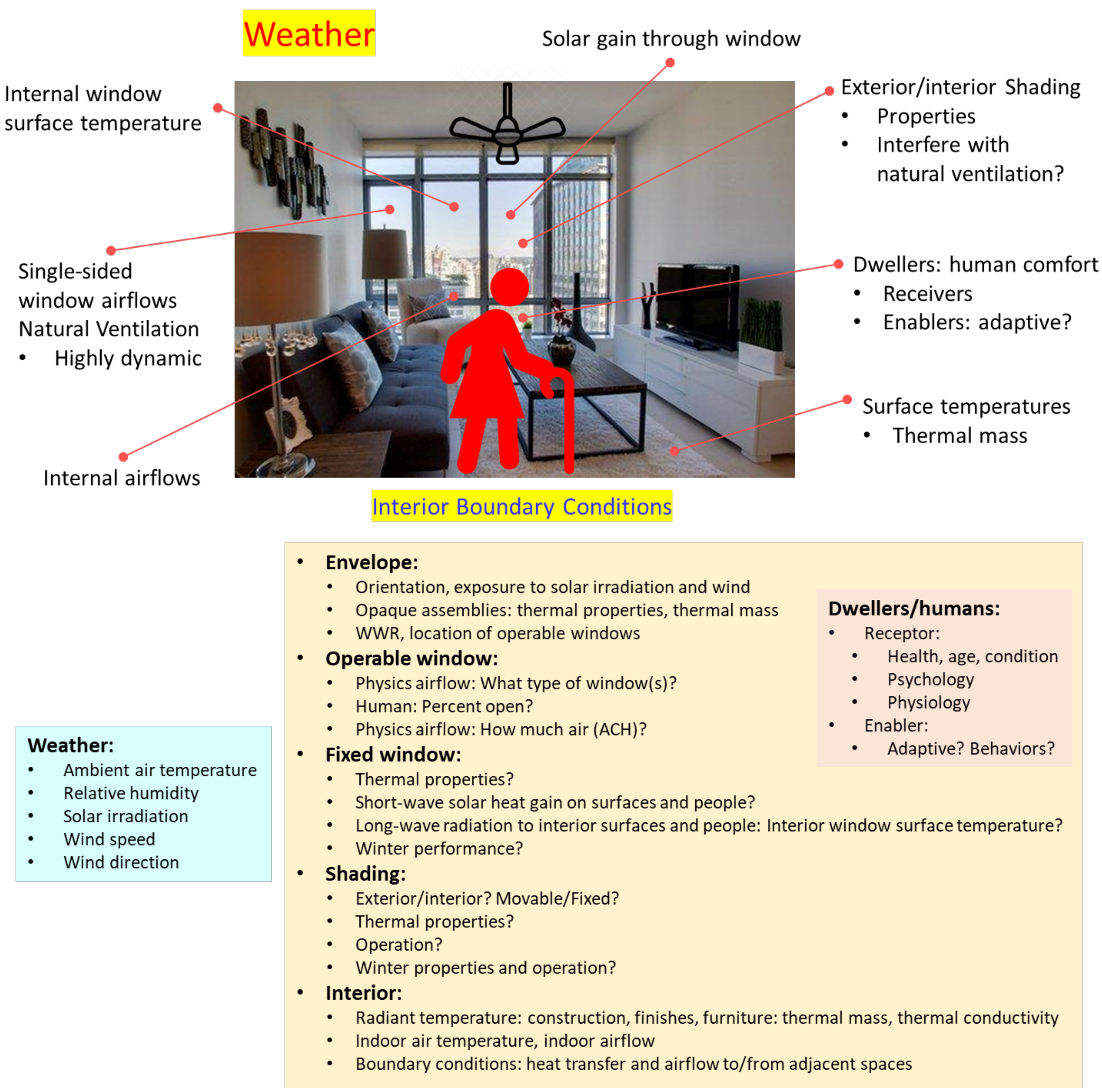


Figure 33. Complexity of factors to be considered in natural ventilation design

The human factors affecting thermal comfort can be categorized as: physiological, psychological, and thermal adaptability factors. A study by Shünemann et al. (2020) concluded that the heat exposure of inhabitants is strongly affected by their actions, not only by window ventilation, but also by their lifestyle, duration of presence and mobility. As discussed by the authors, dwellers' use of ventilation has an enormous influence on the overheating risk of the dwelling, which concluded *that "there is still an enormous knowledge gap in the evaluation of inhabitant behaviour."* Another study by Miller et al. (2021) on resilient cooling concluded that resilient cooling strategies must start with *"individuals, households, and communities as active agents in managing their own exposure and vulnerability, and in the selection and development of indicators that enable them to track progress towards resilience."* An overheating study in London care homes (Gupta et al. 2021) concluded that there is a need for overheating metrics for care homes, coupled with field studies to gather empirical data.

- **Physiological factors** involve the body thermoregulatory response to the environmental conditions to maintain thermal comfort. However, extreme conditions can lead to discomfort and even sweating and shivering. Buildings are not designed for occupants to experience thermal discomfort. But if occupants are able to adapt, they can extend the indoor temperature bands to wider temperature ranges and still remain comfortable.
- **Psychological factors** are more difficult to predict; they depend on the level of thermal expectations by the occupants. In general, occupants' thermal expectations in turn vary depending on their economic, social, and cultural background. Research has shown that "green conscious dwellers" tend to make greener choices on their homes, including thermal adaptation to the outdoor weather. However, our thermal expectations also depend on the type of building. In the office we need to be productive, therefore we expect a narrow band of indoor temperatures for comfort. At home, however, we are more "in-control" of the thermal environment, and we are willing to tolerate wider temperature fluctuations, if we are able to adapt thermally.
- **Thermal adaptability factors** refer to the actual individual's capacity for thermal adaptation, which can be impaired mainly by the physical and health condition of the individual, and by individual's age (e.g. an elder, a newborn). Physically and mentally impaired individuals have reduced capacity for adaptation (Mora and Meteyer 2019).

In some jurisdictions that heating and cooling equipment be interlocked with windows so that the equipment automatically turns off or resets heating and cooling set points when windows are open (ASHRAE 2022).

Figures 34 and 35 show dynamic thermal modeling results from a MURB suite in Vancouver, facing south (Figure 34) and facing north (Figure 35). Weather data used for the simulations was obtained from a BCIT weather station in 2020. The window to wall ratio (WWR) is 80%, the window is a double-pane window with thermal transmittance of 0.7, and the suite thermal mass is 80 kJ/m^2-K. The model uses a window opening algorithm that opens the window deterministically depending on the indoor-outdoor temperature differences, which oversimplifies the human window opening/closing behaviors. The model considers the key parameters in Figure 33 above, except movable/dynamic exterior shading. The model allows obtaining indoor surface temperature as well as the interior temperatures of the temperature of the glass pane. The adaptive comfort bands are not shown in Figures 34 and 35; however, Figure 34 shows that the operative temperature (weighted average of the radiant temperatures from the window and other room surfaces and air the temperature) reaches the upper limit of adaptive thermal comfort, which is about 29°C, whereas Figure 35 shows that the operative is well within both the adaptive and the PMV comfort bands. Reducing the window thermal transmittance to 0.3 or even 0.2 will significantly reduce the solar gains and the internal surface temperatures. However, it will also reduce solar gains in winter.

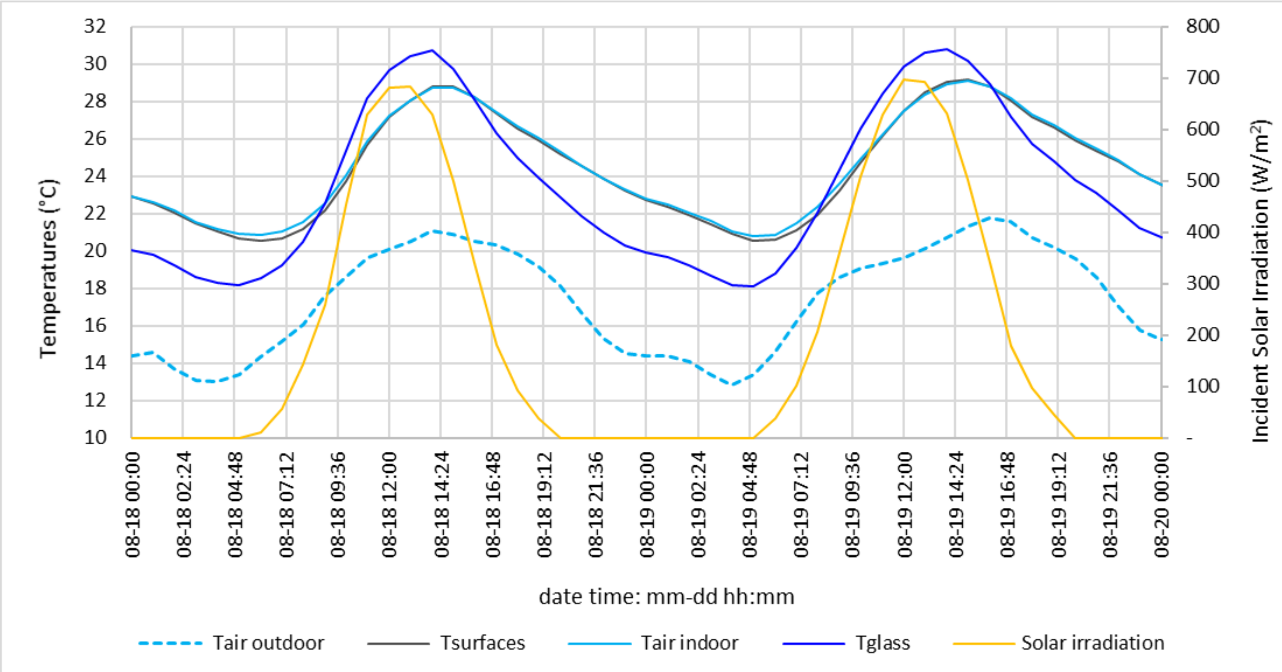


Figure 34. Suite temperatures using a dynamic room thermal model for a south-facing suite

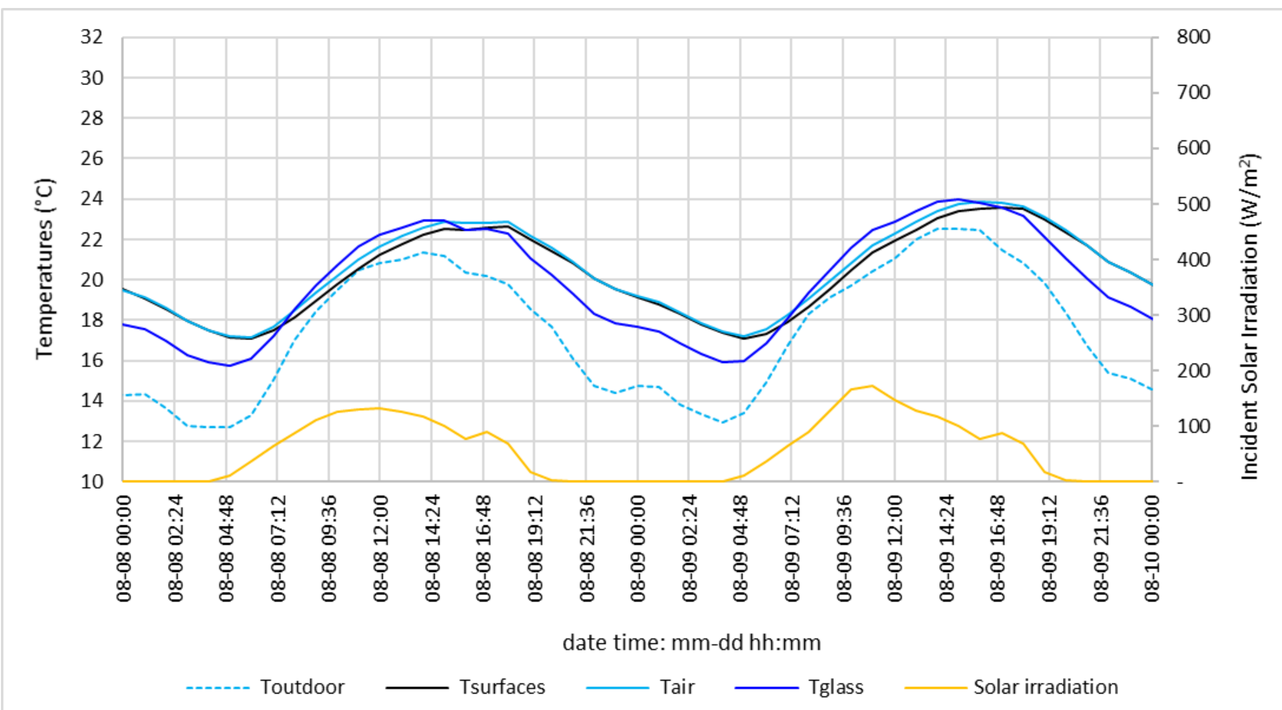


Figure 35. Suite temperatures using a dynamic room thermal model for a north-facing suite

Thermal comfort metrics are available that rely on results, like the ones above, from dynamic thermal simulations as inputs to calculate yearly exceedance hours (EH) over the thermal comfort limits. The most well-known metrics are presented below:

- *ASHRAE Standard 55-2021 (Adaptive Thermal Comfort Model):*
  - Exceedance hours: outside the comfort zone (< 3%)
- *UK-CIBSE TM52 (ISO 7730 / EN 15251):*
  - Exceedance hours: exceed comfort limits by 1 degree or more (< 3%)
- *UK-CIBSE TM59 (residential):*
  - Sleep quality may be compromised at temperature above 24°C
  - Peak bedroom temperatures should not exceed and absolute threshold of 26°C
  - Living rooms, kitchens, bedrooms follow TM52 exceedance hours criterion
  - Bedrooms: 10 PM to 7 AM: not exceed 26°C for more than 1% of occupied hours (> 32 hours fails)
- Germany DIN 4108-2:
  - Overtemperature degree hours (TDH): describes the cumulative product of exceedance time and exceedance magnitude of the temperature over one year, given in Kh/year (Kelvin-hours/year). The critical threshold of TDH is defined to be 1200 Kh/year according to DIN 4108–2

Overheating occurs when indoor temperatures exceed the limits of thermal comfort and human body thermal stress is experienced. Under these conditions, mechanical cooling becomes the only mechanism that can guarantee occupants' thermal comfort. To save energy in the climate of Vancouver, mechanical cooling should be used only to help occupants cope with the extreme temperatures beyond the thermal comfort bands. For example, Figure 36 below shows simulation results on a north-facing MURB suite during the extreme conditions during the "heat dome" days in 2021. Based on the adaptive comfort model, only 7 days would require reliance on AC, roughly when the indoor operative temperature is above 29°C, the rest of the days are at the adaptive threshold, but night cooling and the use of fans can help cope with the high temperatures. However, based on the PMV model (for occupants that cannot thermally adapt), AC would be required for all days, except for the first one and the last one.

Under extreme conditions, such as the "heat dome", the body loses its capacity to dissipate heat by convective cooling. This happens when the ambient operative temperature approaches the mean skin temperature of 35°C under warm ambient conditions. Under such conditions, evapotranspiration becomes the most important cooling mechanism for the human body. However, evapotranspiration becomes less effective under high humidity conditions (wet-bulb temperature about 35°C), which will cause excessive sweating to accumulate and may lead to body dehydration. Therefore, AC becomes the only effective cooling mechanism.

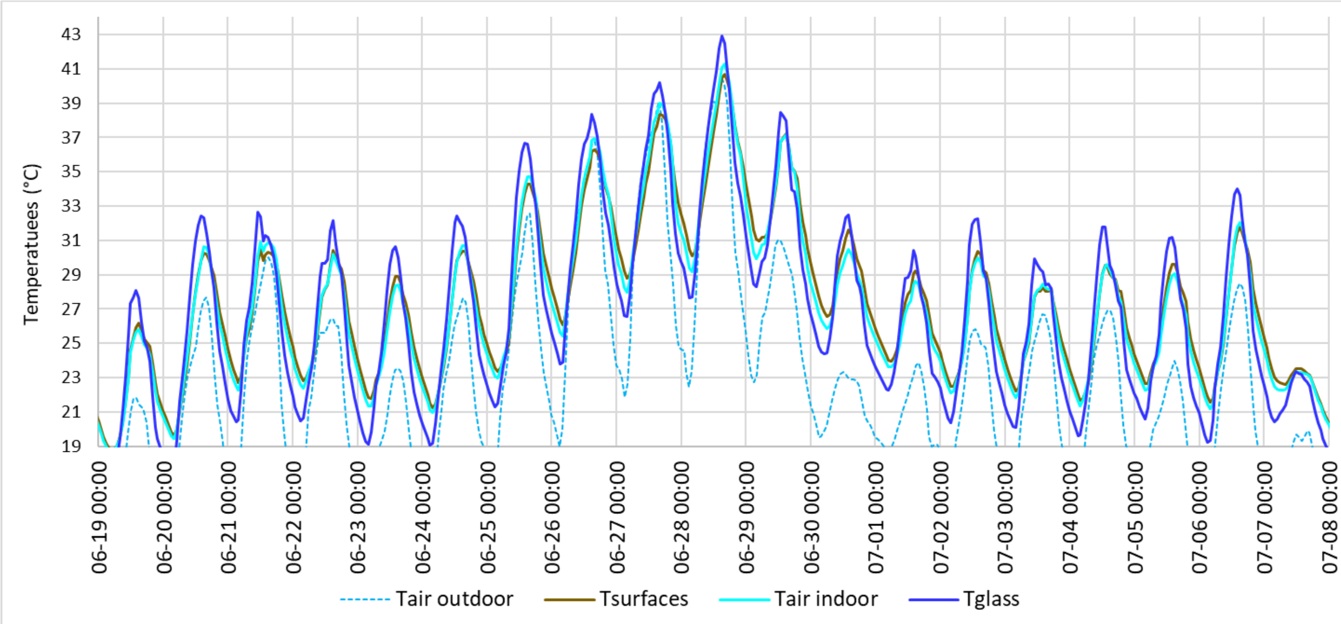


Figure 36. Suite temperatures using a dynamic room thermal comfort model under the heat dome phenomenon

The adaptive thermal comfort limits are ultimately dictated by the individual's ability to thermally adapt (i.e. physiology, psychology, and thermal adaptability). Psychological factors further complicate the accurate prediction of overheating and its repercussions on energy performance. When facing thermal discomfort, humans tend to seek thermal pleasure, which often results in excessive mechanical cooling, i.e. overcooling. Furthermore, once thermal pleasure is achieved, humans tend to want to remain in this condition for as long as possible even the entire summer, which defeats the intended energy saving targets. Readers interested in learning more about human thermal comfort in buildings and its prediction are encouraged to read Mora and Bean (2018), and Mora (2019).

4.5.9 Cook stove/range hood ventilation source control

Most residential ventilation standards do not include requirements on the kitchen range hood pollutant source control. Instead, they prescribe kitchen ventilation requirements, e.g. the ASHRAE Standard 62.2 requires either an intermittent ventilation rate of 50 L/s (100cfm) or a continuous air exchange rate of 5 Air Changes per Hour (ACH) for the kitchen (Rojas et al. 2011). The elimination of pollutants at the source is the most effective strategy for improving indoor air quality, thus avoiding the chance of migration of harmful pollutants from the cooking process. Research is needed for energy-efficient ventilation systems to deal with cooking contamination (Zhao et al., 2020). The exposure to cooking pollutants can be significantly reduced using efficient ventilation systems with source-control devices such as range hood and fume extractor. The range hood is the most effective ventilation strategy to remove the cooking contaminants from its source. A range hood's function is to capture and vent airborne contaminants out of the kitchen. Many factors affect the performance of the cooking range hood. Obviously, higher exhaust hood performance can be achieved using higher fan speed (Singer *et al.* 2021). However, the movement of the air in front of the hood can result in the lower performance of the range hood (Dobbin *et al*., 2018).

As noted by Iain Walker from LBNL (2021) *"one thing is to have a range hood in your home and another thing is to use it".* Walker adds that most households do not have the habit of using the range hood exhaust. For this reason, LBNL is testing automated range hoods that operate on demand based on PM2.5 measurements. The hood adjusts the fan speed based on PM2.5 concentration at the hood, and includes a timer for delayed shut-off to take care of lingering odours. Noise is often a leading cause for people not using the range hood.

Following are the leading causes for reductions in the kitchen exhaust hood performance.

1. **Disturbing air Flows.** The efficiency of the hood is strongly affected by the local drafts and movement in front of the exhaust hood (Liu et al., 2020).
2. **Hood style and geometry.** The performance of various style hoods varies based on its shape, angle of the hood, Depth of hood, the side panel position etc. (Pietrowicz et al., 2018).
3. **Mounting height.** The hood placing far away from the burners will cause a chance for leakage of the pollutants (Han et al., 2019).
4. **Hood/stove location.** Placing the range hood close to the wall has higher capture efficiency than the island type exhaust hood (Han et al., 2019) (Pietrowicz et al., 2018).

The range hood capture efficiency (CE) is the fraction of cooking pollutants eliminated by the hood without mixing with the indoor air (Kim et al., 2018). The capture efficiency (CE) of the range hood defines its ability to extract the cooking pollutants. CE of the hood is influenced by the exhaust airflow rate and duration of operation during and/or after cooking, the fraction of stovetop covered by the range hood, and the height of the hood placed above the kitchen range (O'Leary, Jones, et al., 2019), (Southern California Edison, 2004). For instance, the kitchen exhaust hood operated fifteen minutes after finishing the cooking process showed a similar CE when the fan speed of the exhaust hood increased by 100 cfm while cooking (Dobbin et al., 2018). Currently, there is no standard or rating system for CE of residential cooking exhaust hoods. Research evidence shows that range hoods can efficiently deal with the kitchen pollutant issues with low energy demand (O'Leary et al., 2019). In the study conducted by O'Leary et al. (2019), it was suggested that using the range hood with 50 % CE during cooking and 10 minutes after cooking can deal with major indoor pollutant issues.

ASHRAE 62.2 requires an airflow rate of 50 L/s (100 cfm) for kitchen range hoods under demand/intermittent operation (Delp & Singer, 2012). The Heating and Ventilating Institute (HVI) provides guidance on minimum and recommended ventilation rates per linear foot of range based on the hood design, width of hood against the wall and location of range: either against a wall or in an island. For a standard residential stove against the wall the HVI provides a recommended rate of 250 CFM, and a minimum rate of 100 CFM (HVI 2021). Energy Star prescribes a fan efficiency of 0.21 Wh/m^3, and a maximum airflow of 500 CFM (235 L/s). All vent hoods make some noise that may prevent people from using them. ASHRAE Standard 62.2 recommends a sound level less than or equal to 3 sones, and Energy Star a sound level of 2 sones. The sound level of the range vent can be reduced in several ways: 1) design hood for better capture efficiency to better capture pollutants and optimize the capacity of the fan, 2) select a fan with quieter noise rating, 3) have a remote inline fan, and 4) use a silencer, 5) select "quieter" grease filters, 6) optimize exhaust vent ducting, and 7) have an exhaust fan with variable speed controls.

From a suite pressure management standpoint, the following five generic types of cooking ventilation systems are available.

System 1: Exhaust range hood with no makeup air

Exhaust range hoods are common in older leaky houses. However, this system is no longer considered acceptable because it can produce significant envelope pressure differentials as indicated in section 5.2. Direct exhaust range hoods cause heavier pressure load in the suite. The negative pressurization in the house leads to uncontrolled migration of indoor pollutants, and may even lead to damage of the envelope.

System 2: Recirculation hood

Recirculation hoods are favourable based on first costs and energy conservation. However, according to Borsboom et al. (2016), exhaust hoods are preferred to recirculation hoods because recirculation hoods re-emit a large fraction of pollutants back into the occupied space. Better recirculation hoods are coming onto the market that include particle filters and systems to capture pollutants and odour, but there are currently no systems that effectively handle all cooking pollutants (Borsboom et al. 2016). Research related to the efficiency of recirculating hoods is lacking (Rojas et al. 2017).

System 3: Exhaust range hood with supply/makeup air

If makeup air is not supplied when the range hood is operated during cooking, the performance of the range hood is lowered (Cao et al. 2017). Part 9 of the BC Building Code suggests using a cooking makeup air system to maintain balanced operation when the exhaust range hood is enabled. The makeup air supply location influences the performance of the range hood. The makeup air supplied in close proximity causes local turbulence, which interferes with capture efficiency (Fisher et al., 2015). Simultaneously, well-designed make-up air systems performed well in many studies and increased the capture efficiency with a lower exhaust flow rate (Han et al., 2019).

Cao et al. (2017) conducted laboratory experiments with local upward makeup air and downward makeup air around to stove to contain the cooking smells above the stove, and compared cooking-generated particle exposure levels with makeup air from an open window. The researchers concluded that both upward and downward makeup air can reduce PM exposures by 2 to 3 orders of magnitude compared to the open window, if the makeup air is well designed. Kim et al. (2021) conducted experiments in an experimental house with various types of kitchen ventilation systems. The researchers concluded that a local linear supply diffuser at the ceiling level is the most effective because it acts like an air curtain that blocks the dispersion of cooking contaminants into the kitchen and adjacent rooms.

System 4: Recirculating range hood + HRV boost when cooking with exhaust at kitchen (Passive House Standard)

The Passive House Standard has a strong energy efficiency focus which include increased envelope air-tightness, high thermal insulation, high-performance windows, minimizing thermal bridges, and heat recovery ventilation. However, this standard has not been particularly characterized by being human-centred. To save energy, the Passive House Standard favours the recirculating range hood systems to avoid makeup-air wall penetrations, and resulting increased energy demand due to the thermal bridging and outdoor air (Militello-Hourigan & Miller, 2018). These systems are provided with particle and gas/charcoal filters. Acknowledging the weakness of the recirculating system, an HRV exhaust is placed at the kitchen, and the HRV is provided with boosting capacity to enhance pollutants' removal on demand. However, a study by Militello-Hourigan & Miller (2018), concluded that no significant difference was found between operating the ventilators at standard rates and utilizing the temporary boost. By contrast, completely-mixed flow reactor models of select homes showed that installing and using a directly-exhausting range hood reduced peak PM2.5 concentrations by 75% or more.

The absence of direct exhaust compromises indoor air quality as per many relevant studies (Jacobs & Borsboom, 2010). A laboratory study by Jacobs and Borsboom (2017) concluded that recirculation hoods based on carbon and plasma filters remove about 30% of PM2.5, and a fresh carbon filter removed about 60% of the NO2, dropping within a few weeks of cooking to 20%, which indicates the inevitably the filtering performance of recirculation hoods deteriorates over time, and to maintain performance regular filter replacement is required. More attention is needed for harmful indoor pollutants while using the recirculating hoods because the recirculating hoods are not designed to capture all kinds of kitchen contaminants (Rojas et al., 2017). Cooking raises the indoor concentration of PM 2.5, aldehydes, CO, other poisonous gases. These pollutants have very slow decay in the indoor environment even after using the temporary boosting system (Lunden et al., 2015). Cooking events significantly reduce the indoor air quality, and the temporary boosting is not efficient in dealing with the higher concentration of cooking pollutants from frequent cooking compared to direct exhaust hoods.

System 5 (proposed): Suite pressure-balancing HRV

The cook stove exhaust fan is interlocked with the HRV fans to maintain the suite pressures balanced. The range hood fan capacity matches the maximum speed capacity of the HRV, so that when the range exhaust fan is activated it turns the HRV supply fan to its maximum speed and shuts-down the HRV exhaust fan. In this cooking-flush HRV operation mode, the HRV makeup air cascades from the rooms towards the cook stove, and the suite pressure remains balanced. This approach has tow main drawbacks. 1) Given that there is no exhaust air entering the HRV, heat recovery is disabled, and therefore the HRV supplies unheated/uncooled air at higher rates (to compensate for the range hood flow) wasting energy and possibly creating thermal discomfort. 2). The bathrooms' fans are disabled during the cooking-flush operation mode, therefore, the risk of accumulation of moisture and other possible contaminants in bathrooms is increased during cooking.

Shrestha et al. (2019) found that indoor pollutant concentrations could spike for short periods by orders of magnitude above the outdoor level during indoor source-induced events like cooking. The type of kitchen hood had a significant impact on indoor pollutant concentrations. Homes with exhaust type stove hoods had PN0.5-2.5 rates 49% less than homes with recirculating hoods & 55% less than homes with no stove hoods installed.

5 BOUNDARY CONDITIONS – ENVIRONMENT AND HUMAN CONTEXT

5.1 ENVIRONMENTAL CONTEXT

Effects of climate change and outdoor air pollution on indoor air quality are of enormous technical and social importance, as they not only raise questions concerning building regulations and standards, retrofitting, ventilation concepts and smart technologies but are also of relevance to health. (Salthammer et al. 2018)

For many years, outdoor air was considered to be "fresh air". Increased concentrations of air pollutants or higher levels of moisture content in indoor spaces have been controlled through adequate ventilation. This principle still applies in areas with a high outdoor air quality, but not anymore in densely populated urban areas (Salthammer et al. 2018). Current World Health Organization (WHO) reports indicate that persistent air pollution levels are rising in all urban areas, worldwide. For example, 90 % of EU citizens live in areas where the WHO guidelines for air quality for PM2.5 is not met (Asikainen et al. 2016). ASHRAE ventilation Standard 62.1 (ASHRAE 2019) requires since 1973 an investigation of outdoor air quality prior to completion of the ventilation system design, and prescribes outdoor air treatment if the outdoor air quality is unacceptable. However, ASHRAE Standard 62.1 does not apply to individual DUs. The health effects of increased urban air pollution due to traffic and factories are being amplified due to increased urban heat island and climate change (IPCC 2014).

There is growing evidence that projected climate change has the potential to have significant effect on public health. In the province of British Columbia, much of this impact is likely to arise by amplifying existing risks related to rising temperatures and extreme heat, poor ambient air quality, wild fires, and flooding (BC-MECCS 2020). All these risks will have effects on the indoor environment and health of building occupants. On the one hand, due to rising temperatures, people will want to spend more time indoors in mechanically cooled spaces, which will increase the reliance of people reliance on air conditioning, and decrease their tolerance to temperature variations, i.e. thermal adaptation (Roaf et al. 2009). According to the Climate Projections of Metro Vancouver (2016), cooling demand will increase to nearly 6 times what is currently required. On the other hand, poor outdoor air quality will force people to spend more time in air-clean and cool indoor environments, particularly those that are more at risk. In both cases, the reliance on outdoor air for either natural cooling or building ventilation will be questioned, and ventilation will likely be minimized or completely disabled. Even in Canadian cities typically characterized by having clean air, such as Toronto, Montreal, and Vancouver, air quality is highly variable, with consistent high air-pollution pockets, up to 150 m far away from pollutant sources such as busy streets (Evans 2019). Notably, Evans (2019) found that large trucks contribute disproportionately to emissions. Diesel trucks emit black carbon (BC), a complex mixture of chemicals from diesel exhaust.

Prevailing urban pollutants coming from mainly from traffic (light and heavy), industry, gas stations etc. are categorized by BC Environmental Protection and Sustainability (BC-EPS 2022) as indicated in Table 16.

Table 16. Common Urban Pollutants (BC-EPS 2020)

Pollutant	Decription
Toxic gases	Benzene, 1,3-butadiene, acrolein, formaldehyde, PAHs, etc.
Carbon monoxide (CO)	Incomplete combustion of vehicle fuels (gasoline emit more than diesel engine)
Nitrogen oxides (NO_x)	Created during combustion (diesel produce much larger amounts than gasoline engine)
Sulphur Dioxide (SO_2)	Combustion of suphur contained in fuel, mostly diesel engines
VOCs	Unburned or partially burned fuel
Coolants	Refrigerants from vehicles emitted through leaks or during repairs
UFP, PM2.5	Primary from exhaust, and secondary formed from air toxics, NOx, SO2, other VOCs

Another common urban pollutant is ground level ozone (O_3). Ozone is a secondary pollutant that is created by photochemical reactions between nitrogen oxides (NO_x: NO and NO_2) and volatile organic compounds (VOCs). Because ozone is formed in the presence of heat and sunlight (photochemical), it is more likely to reach unhealthy levels on hot and sunny days. Fine particulate matter (PM2.5) is one of the major components of smog. PM2.5 is the pollutant that accounts for much of the adverse health effects associated with outdoor air pollution (EPA 2019). Therefore, PM2.5 is the outdoor pollutant that is used as commonly tracked and monitored to assess the effect of outdoor pollution on indoor air quality.

Climate change will also increase the frequency of episodic high air polluting events, such as forest fires. Drier summers worsen the three major factors that influence wildfire: having dry fuel to burn, frequent lightning strikes that start fires, and dry, windy weather that fans the flames (Flannigan et al. 2009), and make the fire seasons longer (Flannigan 2020). According to Wang et al. (2017) western Canada will see a 50% increase in the number of dry, windy days that let fires start and spread, whereas eastern Canada will see an even more dramatic 200% to 300% increase in this kind of "fire weather."

Indoor exposure to fine particles of outdoor origin

"The overwhelming burden of evidence impugns PM2.5 as the principal air pollutant posing the greatest threat to global public health" (Rajangopalan et al. 2018)

Elevated concentrations of PM2.5 in the atmosphere have been associated with increased morbidity and mortality in the population (Logue et al. 2015). However, studies have demonstrated that exposure to PM2.5 predominantly occurs indoors in large cities (Meng et al. 2005, Ji and Zhao 2015). A study by Van Ryswyk et al. (2014) showed that even though outdoor exposures are higher, they are also short, minutes to a few hours, compared to the less intense but more persistent indoor exposures. A study by Azimi and Stephens (2020) estimates that in the U.S. indoor exposure to PM2.5 of outdoor origin is typically the largest total exposure, accounting for ~40–60% of total mortality, followed by residential exposure to indoor PM2.5 sources (from cooking). A study across the U.S., Europe, China and globally, by Ji et al. (2015), concluded that indoor PM pollution of outdoor account for 81% to 89% of the total increase in mortality associated with exposure to outdoor PM pollution for the studied regions. The study suggests that enhancing the capacity of buildings to protect occupants against exposure to outdoor PM pollution has significant potential to improve public health outcomes.

Canada Air Quality Standards and Health Index (AQHI)

Canadian Ambient Air Quality Standards (CAAQS) are the reference for ambient air quality management across Canada (CCME 2022). These standards prescribe threshold-limiting values (CAAQS TLVs) for selected outdoor air pollutants, based on their potential to impact the environment and human health. They form the basis for the implementation for a Canada-wide Air Quality Management System (AQMS). The AQHI developed by Environment Canada and Health Canada is based on health studies that link the interaction of different pollutants on health risks. The AQHI uses a scale of 1 to 10+, the higher the number, the higher the health risk (EC-HC 2020). The AQHI (Figure 23) is calculated based on the relative risks of a combination of priority air pollutants that is known to harm human health: Ozone (O_3) at ground level, particulate matter (PM2.5 and PM10), and Nitrogen Dioxide (NO_2).

Figure 37. Canada Air Quality Health Index (AQHI)

Metro Vancouver and Lower Frazer Valley (LFV) air quality network

Metro Vancouver manages and regulates air quality in the Greater Vancouver Regional District, under authority from the Province, including an air quality-monitoring network including 23 air quality-monitoring stations, which is part of the Lower Frazer Valley (LFV) air quality network. Table 17 shows the pollutants monitored by the network. The table indicates priority pollutants as those being associated with serious health effects.

Table 17. Pollutants monitored by the Metro Vancouver and LFV air quality network

Pollutant type	Pollutant		CAAQS	AVG	Sources
Gases	Ozone (priority)	O_3	62 ppb	8 h	Secondary pollutant
	Nitrogen dioxide (priority)	NO_2	213 ppb	1 h	Transportation fuel combustion, oil and gas industry, forest fires
	Sulphur dioxide	SO_2	105 ppb	8 h	Oil and gas industry, ore and mineral industries, forest fires
	Carbon Monoxide	CO	13 ppm	8 h	Transportation, forest fires
	Volatile Organic Compounds	VOC			Oil and gas industry, lumber, consumer products (paints, solvents, etc.), forest fires
Particulates	PM2.5 (priority)		25 $\mu g/m^3$ * 27 $\mu g/m^3$	24 h	Forest fires, agriculture, diesel, transportation fuel combustion, home firewood burning
	PM10		-	-	Dust

CAAQS: Canadian Ambient Air Quality Standards 2020, AVG: averaging time, * British Columbia

Metro Vancouver publishes comprehensive regular Air Quality Monitoring Reports showing the air quality issues and trends of the region, as well as more concise Caring for the Air reports for the wider audience.

5.2 HUMAN CONTEXT

"Actions taken by individuals can profoundly influence the IAQ in individual buildings… Negligent or ill-informed behavior by individuals can cause serious harm." (Institute of Medicine [IOM] 2011). Surprisingly, all the local case studies presented by industry experts so far on high-performance residential buildings and existing building retrofits lack a post-occupancy protocol to obtain formal feedback from dwellers. At most, the presenters limit the feedback to positive anecdotal quotes from a few residents. A field study by Patton et al. (2016) on indoor air quality in green high-rise residential buildings reported that low-income dwellers living in high air pollution areas suffer from poor indoor air quality and highest asthma prevalence in the region, in part because they often prefer to leave their windows open, rather than using the AC, to lower the utility bills. The study concludes that it is important to account for indoor air quality as well as energy and environmental impact when deciding whether a building should be considered green. For example, occupant education on air quality through behavioral

interventions or other means could be adopted as an integral green building feature to improve air quality in buildings. In the same study, measurements showed that the large amounts of variability between green buildings may be related to variable outdoor PM mass concentrations between buildings at different locations, and participant behaviors, including incense/candle burning, cooking on gas stoves (particularly with oil), and smoking.

As indicated in Figure 2, occupants play a central role in maintaining acceptable indoor air quality, and affecting the ventilation system performance. In fact, occupants play three roles (Figure 38, Table 18): 1) as contaminant source (emitter, enabler, and producer), 2) as contaminant receptor by being exposed to air contaminants, and 3) as environment modifier by either directly or indirectly affecting the performance of the ventilation system. Each of these roles is a subject of active research on its own. The role of occupants as sources of pollutants is outlined in Chapter 3 of this report. Studying the role of occupants as receptors that are exposed to contaminants is from the realm of medicine. Studying the role of occupants as environment modifiers belongs to the field of behavioural science, which is an active area of research nowadays that spans multiple disciplines. Human behaviors affect the role of occupants on IAQ in many ways as either contaminant sources or environment modifiers by causing or exacerbating harmful indoor environmental conditions (Institute of Medicine [IOM] 2011), or as contaminant receptors by not protecting themselves and other occupants from exposures, e.g. when cooking, cleaning, smoking, etc.

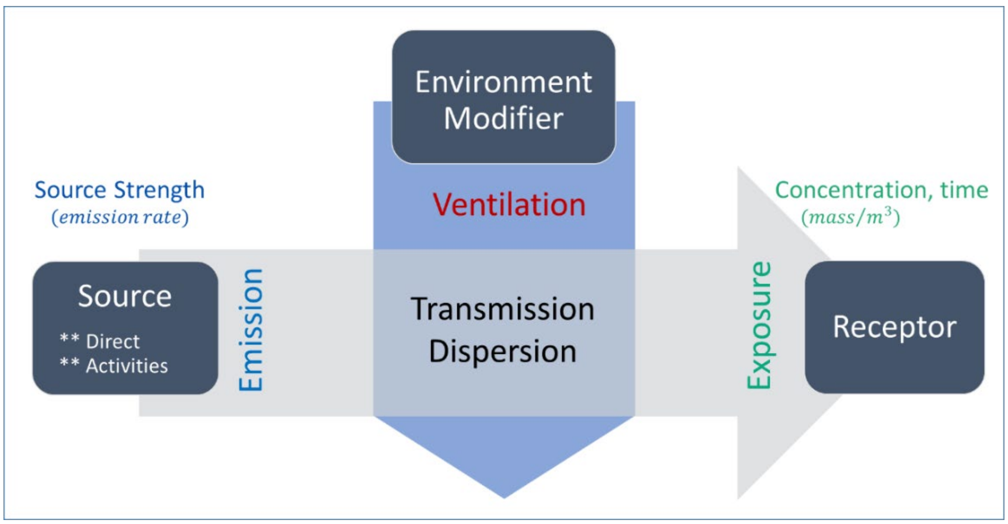


Figure 38. Three roles of occupants on indoor air quality and ventilation of MURB suites

Table 18 gives examples of the IAQ effects of the three roles of occupants on indoor air quality.

Table 18. Occupants' roles in affecting IAQ at home

Role	Examples
1. Source: Emitter: presence Polluter: activities	• Bio effluents, perfumes • Selection of interior furniture, carpets, finishes • Cooking, shower • Excessive cleaning, smoking, use and store pesticides, garbage handling • Clutter, overcrowd
2. Environment modifier Enabler Disabler	• Disable ventilation • Disable/not use cooker exhaust fan • Disable/not use bathroom exhaust fan • Venting/ not venting: open/close windows
3. Receptor Exposed	• Inhaling chemicals: smoking, painting, cleaning

5.2.1 Human as environment modifier

Lin et al. (2017) collected occupant behavior data and indoor air quality data from two smart homes, and found a strong relationship between in-home human behavior and indoor air quality. A study by Guyot et al. (2017) concluded that occupants are rarely aware of the quality of their indoor air, particularly with regard to health issues, and are not proactive to operate the ventilation systems when recommended for optimal indoor air quality or energy efficiency. A study titled "Proposed research agenda for achieving indoor air quality supporting health and comfort in highly energy efficient buildings" Wargocki et al. (2013) identified impact of user behavior with respect to control of indoor environmental quality, as the number one research priority. As part of this research, the authors argue that it is important to investigate the reasons behind certain actions taken by the occupants in buildings, and the motivations to perform these actions. As well as the importance to engage and motivate occupants to be more responsible for the environments in which they live. The question on the level of control to be given to occupants is also raised. One of the solutions proposed in this study is to develop means to influence people's habits to motivate their active involvement in creation of healthy ad comfortable indoor air quality.

Similar to Wargocki et al. (2013), Borsboom et al. (2016) on Technical Note 68 on Residential Ventilation and Health conclude the following: *"The impact of occupant behaviour on the control of indoor environmental quality is clearly assigned the highest priority… Research data indicate that even most advanced policies, technologies and regulations will only be effective if they address occupant behaviour. Consequently, it is strongly encouraged that the focus in future should be on the real reasons that certain actions are taken, and occupants' motivation to perform them, on identification of those aspects of the control of indoor environmental quality in highly energy-efficient buildings that should be delegated to occupants, and to what extent, an on ways of engaging and motivating occupants to be more responsible for the environments in which they live and work."*

Contextual differences exist between residential and non-residential applications that affect the indoor environmental perception, acceptability, and behaviors of dwellers. On the one hand, occupants at home are more in-control, than elsewhere, of all aspects affecting the indoor environment and therefore are free to act upon their preferences. On the other hand, the needs and expectations at home are fundamentally different from those in other buildings. For example, productivity has not been a main concern at home. However, the COVID-19 pandemic may lead to rethinking the concept of occupant productivity at home. Table 19 outlines the contextual factors that affect occupants' indoor environmental quality (IEQ) expectations, perception, acceptability, and resulting behaviors at home.

Table 19. Contextual factors affecting occupant IEQ behaviors at home

Factors	Main variables
1. Personal	• Social, economic, cultural • Education • Age, gender • Health condition
2. Local/site	• Climate, urban, neighborhood • Pollution, noise, wind
3. Building/suite	• Type of building/suite: design, construction, envelope • Performance, quality, leaky, airtight • Condition: maintenance, condensation, plumbing, water leaks, pests • Owned/rented
4. Environmental system	• Noisy/quiet • Responsive • Controls: usable, friendly, accessible, feedback

Table 20, from Raw (2017) groups the household needs and expectations affecting their IEQ behaviors at home. Tables 18, 19 and 20 can be used to help prepare and organize questionnaires and data to study occupants' behaviors at home with three purposes. 1) To learn how to positively influence occupants' behaviors. 2) To inform the development of ventilation technologies that reliably respond to occupants' interactions. And 3) to develop dwellers' archetypes to help tune residential systems for the intended needs and expectations of dwellers.

Table 20. Household needs and expectations at home (Raw 2017)

Needs and Expectations	Examples
1. Comfort	• Thermal, visual, olfactory, acoustic comfort • Relaxation, feeling in control, aesthetics
2. Health	• Hygiene, cleanliness, tidiness, fresh air
3. Simplicity	• Ease, familiarity, accessibility, usability, responsiveness
4. Resources	• Economy, energy, environment, time
5. Social	• Owner, tenant • Appearance, community
6. Safety, security, privacy	• Design, neighborhood

Research has shown that outcomes from residential studies are highly dependent on the types of dwellers and their social and economic background. A literature review by Moreno-Rangel et al. (2020) concluded that indoor air quality in Passivhaus-certified dwellings is generally better than in conventional homes, but both occupant behaviour and pollution from outdoor sources play a significant role in indoor concentrations.

Singer et al. (2020) conducted measurements in 70 single-family new low-energy homes constructed in 2011-2017, built under California building standards and code-required mechanical ventilation. They demonstrated that new homes can be built to stringent efficiency standards while maintaining indoor air quality. Furthermore, the authors found that a combination of code-compliant mechanical ventilation and implementation of a standard that reduce formaldehyde emissions from manufactured wood products resulted in significantly reduced formaldehyde concentrations compared to homes built prior to the standards. However, the authors acknowledged that the sampled households were biased toward higher income and higher education and potentially also toward higher interest in IAQ (since they volunteered to participate in the study). This study limitation emphasizes the role of the human factors on ventilation performance.

A large study conducted by Sharpe et al. (2015), concluded that higher energy-efficient homes are associated with increased risk of doctor-diagnosed asthma in a UK social housing. The study used postal questionnaires and collected data, including property data, residency periods, and household energy efficiency ratings. However, the study also reported the provision of inadequate heating, and ventilation in those homes, as well as the complex interactions between occupant behaviours and changes to the built environment as affected by social demographics and poverty.

Patton et al. (2016), conducted measurements of PM2.5 in two multi-family green buildings, with focus on the effects on occupant behaviours on PM2.5 exposure. The authors compared their results with other studies on PM on green buildings, and found great variability in indoor concentrations. The authors observed several associations of occupant behavior and environmental conditions with PM mass concentrations in a single building. Combustion, particularly cooking on gas stoves and cooking with oil, or burning incense, greatly increased PM mass concentration. Lower PM concentrations were found for closed windows with or without AC, indicating the effect of outdoor air pollution on indoor PM. The authors point out that since green buildings may be newer than traditional buildings and some green building occupants may have self-selection bias, occupants of green buildings may more carefully control their indoor air quality, or at least have higher awareness about air quality issues.

It has been proposed that the modeling and design of ventilation, air quality, and energy performance of dwellings need to be tailored to the occupancy using household profiles. For example, Barthelmes et al. (2016) used low consumer, standard consumer, and high consumer profiles in the modeling of the impacts of occupants' behavior lifestyles on the performance of a nearly zero energy building. Developing dwellers' archetypes has been proposed as an approach for categorizing occupants or household profiles, to help understand their motives and behaviors affecting health, comfort, and energy use at home (Ortiz and Bluyssen 2019). According to Ortiz and Bluyssen (2019), archetypes can be used as part of the design process to develop potential tailor-made lines of action for each archetype: their particular characteristics need to be translated into design parameters, such as interfaces that can give the right feedback to the specific archetype. This document proposes a BC province-wide campaign designed to collect systematically post-occupancy field data on dweller-archetypes characteristic profiles (e.g. family with children, young couple, elder couple, etc.) including contextual factors in Table 19, and needs and expectations in Table 20 (e.g. social housing, high-end multifamily, etc.), along with data on: household size, composition and demographics, time-based room-by-room location/presence, activities, satisfaction, preferences, behaviors, and other relevant parameters to support design decisions that are tailored towards a satisfactory indoor environment for the dwellers. To acknowledge the influences of climate and local factors on household characteristics, the data can then be organized by climate region and specific location.

5.2.2 Human as a receptor (exposure)

Whenever possible, the design of ventilation systems in buildings needs to consider the type and vulnerability of the intended occupants (e.g. senior housing), with carefully consideration for buildings and spaces intended to be occupied by elders, children, babies, and even sick occupants. As explained on section 3.5 Human Exposure and Health Effects, and illustrated in Figures 9 and 26, from a ventilation perspective, reducing human exposure to a pollutant requires eliminating the source or reducing its source strength, and reducing its concentration to "safe" levels through dilution. However, reducing the concentration of pollutants to safe concentration levels requires knowing (sensing) the types of pollutants present, and when they are present, which is not feasible considering the large amount of pollutants that may be present at any given time, and that most may be present for short moments or at very low levels (Chapter 3). This is why researchers have identified priority pollutants to be removed at the source or surrogates, such as CO2 or TVOCs, that can be monitored closely as indicators of adequate ventilation and the likelihood of achieving high concentrations of unknown air pollutants.

5.2.3 Human as an emitter: pathogens (COVID-19) "Behave tight, ventilate right"

Viruses, such as COVID-19 (SARS-CoV-2), are insidious, very subtle but potentially harmful pathogens. Their size varies from 100 nm to 0.1 μm. However, viruses are emitted as droplets of diameter typically > 100 μm agglomerating virus particles, that either drop within 2 m of the source and desiccate to smaller diameter residue, or remain suspended (typically < 100 μm) for at least 30 minutes in motionless air but eventually fall on the ground if the air remains motionless (Tang et al. 2021), or evaporate forming much larger airborne particles of about 2.5 to 5 μm in size (WHO 2020). These airborne droplet residues are called "droplet nuclei". The emission rate (volume/amount and speed) depends on the respiration rate, and on whether the infected person sings, shouts, coughs, or sneezes.

"viruses that are involved in transmission of infection are not generally 'naked'. They are expelled from the human body in droplets containing water, salt, protein and other components of respiratory secretions. Salivary and mucous droplets are much larger than the virus, and it is the overall size that determines how the droplets and aerosols move and are captured by mask and filter fibres." (Tang et al. 2021)

Table 21 summarizes the common wisdom to date, on the COVID-19 modes of transmission. Like with common flu, it is clear that virus particles can remain airborne and be transmitted in small, enclosed, and poorly ventilated rooms (transmission mode 3 in Table 21). The probability of transmission in a room air depends on the source strength (sneezing versus coughing, versus talking, versus yawning, versus breathing), the proximity between the source and the receptor, and the relation between room occupancy and ventilation. Therefore, to minimize the risk of human-to-human transmission, in Table 21, transmission modes 1 and 2 need to be avoided, and transmission mode 3 minimized using proper precautions and protection.

Table 22 shows that the likelihood of airborne transmission of a pathogen depends on the type of pathogen. For example, tuberculosis is only transmitted through the air, but the airborne transmission of COVID-19 through the air is opportunistic, e.g. when many people gather in enclosed spaces with poor ventilation. Due to the opportunistic nature of COVID-19 airborne transmission, mitigation needs combine human controls (i.e. behave tight) and a robust and reliable ventilation (ventilate right).

Table 21. COVID-19 virus transmission mechanisms

Transmission modes	Dose & Contagion Probability	Protection / Precaution
1. Contact (fomites)	High: direct contact & indirect contact	Change behaviours Use gloves Hand hygiene
2. Droplet (short-range)	High: close proximity to source Source strength: sneeze, cough, talk, breathe	Social distancing Wear a mask
3. Room air (long range)	Possible: source strength versus removal rate Proximity to source Ventilation: removal rate, room air distribution	Social distancing Avoid overcrowding Wear a mask Room air filtration
4. Dispersion/HVAC	Low: no evidence of virus transmission by air circulation between contiguous rooms or via the HVAC system	Verify pressure drop at filter, commission, maintain

As illustrated in Figure 9 *"the dose makes the poison"*. For aerosol-based transmission, the dose (viral charge) can be controlled in two ways: by the health condition, level of protection, and proximity of people in enclosed spaces, and by the ventilation system. Therefore, during pandemics, such as COVID-19, the most convenient motto for indoor air quality and ventilation may be **"Behave tight, ventilate right"**.

"…there is a growing body of data in support of the conclusion that air transmission within enclosed spaces plays an important role in the communication of many bacterial and viral diseases, especially those of the respiratory tract." (Robertson 1943)

Table 22. COVID-19 virus transmission mechanisms *(Roy and Milton 2004)*

Aerosol Pathogen Transmission	Description	Example
Obligate	Only mode of transmission: Exhale/cough/sneeze → air → inhale NOT spread by: contact, food, saliva	Tuberculosis
Preferential	Can initiate infection through multiple routes: contact, proximity, airborne Airborne could become dominant	Measles Smallpox Influenza?
Opportunistic	Airborne propagation in favourable environments: Crowded spaces, poorly ventilated confined spaces, downwind of an infected person, unintended paths and pressures (system design, operation, and maintenance)	COVID-19 (SARS-CoV-2)

6 VENTILATION REGULATIONS

The British Columbia Building Code (BCBC 2018) is a provincial regulation that governs how new construction, building alterations, repairs and demolitions are completed. This code establishes minimum requirements for safety, health, accessibility, fire and structural protection of buildings and energy and water efficiency. It applies throughout the province except for some federal lands and the City of Vancouver. BC Building Code 2018 is the latest BCBC version. The Vancouver Building By-law 2019 is based on the BC Building Code 2018. It includes the By-law provisions regulating the design and construction of buildings in the City of Vancouver.

The BC Energy Step Code is an optional compliance path in the BC Building Code that local governments may use, if they wish, to incentivize or require a level of energy efficiency in new construction that goes beyond the requirements of the BC Building Code. The BC Energy Step Code intends to set the path to meet the province's target that all new buildings must be "net-zero energy ready" by 2032. Interestingly, the BC Energy Step Code website includes the following claim *"Studies have shown that high-performance homes are more comfortable and healthier, because they effectively manage temperature and fresh air throughout the building."* Therefore, it assumes that health and comfort are high-performance by-products, not targets. Phillips and Levin (2015) recommend explicitly integrating indoor environmental quality (IEQ) into building energy related initiatives and plans. For example, codes and standards could require documentation indicating the steps to address health and comfort requirements in designs.

Another important BC government initiative, not substantiated in codes, but through incentives is the BC Carbon Neutral Program that set targets to reduce green house gas (GHG) emissions by 40% by 2030, 60% by 2040 and 80% by 2050. Under the Greenhouse Gas Reduction Targets Act, B.C.'s provincial public sector organizations must achieve carbon neutrality each year by measuring their emissions; planning and taking action to reduce emissions where possible; offsetting remaining emissions; and reporting to the public on these efforts annually. The 2018 BC Housing Carbon Neutral Report indicates major initiatives to achieve carbon neutral targets such as energy conservation, green building technologies, building innovation and energy efficiency in new construction, and building resiliency.

As seen above, none of these regulations addresses explicitly indoor environmental comfort and health.

However, as part of the net-zero energy and carbon neutral programs, the province incentivizes the use of green building rating systems such as LEED, and high-performance building standards such as the BOMA BEST (Building Owners and Managers Association's Building Environmental Standards), and Passive House Standards. These rating systems and standards prescribe high-performance targets intended to provide healthier and more comfortable indoor environments. The WELL Building Standard (WELL), a health-related standard, established in 2016 by the International WELL Building Institute (WELL 2020), prescribes stringent air pollutant control limits, enhanced air filtration and increased ventilation rates over those prescribed by ventilation standards. Stringent indoor environmental quality standards contribute to improving indoor environmental health, but are criticized by being costly to achieve in typical buildings.

6.1 RESIDENTIAL VENTILATION

Residential ventilation in MURBs is regulated by the British Columbia Building Code (BCBC 2018), as follows:

- Ventilation systems serving only one dwelling unit (DU). Part 9 - Housing and Small Buildings, Section 9.32. Ventilation.

- Ventilation systems serving MURBs, the BCBC refers to ASHRAE Standard 62.1 Ventilation for Acceptable Indoor Air Quality" to provide ventilation rates for common areas (CA).

6.1.1 Dwelling units (DU)

*Ventilation standards prescribe **minimum** ventilation requirements for human health and comfort. Therefore, ventilation standards are not recommended best practices to achieve optimum ventilation.*

Standards are comprehensive documents. The intent of this section is not to conduct an in-depth evaluation of the residential ventilation standards, but rather to expose the salient features and differences of the standards that are used in North America. In general, ventilation requirements in standards are determined based on agreements between experts, practitioners and researchers. Residential ventilation standards typically focus on the needs of individual dwelling units (DU) rather than whole buildings. To reflect on the importance of residential ventilation, and the challenges in ventilating MURBs, the evolution of two notable ventilation standards is described below.

ASHRAE Standard 62.1 Ventilation for Acceptable Indoor Air Quality – This standard is probably the most well-known ventilation standard in the world. It has traditionally encompassed all types of buildings including common and private areas, as well las DUs. Acknowledging the need to develop ventilation requirements for specific buildings, over the years, standards targeting specific types of buildings have emerged, including health care and residential building standards. Therefore, ASHRAE Standard 62.1 no longer includes DUs and health care facilities as part of its scope. It still includes, however, all common areas in residential buildings (corridors, recreational facilities, gyms, etc.).

ASHRAE Standard 62.2 Ventilation for Acceptable Indoor Air Quality in Residential Buildings – This standard originally targeted low-rise residential buildings only (DUs). However, since its 2016 version the standard has been revised to apply to all residential buildings, including high-rise. While the standard remains heavily focused on the DUs, its purpose now encompasses the building envelope including enhanced airtightness and new compartmentalization requirements to reflect the influence of these on the effectiveness of DU and whole-building ventilation. However, the standard does not address ventilation requirements of residential common areas. For these areas, users of the standard still have to refer to ASHRAE Standard 62.1. As indicated by Iain Walker through a personal communication, the standard standing committee chair, *"the standard is still at its infancy in reflecting the complexities that are specific to multi-unit residential buildings"* (Walker 2020).

The ventilation requirements of residential ventilation standards typically focus on individual DUs. The dispersion-control, cascade ventilation, principle (section 4.1) guides the ventilation of dwellings:

1. Supply fresh outdoor air to the rooms where people spend more time. These are typically the bedrooms, the family room, and the living/dining room.
2. Exhaust/Extract air from most polluted, wet, and less frequented rooms: bathrooms, laundry room, kitchen, storage room.

Due to the application of this principle, air in a dwelling circulates from home leisure/resting spaces to transient/polluting spaces. Kitchens are not transient spaces. In fact, they are often considered the central gathering and entertainment place a home. However, because they are typically more polluting (section 2.1.1), they require particular source-control ventilation considerations.

Table 23 compares supply and exhaust requirements for continuous operation of selected standards. The Canadian Standard CAN/CSA F326-M91 was released in 1991 and reaffirmed in 2019. REHVA is the Federation of

European Heating, Ventilation and Air Conditioning Associations. The REHVA requirements in the table are compiled from the latest European standards. As seen in Table 23, in some standards, the **ventilation requirements are room-based**, while in others these are person-based, and per unit area. For balanced ventilation, the total supply and exhaust ventilation rates are equaled to the highest between these two. Both REHVA and Passive House standards also prescribe minimum air change rates of 0.6 ACH and 0.3 ACH respectively.

As seen in Table 23, the British Columbia Building Code Section 9.32 (BCBC 2018) requirements are based on those of ASHRAE Standard 62.2. In this standard, the supply airflow rates have two components: an area-based component (15 L/s/m^2) and a person-based component (3.5 L/s/person). Therefore, it assumes one person per single bedroom, and two persons in the master bedroom. The area component in BCBC 2018 is lower (5 L/s/m^2). The area-based component accounts for contaminant sources that are not person dependent, such as VOCs from materials. The area component in ASHRAE 62.2 is also used to set a minimum ventilation rate, to dilute contaminants from building materials and from consumer products, when the occupants are not in the house. REHVA prescribes an unoccupied ventilation value of 0.1 $L/(s \cdot m^2)$. REHVA (2018) groups living, dining, and family rooms as one zone with person-based and area-based ventilation requirements.

Each standard considers its own set of specific requirements to address all aspects of ventilation, and accepts or prevents various ventilation strategies to comply with the standard. For example, ASHRAE Standard 62.2 allows different strategies to control and operate the ventilation system. However, when the ventilation is not continuous, the fan must run at higher speed while they are ON, to compensate for the accumulation of contaminants when they are OFF. Walker sand Sherman (2013) show that such mode of operation can produce peak indoor concentrations of pollutants of outdoor origin about double those of continuous operation. BCBC-2018 requires continuous operation of the ventilation system.

Table 23. Summary of air supply and exhaust requirements of selected standards

Standard	Supply airflow rate (L/s)					Exhaust airflow rate (L/s)		
	Master	**Single**	**Living**	**Dining**	**Family**	**kitchen**	**Bathroom/laundry**	**Storage /Utility**
CAN/CSA F326-M91	10	5	5	5	5	Continuous: 30 Cook demand: 50	Continuous: 10 Demand: 25	5
BCBC-2018 (9.32)	$0.05A_{floor} + 3.5(N_{br} + 1)$					Continuous: N/A Cook demand: 47	Continuous 9 Demand: 23	-
ASHRAE 62.2-2019	$0.15A_{floor} + 3.5(N_{br} + 1)$					Continuous 5 ACH Cook demand: 50	Continuous: 10 Demand: 25	-
REHVA 2018	12 - 14	8 - 12	$8 + 0.27\ L/(s \cdot m^2)$			Continuous: 6 – 8 Demand: 25 - 30	10 - 15	8
Passive House 2018	$8\ L/s\ per\ person \times \#\ persons\ in\ dwelling$ $30\ m^3/h\ \times \#persons\ in\ dwelling$					Continuous: 17 $60\ m^3/h$	Continuous: 11 $40\ m^3/h$	6 $20\ m^3/h$

$A_{floor} = dwelling\ unit\ floor\ area, m^2, N_{br} = number\ of\ bedrooms$

A local mechanical exhaust is required by these standards in the kitchen and bathrooms, and possibly in the laundry and utility room. For cooking, the standards are not consistent about the need for a range hood exhaust. For example, ASHRAE 62.2 indicate that either a continuous 5 ACH extract ventilation be provided in kitchens and operate continuously, or a 50 L/s vented range hood be provided and operate on demand. By contrast, the Passive House Standard prescribes continuous extract ventilation of 17 L/s (60 m3/h) at the kitchen located 8 to 10 feet away from the stove to avoid short-circuiting, and on-demand range hood ventilation system that is preferably recirculating (with activated carbon filter) rather than extract for energy saving purposes. However, as noted by

Iain Walker from LBNL in a personal communication: *"one thing is to have a range hood in your home and another thing is to use it".* Their research reports that most households do not have the habit of using the range hood exhaust. This is why, LBNL is testing automated range hoods that operate on demand based on PM2.5 measurements.

In general, most standards require a balanced ventilation approach (Table 13, section 4.3.1.), with the exception of ASHRAE 62.2 which provides flexibility to select the ventilation strategy that better adjusts to the design needs. However, a standard supplement (ASHRAE Guideline 24) provides guidelines and details to follow in order not to depressurize or over-pressurize the dwelling. In airtight dwellings, the operation of cooker exhaust hoods can create large pressure differentials that will result in unintended negative effects. To avoid this problem, REHVA recommends that the cooker hood flow be compensated with equal additional supply makeup air.

Figure 39 illustrates the negative pressure that a non-compensated kitchen cook stove fan can generate at the suite boundaries (envelope, main door, neighbouring suites) depending on the suite airtightness. The figure was obtained using a steady-state suite air mass balance simulation. Beyond a pressure differential of 12 Pa, occupants will have difficulty closing the suite main door.

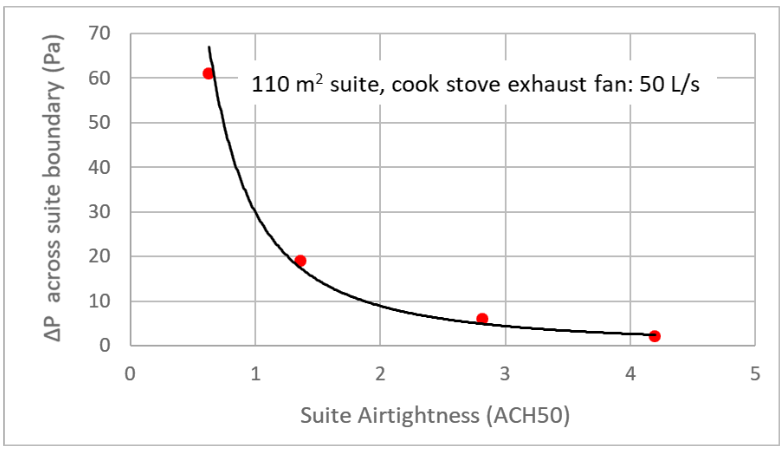


Figure 39. Negative pressure differential generated by non-compensated kitchen cook stove exhaust fan: 50 L/s

6.1.2 Common areas (CA)

As described in Chapter 4, many common areas have transient occupancies. Therefore, the time of exposure to any air pollutants is limited, and even in the non-transient ones, such a gyms or recreation rooms, the exposure time could range only from one to a few hours. Therefore, from an exposure science perspective (section 3.5, equation 1), the risk of exposure to air pollutants is reduced in transient common areas (lobbies, corridors, and elevators). ASHRAE Standard 62.1 (2019) prescribe ventilation requirements for corridors, amenities, recreation facilities, and enclosed parking garages. For example, ASHRAE 62.1 prescribes ventilation rates for common corridors and lobbies of 0.06 cfm/ft^2 (0.3 L/s/m^2).

A major risk to air quality is the migration of toxic gases from enclosed parking to the stories above. This is addressed by the BCBC (2018) through induced ventilation that uses exhaust fans to draw air from the parkade and depressurize it with respect to the rest of the building. The BCBC (2018) requirements for enclosed parking garages are the following:

a) Limit the concentration of carbon monoxide to not more than 100 parts per million parts of air.

b) Limit the concentration of nitrogen dioxide to not more than 3 parts per million parts of air, where the majority of the vehicles stored are powered by diesel-fuelled engines.
c) During operating hours, provide a continuous supply of outdoor air at a rate of not less than 3.9 L/s for each square metre of floor area.

6.1.3 Fire and smoke control

In the event of a fire, the chimney (stack) effect amplifies in high-rise buildings and strong smoke fumes rise through the vertical shafts. In those buildings, occupant's evacuation becomes more critical, including with provisions for occupants to escape safely through narrow corridors and staircases. Therefore, all evacuation routes must be clear from smoke. Figure 40 (adapted from Mehta et al. 2009) illustrates the different measures to provide fire safety in buildings, including passive measures and active measures prescribed by codes (BCBC 2018). Central to the passive measures is the compartmentalization of buildings through fire separations, and the detailed sealing of any penetrations at the fire separations. Unlike other types of buildings that favor interconnectedness architecturally (e.g. malls, university buildings, modern offices, etc.), MURBs naturally lend themselves to being compartmentalized, which simplifies their fire and smoke control design. However, proper compartmentalization needs to be designed and materialized. The British Columbia Building Code (BCBC 2018) requires continuous fire separation, with smoke-tight joints, between suites (DUs) and the rest of the building, and between different functions and occupancy areas in the building. The British Columbia Building Code (BCBC 2018) requires continuous fire separation between enclosed parking garages and other building occupancies. Ventilated vestibules are also required for access from an enclosed parkade through a fire separation.

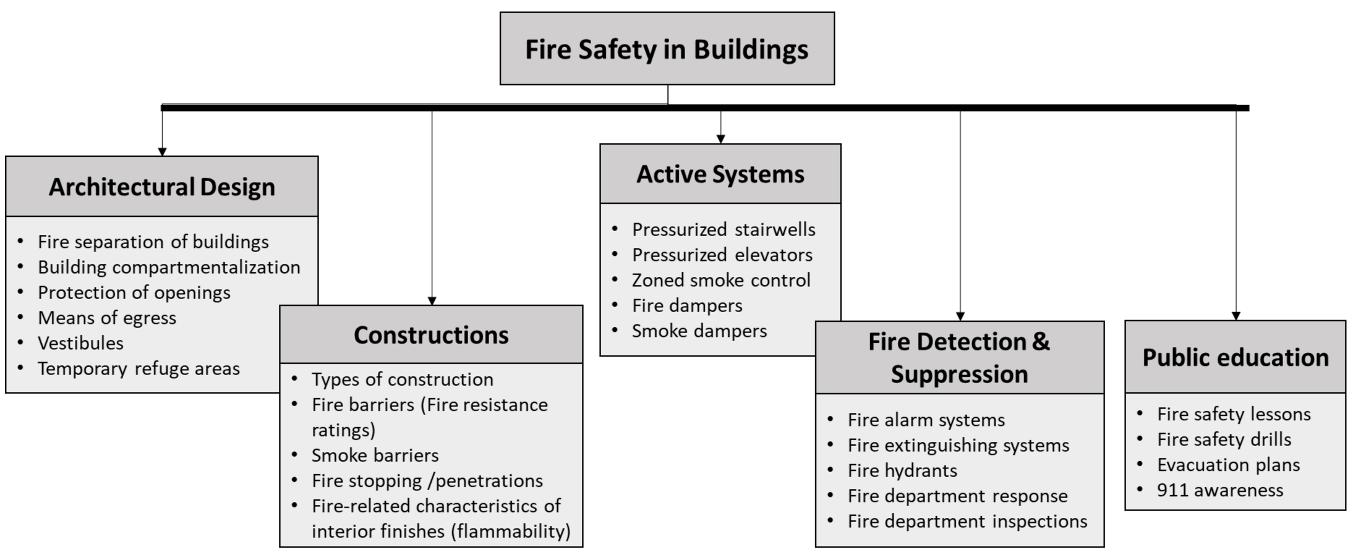


Figure 40. Fire safety in buildings (Adapted from Mehta et al. 2009)

Active systems are enabled in the event of a fire to maintain the circulation/evacuation areas free of smoke, while the ventilation system for common areas is disabled. The BCBC (2018) also prescribes fire dampers having a fire-protection rating in ducts or air-transfer openings that penetrate an assembly required to be a fire separation, as well as a smoke damper in ducts or air-transfer openings that penetrate an assembly required to be a fire separation with residential occupancy.

7 GENERIC VENTILATION PERFORMANCE REQUIREMENTS

This section outlines essential requirements of residential ventilation systems with the intent to provide the necessary background to enable a fair comparison of ventilation systems in MURB suites.

7.1 RESPONSIVENESS

Ventilation responsiveness involves being capable to provide adequate ventilation where required and on demand. Below is a list of ideal characteristics of a responsive ventilation system:

1. Operate when needed: no need for occupant intervention (controls).
2. Operate only when needed: when occupants are in house & fresh air is needed (controls).
3. Operate selectively where needed: distribute air according to occupancy, provide more air to the more occupied rooms at any given time, on demand.
4. Provide needed amount of air exchange: provide just the right amount (controls).

System responsiveness according to item 3 in the list above would require an advanced control system that apportions the "right" amount of air to each room according to its occupancy. However, it is argued that such systems are not viable in residential buildings because they require regular balancing and maintenance.

7.2 EFFECTIVENESS

Room ventilation effectiveness measures the quality of the ventilation air distribution in a room (Table 12: Elements of Ventilation, section 4.2), which is reflected by the capacity of the supplied air to dilute and remove indoor airborne contaminants in the room breathing zone. The sources of air motion in a room are the following (**Appendix C, Figure C2**):

1. **Momentum induced air flow**
   - The flow of air caused by a momentum source is called a *jet*
3. **Buoyancy induced air flow (natural convection)**
   - Plumes originating from heat sources: people, equipment, emitters
   - Boundary layer flows along walls: upward plumes and downward gravity currents
2. **Static pressure difference across an opening:**
   - When a door or a window to a space with another temperature is opened a gravity current occurs
   - When a door is opened hydrostatic energy is released & horizontal flow occurs, i.e. conversion to kinetic energy
4. **Motion of people or equipment**

Ventilation effectiveness is affected by several factors: the supply airflow rate from the room diffuser, the type of diffuser, the room configuration, the location of the supply diffuser in a room with respect to its door, the location of the closest return diffuser in the nearest bathroom, the location of the supply diffuser with respect to cold envelope windows, the location of the diffuser on a wall or ceiling, the presence of obstacles in the path of the supplied air, and the supply air temperature (heating/cooling). The above list of factors is an indication of the importance of the proper selection and location of supply diffusers in a room, in order to deliver a proper amount of ventilation air to the occupants' breathing zone.

The sizing, selection, and location of room supply air diffusers is critical for the ventilation air to reach the room occupants' breathing zone and avoid any stagnant air pockets in the room. Residential ventilation systems in particular, are low-flow systems that produce negligible air movement in the room, with typical air speeds at the breathing zone below 0.1 m/s. With such low flows, the risk of the supply ventilation air bypassing (short-circuiting) the room is high if any of the factors above is not properly considered. Short-circuiting of ventilation air happens when air enters and leaves the occupied space prior to mixing well enough with the room air to adequately dilute pollutants.

Room ventilation effectiveness is measured using tracer gas (e.g. CO_2) and modeled using Computational Fluid Dynamics (CFD). The standard indicators used to assess room ventilation effectiveness are described below.

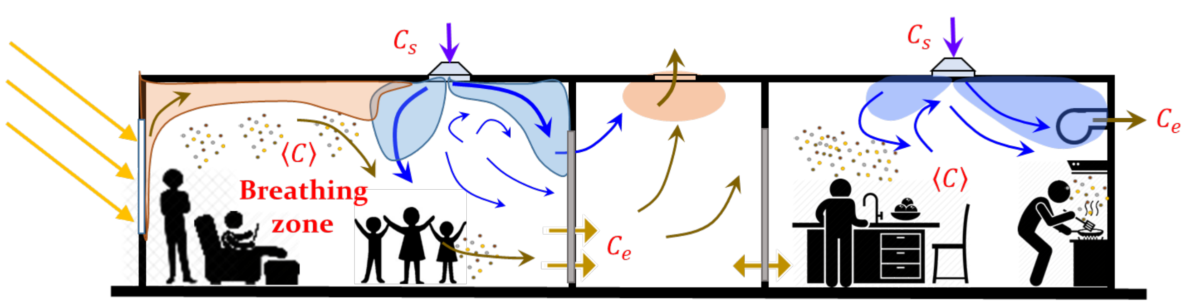
Contaminant Removal Effectiveness:

The contaminant removal effectiveness (CRE) index represents the ability of the supply air to remove contaminants in the room. In dwellings, the flow patterns is intended to be fully mixed: the supply air fully mixes with the room air before leaving the room. Therefore, the contaminant concentration in the exhaust should be the same as the mean concentration in the room. If the contaminant concentration in the exhaust is less than in the room, then the supply air is short-circuiting the room. Table 23 outlines the CRE that is obtained depending on the prevailing room airflow patterns. In Table 24 displacement airflow in suite rooms is produced for example by cross-ventilation.

$$CRE = \frac{contaminant\ concentration\ in\ the\ exhaust}{mean\ contaminant\ concentration\ in\ the\ room} = \frac{C_e}{\langle C \rangle} \quad ; \qquad \text{(Equation 2)}$$

Table 24. Flow patterns and Contaminant Removal Effectiveness (CRE)

Flow Pattern	CRE
Displacement flow	CRE > 1
Fully mixed flow (perfect mixing)	CRE = 1
Short-circuit flow (poor mixing)	CRE < 1



$$\text{CRE} = \frac{c_e - c_s}{\langle c \rangle - c_s} \qquad \text{if } C_s = 0 : \quad \text{CRE} = \frac{c_e}{\langle c \rangle} > 1$$

Figure 41. Contaminant Removal Effectiveness (CRE) ventilation effectiveness indicator

Air Change Effectiveness (ACE):

The air change effectiveness index (ACE) represents the ability of the supply airflow to exchange air in the room. It uses the age of air concept, which indicates how much time has the air spent in the room (Table 25).

$$ACE = \frac{average\ age\ of\ air\ at\ the\ exhaust}{average\ age\ of\ air\ at\ the\ breathing\ zone} = \frac{\tau_n}{\langle\bar{\bar{\tau}}\rangle} \quad ; \qquad \text{(Equation 3)}$$

Table 25. Flow patterns and Air Change Effectiveness (ACE)

Flow Pattern	ACE
Displacement flow	1 < ACE < 2
Fully mixed flow (perfect mixing)	ACE = 1
Short-circuit flow (poor mixing)	ACE < 1

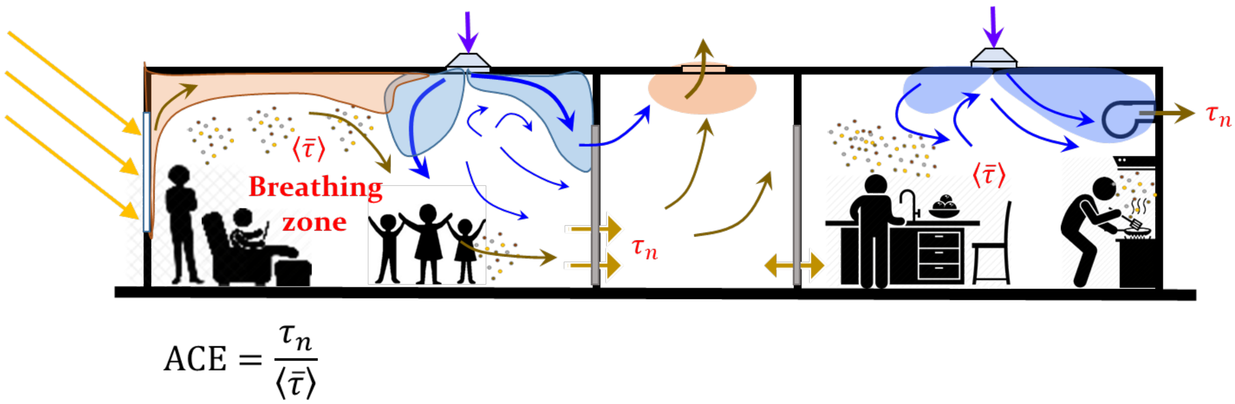


Figure 42. Air Change Effectiveness (ACE) indicator

7.3 Energy Efficiency

Over many years, several studies have focused on the energy implications of ventilation, including the energy impacts of using high-efficiency filters (Stephens et al. 2010). It is out of the scope of this document to synthesize the findings of those studies. Ventilation systems use energy to draw outdoor air (air intake), distribute it through ducts and overcome filtration (overcome losses), and condition the supplied air. To illustrate the use of energy by ventilation system, Figure 43 (Walker and Sherman 2008) compares the energy use of a house with different ventilation systems: leakage-based ventilation on a leaky house, and continuous and intermittent exhaust ventilation, and heat recovery ventilation (HRV) on an airtight house. For the relatively mild climate of Seattle, the energy penalty of no recovering heat is reduced, and therefore, from an energy efficiency perspective, exhaust ventilation seems more convenient because it does not need energy distribution and filtration.

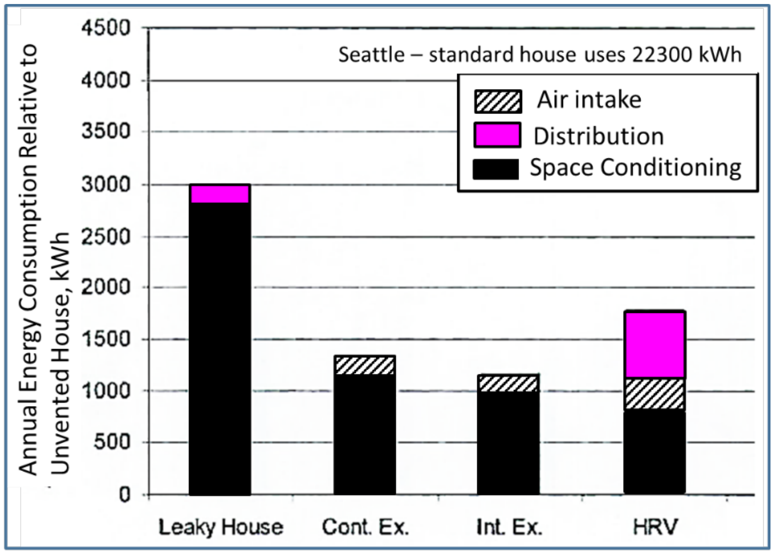


Figure 43. Energy Implications of meeting ASHRAE Standard 62.2 (Walker and Sherman 2008)

Figure 44 adapted from Persily (2005), illustrates how indoor generated pollutant concentrations depend on the balance between ventilation and energy efficiency. Figure 44 further illustrates the diminishing returns of ventilation on contaminant concentration reductions, i.e. increasing ventilation is effective in reducing contaminant concentration down to a point or a threshold (in red) where further increases in ventilation lead to only marginal reductions of contaminant concentrations. Therefore, the amount of ventilation indicated with the dotted lines may be unnecessary unless it is absolutely necessary to reduce the contaminant concentrations from the level indicated by the red arrow to that indicated by the dotted arrow.

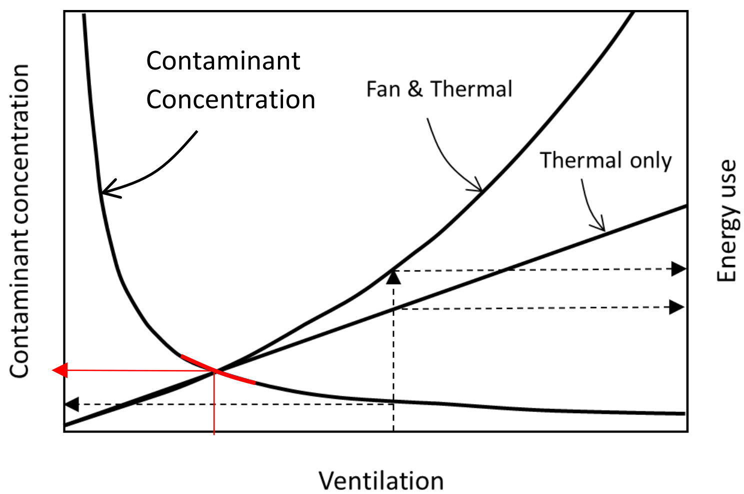


Figure 44. Dependence of concentration and energy use on ventilation (adapted from Persily 2005)

As discussed in sections 1.1 and 2.1.1, nobody knows with certainty what is in the air, and even if we knew, it is difficult to predict actual emission rates of all possible indoor air contaminants present under normal conditions. However, now knowing the source strength of indoor contaminants implies not knowing the removal rate. Knowing the ventilation contaminant removal rate involves answering the following question:

Can we adequately assess indoor air exposures to any contaminant, such that we may confidently reduce outdoor air ventilation rates, to save energy, without compromising health?

Heat Recovery Ventilation

Heat and Energy Recovery Ventilation (HRV/ERV) are now widely accepted solutions to reduce the space conditioning energy, thermal energy in Figure 44. While HRVs recover only sensible heat, ERVs recover sensible and latent heat (i.e. moisture and its energy) from the extracted house air. The performance of HRV/ERV systems is a function of the indoor-outdoor temperature (HRV/ERV) and humidity (ERV) differences, but its effectiveness in heat and moisture recovery as well as filtration, depends on the airtightness of the envelope, the thermal performance of the envelope, and the indoor thermal and moisture loads. Figure 45 shows overlapping acceptable indoor thermal comfort and relative humidity conditions (dark blue), which are not fixed, but can move to the left or right depending on human and climate factors. The HRV/ERV are required to pre-condition the outdoor air to bring it closer to the acceptable indoor conditions. Figure 45 shows that ERV should be used in hot-humid climates to help dehumidify the supply air into the dwelling, and in very cold climates to help pre-humidity the supply air. In cold climates pre-humidification seem not to be a priority, therefore HRV seems to be the logical choice. However, in cold climates, summers tend to get warm and humid, in which case dehumidification is preferable, thus the choice of ERV mainly for summer operation, with possible benefits in winter. Finally, in hot and dry climates, the benefit of using ERV is not clear. The daily temperatures in these climates tend to fluctuate drastically as well as the relative humidity levels. In either case, the relative humidity levels are so low, that summer dehumidification could be counterproductive. Furthermore, cities like Montreal are characterized by having very cold winters and hot-humid summers, therefore, ERV is beneficial for both summer and winter seasons. Regardless of the climate, a main requirement in the design of controlled mechanical ventilation (filtration), heat, and moisture recovery/rejection is that the dwelling is sufficiently airtight, so that pollutants, heat, and moisture transfer through the envelope cracks do not bypass the treated air through the HRV/ERV.

Figure 45 shows only points that are meant to represent typical summer and winter conditions. However, even in those seasons, and mainly in transition (i.e. shoulder) seasons, there will be many hours where heat and/or moisture recovery will not be necessary or will be counterproductive, pre-heating out door air or pre-humidifying supply air when the indoor thermal and moisture load is higher than outdoors respectively, or vice versa. This is why regardless of the climate, specifying HRV/ERV with heat/moisture core recovery bypass is necessary.

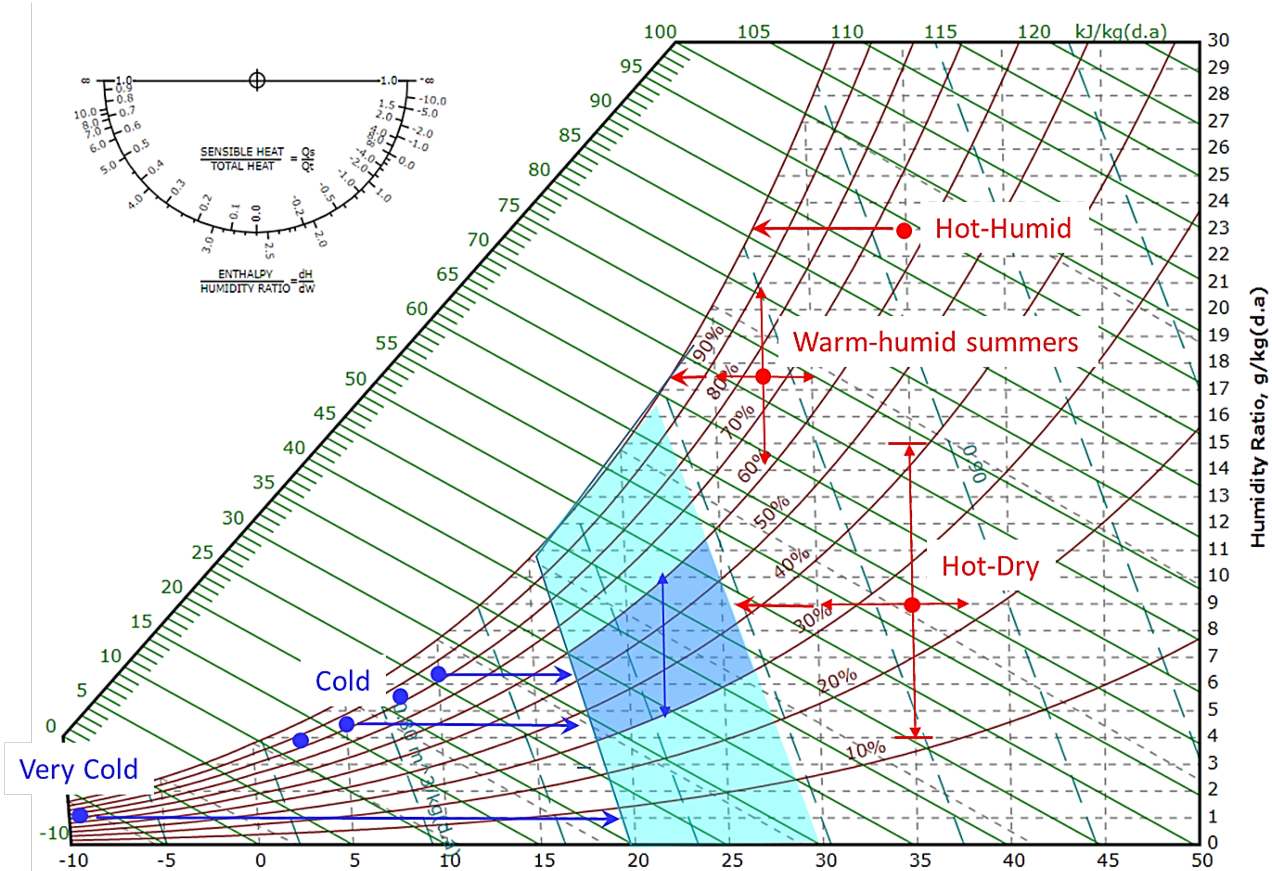


Figure 45. The section of HRV versus ERV technologies depending on climate

7.4 Systems Integration

Integration refers to how the ventilation system interacts with other systems' requirements. The interaction can either be negative or positive. For example, a negative interaction occurs when the ventilation system introduces too cold or warm air that affects the energy performance and may cause thermal discomfort of the occupants. An example of a positive interaction is by integrating heat or energy recovery, or when increased ventilation can enhance heating and cooling. Below is a list of ideal characteristics of an integrated ventilation system:

1. Be responsive (Section 7.1)
2. Do not waste energy by operating excessively when not required, or by overcooling or overheating the indoor air (Figure 44).
3. Do not cause thermal discomfort.
4. Be quiet: so that occupants are not tempted to turn it off.
5. Do not interfere with other systems: pressurize or depressurize the house, e.g. pressure compensated, or boosting both supply & exhaust airflows on demand.
6. Do not interfere with the building envelope: in cold climate: positive pressure could drive humid air from the house through the envelope.

In some jurisdictions that heating and cooling equipment be interlocked with windows so that the equipment automatically turns off or resets heating and cooling set points when windows are open (ASHRAE 2022).

7.5 RELIABILITY

The reliability of the ventilation system is its ability of the system to **perform as intended** under normal service conditions, and its **robustness** to **respond to deviations** from the design assumptions and conditions. Ventilation system reliability involves consistency in delivering adequate ventilation in response to daily and seasonal variations. Considering the generic types of ventilation systems in residential building in Table 14 and Figure 16 (Section 4.5.1), how do they compare in terms of ventilation system responsiveness, effectiveness, and energy efficiency? How can these systems be improved to be more reliable?

Table 26 compares the reliability of the four generic types of residential ventilation systems. For convenience, Figure 16 is repeated below. It is noted that systems S1 and S3 are only applicable to houses, and not used in MURB suites. However, the comparison helps gain insights into how systems can be better in certain aspects and weaker in other aspects. In terms of ventilation reliability, it is important to note that cold and hot climates present the most critical performance test for a ventilation system, i.e. when the dwelling windows are closed. Therefore, the ventilation system cannot be assumed to rely on the windows' operation by occupants alone to perform its IAQ function.

Table 26. Reliability of residential ventilation systems in Figure 46

Requirement	Response				Comments
	S1	S2	S3	S4	
1. Consistency and Responsiveness in the outdoor air intake	Marginal	Good	Fair	Poor	S1: vulnerable to envelope leakage S3: when AHU off, ventilation is compromised
2. System air distribution	Good	Good	Good	Poor	S4: non-ducted make it difficult to control room air distribution to occupied areas
3. Room ventilation effectiveness	Good	Fair	Good	Poor	S2: vulnerable to poor CRE & ACE Low airflow system
4. Air circulation between rooms	Good	Fair	Good	Poor	S1, S3: high airflow recirculation mixing which equalize pollutant concentrations in all rooms
5. Energy efficiency	Poor	Good	Poor	Marginal	S1, S3: large air flow rates, fan energy use S2: heat/energy recovery, controlled low flow
6. Weather independence	Poor	Good	Marginal	Marginal	S1: operate only when heating and cooling S3: when HVAC off, delivers air through return
7. Response to dynamic occupancy patterns: family dining, family watching TV, sleeping	Fair	Poor	Fair	Poor	S1, S3: high bulk recirculating air volume Mixes well entire DU air
8. Response to high indoor polluting events: gatherings, high moisture, cooking, etc.	Marginal	Marginal	Marginal	Poor	S1, S3: mixes well entire DU air S2: limited boosting capacity
9. Vulnerability to occupant misuse, tampering, altering effectiveness	Fair	Good	Fair	Marginal	S1, S3: subservient of heating and cooling S4: closing doors, blocking transfer grilles
10. Enhanced filtration	Fair	Marginal	Fair	Poor	S2: some HRV has up to MERV 13 (Zehnder), in houses, not in MURB suites
11. Pressure compensation: kitchen, bathroom exhaust fans (Figure 39)	Fair	Fair	Fair	Poor	S1, S2, S3: possible to implement
12. Cooking pollutants (venting)	OK	OK	OK	OK	Possible, Independent of the system Requires pressure compensation
13. Safety: pollutant drawn from garage, back-drafting, Radon from ground	Fair	Fair	Fair	Poor	S1, S2, S3: more reliable management of pressures, pressure compensation possible
14. Systems integration	Marginal	Marginal	Good	Poor	S1, S2: ventilation is surrogate to heating/cooling, can easily be compromised
Score	22	27	24	3	Note. S1 and S3 not applicable to MURB suites

Colors: Good (3) [green] | Fair (2): [light green] | Marginal (1) [yellow] | Poor (0): [red] | OK | NA

The ventilation of systems 1 and 3 is significantly reduced, turned OFF, of become intermittent, when the air handling unit is off because heating or cooling are not required. This seems to be a minor limitation given that when the air handler is turned off for long periods coincides with mild outdoor temperatures and increased house venting through open windows. Whereas the air handler is ON for longer periods when heating and cooling are required, which is when the windows are closed. System 3 performs slighlt better than System 1 when the air handler is OFF because the HRV would still supply ventilation to the duct system. However, this ventilation will not be distributed properly through the duct system and reach its intended destination.

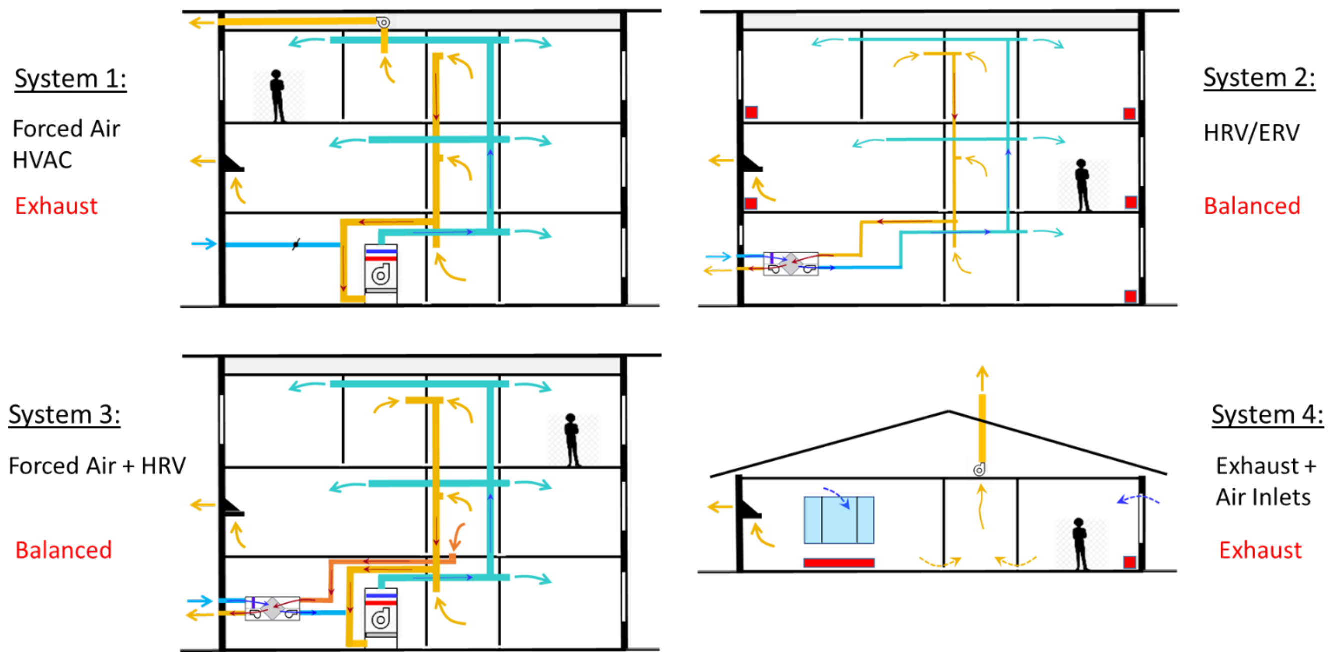


Figure 16 (repeated from Section 4.5.1). Generic types of ventilation systems in DUs

7.6 Resilience

Wilson and Lazarus (2020) describe resilience as *"the capacity to adapt to changing conditions and to maintain or regain functionality and vitality in the face of stress or disturbance"*. Section 5.1 Environmental Context, synthesizes climate change related environmental stressors that are leading to the increased number and intensity of high air polluting events. Similarly, section 5.3 Human Context describes the roles of humans on indoor environmental quality as contaminant emitters, receptors, or environment modifiers, and elaborates on unprecedented pandemic events, that may become more recurrent in the future.

In certain disciplines, such as structural engineering, the concepts of lines of defense and redundancy are explicit in design (if one subsystem of component fails other subsystems or components can still hold/resist the loads without compromising human safety). In building science these concepts are implicit in the design of lines of defense against the penetration of moisture into the envelope, and the prevention of moisture deterioration of materials and components. **Surprisingly, these concepts do not seem to be present in the design of mechanical systems in residential and commercial buildings**. Due to climate change, the concept of redundancy is also being proposed as a priority measure to implementing resilience in all areas of building performance, to make sure the building remains functional to an extended degree during extreme events and is able to rapidly recover from those events.

Ventilation system resilience can be defined as the ability of the ventilation system to help dwellers cope with indoor air pollution threats that are not the normal indoor emissions from dwellers, their activities (including cooking), and building materials. From sections 5.1 and 5.3, these IAQ threats are 1) prevailing urban air pollution, 2) smoke from episodic wildfires, and 3) episodic emission of pathogens from humans. These threats call for an integrated approach to design buildings to endure these events. Depending on weather pollutant threats originate indoors (pathogens) or outdoors (urban pollution, wild fires' smoke) demands a different envelope adaptive strategy either to open it or to seal it, and a consistent mechanical ventilation, and cooling and heating strategies. A major complication during co-occurring extreme events is the possibility for power outages that would force most buildings to operate passively. In certain areas, resilience metrics have already developed. For example, two well-known building thermal resilience metrics. 1) Thermal autonomy (Levitt et al. 2013): aims to passively **expand the thermal comfort bands with limited/mild excursions to maintain thermal comfort without an active system** enabled. 2) Passive survivability (Wilson 2006), also called thermal resilience or thermal habitability, which aim to maintain shelter habitability under extreme outdoor thermal conditions, where buildings would **operate beyond the accepted human thermal comfort bands**. The definition implies enduring more prolonged and harsher excursions from the comfort bands, with increased capacity of people to tolerate thermal discomfort to a certain degree. Furthermore, the definition implies a human-building relation as an enhanced coping-recovering system under extreme events, with increased capacity to endure harsher thermal conditions and recover (regain functionality) when these conditions have passed. Arguably, such passive survivability conditions cannot be imposed on occupants, specially to vulnerable populations. Nevertheless, it could be inferred that designing a building for passive survivability would also make it more robust and efficient in the use of mechanical active systems when needed.

Aside from the standard passive design features (proper shade, improved windows and window-to-wall ratios, high thermal mass, etc.), resilient buildings can be designed to be adaptive to changing climate and environmental conditions, facilitate human adaptation, and safeguard occupants against increased environmental hazards. Figure 46 illustrates a four-step framework for building resilience that aims to integrate concepts of building-human adaptability to safeguard building occupants from environmental threats. An initial task in designing resilient buildings is assessing and prioritizing the building' and the occupants' potential vulnerabilities to foreseen environmental hazards. At the top of the framework, a highest standard of care is required in designing against environmental hazards to provide a required level of resistance and robustness for the building to withstand hazards and minimize occupants' exposure to these. This involves designing a system of control measures (**lines of defense**) that implement **"load sharing"** in case of suboptimal performance or deficiencies in one measure, and offer response **"redundancy"** in case of failures in one measure. Step 1) includes measures to improve a building's adaptability to environmental threats such as designing a ventilation system with varying levels of ventilation and filtration, and mechanical cooling capacity in the likely scenario of a concurrent demand for ventilation and cooling. Step 2) includes measures to facilitate human adaptability to threats by use of proper sensors providing timely feedback to occupants on indoor and outdoor conditions, and advising on actions to mitigate exposure to threats. Step 3) involves anticipating threats and raising alarms to avoid conditions that will pose a health risk, and maximizing the building systems' response to threats to protect the occupants. It also involves designing provisions to protect occupants and prolong their use of the dwelling, while minimizing their exposure to threats; for example, designing a protection that can be easily maintained cleaner or cooler than the rest for short periods of time. Step 4) involves monitoring key environmental and human parameters, for example outdoor and indoor PM2.5, that measure the severity of the threat and the human exposure and provide continuous feedback for improving designs and maintain reliable operation.

Implementing the resilience framework in Figure 46 implies a reliance on smart systems (Section 4.5.7, Section 7.6.1. Figure 48) that implement continuous sensing and monitoring of selected parameters, intelligence to forecast and anticipate upcoming threats, continuous and opportune feedback to occupants and facility managers, and the ability for the building systems and humans to adapt in response to threats.

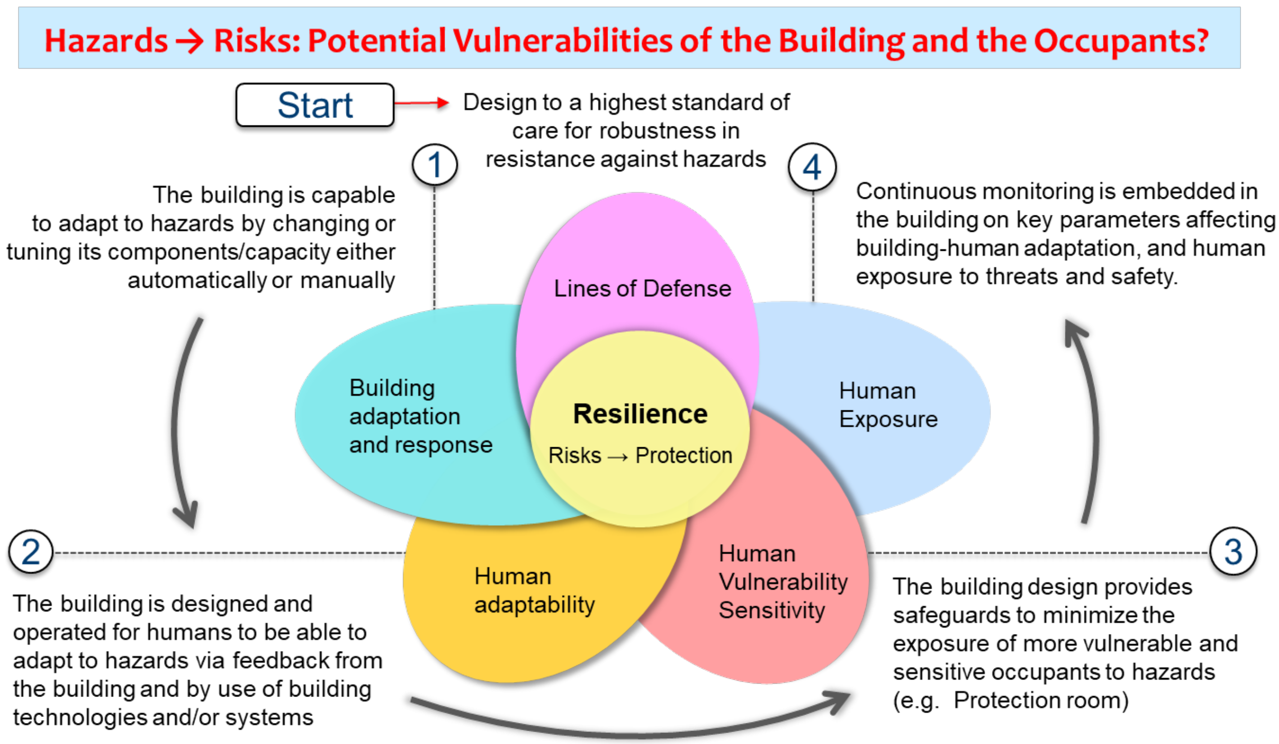


Figure 46. Framework for building resilience (adapted from Nazarian et al. 2022)

The Framework in Figure 46 is applicable not only to ventilation and indoor air quality. The resilience framework can be generalized to mechanical cooling, and adaptive thermal comfort under natural ventilation as in Section 4.5.8 of this document.

7.6.1 Episodic wildfire events, ventilation and IAQ

Wild fires are episodic exceptional events that cause large temporary increases in outdoor pollutants. Therefore, the measures to protect dwellers from inhalation of smoke pollutants are extreme and intended to be short-lived (hours to days, up to weeks). Research shows that eventually fire smoke pollutants will slowly gain their way indoors, with time lag dependent on envelope airtightness (Munro and Seagren 2020). Smoke from combustion of natural biomass is a complex mixture of particles, gases, and vapors (Table 27). The individual compounds number in the thousands (Lyon et al. 2021). Given that the specific effects of these pollutants are hard to quantify and measure during an active smoke incident, PM2.5 is typically the pollutant that is tracked and monitored, and the pollutant that is used to estimate public health effects from wildfire smoke (Lyon et al. 2021). Furthermore, as seen in Table 27, fine and ultrafine particles are carriers of gaseous air pollutants.

Emergency BC recommends that sheltering-in-place (staying where you are) is often the best way to reduce your exposure to wildfire smoke, but only if you have access to clean indoor air in your home or community. ASHRAE Guideline 24 (2015) includes the following recommendations for dwellers during fire events:

- **Shelter in Place**. The building envelope serves to delay penetration of outdoor pollutants. Effectiveness of the delay depends on house airtightness. What if the building is too leaky?
- **Create a Clean/Protection Room**. Seal an interior room temporarily. Clean the room air with a portable air cleaning device including HEPA + carbon filtration. If possible pressurize the room with respect to other rooms.

Table 27. Pollutants from Wild Fires

Pollutant	Description
Toxic gases	Benzene, 1,3-butadiene, acrolein, formaldehyde, PAHs, acetaldehyde, etc.
Organic Carbon (OC)	Incomplete biomass combustion, short lifetime (days, weeks), not well-mixed in atmosphere Carcinogenic PAHs: polycyclic aromatic hydrocarbons (PAH) 50 nm – 500 nm (0.05 µm - 0.5 µm)
Soot	Elemental carbon particles Carcinogen PAHs 20 nm – 60 nm (0.02 µm - 0.06 µm)
Carbon Monoxide (CO)	Incomplete biomass combustion, dilutes rapidly, not a health concern unless very close to fire Of concern for firefighters
NOx: NO & NO2	Burning biomass
SO2	Burning biomass
VOCs	Multiple VOCs
UFP, PM2.5	Contain most of the above
Ash	> 2.5 µm
Ozone (O3)	Elevated levels of ozone form downwind of fires

Table 28 summarizes the recommendations for dwellers to shelter from several sources (Lyon et al. 2021, LBL 2020, EPA 2020). In Table 28 it is recommended to seal off air intakes, close dampers, and turn off the HRV/ERV ventilation system. However, this measure seems applicable only when the air pollution gets dangerously high (AQHI: high or very high, Figure 37), and the ventilation cannot be fitted with an adequate level of filtration. Otherwise, shutting down the ventilation system will increase the risk of occupant exposure to potential indoor pollutants.

Table 28. Recommendations for dwellers to shelter-in-place to maintain indoor air quality during wildfire events

Strategy	Measures
Airtightness	Keep all windows closed Seal envelope cracks & gaps
Pressure control	Turn off exhaust fans
Ventilation-Filtration	Seal off air intakes, close damper Turn off the ventilation system Set central air system to recirculate Run continuously to maximize filter pollutant removal Replace/Upgrade air filter
Room air cleaning	Use room air cleaners
Dwellers - Cooling	Do not contribute to poor indoor air quality When smoke clears open windows Under overheat risk, use AC if needed If IAQ is still not adequate, vulnerable dwellers may have to move to a clean air shelter

To assess indoor exposure to outdoor pollutants, three indicators are used that compare the PM2.5 concentrations between indoors and outdoors (Chen and Zhao 2011):

1. The I/O (Indoor/Outdoor) ratio represents the relationship between indoor and outdoor particle concentrations, which is very easy to understand and widely used in field studies.
2. The infiltration factor (F_{inf}), represents the fraction of ambient particles that penetrate indoors and remain suspended.
3. The penetration factor (P), is a number between 0 and 1 that represents the fraction of particles in the infiltration air that passes through the building envelope.

Two other metrics could be considered to assess the building ability to mitigate the penetration of particles into the indoor air:

$$Peak\ concentration\ attenuation \quad PCA = \frac{(C_{peak\_outdoor} - C_{peak\_indoor})}{C_{peak\_outdoor}} \times 100 \qquad \text{(Equation 4)}$$

$$Peak\ concentration\ delay \quad PCD = time_{C_{peak\_outdoor}} - time_{C_{peak\_indoor}} \qquad \text{(Equation 5)}$$

Figure 47 summarizes cascading control measures to be considered to mitigate the indoor exposure to wildfire smoke in MURBs. The measures are cascading (prioritized) because each measure in Figure 47 affects the effectiveness of all the subsequent measures. For example, the effectiveness of 4) a portable air cleaner and 5) mechanical cooling depends on 1) proper ventilation and 2) and 3) proper pressure control. The list was created based on discussion in Chapter 2 of this document, on the literature review, as well as on simulations presented in Chapter 10 of this document. Modeling case studies in Chapter 10 use simulations to demonstrate the most effective measures to control wildfire pollutants penetration in multifamily buildings. Measures 1), 2), and 3) are not necessarily cascading. In fact, these measures should be implemented together because **proper ventilation and tight pressure control can only be achieved in airtight and compartmentalized buildings.**

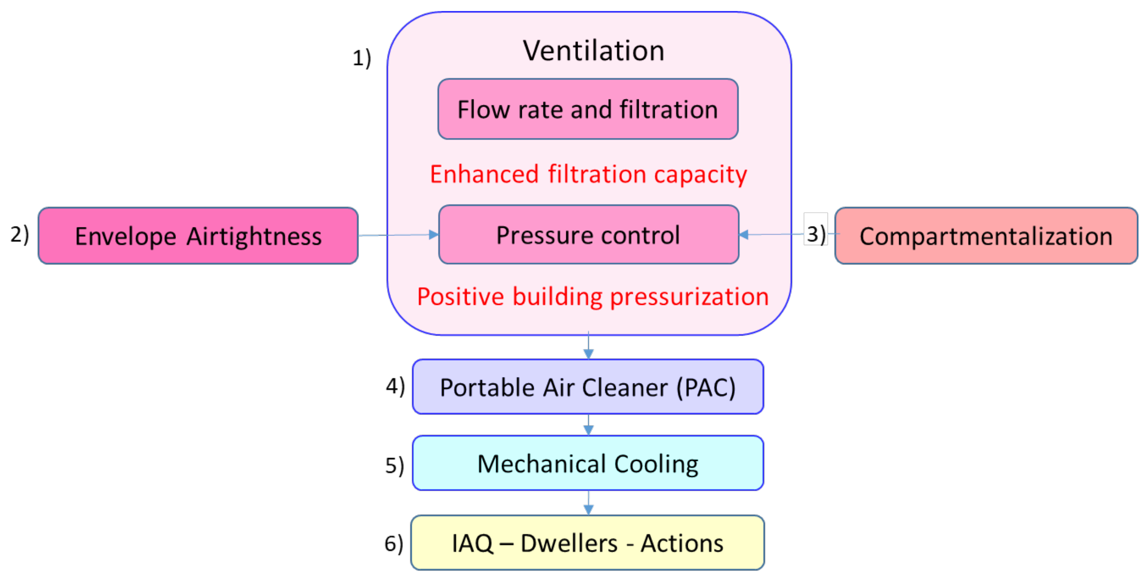


Figure 47. Cascading control measures to be considered to mitigate the indoor exposure to wildfire smoke in MURBs.

Notice that Measures 1 to 6 in Figure 47, implement all the steps required in the Framework for Building Resilience in Figure 46, applied to the hazard of wildfire smoke. The minimum standard of care in this case consists in making sure the building is airtight and well-compartmentalized (design, testing, commissioning).

Measures 1 – Filtration, ventilation, and pressure control

Providing proper outdoor air filtration during wildfires is also critical because building ventilation has the highest capacity to introduce polluted outdoor air into the building if proper filtration is not provided. Enhancing air filtration to MERV13 or MERV16, and adding activated carbon filtration would be recommended, which involves increasing the capacity of the mechanical system to manage higher pressure drops from enhanced filtration. The ventilation rate itself can be adjusted depending on the level of outdoor-indoor air pollution and the level of filtration in the system (i.e. low filtration would result in low ventilation). If the ventilation system is adequate, maintaining the building slightly pressurize or at least balanced would be recommended. For example, the air handler could be temporarily set to wildfire-smoke-protection mode. Under such mode, the air handler (HRV/ERV) could operate either in recirculation/filtration mode, or in pressurization mode by partially closing an exhaust damper or adjusting the supply/exhaust fan speeds to pressurize the building. However, this type of ventilation system response can only be achieved with centralized or semi-centralized ventilation systems (section 8.1). Combined with enhanced filtration, slight building pressurization can help the building overcome stack and wind pressures. These measures are consistent with Step 1 in Figure 46 of Building Resilience. The measures above are also consistent with ASHRAE-BC's Building Sustainability and Resilience Guide (ASHRAE-BC 2022).

Surprisingly, the author found only one paper that studies the effectiveness of control measure 1 above to control the penetration of wildfire pollutants. The reason may be because studying these systems in the field involves careful advanced planning of the filter replacement and the operation of these systems, which is difficult to achieve due to the uncertain nature of wildfires. This is opposed to studies on PACs that involve only buying PAC or a set of PACs, deploying them in rooms, and monitoring indoor pollutants when the PACs are turned on and off. Dev et al. (2021) monitored indoor and outdoor wildfire pollutant concentrations in Fairbanks Alaska during fire seasons and observed that The indoor to outdoor ratio (I/O) of pollutants during the fire season was significantly lower for an unventilated building (I/O = 0.13 ± 0.001) as compared to those with active (filtered) ventilation (I/O = 0.76 ± 0.11 and 0.62 ± 0.02), suggesting that lower efficiency filters (< Minimum Efficiency Reporting Value or MERV rating 11) often used in residential and public buildings may not control the infiltration of smaller smoke particles during a wildfire event. Therefore, when the HVAC filtration is low (MERV11), the authors recommend turning off the ventilation system in the building.

Measures 2 and 3 – Envelope airtightness and compartmentalization

Research have demonstrated that increasing the envelope airtightness delays outdoor pollutant penetration. However, pollutants slowly gain way indoors, depending on the smoke severity and duration. Even though the stack effect is weak during wildfire events, as demonstrated in section 10.1 (Case study WS-1), because the indoor-outdoor temperature differences are small, effective ventilation/filtration and pressure control can only be achieved in airtight and adequately compartmentalized buildings (sections 8.2 and 8.3).

Munro and Seagren (2020) monitored indoor and outdoor PM2.5 concentrations in Passive House and leaky homes in Australia during wildfire events. From the data reported, a PCA of about 47% to 53% for Passive Houses versus 20% for a leaky house are estimated, with a PCD of about 4 hours in both houses. However, Munro and Seagren (2020) conclude that even though ensuring a home is as airtight as possible will reduce particulate concentrations indoors, when extreme outdoor air pollution is too high and/or prolonged, the envelope (Control Measure 1) on its own is insufficient to maintain a healthy indoor environment. In these exceptional events, additional ventilation filtration, e.g. MERV13 (Control measure 4), and even PAC with HEPA filtration (Control Measure 5) are necessary by installing these filters even only for short periods, on demand.

Many studies have reported indoor/outdoor I/O ratios and infiltration factors (F_{inf}) from wildfire pollutants in houses monitored during wildfire events. However, most of these studies fail to provide sufficient information to evaluate the contribution of the key relevant factors to the I/O and F_{inf} results, such as the type of ventilation, the presence and type of air filtration, the airtightness of the house, the opening of windows by dwellers, etc. For example, Reisen et al. (2019) report I/O ratios during hourly peak $PM_{2.5}$ concentrations in twelve houses In Australia ranging from I/O = 0.17 (PCA = 83%) in one house to I/O = 0.83 (PCA = 17%) in another house. These results indicate the high variability in the level of protection provide by different houses against outdoor PM2.5. What are the main factors contributing to such high variability? Studies also report I/O ratios and F_{inf} factors as box-plots that display the widespread distribution of the I/O and F_{inf} values around their median value. The plots show significant variability of the data for a single house and among houses. However, the details provided in those papers make it difficult infer the reasons for such high variability. Furthermore, since the box-plots are calculated for the entire wildfire event, their results mask the house protection against peak values, which are of shorter duration (hours) compared to protection for the entire wildfire event (days or weeks). This is particularly important because during moderate to high air pollution hours (AQHI, Figure 23, Section 5.1) the house may be sufficient to offer adequate level of protection against outdoor pollutants; whereas, as air pollution gradually increases to AQHI high to very high, then more drastic measures are required to protect the occupants.

Measure 4 – Portable air cleaner (PAC)

Portable air cleaners (PACs) can be very effective in removing indoor pollutants as demonstrated by several studies, because they can include superior particle and gas filtration, including HEPA filters. As such, PACs can supplement ventilation to improve IAQ. However, PAC air cleaning effectiveness is dependent on measures 1), 2) and 3); poorly filtered ventilation air in a leaky building introduce large loads of pollutants that can easily overwhelm a PAC. Most studies on mitigation measures to control the penetration of wildfire pollutants into buildings are field studies that focus on portable air cleaners (PACs). Reports have been produced about PACs, including the air cleaning mechanisms and their effectiveness (US-EPA 2018, ASHRAE Handbook 2017). A conclusion from US-EPA (2018) is the following *"Intervention studies of air cleaners operating in homes have consistently found statistically significant reductions in indoor exposures to indoor PM2.5, PM10, and/or particle number counts with the use of portable air cleaners, including HEPA filters. Studies of air cleaners in homes that address gas-phase pollutants are extremely limited, and consistent reductions have not been demonstrated."* A field study on homes by Henderson et al. (2005) concluded that air cleaners reduced concentrations by 63% to 88%. A study by Barn (2006) on a group of houses monitored during wildfires in BC found that houses that use HEPA filter portable air cleaners can dramatically reduce indoor concentrations across different homes. Variability in air cleaning effectiveness could not be explained by house characteristics. Many more studies are available that demonstrate the effectiveness of different types of portable air cleaners, even low-cost custom-made ones (BCCDC et al. 2022). Joseph et al. (2020) provides a comprehensive literature review of the performance of these systems.

Measure 5 – Mechanical cooling

Kirk et al. (2018) found that Indoor-outdoor pollutant concentration rate is highly related to the house air change rate. The use of air conditioning reduces the air change rate in houses, thus significantly reducing the indoor-outdoor pollutant concentration rate. Furthermore, a study by Shrestha et al. (2019) found that low-income dwellers are more exposed to outdoor wildfire pollutants because their homes do not provide air conditioning and therefore have to rely on the opening of windows to attempt to cool down their dwelling. Therefore, mechanical cooling has a positive impact on wildfire pollutants reduction indoors, as long as the mechanical cooling system does not interfere with the ventilation pressure control (see Sections 8.1.5 and 8.1.6).

Measure 6 – Dwellers

To protect themselves during wildfires, dwellers can close/seal envelope openings, operate portable air cleaners, and turn on mechanical cooling if necessary, and minimize the generation of pollutants indoors. Kirk et al. (2018) found that human activity can significantly increase the house air change rate by opening/closing windows at inconvenient times. Similarly, Shrestha et al. (2019) window opening significantly increased the concentrations of wildfire pollutants indoors. For the most vulnerable, dwellers can create a protection room that is more sheltered from the outdoors.

With respect to indoor PM2.5, Health Canada does not propose a specific maximum exposure limit, but recommends that indoor PM2.5, at a minimum, be lower than PM2.5 outside the home (Health Canada 2020). Clearly, this recommendation is not practical during wildfire events. However, even during wildfire events, Indoor pollutant concentrations could spike for short periods by orders of magnitude above the outdoor level during indoor source-induced events like cooking (Shrestha et al. 2019).

Taking advantage of the real-time air pollution data available from a network of ambient stations, provided by the Government of British Columbia (Office of Environmental Protection and Sustainability), Smart Ventilation Systems (section 4.5.7) could inform ventilation strategies and warn occupants as conditions deteriorate. Furthermore, these systems could be supplemented with their own outdoor and indoor PM2.5 monitors in complexes and homes. The flow chart in Figure 48 outlines the decision making for such a predictive smart system of sensors during a wildfire event. These systems can combine multiple sensors, including CO2, to provide dwellers with continuous feedback to occupants on the indoor and outdoor air quality, that can also warn them or inform them about the consequences of their actions (e.g. when to open or not to open windows, when indoor PM2.5 is dangerously high, or when indoor PM2.5 is greater than outdoors).

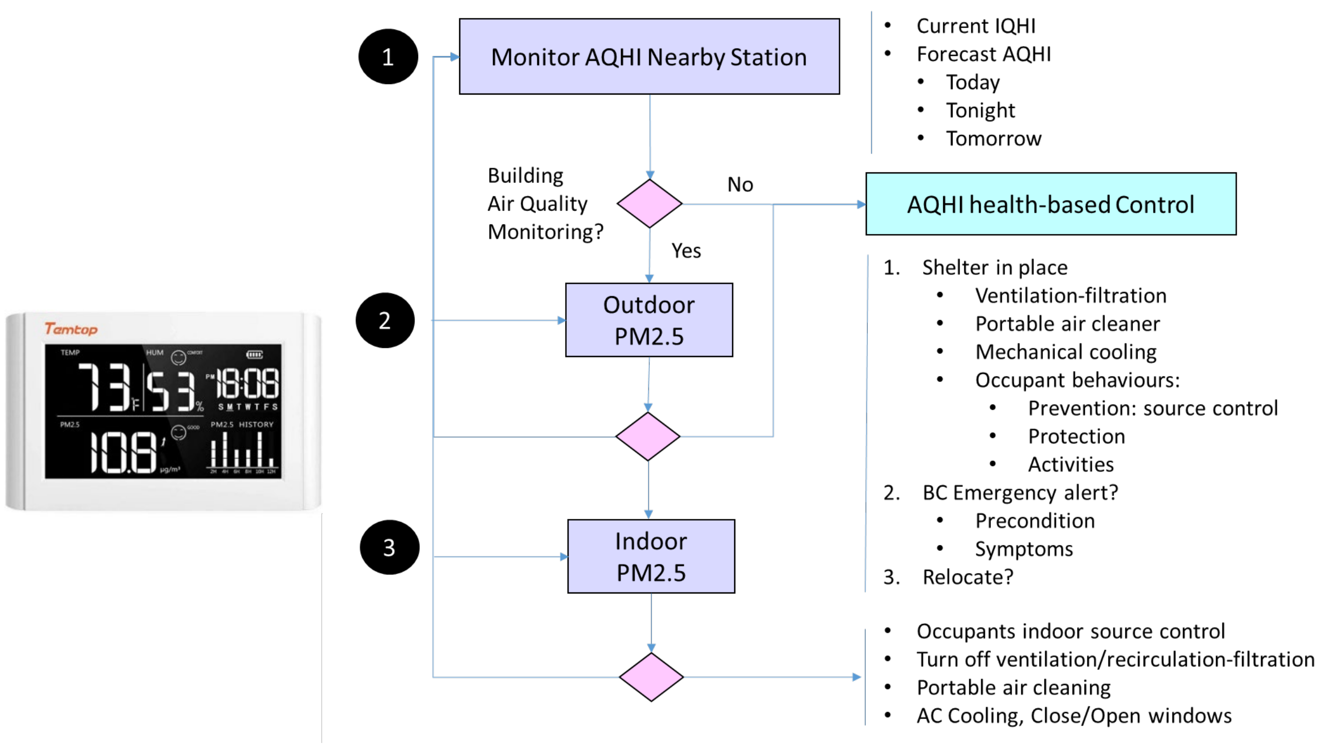


Figure 48. Decision-making flowchart for predictive "smart" ventilation system during wildfire events

Figure 49 proposes ventilation measures to mitigate wildfire pollutant penetration indoors, based on the severity (concentration) of outdoor air pollutants from wildfires, and using AQHI categories as a reference of air pollution severity. The proposed table is preliminary and needs to be tested with field and laboratory studies.

AQHI	**LOW Health Risk**			**MODERATE Health Risk**			**HIGH Health Risk**				**VERY HIGH**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**+**
$PM_{2.5}$ (µg/m^3, 1 hr)	0-5	5-15	15-25	25-40		40-60	60-80	80-100	100-250	250-500	500+
O_3 (ppb, 1 hr)	0-15	15-25		25-35	35-45		45-62	62-82	82 +		
NO_2 (ppb, 1 hr)	0-10	10-15		15-20	20-25		25-50	50-100	100 +		
SO_2 (ppb, 1 hr)	0-30	30-50		70-110			110-150	150-185	185 +		
Ventilation	No air filtration necessary			Enhanced filtration MERV 11 +			Enhanced filtration MERV 13 + Carbon		Outdoor air: MERV16 + Carbon Recirculation: MERV16 + Carbon		
Portable air Cleaning (PAC)	Not necessary			Not necessary			Recommended		Required		
Airtightness	Not relevant based on AQHI			Desirable			Recommended		Required		
Pressure Control	Not relevant based on AQHI			Desirable			Recommended		Required		

Figure 49. Proposed ventilation measures depending on the severity of the wildfire exposure events

Wildfires are high filter loading events. Furthermore, during wildfire smoke threats, filters are intended to run continuously to maximize filter pollutant removal. Therefore, in extreme polluting events it is important not only to consider filtration efficiency in the size range of interest, but also filtration system run time, and have sufficient filter capacity to allow for reasonable cost-effective maintenance schedules without adversely affecting airflow and efficiency. This is illustrated in Figure 50 below (Sublett 2011), where the amount and quality of the filtered airflow is a function of the filtration efficiency, the duct holding capacity of the filter, and the filtration system run time. Therefore, having the best filter does not necessarily mean better protection against air pollutants, if provisions are not in place to maintain and replace the filter regularly.

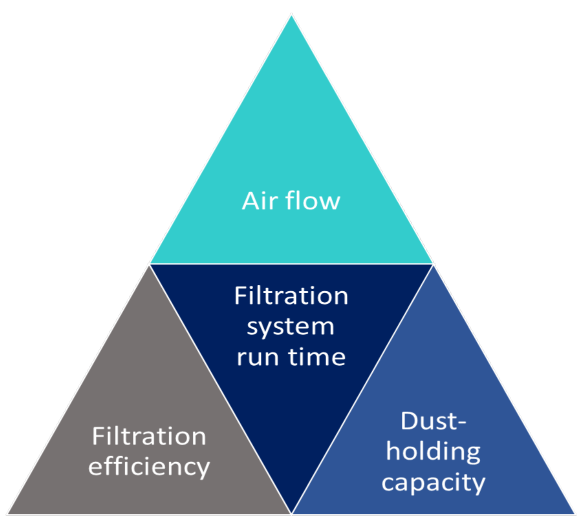


Figure 50. Factors affecting air filtration performance during wildfire events (Sublett 2011)

7.6.2 Human pathogens

Aside from specialized clean-room environments, ventilation systems alone cannot be relied to guarantee pathogen airborne transmission-free environments. As discussed in Figure 9 and section 5.2.3, “the dose makes the poison”. For aerosol-based transmission, the dose (viral charge) can be controlled in two ways: by the health condition, level of protection, and proximity of people in enclosed spaces, and by the ventilation system. Therefore, during pandemics, such as COVID-19, the most convenient motto for indoor air quality and ventilation may be **“Behave tight, ventilate right”**.

In theory, particles that are 5 µm or smaller in size, such as viruses, can remain airborne indefinitely in stagnant air (Wells 1955), unless there is removal due to air currents or dilution ventilation. Experimental laboratory studies found COVID-19 virus in air samples within aerosols for up to 3 hours in one study (van Doremalen et al. 2020), and 16 hours in another study (Fears et al. 2020). Evidence from air samples in COVID-19 patient rooms detect airborne viable virus 2 m to 4.8 m away from patients (Lednicky et al. 2020). This finding suggests that *“for aerosol-based transmission, measures such as physical distancing by 6 feet (about 2 m) would not be helpful in an indoor setting and would provide a false-sense of security”*. However, the complexity of indoor airflow patterns makes it difficult to predict the level of exposure in a room. Airflow direction and airflow patterns affect the dilution effectiveness. As discussed by (Archordoqui L. and Chudnovsky M. 2020) airflow patterns in a room depend on the location of air conditioners, radiators, windows, and all items in the room, as well as on people producing vortices by moving around. Air vortices can trap pollutants and increase concentrations far away from the source. Therefore, airflow patterns need to be carefully planned (Li et al. 2007). Air should not be recirculated as far as practically possible.

Higher ventilation rates are able to provide a higher dilution capability to reduce the cross infection. However, there is a lack of scientific evidence on a minimal airflow rate (Qian and Zheng 2018). According to Morawaka et al. (2020) the air system should operate on 100% outdoor air if possible. Addition of local air cleaning and disinfection devices, such as UVGI may offer benefits (Morawaska et al. 2020). Unlike in hospitals, ventilation systems in residential buildings are not designed to remove or contain human pathogens. However, with the COVID-19 virus pandemic our home has become our refuge against the virus transmission, causing an unprecedented presence of occupants at home, which has become our workplace during the pandemic. Ever since the COVID-19 pandemic outbreak, there has been an enormous amount of research on all kinds of aspects related to how the virus spreads in buildings. Using masks is the most well-accepted measure to minimize the virus spread. A general, common-sense, recommendation related to buildings is to avoid crowds of people in enclosed, seemingly inadequately ventilated, spaces. Therefore, from section of this document, 4.4 Elements of Ventilation, attention has been centered on Element 1: Outdoor air intake, and Element 3: Room air distribution (Table 12, Figure 14). Research evidence, and aerosol physics, have demonstrated that these are the elements that pose the highest risk for airborne transmission. Short-range transmission, the highest mode of transmission, occurs when people are face to face. Long-range transmission occurs when droplets evaporate into 2.5 to 5 µm diameter airborne particles that disperse in the room air. The air temperature and relative humidity are also relevant factors because evaporation is enhanced by high temperature and low humidity conditions. Proper room air distribution is also affected by the convection patterns in a room that are affected by the location of air conditioners, radiators, and windows, and the movement of people. The use of room Portable Air Cleaners (PAC) have also gained attention for enclosed seemingly inadequately ventilated and crowded spaces.

ASHRAE (2020) recommends the measures in Table 29 to protect household occupants in the case there is possibility of having an infected individual at home. As seen in Table 29, proper **compartmentalization** and **pressure management** are critical to minimize COVID-19 airborne transmission. COVID-19 airborne transmission mitigation measures (Table 29) often contradict mitigation measures to control wildfire pollutant penetration indoors (Table 28). Interestingly, the cascading control measures in Figure 47, also apply to COVID-19, but in different ways. For COVID-19, compartmentalization becomes more important than air-tightness, to minimize pathogen migration between indoor spaces ands suites. Furthermore, a main recommendation to minimize the airborne transmission of COVID-19 is to open the windows when the weather permits. However, in cold weather, when windows are not opened, airtightness is still a main control measure for COVID-19 transmission because it decreases the potential for developing stack effect if the building is not well compartmentalized.

Table 29. Recommendation when infected or vulnerable individuals at home (ASHRAE 2020)

Requirement	Infected individual	Vulnerable individual
Exposure control	Isolation room	Protection room
Ventilation	Separate ventilation if possible	Separate ventilation if possible
Airflow control pathogen migration	Install air barriers	Install air barriers
Airflow control cascade ventilation	Exhaust ventilation	Supply ventilation
Portable air cleaning (PAC)	NA	Air cleaner recommended

For MURBs however, there seem to be concerns among dwellers about 1) virus transmission in common areas (CA) such as elevators, laundry rooms, gym, and corridors, and 2) virus spread from a suite with an infected individual to the corridor or to other suites. Following the Ventilation Principles of chapter 4 (Table 11), concern number 1) is valid for rooms such as amenities (AA) and the laundry room (SA) where several people may spend hours in an enclosed space. Circulation areas (CI) pose minimum risk for airborne transmission because they are inherently transient, and because of regular occupant circulation across those areas, they experience more regular air exchanges while being used. In such areas they highest risk of transmission comes from people touching surfaces such as door knobs and elevator buttons. For amenities and the laundry room, occupants should avoid crowds, maintain a safe distance, and wear masks, during pandemic and flue seasons. The ventilation of those common areas (CA) need to be carefully assessed by building professionals. Concern number 2) relates to Element of Ventilation number 4: Air circulation between rooms. This concern is unfounded because there is no evidence from research about virus transmission between rooms, through partitions or through mechanical systems.

7.6.3 Comparison of ventilation systems for building environmental resilience

Table 30 below compares the resilience of the four generic ventilation systems illustrated in Figure 16, based on how they help protect dwellers from emerging environmental threats.

Table 30. Resilience of ventilation systems to emerging IAQ and health issues

Event	Response				Comments
	S1	S2	S3	S4	
1. Prevailing urban air pollution	Fair	Marginal	Fair	Poor	Houses: S1, S3 recirculation, filtration up to MERV 13+ MURBs: S1, S3 NA / S2: limited enhanced filtration
2. Smoke from episodic wildfires	Fair	Marginal	Fair	Poor	Houses: S1, S3 recirculation, filtration up to MERV 13+ MURBs: S1, S3 NA / S2: no enhanced filtration
3. Emissions human pathogens	Poor	Fair	Poor	Fair	S1, S3: recirculate indoor air & equalize concentration of contaminants in dwelling
4. Sustainable heating and cooling	Marginal	Good	Marginal	Poor	S1, S3: gas furnace, air-based heating/cooling S1, S3: recirculation conserves, AHU fan wastes energy
Score	5	7	5	2	Note. S1 and S3 not applicable to MURB suites

Colors: Good (3) | Fair (2) | Marginal (1) | Poor (0) | OK | NA

Figure 16, page 100:

S1: Forced air system (exhaust, depressurization)

S2: HRV/ERV system (mechanically balanced)

S3: Forced air system + HRV/ERV (mechanically balanced)

S4: Exhaust – Air inlets (exhaust, depressurization)

Table 30 demonstrates the complexity involved in meeting all the requirements for resilience under the possibility of multiple environmental and climate threats. Recirculation/filtration systems (S1 and S3) are better suited to handle wildfire smoke because they can be set to work in recirculation model only (without air intake and exhaust). However, outdoor air HRV/ERV systems are better suited to when the pollutant sources are indoors because they minimize the air mixing between rooms.

8 MURB SYSTEMS

As discussed in this document, two main ventilation and air quality concerns in MURBs are following:

- The reliability/robustness of the ventilation system to supply adequate ventilation to each suite.
- The control of contaminant migration between suites, and between common areas and suites.

From previous sections of this document, it is clear that the ventilation system alone cannot be counted on to deliver conditions for acceptable indoor air quality. The building envelope, the construction, and the dwellers impact the reliability of ventilation. The section compares ventilation systems commonly used in MURBs, and studies measures to render the ventilation system more effective, while considering the human aspect affecting ventilation performance. To provide a framework for the discussion in this chapter, Figure 51 below shows the factors involved and measures that are necessary to achieve effective ventilation system in MURBs. In Figure 51, it is acknowledged that heating and cooling affect ventilation, and vice versa. Furthermore, in this document, dwellers are not simply considered as passive receivers of ventilation, but are also as potential polluters as well as enablers/disablers of ventilation in buildings as discussed in sections 4.5 and 5.2 of this document.

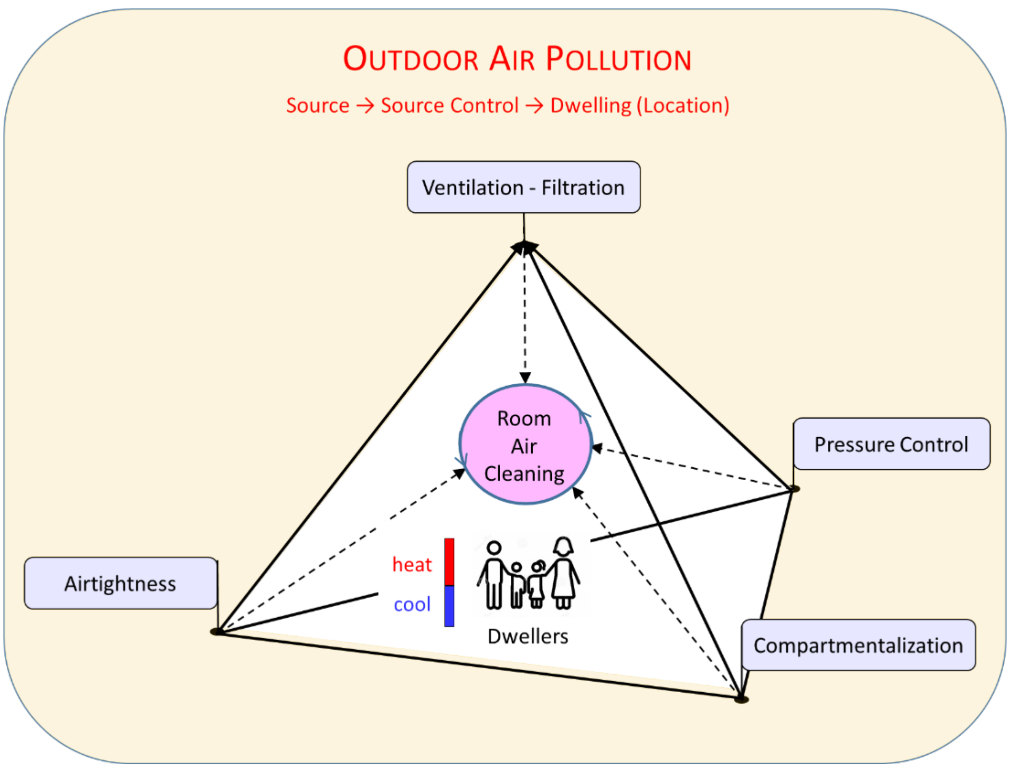


Figure 51. Outdoor Pollutant Penetration Control and Influencing Factors for MURB DUs

8.1 MURB VENTILATION SYSTEMS

Ventilation systems in MURBs have been studied in Canada for more than 20 years. A publication by the CMHC (2003) compares the performance of four MURB suite (i.e. DU) ventilation systems against the conventional corridor pressurization system. Guidelines by BC Housing (2015) and CMHC (2015) provide detailed guidance to assist designers, developers, builders, contractors and owners with the design, installation and operation of heat and energy recovery ventilation (HRV and ERV) systems in multi-unit residential buildings (MURBs) throughout Canada. This section aims to synthesize knowledge from the literature to compare MURB ventilation systems based on the metrics described in Chapter 7 of this document.

In the following discussion, MS stands for MURB-Suite ventilation system.

MS-0. **Conventional system: corridor pressurization.** This system uses the corridors as leaky ducts to supply "fresh air" to the suites under the main suite's door. In supplying air to the suites, it pressurizes the corridors with the intent to limit the migration of contaminants between suites and into the corridors. To maintain a consistency of air intake to the suites (reliability requirement 1 in Table 26), the system is often "coupled' with bathroom suite exhaust fans that run continuously to draw a "consistent" amount of air from the corridor. However, it is well acknowledged now that conventional corridor pressurization systems (MS-0) are not reliable because they fail to meet ALL the reliability requirements in section 7.5 as demonstrated by several studies (Wray et al. 1998, Edwards 1999, Ricketts and Straube 2013, Carlsson 2017). With failing requirement number 13 "Safety" in Table 26 being the most critical: *"conventional ventilation systems can compromise the integrity of fire and smoke control because they are dependent on a high level of interconnectivity between individual apartments and public areas"* (CMHC 2003).

MS-1. **Centralized**. Balanced central system with heat recovery - A rooftop-mounted air-handling unit with energy/heat recovery supplies air to the suites, which is then distributed to the bedrooms and living rooms of the suites, and exhausted from the bathroom(s) in each suite, while partially recovering the exhausted air to preheat the supply air. Corridor ventilation is provided separately.

MS-2. **Semi-Centralized**. Balanced floor-by-floor systems with heat recovery or ventilation stacks with ventilation units on the roof, each serving a stack of suites below via air risers – Air handling units with heat recovery mounted on each floor supply air to the floor suites, which is then distributed to the bedrooms and living rooms of the suites, and exhausted from the bathroom(s) in each suite, while partially recovering the exhausted air to preheat the supply air. Corridor ventilation is provided separately.

MS-3. **Decentralized (in-suite)**. Balanced individual suites with HRV units – A heat recovery ventilator (HRV) in each suite delivers outdoor air continuously to bedrooms and living room, and exhausts air from the bathroom(s), with partially recovering exhausted heat to preheat the supply air. Corridor ventilation is provided separately.

MS-4. **Exhaust**. Passive air inlets + suite exhaust – A bathroom fan exhausts air continuously, which draws makeup air through passive air inlets integrated in the envelope walls or windows. Corridor ventilation is supplied separately.

Figure 52 illustrates schematically a modern centralized (MS-1), or semi-centralized (MS-2) air distribution system with heat recovery. In Figure 52, the suite room-by-room air distribution system is missing. The suite ducting can be directly coupled to the central supply-return ducting, either branching out from/to these or coupled through supple/return plenums at the suites. The boxes with a damper inside are airflow regulators that maintain constant or demand-controlled airflow to each suite (see discussion in section 2.3). The dampers can be set to maintain constant airflow to the suites, or set to modulate for suite-level ventilation-schedule, temperature, humidity, or CO_2 based demand control ventilation (DCV). The basic mode of operation can enable one of three ventilation rate settings: setback, normal, or boost (Swegon 2022). Enabling suite-level DCV in centralized and semi-centralized air distribution systems combine the advantages of centralized whole-building and decentralized suite-level pollutant and thermal control. Mechanical cooling can be added to suites served by MS-1 and MS-2 either at the central level or at the suite level.

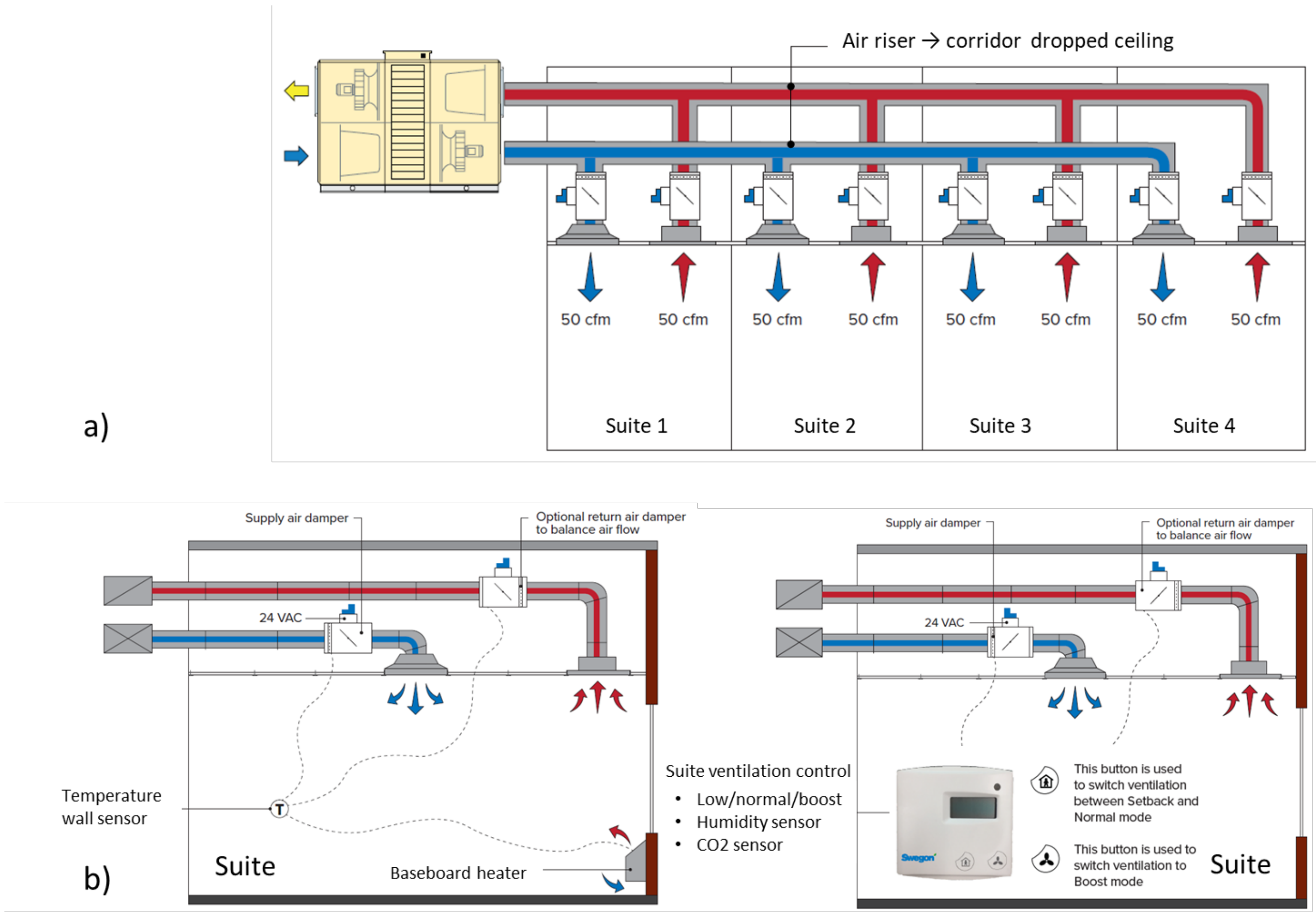


Figure 52. A modern centralized (MS-1) or semi-centralized (MS-2) ventilation system with airflow damper/regulator: a) central system, b) suite-level airflow control, missing suite room-by-room air distribution (Adapted from Swegon 2022)

8.1.1 Systems reliability

For comparing these systems, the requirements in Chapter 7 are applicable. Table 31 compares the four ventilation systems above based knowledge from an original comparison by CMHC (2003), from BC Housing (2015) and CMHC (2015) reports, from a few studies in the literature, and from modeling and simulations conducted in Chapter 10. The first five requirements are related to the five elements of ventilation described in section 4.2 (Table 12, Figure 14). In theory, systems MS-1, MS-2, and MS-3 would perform equally well in these five requirements. However, MS-3 has the inherent ability to provide more consistent/reliable and responsive ventilation to each suite, because it can boost (e.g. high occupancy, high humidity/pollutants load) and reduce (e.g. when unoccupied) the HRV/ERV ventilation rates to the suite on demand. This level of control is only possible with modern centralized (MS-1) and semi-centralized (MS-2) systems having airflow regulator dampers set to suite-level demand-controlled ventilation (Figure 52.b). DCV increase the costs of MS-1 and MS-2, compared to simply implementing constant-flow airflow regulators. In general, central systems offer higher reliability because they offer whole-system operation, control and maintenance, compared to decentralized systems whose operation and maintenance is dependent on the individual dwellers. However, a failure or imbalance in a centralized system is more critical because it affects many suites.

Table 31 below compares the reliability of the four systems described above. For centralized and decentralized systems, the evaluation assumes that they contain a constant flow airflow regulator, as opposed to DCV. Table 31 is an example of a comprehensive and systematic reliability evaluation of these systems. To compare other systems (e.g. centralized with suite-level DCV), the systems' features and capabilities, as well as the scoring of each requirement, can be changed.

Table 31. Reliability of MURB ventilation systems (MS1 and MS2 in constant airflow mode)

Requirement	Response				Comments
	MS1	MS2	MS3	MS4	
1. Consistency and Responsiveness in the outdoor air intake					MS1, MS2: no absent mode / boost mode MS4: affected by weather & air leakage
2. System air distribution					Dependent on 1 MS1, MS2: vulnerable to duct air leakage
3. Room ventilation effectiveness					Dependent on 1
4. Air circulation between rooms					Dependent on 1
5. Energy efficiency					MS1 and MS2 cannot reduce speed in response to absent-mode, MS4 does not have heat recovery
6. Migration from pollutants suites/building					MS1, MS2, MS3: balanced ventilation MS4: exhaust ventilation
7. Weather independence					MS1, MS2, MS3: balanced, constant airflows MS4: envelope more sensitive to weather
8. Response to dynamic occupancies: family dining, watching TV, sleeping					e.g. adjust room airflows on demand No response from any of the systems
9. Response to high indoor polluting events: gatherings, high moisture, cooking, etc.					MS3: boost HRV in high polluting events MS3: boost on cooking
10. Vulnerability to occupants' misuse, tampering, altering effectiveness					MS3: subject to vandalism or misuse MS4: vulnerable to blocking air flows
11. Enhanced filtration in extreme events					MS1, MS2: up to MERV 13/16 + active carbon MS3: limited filtration
12. Pressure compensation: kitchen, bathroom exhaust fans (Figure 21)					MS3: limited boosting supply/exhaust fans
13. Cooking pollutants (venting)					MS3: limited boosting HRV/ERV fan flow
14. Fire safety: smoke & pollutant migration from parking & other suites					MS1, MS2: require fire/smoke dampers at fire/smoke penetrations
15. Balancing					MS1, MS2: difficult to balance, unbalancing MS3: easier to balance, MS4: unbalanced
16. Maintenance					MS3: individual maintenance per suite
17. Capital cost					MS3: one HRV unit per suite $
18. Systems integration					MS1, MS2: interfere with compartmentalization MS3: interfere with envelope, MS4: energy penalty
19. Other practical considerations	MS1: fire dampers, duct risers, overhead ducts in corridors MS2: fire dampers, equipment at each floor, overhead ducts in corridors MS3: two envelope penetrations per suite				
Score	30	31	36	9	

Colors:	Good (3)		Fair (2):		Marginal (1)		Poor (0):		NA	NA

In the MURB ventilation systems comparison of Table 31 the decentralized system (MS-3) is the most reliable ventilation system. However, if DCV is implemented in centralized (MS-1) and semi-centralized (MS-2) systems, then MS-1 and MS-2 will be more reliable.

8.1.2 Systems resilience

Considering ventilation system resilience in Table 32, systems MS-1, and MS-2 seem to performance better than MS-3 because the central HRV can accept MERV-13 type filtration enhanced with activated carbon filtration to remove a high percentage of outdoor urban pollutants or pollutants from wild fires, as well as gases. Considering emissions of human pathogens, in theory, systems MS-1, MS-2, and MS-3 should perform equally. However, the better consistency and responsiveness of MS3 (Table 32) to supply the right amount of ventilation to each suite, should theoretically lead to improved suite and room levels of ventilation control.

Table 32. Resilience of MURB ventilation systems to emerging IAQ and health issues

Event	Response				Comments
	MS1	MS2	MS3	MS4	
1. Prevailing urban air pollution					MS1, MS2: enhanced filtration up to MERV13/16 + carbon MS3: +portable air cleaner if suite is airtight
2. Smoke from episodic wildfires					MS1, MS2: enhanced filtration up to MERV13 + carbon MS3: +portable air cleaner if suite is airtight
3. Emissions human pathogens					MS3: improved suite and room ventilation control MS4: cannot control airflows
4. Resilient Sustainable cooling					MS4: cannot seal envelope openings
5. Responsiveness to events 1 through 4					MS1 and MS2: enable whole-building response
Score	13	13	8	2	

Colors:	Good (3)		Fair (2)		Marginal (1)		Poor (0)		OK	NA

8.1.3 Mechanical filtration

Air system filtration technologies may combine pre-filtration, high-efficiency filtration, and activated carbon filtration. However, filters are not the "silver bullet" for indoor air quality. As discussed in section 1.1, building ventilation is a risk mitigation approach to indoor air quality. Filtration can be part of the overall risk mitigation strategy but it should not be regarded as a solution by itself (Siegel 2020). Scientific evidence shows that filters can reduce exposure to certain pollutants and can even improve health outcomes of the building occupants. However, studies on air filtration, indoor air quality, and health need to be examined carefully to relate study conclusions to context: contaminants of concern, ambient conditions, etc.

The use of high-efficiency filters can also be counterproductive. The pressure drop increase of the filters throughout their service life must be minimized, and therefore proper filter maintenance and replacement are crucial. Furthermore, system air filters may create a pollutant reservoir for triggers if they are not well-maintained. A high-efficiency filter typically has a high initial pressure drop and depending on the pollutant loading may accumulate dust and particles very quickly, thus requiring frequent filter changes. A high efficiency filter can also cause more air to bypass the filter (due to its increased obstruction to airflow) if it is not properly installed and well sealed. A high pressure-drop filter can also reduce the amount of air supplied to the building, making the filter less effective. Long term residential tests have shown that protecting fine filters with coarser pre-filters, reduces the filter pressure drop, and improves the ventilation energy efficiency (Ginestet et al. 2013).

8.1.4 Ventilation integration with heating and cooling in new buildings

Figure 53 shows combination of ventilation, heating, and cooling alternatives that can be used in new MURBs (TD Systems 2020). Note that in these alternatives, delivering centralized heating and cooling via the air distribution system is not contemplated for three reasons. 1) It couples ventilation with heating and cooling, which may compromise the ventilation performance, and make it subservient of heating and cooling. 2) Even with DCV airflow regulators (Figure 52), it is challenging to deliver satisfactory centralized heating and cooling to multiple suites with very different thermal loads. 3) The low thermal capacity of air makes it a very inefficient heating and cooling medium, particularly for entire buildings.

Except for alternatives 3 and 4, in all the alternatives the ERV ventilation works independently of heating or cooling. Ventilation alternatives 3 and 4 are analogous to System 3 in Figure 16 (HRV coupled to the AHU) for single houses. The ERV supplies the air to the return plenum of the fan-coil unit (FCU). The system works well as long as the FCU is operating in either heating or cooling. However, the FCU does not operate when heating and cooling are not required, in such case the ventilation air from the ERV is properly distributed to the rooms as intended. Therefore, alternatives 3 and 4 provide effective ventilation only if the FCU operates continuously, unless a variable speed FCU is specified that can operate in heating, cooling and ventilation-only modes.

Alternatives 1 and 2 use electric baseboard heaters (EBH) for heating. Alternative 1, in-suite through-the-wall heat pump (HP-TW) provides cooling only to the room where the unit is located, whereas the other alternatives provide cooling to the entire suite. Alternative 2 is an in-suite mini-split heat pump (MSHP) system that circulate a refrigerant to cool individual rooms. Alternative 3 combines an in-suite air-source heat-pump (ASHP) with a fan-coil unit (FCU) for heating and cooling, with refrigerant circulating through the FCU coils. Alternative 4 uses an in-suite water-source heat-pump (WSHP) unit to heat or cool water from a central loop that is then supplied to the heating/cooling coil of the FCU. Alternative 5 provides central district heating and chiller cooling that is delivered via hot/cool water loops to in-suite hydronic baseboard convectors or radiators.

	In-suite			Central	Notes	
1	ERV	Ventilation	or	ERV		ERV: Energy Recovery Ventilator
	EBH	Heating				EBH: Electric Baseboard Heater
	HP-TW	Cooling			Living room or bedroom only	HP-TW: Heat Pump Thru-Wall
2	ERV	Ventilation	or	ERV		
	EBH	Heating				
	MSHP	Cooling			Entire apartment	MSHP: Minisplit System
3	ERV	Ventilation	or	ERV	ERV supplies air to plenum of FCU	
	ASHP-FCU	Heating				ASHP-FCU: Air-Source Heat Pump Fancoil heating/cooling
		Cooling			Entire apartment	FCU: fancoil unit
4	ERV	Ventilation	or	ERV	ERV supplies air to plenum of FCU	
	WSHP-FCU or VRF-FCU	Heating	&	Water loop or VRF		WSHP-FCU: Water-source heat pump to fan coil unit or
		Cooling			Entire apartment	VRF-CFU: VRF heat pump to fancoil unit
5	ERV	Ventilation	or	ERV	ERV supplies air to plenum of FCU	H-H/C: hydronic heating/cooling
	H-H/C	Heating	&	District	Connected to district heating	District: district heating, hot water loop
		Cooling	&	Chiller	Entire apartment	Chiller: central chilled water loop

Figure 53. Ventilation, heating, and cooling alternatives for new MURBs

8.1.5 Ventilation-cooling retrofits

Energy retrofitting existing buildings is key priority to improve the energy efficiency and decarbonize buildings to mitigate climate change. Energy retrofits involve envelope and mechanical upgrades. Envelope upgrades can involve replacing windows, adding insulation and recladding the envelope, which can result on improved building airtightness. Improving the airtightness of an existing building with much of its ventilation relying on air leakages results in diminished ventilation, reduced indoor air quality and possibly increased moisture problems. Mechanical upgrades involve replacing the mechanical systems for more efficient ones. Due to climate change, a recommended mechanical upgrade is to add mechanical cooling to suites; focus is on low-energy and low-carbon retrofits, and minimizing suite overheating with mechanical cooling. Ventilation is not a priority in low-energy and low-carbon retrofits for existing buildings. Adding ventilation proper alone may not be attractive or even feasible for many existing MURBs. However, combining ventilation and cooling, even partial cooling, may be an opportunity to address both challenges synergistically.

Ventilation systems for existing MURBs can also be classified as centralized, semi-centralized, and decentralized (our in-suite). Adding proper ventilation to existing MURBs, that considers the ventilation principles in section 4.3 and applies all the required the elements of ventilation in section 4.4, is challenging. In particular, for existing MURBs that have a corridor pressurization system for ventilation or that may not have any mechanical ventilation at all, such as older low-rise buildings, adding proper ventilation involves the following five main challenges.

1) Air tightening and compartmentalizing the existing building to enable proper ventilation control, which would involve isolating dwelling units from corridors and multistory shafts, and sealing the leaks in existing multistory shafts, with priority to duct and ventilation shafts. As explained by Ueno et al. (2012), *"Leaky exhaust duct shafts pull additional exhaust air out of interstitial spaces (i.e., "stealing" air), which does not help meet the minimum exhaust requirements and results in overventilation."*
2) Adding ducts to distribute ventilation air to suites. Adding ducts for a fully centralized ventilation system may not be physically possible due to existing space constraints. One solution may be to design a semi-centralized ventilation system consisting of stacks with ventilation units on the roof, each serving a stack of suites below. This arrangement would only require one duct riser per stack of suites, thus eliminating the need for horizontal duct systems.
3) Achieving proper room-by-room air distribution and cascading air circulation in the suite from bedrooms and family areas to the bathrooms and kitchen. This is another big challenge because of height and space limitations in existing suites that reduce the possibility to lay out ducts for air distribution. One possibility may be to lay out ducts in soffits along perimeter walls.
4) Adding heat recovery to ventilation. Adding heat recovery to centralized and semi-centralized systems involves designing return air ducts to connect the suite bathrooms to the central air handling units on the roof. This is probably the biggest challenge. One possible solution, again, is if the building already has stacks of bathrooms exhausting used air to the roof, then the same stacks can serve as duct risers to return the air from bathrooms to the central air handling unit.
5) Adding ventilation air intake and exhaust openings to the building envelope for decentralized (in-suite) ventilation systems. From an energy efficiency perspective, adding openings to the envelope is not

recommended because they introduce envelope thermal bridges and additional envelope airflows that reduce the possibility to reach energy efficiency targets.

Ueno et al. (2012) documented a ventilation retrofit in a mid-rise (4-storey) residential senior housing building constructed in the mid-1980's in Philadelphia. The ventilation upgrades were one component of the retrofit, which also included lighting, space heating, domestic hot water, and appliance upgrades. The existing building ventilation for the dwelling units consists of a rooftop-mounted gas-fired makeup air unit serving a central corridor pressurization system, coupled with separate kitchen and bathroom exhaust duct-stacks, with rooftop exhaust fans, connected to registers in the bathrooms and kitchens of the suites. However, as explained by the authors, the rooftop makeup air unit had been disabled for approximately two years due to poor performance, resulting in poor indoor air quality and fire safety hazard due to building depressurization. The solution decouples/separates corridor ventilation from suites ventilation. As such it required that the main entry doors of the suites be air-tightened. The supply air solution replaced the existing corridor-pressurization centralized rooftop make up air unit with floor-by-floor corridor-supply ventilation, with recirculation of corridor air to temper the supply air, and save air heating energy. The solution abandoned multistory shafts, which are associated with stack-driven airflow problems. The exhaust system solution air-sealed the existing bathroom and kitchen ducts, and replaced the existing rooftop exhaust fans with variable-frequency-drive (VFD) variable speed fans that rely on a pressure sensor in the ducts to maintain a negative pressure in the exhaust ducts with respect to the exterior in response to the operation of apartment bathroom and kitchen exhaust fans. The suite kitchen and bathroom fans provide ventilation (i.e. exhaust air) on an as-needed or time control basis. With this solution, the suites remain depressurized. Because the envelope airtightness remained unchanged, the exhaust ventilation relies on the envelope air leakages for makeup air. The main weakness of this retrofit system is that it relies on air leakages for ventilating the suites, thus the ventilation air cannot be filtered, in case of outdoor pollution or wildfires smoke. Furthermore, makeup air is un-tempered, thus is wastes energy and may produce discomfort of the dwellers.

Neuberger and Lang (2017) describe the makeup air ventilation and heating retrofit of a tall (24-storey) multi-unit residential building constructed in 1989 in Vancouver. The ventilation of the existing building consists of a rooftop-mounted gas-fired makeup air unit serving a central corridor pressurization system. The retrofit maintained the corridor pressurization ventilation strategy, which couples the ventilation air of the corridors and the suites. The retrofit involved replacing the existing gas-fired ventilation unit with ASHP gas-fired hybrid unit. The design team calculations indicate that for the vast majority of the heating season, electricity, instead of gas, is used to condition the ventilation air. In addition to ventilation and heating, the new rooftop unit supplies cool air in summer that can cool the corridors and potentially supply partial cooling to the suites to offer partial relief from overheating. As indicated in the document, a primary concern is the electrical capacity at the roof to accommodate the heat pump itself. Unfortunately, the project consisted only on an equipment upgrade. As such, the project did not include any verifications and upgrades of ducting, pressures, or airflow controls to optimize the system performance. Furthermore, the document does not mention any enhanced air-filtration or variable-speed enhancements to the new rooftop unit to better respond to the challenging climate demands. Last but not least, improved airtightness and compartmentalization of the accesses and vertical circulations and shafts would make the newly installed system ventilate better and be more energy efficient.

Neuberger and Lang (2017) also describe a decentralized ventilation retrofit for a townhouse complex consisting of 3-storey buildings constructed in 1983 in Burnaby. The townhouses suffered from poor air quality, and condensation problems on exterior walls and on window frames. The envelope walls of the townhouses were upgrades and the windows replaced with high-performance windows. The upgrades made the townhouses more airtight, and therefore a ventilation solution was required. The ventilation upgrade consisted of a pair of ductless HRVs, called Lunos e^2 from Germany, embedded in exterior walls, in two separate rooms of each townhouse. The two HRVs operate in a paired synchronized and cycling mode, shifting between supply and exhaust at a specified time interval: when one HRV unit supplies air the other HRV unit is exhausts it. Apparently, the only issue with these HRV units are the noise complaints by the dwellers because of the continuous cycling of the units. However, the document does not mention important aspects of ventilation: do the ventilation rates provided by these units comply with the BC Building Code requirements? Or do the pair of HRVs achieve proper fresh air distribution and adequate air circulation between rooms?

The Ken Soble Tower Transformation is a large apartment tower rehabilitation of an 18-storey apartment tower built in 1967 in Hamilton, Ontario to a Passive House standard (Era 2020). The building was empty during the retrofits because it was in such bad conditions that it could not be occupied. The envelope of the building was fully renewed to increase occupants' thermal comfort and enable the downscaling of the mechanical system. The ventilation of the existing building consisted of a rooftop-mounted gas-fired makeup air unit serving a central corridor pressurization system. The solution decouples/separates corridor ventilation from suites ventilation. As such it required that the main entry doors of the suites be air-tightened. Surprisingly, the design team of this project managed to make use of the existing riser shafts in the building to design a centralized ventilation system with direct ducting to the suites, central heat recovery, and central partial cooling/dehumidification. The available documentation also describes a *"decentralized cooling "boost" in each suite through a variable air volume unit activated by in-suite controls."* However, there is no description available on how this terminal VAV unit enables cooling. From the limited information on this project, it seems that the design used existing exhaust duct risers, exhausting the air from kitchens and bathrooms in the building, to channel ventilation ducting to the suites. According to the documents available, the existing exhaust risers were "modernized" to enable fully ducted supply and exhaust ventilation to the suites. An important ventilation factor not discussed in the documents available is how the retrofit addressed the kitchen/cooking ventilation. The existing kitchen most likely had a cook-stove hood that exhausted cooking pollutants to the exterior, possibly through shafts up to the roof. These were likely replaced with a recirculating hood with charcoal filter, as is customary practice by the Passive House standard. The likely solution freed ducting shaft space that was likely used for ventilating the suites, and kept the suite air balanced. Another important factor not mentioned in the documents available is any compartmentalization of the building, aside from air-tightening the suite entry doors.

Table 33 describes five possible ventilation retrofit strategies for existing MURBs. The implementation of any of these strategies needs to be considered on a case by case basis depending on the existing MURB typology, type of occupants (owners, renters, social), and the budget availability for the retrofit. A key concern regarding all the strategies in Table 33 is how to effectively address cooking pollutants and cooking moisture. Answering this question is particularly critical to strategies that aim to maintain balanced ventilation air, and to retrofits that involve envelope airtightness and compartmentalization measures.

Table 33. Alternative ventilation retrofit strategies

No	Ventilation strategy	Decouple corridor & suites	Ducts to suites	Ducts in suites	Balanced suite air	Heat recovery (HRV)	Cooling AC	Notes
1	Centralized balanced ventilation ducted to the suites with bathroom heat recovery	Yes	Yes	No	Yes	Yes Bathroom central	Partial central + in-suite?	Expensive solution Enhanced filtration Repurpose existing duct shafts to serve stacks of apartments
2	Centralized enhanced corridor pressurization with bathroom heat recovery	No	No	No	No Negative	Yes Bathroom central	Partial central + in-suite?	Use existing bathroom shafts Variable speed for enhanced flow and pressure control Enhanced filtration
3	Centralized enhanced corridor pressurization	No	No	No	No Negative	No	Partial central + in-suite?	Use existing ducts to corridors Variable speed for enhanced flow and pressure control Enhanced filtration
4	Decentralized, in-suite, ventilation	Yes	No	Maybe	Yes	Yes In suite	In-suite?	HRV in-suite ducted Repurpose existing envelope bathroom & kitchen openings Recirculation hood filter cooking pollutants HRV ductless through wall Limited filtration
5	Semi-centralized: one makeup air unit per floor	Maybe	Maybe	Maybe	Maybe	Maybe	Partial? + in-suite?	Enables better ventilation control than centralized Design possibilities depend on floor-to-ceiling height

Introducing in-suite mechanical cooling, as part of any of the retrofit ventilation strategies in Table 33, can be accomplished in three possible ways, all relying on local electric heat-pump technology for cooling:

a) **Terminal unitary air conditioning**. Most of these units recirculate/cool indoor air, thus they help mix the indoor air, but do not ventilate. However, some units introduce outdoor ventilation air into the room. A concern related to these latter units is that they may interfere with the suite pressures. For example, a commercial unit introduces outdoor ventilation air and mixes it with recirculation room air. The mix is then filtered, using a MERV8 filter, and cooled and supplied the room. In doing so, the unit pressurizes the suite, which promotes the migration of pollutants from the suite to the corridor. Another unit that integrates an HRV with the cooling unit does not interfere with the suite pressures. However, commercial terminal AC units that integrate ventilation, provide very limited, MERV8, filtration. Furthermore, these units provide ventilation air only when cooling is in operation, which is during very short periods of the year.

b) **Mini-split systems**. These systems circulate refrigerant to terminal units in different rooms. The terminal units use a fan to recirculate the room air though the refrigerant coil and cool the room. In this case, cooling is completely independent from ventilation.

c) **A fan-coil unit (FCU) in a ceiling plenum**. If the ventilation strategy incorporates HRV supply air to the suite (strategies 1 and 4), then HRV supply air can be semi-coupled with the FCU at the ceiling plenum. The Central or in-suite HRV supply fresh air to the FCU plenum where it mixes with suite return air, then the mixed air in the plenum is drawn by the FCU, cooled, and supplied to the suite. The exhaust air back to the HRV is located in a bathroom, possibly far from the plenum to avoid ventilation air short-circuiting the suite, no matter if the FCU is ON or OFF. If the ventilation strategy does not contemplate and HRV (Strategies 2 and 3), then the FCU would simply recirculate and cool the room air. In such case, it is probably more convenient to select a mini-split system for cooling. A disadvantage of solution c) is that when the FCU is not in operation, the HRV air is supplied to the suite through the return grille of the FCU plenum. Therefore, it is important to locate both the supply and return grilles of the FCU in strategic locations to achieve proper air distribution, and avoid supply-return short-circuiting, no matter if the FCU is ON or OFF.

Cost wise, the less expensive solution for cooling is selecting a terminal unitary AC (solution a). Solutions b) and c) involve running refrigerant lines either to the rooms to be cooled (solution b), or to the FCU (solution c). From a ventilation perspective, all the cooling solutions promote indoor air mixing, due to the volumes of air moved and the temperature differentials they create, which enhances ventilation. However, providing proper suite air circulation that implements the cascading effect of air flow, can only be achieved with ducted suite ventilation, which will likely not be feasible for existing buildings.

8.2 THE BUILDING ENVELOPE AIRTIGHTNESS

Being the building indoor-outdoor environmental separator, the building envelope performance is integral and overarching to the building (thermal/energy, durability, air quality, acoustic, lighting, and environmental) performance and sustainability. Airtightness is defined in Chapter 2; in simple words, airtightness is the ability of envelope materials and assemblies to resist airflow. Building envelope airtightness testing is used to predict outdoor air leakage (infiltration) in buildings under normal operation. The airtightness metrics and testing/measurement are summarized in BC Housing (2017). Improving envelope airtightness has implications in building thermal/energy performance, envelope moisture-durability, and of course indoor air quality. The theory and impacts of airtightness on building airflows is described in Chapter 2 of this document. The airtightness of multiunit residential buildings has been studied in British Columbia for several years now, pioneered by RDH Building Science (Finch et al. 2009, RDH 2013, BC Housing 2017), as well as by CMHC at the national level (CMHC 2017). Building airtightness for pressure/airflow control in buildings is effective only if combined with proper building compartmentalization.

Airtightness can be considered a property of a material, component, assembly, or a whole building. It is expressed in $L/s \cdot m^2$, thus being normalized m^2 of tested air barrier area. Airtightness tests are conducted in the laboratory, for materials and smaller components, and in the field, for large assemblies and whole buildings. The tests are conducted at a specified set of differential pressures to enable flow-pressure curve fitting. For test repeatability and reproducibility, the set of differential pressures that the component is subjected to are much higher than the pressures experienced by the assembly in service life. The airtightness value is then reported at differential pressures of 50 Pa or 75 Pa depending on the component and the standard used.

Air leakages through assemblies and components are the result of natural and mechanical forces in buildings, that produce much smaller, highly dynamic and highly variable, pressure differentials across these assemblies/components. Airtightness test results under controlled high-pressures are often extrapolated using empirical methods to predict the air leakages through assemblies/components while in service. However, empirical extrapolations suffer from limitations due to: a) inaccuracies in predicting dynamic in-service boundary conditions using static high-pressure test methods, and b) curve-fitting coefficients applying only the assemblies/components of the same type to those tested.

Even though, airtightness refers to testing conditions, and air leakage refers to in-service field conditions, these two terms are often used interchangeably. For example, ASTM Standards call airtightness testing air leakage measurement or air leakage determination. In general, cracks in building components can be broadly characterized as 1) local cracks and 2) area leakages.

1) Local cracks are direct paths that can be easily identified, characterized, and addressed individually, examples are cracks around individual vents, cracks around door frames, cracks in window frames, etc. Local cracks can be point cracks or linear cracks. Passive vents and self-regulating vents can also be categorized as local cracks. Tests can be conducted to characterize the airflow through these cracks under various pressure differentials. Leakages through local cracks are expressed in $L/s \cdot m\,, and/or\, L/s \cdot m^2$, thus being normalized per meter of crack or m^2 of component area. For example, standard ASTM E283 specifies an air leakage test through windows and doors in the field, while standard ASTM E283M specifies an air leakage test through window and door specimens in the laboratory. Leakages through local cracks can also be expressed as a power-law air flow versus pressure difference $(Q\ vs. \Delta P)$ curve fitting equation, or a power-law orifice equation if the orifice area is known.
2) Area leakages are distributed through materials, wall assemblies, and large areas. Leakages through materials are due to their inherent porosities. Leakages through assemblies and large areas occur through orifices, poorly sealed joints at interfaces and material overlaps, fastener and nail perforations etc. These cannot be practically characterized individually. Therefore, area leakages are expressed in $L/s \cdot m^2$, thus being normalized per m^2 of test area. Standard ASTM E2178 specifies a laboratory air leakage test through materials (air permeance), standard ASTM E2357 specifies a laboratory air leakage test through air barriers and wall assemblies; the test can also be conducted in field mock-ups. For whole buildings, ASTM E779 specifies air leakage testing by fan pressurization.

8.3 BUILDING COMPARTMENTALIZATION

In theory, aside from the common areas, multifamily buildings are inherently compartmentalized because with functional spaces intended to be "almost self-contained cells" that operate almost in isolation for safety, privacy and well-being of the occupants. As described in Chapter 2 of this document, to achieve proper airflow control in the building it is important to control both the airflow across the envelope as well as the airflow within the building. The theory and impacts of compartmentalization on building airflows is described briefly in Chapter 2 of this report. Section 6.1.3. Fire and Smoke Control (Figure 40), synthesize the fire safety strategies in buildings. Out of these strategies building compartmentalization (i.e. internal air sealing: suite-suite, suite-corridor, corridor-staircase, floor-floor, etc.) is overarching because it affects the effectiveness of all other strategies by helping contain the fire and smoke as close as possible to its source. Furthermore, building compartmentalization is the only strategy that would permit opening windows in suites without affecting the whole-building building pressure control, and generating unintended airflows across the suite and the building.

As explained by Lstiburek (2019), coupled with the envelope airtightness, building compartmentalization is also fundamental for controlling unwanted/uncontrolled building airflows and achieving effective and robust building ventilation in MURBs. The strategies for building compartmentalization are the following:

- Air tightening (i.e. creating air barriers) all interior walls and floors: suite-suite, suite-corridor, corridor-staircase, floor-floor.
- Designing vestibules (air locks) to isolate vertical staircases and elevators from horizontal corridors and lobbies.
- Designing dedicated elevators and staircases for underground parking
- Designing vertical zoning of elevator shafts.

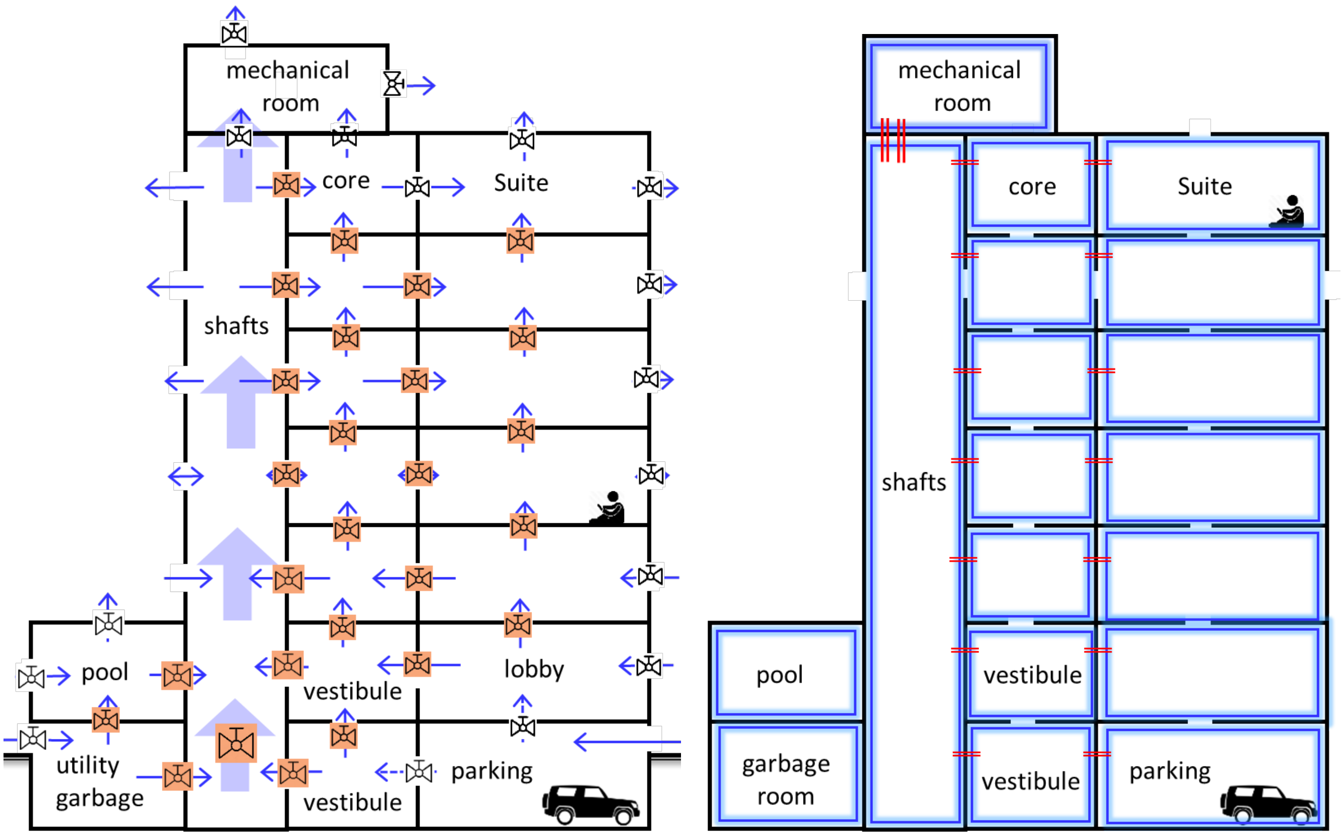
Lstiburek (2019) further proposed designing entirely distributed, decentralized, suite-level mechanical systems, as opposed to centralized or semi-centralized systems, to avoid running ducts across compartments.

Figure 54.a below illustrates a building compartmentalization using water valves. The valves represent all the openings at floors and walls through vertical shafts, doors, pipe and duct penetrations, and other wall perforations. As discussed in ASHRAE (2021) citing Tamura and Wilson (1967): *"…when vertical shaft leakage is at least two times envelope leakage, the thermal draft coefficient is almost one and the effect of compartmentation is negligible."* Shafts are most direct airflow paths in a building, and therefore, are the paths that need to be compartmentalized first by sealing their entry doors, and enclosing them in vestibules if possible. Equation 6) under Figure 54 describes the thermal draft coefficient (γ) that represents the degree of building compartmentalization in the calculation of the stack effect. The value of the thermal draft coefficient depends on the airflow resistance of exterior walls relative to the airflow resistance between floors (ASHRAE 2021).

The most direct air circulation paths in a high-rise building are the human circulations and the service distribution spaces and shafts that act like large conveyance pipes. These "pipes" collect the air from the higher-pressure envelope "pores" and push it through the building towards the lower-pressure envelope "pores" at the other end. Because the central shafts collect the airflows, their doors/walls can potentially experience the highest pressure-differentials, pushing large amounts of air through their cracks. At the floors air collects from or disperses towards the suites, thus producing smaller differential pressures/forces at each suite door/wall, which draw less air through them.

If the building is not well-compartmentalized, the incoming air is easily collected at the shafts, with little resistance at the floors, increasing the differential pressure at the shaft doors. In other words, the differential pressure builds-up at the shaft doors, because the differential pressures at the suite doors and other interior cracks are small due to poor compartmentalization. Vice versa, if the building is well-compartmentalized, air flow at the floors will face resistance from floor cracks and suite doors before reaching the shafts, thus the air pressure at the shaft doors become less critical, which is the driving force for the airflow through the shaft door cracks. Either way, highest pressures are always expected at the main conveyance "pipes", and therefore, addressing leaks between these "pipes" should be prioritized. Luckily, these leaks consist mostly of direct local cracks that can be addressed more easily than distributed area leakages that are mostly hidden and tortuous.

Figure 54.b illustrates the building compartments as completely sealed enclosures around self-contained ventilation zones. The red double lines crossing compartments are controlled paths passing through compartment walls that can be either pipes, or ducts, or doors that remain air-tight when closed.



$$\Delta P_s\{h\} = \gamma \frac{g h_n}{R_a} P_0 \left(\frac{1}{T_e} - \frac{1}{T_i}\right) \qquad \text{(Equation 6)}$$

Figure 54. Building compartmentalization illustrated a) using a water-valve analogy, b) showing the compartments in the building

8.4 MURB AIR LEAKAGE CONTROL

The strategy to control air leakage in buildings effectively is straightforward: identify and prioritize localized leakages connecting services, circulations and other areas that can potentially channel large amounts of air, and therefore can potentially have bigger impacts on the whole-building airflows.

*The strategy follows the **Pareto Principle**: "for many outcomes, roughly 80% of consequences come from 20% of causes" The Pareto Principle is the observation that **most things in life are not distributed evenly. The key point is that each leakage path or crack does not contribute the same amount to the air leakage.***

Management of airflows is critical for achieving high-performance buildings. Sealing envelope and internal air leakages is a top priority to achieve healthy, high-performance buildings. However, as stated in the ASHRAE Handbook of Fundamentals (2021) *"It is much easier and more cost-effective to build a tight building than to tighten an existing building."* Ideally, all leakages should be sealed. In practice however, the sealing of unintended construction leakages or cracks requires a systematic approach that categorizes leakages based on levels of priority given by the areas/zones that they communicate, the characteristics of the leakage (size and directness of the path itself), and the assembly/component where it belongs, which indicates the ease of access and feasibility of sealing or replacement.

Chapter 4 divided MURB areas or zones into the following generic functional compartments: 1) Transient or circulation areas (CI), 2) Amenity Areas (AA) for leisure, 3) Service Areas (SA), and 4) Dwelling Units (DU) of the suites. Common areas (CA) are a combination of TA + AA + SA. Enclosed parkade areas (PA) are differentiated due to the risk they pose of pollutants migrating into the occupied areas of the building. These zones are described in Table 11, repeated here for convenience as Table 34.

Table 34. Ventilation and exposure characteristics of generic MURB compartments

Space type		Purpose	Occupancy time (exposure time)	Examples	Ventilation	Important considerations
PA		Parking	Minutes	Enclosed parkades	Induction - exhaust	Due to high risk of toxic pollutant propagation, requires decoupling from the rest of the building
CA	**CI**	Circulation Transient	Seconds – minutes	Lobbies, corridors, elevators	Slightly pressurized ASHRAE Standard 62.1	Fire propagation, evacuation, pollutant migration between spaces
	AA	Amenities Leisure	Minutes – hours	Gym, recreation, community	ASHRAE Standard 62.1	Self-contained, independent from the rest of the building
	SA	Services Mechanical Electrical Laundry Garbage	Minutes - hours	Mechanical service shafts, storage, cleaning, laundry, mechanical rooms, garbage rooms	Source-control, induction-based exhaust ventilation	Risk of chemicals stored, migration into the building
DU		Dwellings	Hours – days	Suites	Balanced: BCBC 9.32	Self-contained

This classification can help prioritize the treatment of leakages in a MURB building. The goal is to prioritize the leakages that can potentially have bigger impacts on the whole building airflows, rather than focusing on the local airflows. In theory, a building that is completely compartmentalized produces only local air flows, within the compartments. Intuitively, the proposed leakage categorization and prioritization are not in agreement with energy performance priorities that focus only on the envelope, and not on building compartmentalization. However, it can be argued that an approach that prioritizes the internal and external leakages that have a bigger impact on whole-building airflows, also achieves higher energy efficiency. Table 35 below presents a proposed categorization and prioritization of air leakages based on the principles described in sections 8.2 and 8.3.

Table 35. Categorization and prioritization of building air leakages

Type of path		Priority	Subcategories	
			A	B
CO	PA-building	0	Vestibule doors, building services penetrations	
EN	CI-EX	1	Access doors, operable windows	Window-walls, walls, roofs, parapets, interfaces, vents
CO	CI-CI	1	Communication doors: entry, vestibule, staircase, elevator shafts	Partition/construction leaks: joints, interfaces, electrical outlets
CO	CI-SA	1	Access door, mechanical services distribution: cabinets, plenums, plumbing and ventilation service shafts, garbage rooms	Service closets, plenums, suspended ceilings, building services penetrations
CO	CI-DU	2	Main suite door	Partition wall, dropped ceiling cavity, floor penetrations, services duct/pipe penetrations
CO	CI-AA	2	Entry door	Partition wall, ceiling, floor penetrations
EN	DU-EX	3	Balcony doors, operable window leaks, passive vents	Window-walls, walls, roofs, parapets, interfaces, vent penetrations, vent risers
EN	CA-EX	4	Access doors, operable window leaks	Window-walls, walls, roofs, parapets, interfaces, services penetrations, vents
CO	DU-DU	5		Partition walls, floor, ceiling, edges, corners, plumbing penetrations, electrical outlets

CO: compartmentalization, EN: envelope, CI: circulation, EX: exterior, SA: service area, DU: dwelling unit, AA: amenity area

The leaks are classified based on the zones they connect and whether they are envelope (EN) or compartmentalization (CO) leaks. The classification/prioritization is further divided into priorities A and B. Group A (local cracks) includes doors and operable windows because they are direct and easier to seal and replace if necessary. Group B (area leakages) includes mostly hidden, tortuous cracks that, even if added together can constitute a large portion of the air leakage, are more subject to careful air barrier detailing, and are more difficult to reach in existing building retrofits. For example, the top air-tightening priority in an existing MURB are type **"CO-0-A"** leaks/paths; and the less critical leaks/path to address are the **"CO-5-B"** leaks, which are mainly leaks between suites. Even though sealing these leaks is important to control fire smoke propagation (Figure 40, section

6.1.3) and to control pollutants migration between suites, it becomes completely impractical to seal all these leaks in an existing building retrofit. Furthermore, unless an uncompensated suite exhaust fan is operated, the pressure differentials and airflows through these leaks is expected to be small.

In Table 35, the top priority is the compartmentalization of central circulation (CI) areas. In Table 35 the staircases and elevator shafts air transient/circulation areas (CI), and the mechanical riser shafts are categorized as service areas (SA).

Figure 55 shows photos of compartmentalization leaks, some of which are sealed with fire-rated sealant. In conclusion from sections 8.2, 8.3, and 8.4, controlling airflows in buildings requires the careful detailing and sealing of all unintended orifices and leaks. For new buildings, all leaks can be sealed effectively. For existing buildings however, the sealing of leaks needs to be prioritized as proposed in the three sections above.

Figure 55. Photos of compartmentalization air leakages, with a few of them being sealed with red fire-rated sealant

9 PERFORMANCE-BASED VENTILATION DESIGN FOR ACCEPTABLE IAQ

Support for performance-based design of building energy, mechanical and envelope systems is now possible thanks to commercial building energy modeling (BEM) software. These are powerful tools that are able to run multiple parametric simulations simultaneously to optimize designs of low-energy and low-carbon systems under varied dynamic boundary conditions. However, most BEM software applications do not model air flows in buildings, even though, some of these applications incorporate a multi-zone airflow modeling module. They model the energy transport by mechanical supply and exhaust airflows from mechanical systems to the building thermal zones. However, without modeling airflows, these applications cannot model intended or unintended airflows between rooms, zones, floors, and shafts, driven by mechanical as well as natural forces. Furthermore, these applications rely on an empirical static equation that provides a fixed infiltration number to consider in the modeling. The fixed modeled infiltration number is a function of the measured airtightness of the building, i.e. normalized air leakage rate at 75 Pa. Therefore, the infiltration does not change with the dynamic operation of the building through the year. This assumption may lead to high inaccuracies in the modeling not only because it does not consider the dynamic pressures from the stack and wind natural forces, but also because the dynamic mechanical forces often result in pressure imbalances in the building. Those mechanical pressure imbalances may magnify infiltration by depressurizing the building, for example due to the operation of bathroom or kitchen fans. Therefore, it can be argued that incorporating airflow modeling in BEM could lead to more accurate energy predictions, and would enable the integration of ventilation and air quality modeling, for example enabling the modeling of CO_2-based demand-controlled ventilation (DCV).

In agreement with Poirier et al. (2021), this document argues that performance-based design should be extended to indoor air quality, beyond energy and carbon performance. Such an approach would enable ventilation to be designed to optimize the ventilation design to achieve satisfactory IAQ, while minimizing risks on the health of the dwellers. Furthermore, the performance-based approach could help quantify the key factors affecting indoor concentrations pollutant concentrations in multifamily housing to identify opportunities for interventions. The performance-based ventilation-IAQ design approach for satisfactory IAQ proposed in this document is outlined in Figure 56. The approach relies on multi-zone airflow network (MZ-AFN) and contaminant emissions and transport modeling (MZ-AFC). The modeling principles are described in Appendix A. A well-known tool to support this type of modeling is NIST CONTAM (2022). The validation of CONTAM and MZ-AFN models in general is well documented, and their application to ventilation and IAQ modeling has also been demonstrated in multiple papers as referred by Guyot et al. (2019). It is acknowledged that the modeling is subjected to multiple sources of uncertainties and error. However, the performance-based approach includes a series of verification and calibration steps to guide the modeller towards reasonable outcomes. Once the model has been verified, it can be used a comparative tool to evaluate alternative ventilation systems and design measures to optimize the ventilation towards acceptable IAQ. The proposed approach is intended to become a foundation for performance-based ventilation design of MURB ventilation systems. Once this type of modeling becomes more common, and more models are verified and calibrated, the goal is that the currently limited set of libraries of airflow components and connections is gradually expanded.

The approach consists of 8 steps described below.

Step 1. Pollutants of concern (PoC) identification. The pollutants of concern in residential buildings have already been identified in Chapter 3, as well as their exposure limits, and their likely sources and characteristic behaviors in the air. Modeling priority pollutants requires a detailed characterization of the pollutants including emission rates, decay rate, deposition rate, diffusion rate, etc. This information is obtained from the literature. Chapter 3, for example, provides data from the literature on acrolein and PM2.5 emissions from cooking.

Step 2. Simulation scope – Based on the sources of the pollutants identified, the second step determines the scope of the analysis which is either whole-building, or a suite-level analysis. The scope of the analysis depends on the location(s) of the pollutant receiver with respect to the source (emitter). As discussed in Chapter 4, in terms of exposure, the priority receiver is the dweller at the suite or dwelling unit (DU), and possibly at a particular room in the suite. However, both the source (emitter) and receiver can be in the same room or zone, a pool or a gym.

a. Whole/suite, or whole/zone whole-building airflow modeling and pollutant migration analyses are conducted when concerned with the migration of a pollutant from one area to another. Examples of this type of analyses are the following. Second-hand smoke migrating from one suite to another, cooking pollutants and smells migrating from one suite to another, chemicals from an indoor pool to the suites, chemicals from a storage room to the suites, and carbon monoxide (CO) or NO_2 from the enclosed parkade to the suites.
b. Suite/room airflow modeling and pollutant migration analyses are conducted when both the source/emitter and the receiver are at the suite. Examples of these types of analyses are the following. Cooking pollutant migration into the bedrooms, formaldehyde concentration accumulation from finishing materials, excessive moisture in a room or suite, CO_2 accumulation in a room. Focusing on the suite/room level of analysis, the performance-based approach by Poirier et al. (2021) selected moisture from the dwellers and their activities, formaldehyde from materials, PM2.5 from cooking, and CO_2 from the dwellers, as the priority pollutants.

Step 3. Model construction: space configuration – topology/connectivity – To build the model, zones and rooms are created first. For whole/suite level analyses, the floor spaces are laid out and then stacked into floors. For convenience, in whole/suite these analyses a suite is represented as a single space or zone. For suite/room level analyses, a suite is created is laid out into rooms. The representation of building spaces in a model is a matter of engineering judgment. Once all the zones are created they are connected together using openings and leakages. Connecting zones using openings and leakages is the most tedious and time-consuming airflow modeling task. Airflow topology includes the description of large intended openings, unintended leakages, and the mechanical air distribution system: ducts and fittings, fans/controls, filters, diffusers, vents, etc.

Step 4. Model verification and calibration – This step has three sub-steps for the whole/suite level model, and one or no step for the suite/room level model.

a. To verify the airtightness of the building envelope, a pressurization test is conducted on the whole-building model, excluding only the areas outside of the air barrier system. This is an iterative process in which the envelope leakages are adjusted and the envelope is tested again until a reasonable airtightness level is achieved according to the values obtained from testing local MURB buildings (e.g. BC Housing 2017).
b. To verify the building compartmentalization, the thermal draft coefficient can be calculated using the equation described in Yoon et al. (2015), and its variations in Lozinsky and Touchie (2020). Yoon et al. (2015) developed a calibration methodology for whole-building airflow simulation in MURBs. The methodology uses the thermal draft coefficient to compare measured and simulated pressure distributions in buildings and uses a genetic algorithm to predict the uncertain parameters.

c. Suite airtightness verification-calibration uses the pressurization test of a suite and calculates the suite air change rate at 50 pascals (ACH50) and the normalized leakage rate (NLR), which are compared to data from actual tests on local suites.

Step 5. Ventilation and boundary conditions – In this step, the boundary conditions, weather and occupants, and the ventilation-infiltration systems are entered in the model. As indicated in the diagram the simulations can be steady-state or transient, using hourly weather and hourly pollutant data, depending on the goals of the analysis. Occupant schedules are entered as well as the pollutant sources from occupants. Poirier et al. (2021) provides a complete description of pollutant sources from occupants with focus on moisture and CO2, depending on their task and activity level (cooking, sleeping, etc.). Residential occupancy schedules are available elsewhere (Poirier et al. 2021).

Step 6. Pollutant transport simulation – The pollutant properties and models are entered in the building airflow model, including emission factor(s), schedules, decay, deposition, penetration, etc. The airflow model can be built decoupled from a thermal model, i.e. the heat transfer and the interior building temperatures are fixed, not calculated. However, for airborne pollutants transient models are necessary, including moisture, and depend on the dynamics of the indoor sources, airflows and transport, and on the weather and outdoor pollutant sources. The thermal-fluid dynamics can also be modelled by coupling thermal and airflow modeling.

Step 7. Model verification-calibration – In this step, further model verifications are conducted following two inter-dependent sub-steps. a) By verifying differential pressures and air flows. b) By verifying room concentrations of CO2 and/or selected pollutants. The verifications can be conducted based on steady-state and on transient simulations. In both steps, the goal is to verify that the values obtained are realistic and within the ranges of values measured on similar buildings. To be systematic, a calibration approach similar to Yoon et al. (2015) can be followed.

Step 8. Performance scenarios – Once the baseline model has been verified and calibrated, the model can be used to build selected ventilation-IAQ modeling and simulation scenarios that are representative of the design goals. The scenarios may involve only enhancing ventilation and controls. However, scenarios that involve evaluating the ventilation-IAQ effects of an increasing the airtightness and/or compartmentalization of the building, including for example adding vestibules for compartmentalization, would require revisiting the topology/connectivity and verification steps on the new model (as indicated by the dashed line). The scenario simulation results should be examined and compared using standard IAQ metrics and TLVs determined by the recognized authorities.

Step 9. Design optimization – Finally, design optimization can be conducted on the promising designs.

In Chapter 1, it was discussed that ventilation design follows a risk management approach because as illustrated in Figure 1, its effectiveness is highly dependent on the boundary conditions including wildfires, urban pollution, and the dwellers themselves. Occupants can disable, enable, or enhance airflows, and therefore the dispersion of contaminants. Occupants can also buy furniture that smell new, thus releasing a range of airborne chemicals, as well as pollutants from smoking, burning candles, and even hobbies and other activities, without caring for properly venting these out. Therefore, to make the approach more robust, a systematic uncertainty analysis needs to be built in all its steps. Refining and evolving the MURB ventilation-IAQ performance-based approach, including uncertainty, requires further research driven by ventilation-IAQ performance data collected from actual buildings.

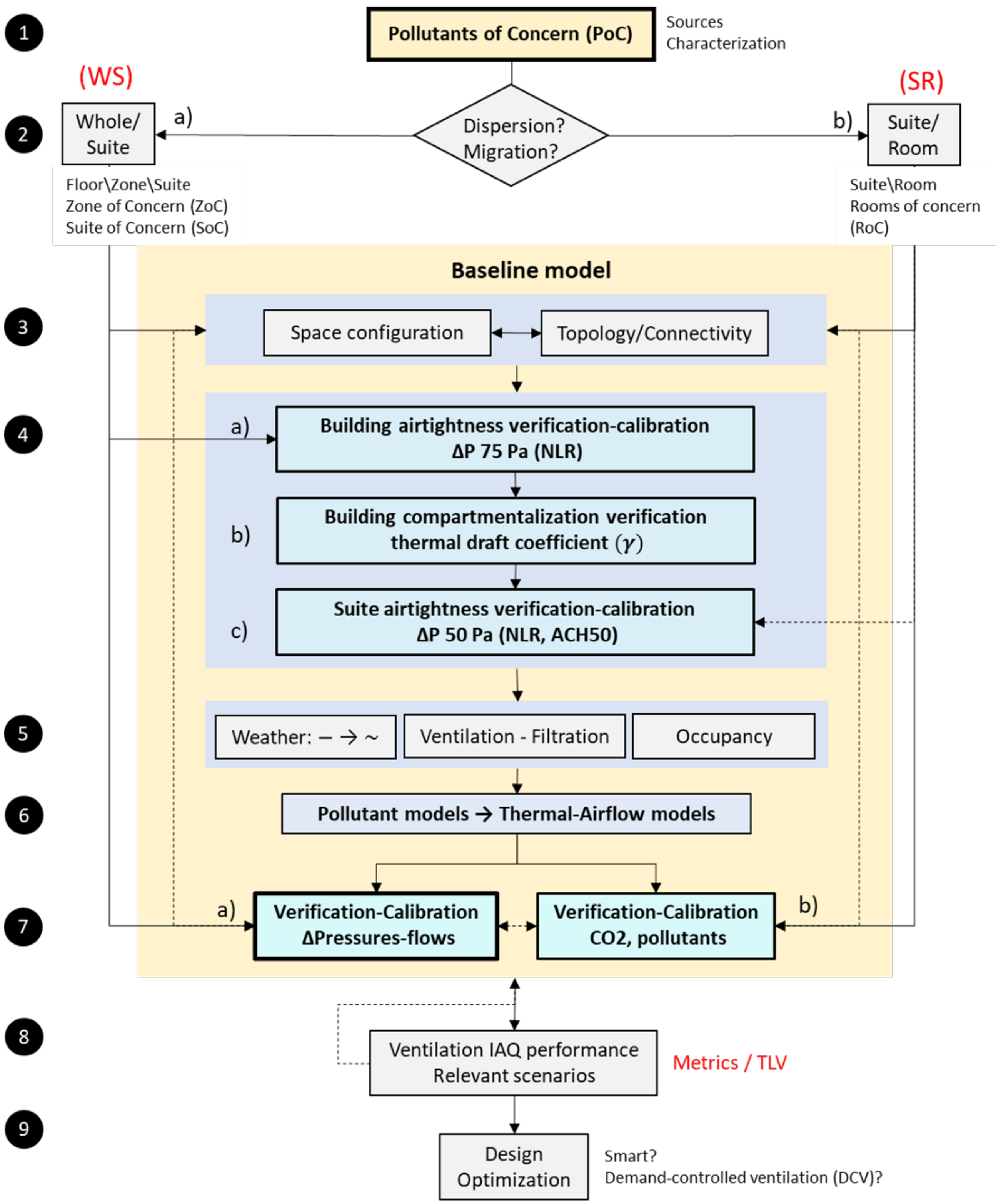


Figure 56. Performance-based MURB ventilation design for acceptable indoor air quality

9.1 OCCUPANCY AND ACTIVITIES

A complete characterization of dwellers into archetypes considering the factors presented in Chapter 5 can provide accurate data to support the modeling of archetypes of dwellers (e.g. family with children, young couple, elder couple, etc.) within a given context (social housing, high-end multifamily, etc.). However, such characterization is out of the scope of this document. A simplified approach considers generic occupancies and activities at two levels: 1) through occupancy schedules indicating the presence of occupants in the suite and in the individual rooms, and 2) through dweller behavioral algorithms describing dweller behaviors affecting pollutant emissions and ventilation.

Similar to energy-focused modeling of occupancy and activities, mainly affecting the internal energy loads, ventilation- and IAQ-focused modeling requires adequate models of dwellers and their activities, as receivers and enablers of the indoor environment (Chapter 5). The household composition is typically based on the number of bedrooms, assuming one person per secondary bedroom, and two people in the master bedroom. Daily occupancy profile schedules are used to estimate the room-by-room presence of occupants in the suite during weekdays and weekends. Occupancy profiles for residential Building America energy simulation protocols in North America have been developed by the National Renewable Energy Laboratory (NREL), as reported by Hendron and Engebrecht (2010), and Wilson et al. (2014). In Europe, residential survey campaigns on hundred of dwellings have collected detailed data on occupancy schedules and their occupancy in the rooms, for example in France Guyot et al. (2019) and Poirier et al. (2021) used data from a French campaign on IAQ in dwellings in their simulations. In Belgium Aerts et al. (2013) used data from a Belgian residential survey campaign. Furthermore, again using data from thousands of country-wide residential surveys, Wolf et al. (2019) developed a stochastic room-level occupancy simulation model; the simulated occupancy profiles consider parameters such as the week day, time of day, occupant age and family type and show good agreement with the measurements. Similarly, Van Den Bossche et al. (2009), used modeling for performance evaluation of humidity controlled residential ventilation systems using Monte Carlo analysis, in which Belgian statistical data was compiled to compute probabilities of room occupancy schedules

Occupant- and climate-responsive smart ventilation systems discussed in section 4.3.7 can be modeled using the proposed ventilation performance-based ventilation-IAQ approach. However, the modeling of smart systems is beyond the scope of this document. The simplest method to model is demand-controlled ventilation (DCV) based on CO_2 concentrations or relative humidity levels in rooms.

9.2 POLLUTANT OF CONCERN (POC) CHARACTERIZATION

Residential pollutant characterization databases are available, such as PANDORA (Abadie and Blondeau 2011), and CONTAMLink (NIST 2022a). However, these databases are not comprehensive and need constant updating. Section 3.1 describes the prevailing indoor air pollutants in residential buildings, and Table 4 describes their presence and behaviors in the air. MZ-AFN modeling uses a room contaminant mass balance equation for each given airborne contaminant to simulate airborne contaminant behaviors (MZ-AFC) as described in Appendices A and B of this document. Modeling airborne contaminants/pollutants requires a good understanding of their emissions and behaviors in the air, and being able to obtain representative emission data and coefficients from experiments or from the literature, as required for the pollutants being modeled. Table 36 shows selected indoor air contaminants/pollutants along with their emissions, decay, and buffering coefficients from the literature. It is acknowledged that there is a great variability in these coefficients, for example assuming electric heat source for cooking, the type and amounts of cooking pollutants depend on the amount of food being cooked, which is related to the size of the household, the type food, the cooking method/media, the type of cooking pan, and the cooking temperature. Formaldehyde emissions from materials depend on the type of material and assembly, its construction, its exposure to the room air, and the room temperature. Wildfire smoke particle penetration factor is diameter dependent, and cracks size and type dependent; the particle deposition rate is also diameter dependent. Some of the references in Table 36 below present their values after collecting data from multiple sources, for example, reference (1), Poirier et al. (2021), and reference (2), Fabian et al. (2012).

Table 36. Selected priority indoor air pollutants with emissions and coefficients from the literature

Source	Pollutants	Type	Parameters		
			Emission rate	Decay Deposition	Buffering Sorption/desorption
Respiration Outdoor	CO2	Gas	18 L/h resting awake 15 L/h sleeping		
Cooking (Section 3.4)	PM2.5	Particulate	High 2.55 mg/min [1] Medium 1.91 mg/min [1] Low 1.26 mg/min [1]	-0.19/h [2]	
	Acrolein	Gas	Low 0.31 mg/h [3] High 1.46 mg/h [3]		Data for modeling not available. Not considered
Tobacco smoke	PM2.5	Particulate	0.33 mg/min [2]	-0.1/h [2]	
	Acrolein	Gas	56 μg/cigarette [4]		Data for modeling not available. Not considered
Moisture: (multiple sources) breathing activities Outdoor	H20	Vapor	Respiration awake 55 g/h [1] Respiration sleeping 40 g/h [1] Shower 25 g/min (10 m) [1] Breakfast 12 g/min (15 m) [1] Lunch 9 g/min (30 m) [1] Dinner 15 g/min (40 m) [1] Laundry 252 g/h 2-h/laundry Laundry dry 137 g/h 3-h/dry Laundry 1 time/week/person Dishwashing 83.3 mg/s [2]		Boundary layer diffusion: Film mass transfer: Low absorbing: 0.72 m/h [7] Partition coefficient: High absorbing: 6.23 kg/kg [8] Low absorbing: 5 kg/kg [7] Surface mass: Thickness 1 cm to 5 cm Material density: drywall, carpet, wood, furniture Density: 400 - 800 kg/m^3 Surface area
Materials	Formaldehyde	Gas	High 23.6 $\mu g/h \cdot m^2$ [1] Medium 12 $\mu g/h \cdot m^2$ [1] Low 4.5 $\mu g/h \cdot m^2$ [1]		Data for modeling not available. Not considered
Wildfire smoke	PM2.5	Particulate	Emission weather file Penetration rate, diameter dependent, crack dependent: Case study Section 10.5 0.7 to 0.8, [6]	-0.19/h [2] Diameter dependent: Case study, Section 10.5, [6]	

(1) Poirier et al. (2021), (2) Fabian et al. (2012), (3) Seaman et al. (2007), (4) Stevens and Maier (2008), (5) Guyot et al. (2019), (6) Lee et al. (2017), (7) Emmerich et al. (2002), (8) Van Den Bossche et al. (2007)

In the list, CO_2 and moisture emission rates are more predictable. Indoor CO_2 emissions, mainly produced by respiration, depend on the age and metabolic activity of the occupants that can be assumed to be either at rest or sleeping while at home. Moisture generation is more variable; however, high, medium, and low moisture generation scenarios can safely be assumed. Poirier et al. (2021), Fabian et al. (2012), Pedersen (2018), and Choi et al. (2020), summarize moisture generation rates from household activities from various references. Table 36 provides sample values; however, all the values fall within the same order of magnitude. Various models exist to simulate moisture buffering, as well as sorption/desorption for gases. However, implementing these models requires obtaining representative coefficients from laboratory experiments under similar boundary conditions and with similar interior materials and finishes to those in the suite. The smell of food of clothing and furniture right after cooking or eating in a restaurant with poor ventilation is due to VOC sorption on these materials.

9.3 MODELING BUILDING TOPOLOGY

The modeling of airflows in buildings requires the characterization and modeling of all possible types of air flow paths connecting zones, including unintended leakages, described in Sections 8.2, 8.3, and 8.4, and large intended openings such as open operable windows and doors. It also requires the modeling of the mechanical air distribution system.

6) **Unintended leakages**. As described in section 8.2 these are categorized into a) local cracks, and b) area leakages, and are characterized using empirical airflow and pressure difference curve fitting equations/models. a) The most common models are the Powerlaw model, $Q = C\Delta P^n$, and the orifice equation, $Q = C_d A\Delta P^n$, where Q and ΔP are the flow and the driving pressure differential, A is the orifice area, C and n are flow coefficient and exponent, and C_d is the orifice discharge coefficient. b) Area leakages are modeled as an equivalent orifice or opening, with a discharge coefficient and a flow exponent, but the metric is expressed as equivalent or effective leakage areas (ELA) and are expressed in cm^2/m^2. The ELA is defined as the area of a special nozzle-shaped hole (similar to the inlet of your Blower Door fan) that would leak the same amount of air as the building does at a pressure of 4 Pa. In Canada, the EqLA is used instead. EqLA is defined as the area of a sharp-edged orifice (a sharp round hole cut in a thin plate) that would leak the same amount of air as the building does at a pressure of 10 Pa.
7) **Large intended openings**. These openings can be open doors and windows, as well as stairwells and shafts connecting floors. This group also includes smaller intended openings such as passive vents, self-regulating vents, and louvres designed for natural ventilation. Empirical models of these openings are created based on testing with resulting performance parameters, coefficients and fitting curves depending on their individual characteristics.
8) **Mechanical air distribution**. Mathematical models of the air distribution system are well documented. These include mathematical airflow models of fans, ducts, fittings, dampers, filters, diffusers, and vents.

The most difficult flow paths to air flow paths to model are the unintended air leakages in category number 1. All cracks and leakages need to be characterized and modeled. Leakage libraries exist but are outdated and not specific to MURBs (e.g. NIST 2022b, ASHRAE 2021). Finch et al. (2009) provide air leakage values from the testing of a MURB building. Stanton (2018) provides a comprehensive synthesis of leakage and opening metrics, models, and coefficients from the literature. However, as recommended by Stanton (2018), proper support for air leakage modeling in MURBs requires the creation of a leakages database that is continuously updated. The database can be organized as a taxonomy by type of leak, system, assembly, and component.

To overcome the current limitation of a lack of models for air flow leakages in MURBs. The approach followed by the proposed performance-based design is to create the flow paths using existing leakage libraries, and fine-tune the paths as the modeling process evolves, following the procedure outlined in Figure 36.

10 CASE STUDIES ON VENTILATION AND IAQ MODELING AND SIMULATION

The case studies presented in this chapter, aim to demonstrate the advantages and opportunities of implementing a performance-based ventilation-IAQ approach to ventilation design. Table 37 below presents the case studies that were modeled to illustrate the approach. The modeling is conducted using multi-zone airflow network (MZ-AFN) and contaminant transport (MZ-AFC) modeling as described in Appendix A, except for the cooking pollutant ventilation case study that uses computational fluid dynamics (CFD) described in Appendix C. For MZ-AFN/C modeling, NIST CONTAM software is used. The case studies illustrate the application of the performance-based ventilation-IAQ approach to test ventilation and whole-building strategies to achieve IAQ targets. Many other relevant case studies can be explored, for example the effectiveness of vestibules to control pressures, air flows, and pollutant migration in the building.

Table 37. Case studies on ventilation and IAQ modeling and simulation

No	Case description	Case study goal	Modeling Method	Pollutant(s) of Concern (PoC)	Author
WS1	Wildfire PM2.5 pollutant penetration passive-house building	Evaluate envelope, ventilation-filtration alternatives to mitigate PM2.5 penetration	MZ-AFN MZ-AFC	Wildfire smoke PM2.5	Amir Salehi, MEng
WS2	Cooking pollutant migration passive-house building	Evaluate cooking ventilation and compartmentalization approaches to control cooking pollutant migration	MZ-AFN MZ-AFC	Cooking PM2.5	Iman Eshghi, MEng
WS3	Ventilation retrofit of an existing low-rise MURB	Evaluate ventilation retrofit alternatives to coupled with increased envelope airtightness	MZ-AFN MZ-AFC	CO2, PM2.5: wildfire, second-hand tobacco smoke	Alireza Asharioun, MEng
WS4	Differential pressures and airflows to suites under stack effect	Study approaches to achieve better airflow control to suites	MZ-AFN MZ-AFC	NA, focuses on pressures and flows	Rodrigo Mora
SR1	Room-by-room air distribution and ventilation alternatives	Compare ventilation alternatives to achieve satisfactory IAQ in bedrooms	MZ-AFN MZ-AFC	CO2, cooking acrolein, cooking PM2.5	Rodrigo Mora
SR2	Room-by-room air distribution and ventilation optimization	Optimize HRV suite air distribution	MZ-AFN MZ-AFC	CO2, cooking acrolein, cooking PM2.5	Anoop Vijayakumar Sobha, MASc
SR3	Wildfire PM2.5 pollutant penetration – a suite-level analysis	Evaluate envelope, ventilation-filtration alternatives to mitigate PM2.5 penetration	MZ-AFN MZ-AFC	Wildfire smoke PM2.5	Amir Salehi, MEng
SR4	Ventilation and moisture control	Evaluate feasible ventilation strategies to minimize moisture risks	MZ-AFN MZ-AFC	H2O: cooking, bathing, people	Rodrigo Mora
SR5	Cooking pollutant ventilation systems	Compare the effectiveness of source-control cooking pollutant ventilation systems	CFD	Cooking PM2.5	Anoop Vijayakumar Sobha, MASc

<u>MZ-AFN/C Main Modeling Limitations:</u>

The main modeling limitations and uncertainties are the following:

- Inherent boundary condition uncertainties.
  - Envelope airtightness uncertainty. The envelope airtightness affects the concentration of pollutants in spaces by contributing to pollutant dilution in an uncontrolled manner. Envelope airtightness uncertainty is reduced in the modeling by adjusting the envelope cracks and virtually testing the envelope airtightness until it reaches a value that is close to that of the building being tested.
  - The actual occupancy of the rooms and the occupancy behaviours. For example, two occupants may live in a suite designed for one occupant, or some occupants may spend more time in certain rooms than predicted (e.g. large time spent in the bedroom or at the living room). This type of uncertainty is inherent and cannot be reduced because the actual occupancy and occupancy changes and the actual occupation of the suite and its rooms can never be predicted with certainty (e.g. a one-bedroom studio suite can house one or two people, and a two-bedroom suite can house two or three people).
- Thermal-fluid modeling uncertainties.
  - This type of uncertainty is related to the capacity of the models to represent the actual thermal-fluid dynamics in and between rooms. Specifically, MZ-AFN models the room air as fully mixed, therefore it does not capture the airflows inside individual rooms and how these affect air exchanges with other rooms. The model assumes that emitted pollutants are instantaneously fully mixed throughout the entire room volume. Therefore, MZ-AFN does not consider thermal-fluid indoor airflows caused buoyant air from the electric heater. Furthermore, it does not consider room thermal-fluid air circulations generated by buoyant cooking air and its pollutants. This type of uncertainty cannot be reduced. CFD modeling is recommended if increased modeling granularity and accuracy in the room airflows are required.
- Pollutant modelling uncertainties.
  - Presence and rate of pollutants and their emission rates cannot be predicted with confidence. In cooking, the amount/rate of cooking pollutant emissions and other cooking pollutant parameters depend on many factors: the type of food, the amount of food, the proportions of food mixes when cooking, the overcooking of food, and the cooking temperature. Therefore, this type of uncertainty is inherently random and cannot be reduced. Aside from the emissions, an accurate prediction of the spatial-temporal variations of pollutant concentrations in rooms depends on the space modeling granularity and the proper characterization of the airborne pollutants, including chemical reactions, particle deposition, surface adsorption/desorption, etc. Models and coefficients that characterize these processes for airborne pollutants are obtained from the literature.

It has been demonstrated that room CO_2 concentrations are highly responsive to CO_2 emissions and ventilation in enclosed spaces, more so particularly in rooms with low ventilation. This is why CO_2 is a reliable indicator of indoor air quality and ventilation. Considering the accuracy of the CO_2 sensors (± 50 PPM), strong thermal forces in rooms such as heaters and cooking heat sources have a smaller effect on CO_2 concentration in rooms. Therefore, the results from the CO2 analysis can be considered to closely represent room CO_2 concentrations based on the scheduled occupancy and ventilation levels. By contrast, cooking pollutants are present as aerosols (a suspension of particles, gases, and droplets that interact chemically and physically with each other). Therefore, the results from the cooking pollutant simulations, even though still useful, are less accurate for two reasons: 1) thermal buoyancy is the main driving force in the emission and dispersion of cooking pollutants, and 2) by comparison with CO_2, cooking pollutants' concentrations are much lower and therefore the fate of the pollutants is more dependent on the interactions with other pollutants and environmental factors. The MZ-AFN models used in the case studies were calibrated by entering representative emission rates and other pollutant parameters from the literature, and adjusting these to obtain reasonable concentration values within the typical ranges from the literature. Therefore, the focus on the analysis is not on assessing the absolute values of concentrations, but rather on comparing the effectiveness of ventilation systems in reducing baseline concentrations.

10.1 WS-1 WILDFIRE POLLUTANT PENETRATION PASSIVE HOUSE BUILDING

Author: Amir Salehi, MEng

The building:

Passive House MURB	No Suites	Suite types	Areas			
Location: Vancouver			Retail	Residential	Other	Net
6 occupied stories: • Ground floor retail, amenities • 5 stories residential 2 stories of underground: • Parkade, deposits	85	Studio, 1, 2, 3 bed	4,501 ft2	59,193 ft2	393 ft2	61,620 ft2

Mechanical/environmental systems:

Heating Cooling	Heating: electric baseboard Cooling: no mechanical cooling
Ventilation	19 Heat Recovery Ventilators @ the top floor, intake/exhaust @ the roof: • HRV Zehnder ComfoAir 550 units: 324 cfm each • Air filtration: MERV7/8 with optional MERV13 • 17 HRV units, each supplying air via risers a stack of suites • Ventilation rates to each suite according to BCBC 9.32 • 2 HRV units, each supplying air via risers to corridor wings @ 65 cfm x 2 = 130 cfm/corridor/floor • Return air from the corridors to the HRV is collected through ducts at the elevator shaft • Corridors are maintained slightly pressurized Retail in the ground floor and amenity area, each with separate ventilation 2 levels of underground parking and deposits, well-compartmentalized with vestibules, self-contained induced/extract ventilation

Modeling:

Goal	Evaluate envelope, ventilation-filtration alternatives to mitigate PM2.5 penetration from wildfire smoke to maximize dweller livability during wildfires.
PoC	Wildfire smoke PM2.5, properties: particle aerodynamic diameter, particle density
Modeling	WS: whole building to suite
Airtightness	Passive house, virtual pressurization test: 0.86 L/s/m2, 0.17 cfm/ft2 @ 75 Pa (baseline case)
Compartmentalization	Interior cracks reduced to minimal, thermal draft coefficient not calculated
Suite airtightness	Suite-level virtual pressurization not tested
Weather	Transient hourly weather and outdoor pollution from Burnaby North Station, during late wildfire season in September of 2020, for simplicity wind is not considered
Occupancy	Occupancy schedules and activities do not affect simulation outcomes. It is assumed that dwellers do not open/close windows, or operate devices that may affect air pressures.
PoC source model	Penetration factor: 0.7, deposition rate: 1 1/h
Thermal-airflow model	Indoor temperature assumed constant at 20°C, outdoor temperature from weather file

Modeling scenarios:

Table 38. Case study WS-1 Modeling Scenarios

Scenario	Envelope	Compartmentalization	Suite ventilation-filtration	Corridor ventilation-filtration
Sc1 baseline	Airtight	Compartmentalized	BCBC 9.32, MERV8	Design, MERV8
Sc2	Moderate	Moderate	BCBC 9.32, MERV8	Design, MERV8
Sc3	Leaky	Uncompartmentalized	BCBC 9.32, MERV8	Design, MERV8
Sc4	Airtight	Uncompartmentalized	BCBC 9.32, MERV8	Design, MERV8
Sc5: Sc1 + MERV13	Airtight	Compartmentalized	BCBC 9.32, MERV13	Design, MERV13
Sc6: Sc3 + MERV13	Leaky	uncompartmentalized	BCBC 9.32, MERV13	Design, MERV13
Sc7: Sc1 + MERV16	Airtight	Compartmentalized	BCBC 9.32, MERV16	Design, MERV16
Sc8: Sc3 + MERV16	Leaky	uncompartmentalized	BCBC 9.32, MERV16	Design, MERV16

Topology/Connectivity modeling:

Ranges of values of local cracks and air leakages are obtained from libraries, and literature sources. From these ranges, leaky, moderate, and tight values are selected for the simulation scenarios. Local cracks are modelled using the orifice equation, while air leakages are modelled using the power law model with discharge coefficient of 0.6 and flow exponent of 0.65 at 10 pascals. The modeling assumes that all intended envelope vents are closed.

Space configuration:

Figures 57, 58, and 59 show the CONTAM modeling of the typical floors of the building.

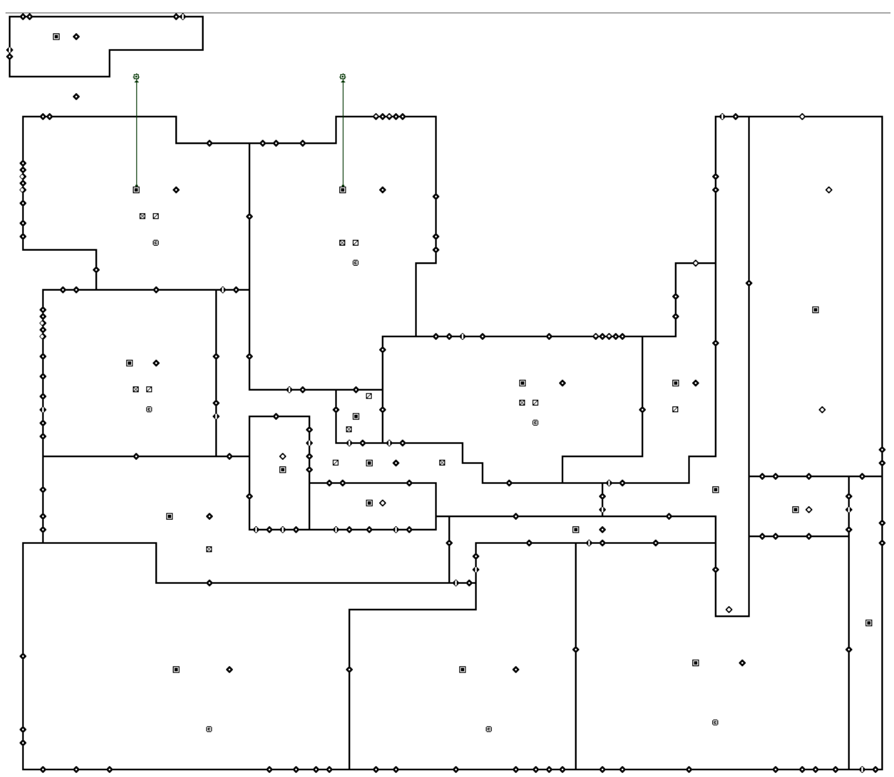


Figure 57. CONTAM model of the main floor

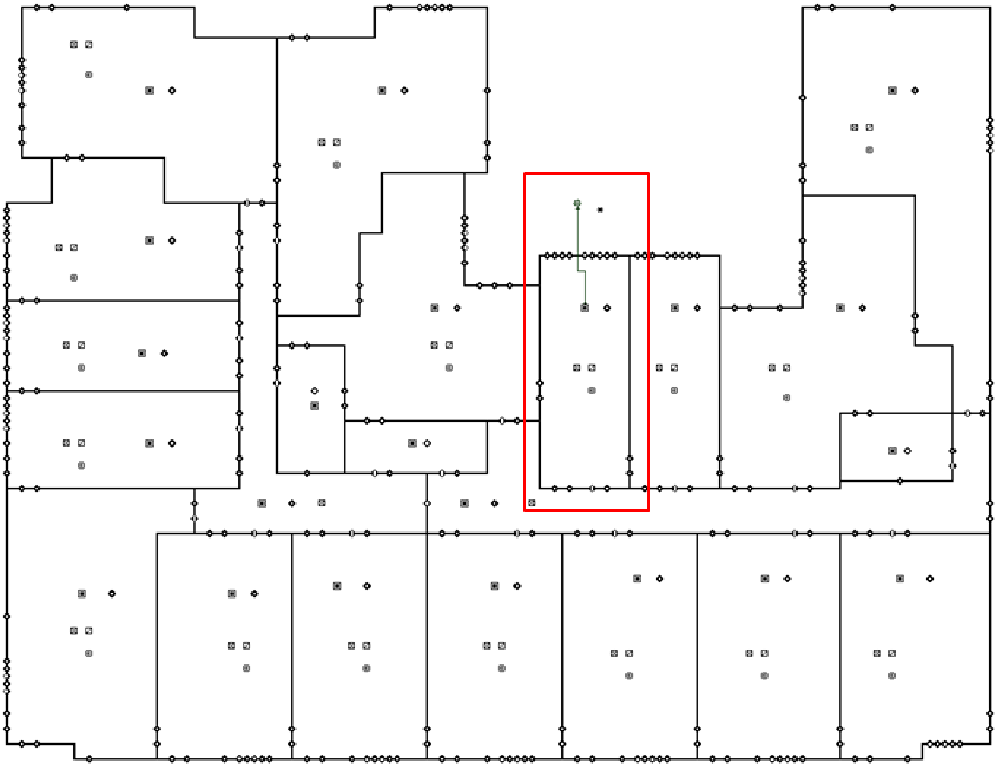


Figure 58. CONTAM model of the second floor

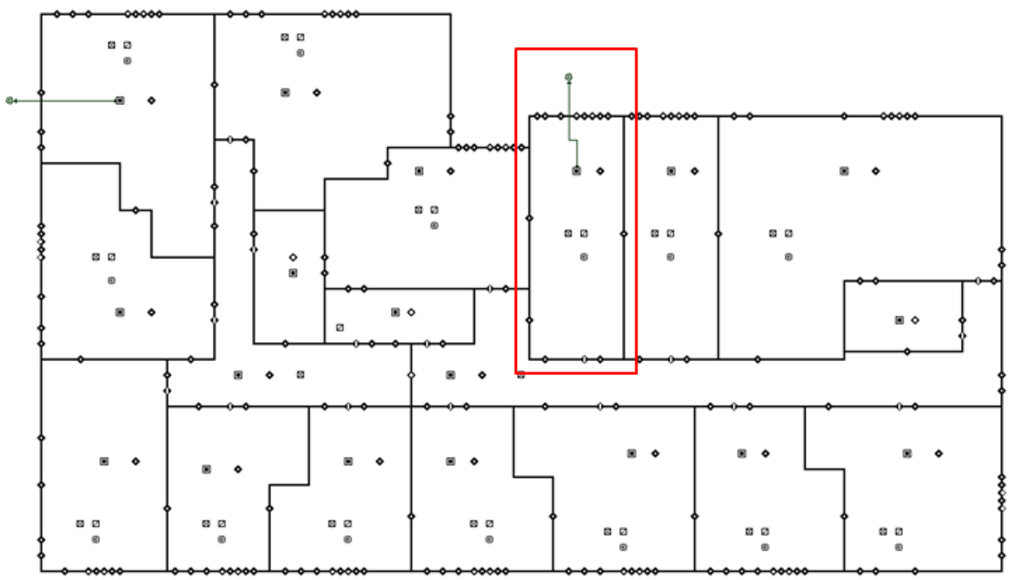


Figure 59. CONTAM model of the sixth floor

Weather and air pollution data:

Figure 60 shows the ambient temperature and outdoor PM2.5 concentrations during the wildfire period, along with the assumed fixed indoor air temperature used in the simulations.

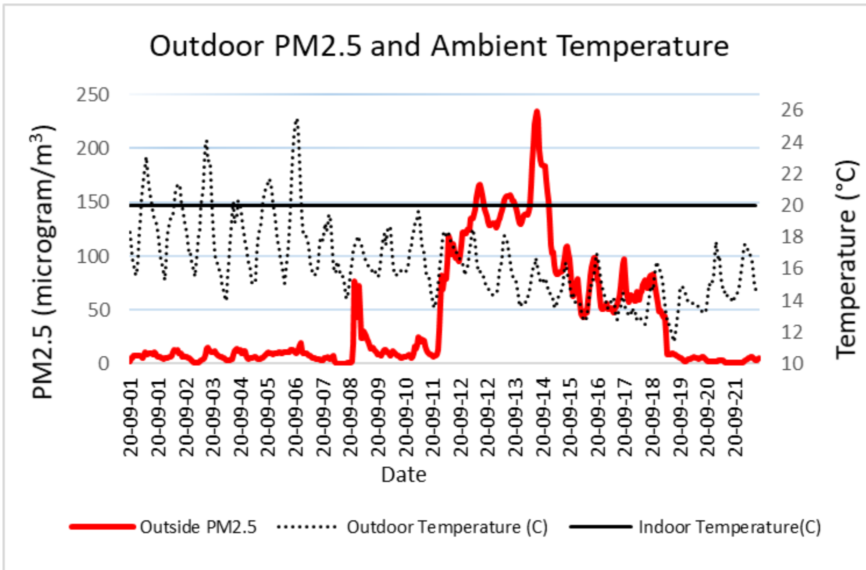


Figure 60. Outdoor air temperature and outdoor PM2.5 data

Stack effect analysis:

To verify the magnitude of differential pressures due to stack effect that the envelope is subjected to, and that will drive PM2.5 into the building, a simple stack effect analysis was conducted below. Figure 61 below shows the hourly outdoor temperatures during the wildfire events, and the hourly difference between the indoor and outdoor temperatures.

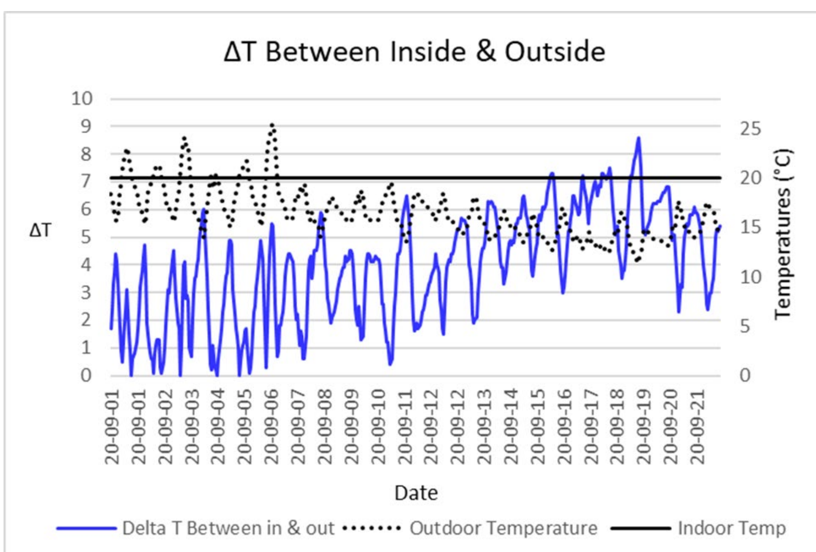


Figure 61. Outdoor air temperature and outdoor PM2.5 data

The stack effect equation below is use to calculate the envelope pressure differentials at the top and bottom floors, assuming that the neutral pressure level is in the middle of the building height, and assuming a thermal draft coefficient of 0.7. Differential pressures are calculated for an assumed indoor temperature of 20°C, and for minimum, maximum, and average outside temperatures.

When Min outside Temperature = 11.4 C; h_n: 18 m

$$\Delta P = 0.7 \times \frac{9.81 \times 18}{287.1} \times 101325 \left(\frac{1}{284.55} - \frac{1}{293.15}\right) = 4.49\ Pa$$

When Max outside Temperature = 25.5 C; h_n: 18 m

$$\Delta P = 0.7 \times \frac{9.81 \times 18}{287.1} \times 101325 \left(\frac{1}{298.65} - \frac{1}{293.15}\right) = -2.74\ Pa$$

Average outside Temperature = 16.35 C; h_n: 18 m

$$\Delta P = 0.7 \times \frac{9.81 \times 18}{287.1} \times 101325 \left(\frac{1}{289.5} - \frac{1}{293.15}\right) = 1.87\ Pa$$

The results show that the driving pressures for air infiltration and PM2.5 penetration into the building are generally low during the wildfire period, and would be even lower if the assumed thermal draft coefficient is smaller. This simple exercise demonstrates that in general, the stack effect is not a large driving force for wildfire pollutants during the fire season, and its effect is reduced if the building is airtight and compartmentalized.

Figures 62, 63, and 64 below show that ventilation air filtration has a bigger impact on the reduction of PM2.5 penetration through the envelope than airtightness and compartmentalization, possibly due to the weak prevailing stack forces during the wildfire season as demonstrated above. Table 38 with the modeling scenarios is repeated below for convenience.

Table 38. Case study WS-1 Modeling Scenarios

Scenario	Envelope	Compartmentalization	Suite ventilation-filtration	Corridor ventilation-filtration
Sc1 baseline	Airtight	Compartmentalized	BCBC 9.32, MERV8	Design, MERV8
Sc2	Moderate	Moderate	BCBC 9.32, MERV8	Design, MERV8
Sc3	Leaky	Uncompartmentalized	BCBC 9.32, MERV8	Design, MERV8
Sc4	Airtight	Uncompartmentalized	BCBC 9.32, MERV8	Design, MERV8
Sc5: Sc1 + MERV13	Airtight	Compartmentalized	BCBC 9.32, MERV13	Design, MERV13
Sc6: Sc3 + MERV13	Leaky	uncompartmentalized	BCBC 9.32, MERV13	Design, MERV13
Sc7: Sc1 + MERV16	Airtight	Compartmentalized	BCBC 9.32, MERV16	Design, MERV16
Sc8: Sc3 + MERV16	Leaky	uncompartmentalized	BCBC 9.32, MERV16	Design, MERV16

Results and discussion:

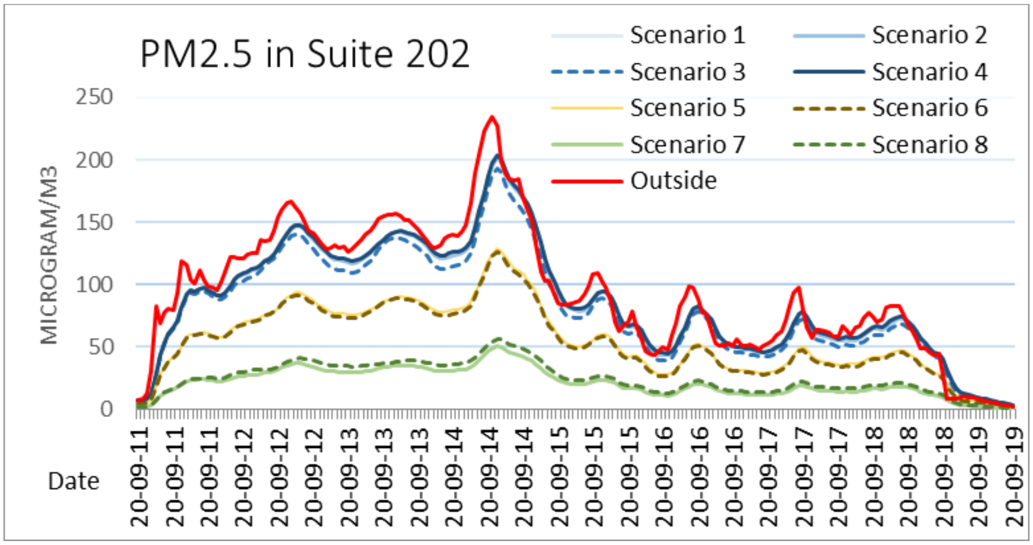


Figure 62. Outdoor air temperature and outdoor PM2.5 data

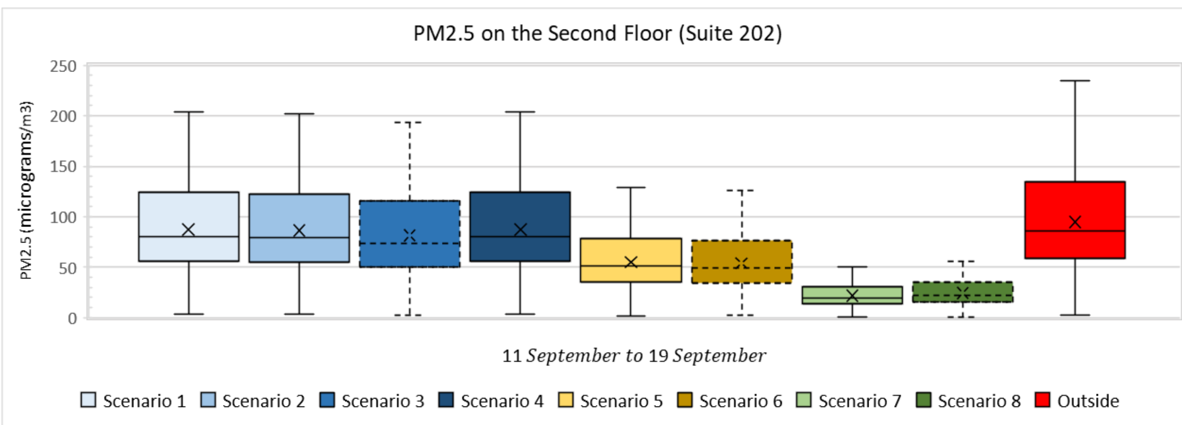


Figure 63. Outdoor air temperature and outdoor PM2.5 data

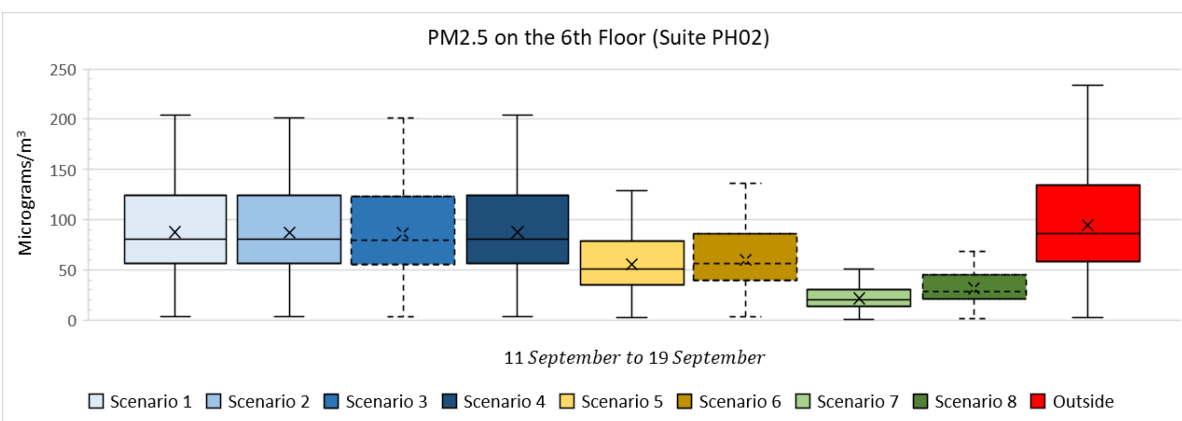


Figure 64. Outdoor air temperature and outdoor PM2.5 data

The Figure 65 below shows differential pressures and airflows across the suite doors, under steady-state simulation assuming outdoor temperature of 12°C. Figure 65 shows that an airtight and compartmentalized building maintains more uniform air pressures across the suite doors under slight corridor pressurization. Whereas a leaky and uncompartmentalized building draws more corridor air into the upper suites.

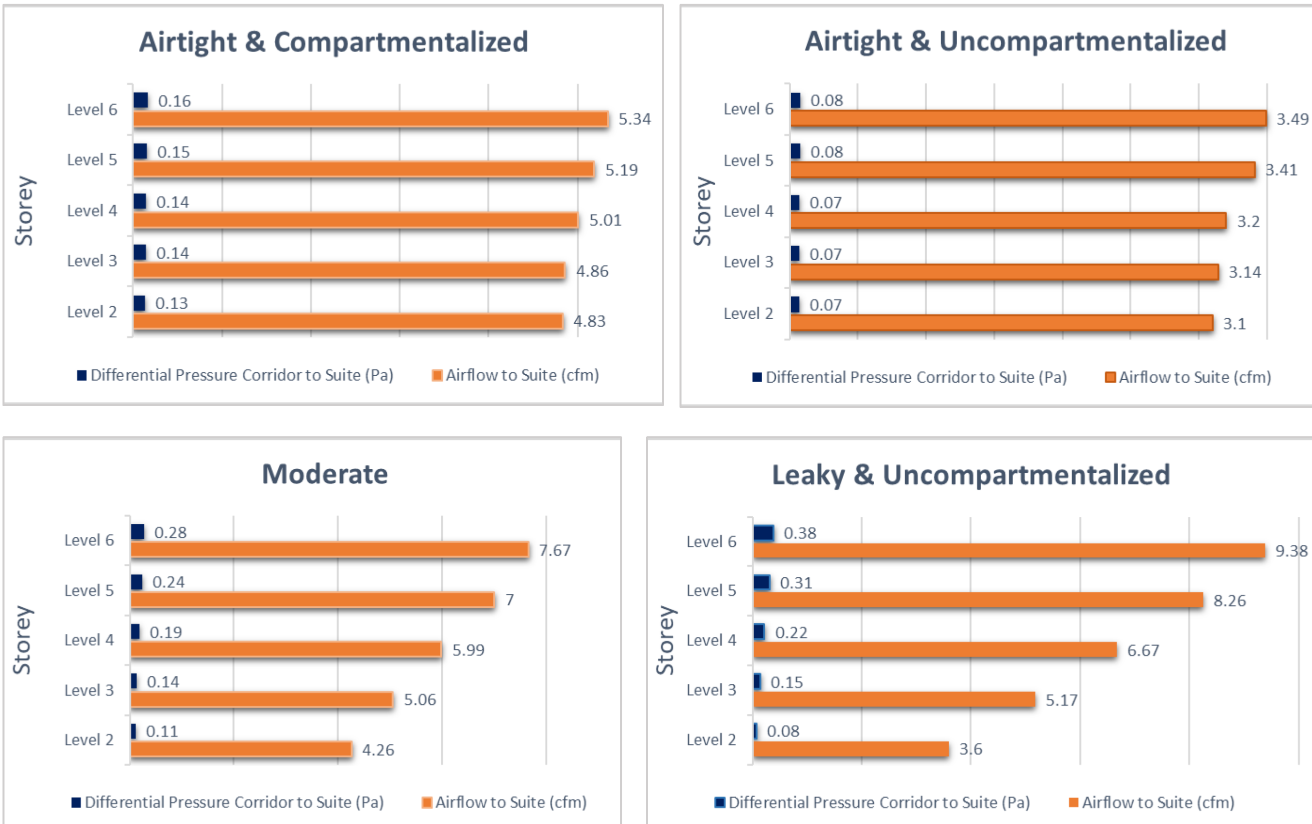


Figure 65. Pressure differentials at the suite doors for the simulated scenarios

Conclusions:

The case study building is a passive house building that is airtight and well compartmentalized. Balanced ventilation helps minimize the airflows across suites and floors. The corridors are maintained slightly pressurized as a common practice to help maintain suite pollutants in the suite, thus minimizing their migration throughout the building. During the late wildfire season in September of 2020 the stack effect is minimal.

For this building, the simulations demonstrate that ventilation air filtration is the most critical factor affecting wildfire PM2.5 pollutant penetration into the building. Given that the stack effect is small, increasing the building airtightness has a very small effect on the PM2.5 pollutant penetration. No matter the level of construction airtightness or compartmentalization, ventilating with a MERV8 filter defeats the ventilation purpose because it pulls polluted air into the building. Furthermore, when the HRV air filtration is poor (MERV 8), increased airtightness is detrimental to indoor air pollution mitigation because the ventilation air brings PM2.5 inside the building, and then it remains trapped indoors “lingering” for longer time when the building is more airtight.

In conclusion, for this type of building, the best measure to mitigate wildfire PM2.5 penetration into the building is to have centralized or semi-centralized ventilation with MERV16 filtration. Furthermore, centralized air HRVs have the capability to add carbon-impregnated filters to control the penetration of toxic gases. A decentralized (in-suite) HRV ventilation system cannot provide enhanced filtration, beyond MERV13, because due to the limited space available and HRV unit capacity, the HRV fan cannot overcome the pressure drops resulting from installing MERV16 filtration. It should be noted that even with MERV16 filters, the indoor PM2.5 levels still exceed the $25\,\mu g/m^3$ 24-hour standard during 5 days. These PM2.5 concentrations may not be suitable for frail and ill dwellers with respiratory conditions. Supplementary portable air cleaners can help reduce PM2.5 concentrations further. Another mitigation measure that could be evaluated is to pressurize the building slightly to maximize the delivery of filtered air, while attempting to eliminate completely the unfiltered air that enters by natural stack effect. Both mitigation strategies can be easily tested using the current model.

10.2 WS-2 COOKING POLLUTANT MIGRATION IN A PASSIVE HOUSE BUILDING

Author: Iman Eshghi, MEng

The case study building is the same building of WS-1, but the goal of this case study is to evaluate strategies to control cooking pollutant migration between suites. While case study WS-1 addressed an outdoor episodic pollutant, this case study (WS-2) addresses a recurrent indoor-generated pollutant.

Modeling:

Goal	Evaluate cooking ventilation and compartmentalization approaches to control cooking pollutant migration between suites
PoC	Cooking PM2.5 (particle aerodynamic diameter, particle density) Cooking acrolein (molecular mass, diffusion coefficient)
Modeling	WS: whole building to suite
Airtightness	Passive house, virtual pressurization test: 0.6 ACH@ 75 Pa, 0.17 cfm/ft2 (baseline case)
Compartmentalization	Interior cracks reduced to minimal, thermal draft coefficient not calculated
Suite airtightness	Suite-level virtual pressurization not tested
Weather	Steady-state winter outdoor temperature of 0°C assumed
Occupancy	Residential occupancy schedules. Cooking schedule assumes three cooking meals per day
PoC source model	PM2.5: emission rate = 0.4 mg/min while cooking, deposition rate = 0.001 cm/s (1) Acrolein: 0.72 mg/h while cooking (2)
Thermal-airflow model	Indoor temperature assumed constant at 20°C, outdoor temperature = 0°C

(1) Lai and Nazaroff 2000, Hu et al. 2012
(2) Seaman et al. 2007

Modeling scenarios:

The modeling assumes a cooking air pollutant source in suite A (indicated in the Figure 66 below) in the second floor, and tests the pollutant concentration in the source suite A, and the migration/concentration at the adjacent suite B, and at suite C in the third floor, right above suite A.

Table 39. Case study WS-2 modeling scenarios

Scenario	Source suite "A" ventilation mode	Centralized Decentralized	HRV Supply/Return (cfm)	Cook stove hood recirculation-filtration (cfm)	Uncompensated cook stove hood exhaust (cfm)	Notes
Sc1 baseline	Design, balanced	C, D	40/40	-	-	Balanced
Sc2	Boost, balanced	D	80/80	-	-	Balanced
Sc3	Design, recirculation	C, D	40/40	100 (CE ≈ 30%) *	-	Balanced
Sc4	Boost, recirculation	D	80/80	100 (CE ≈ 30%) *	-	Balanced
Sc5	Design, exhaust	C, D	40/40	-	100 (CE ≈ 50%) *	ΔP = -13 Pa

CE: hood Capture Efficiency (Rojas et al. 2011)

The case study assumes that ventilation boosting can only be practically achieved using a decentralized (in-suite) HRV system. When ventilation boosting is not selected, both, centralized and decentralized systems can be used. Scenario 5 is modeled only for comparison purposes, as it has been acknowledged that it depressurizes the suite, enhances air infiltration, and draws pollutants from the rest of the building (section 4.3.9, section 6.1.1). In principle, scenario 5 would work for both centralized and decentralized ventilation systems because the HRV can keep supplying and exhausting the same flow rates, while the exhaust hood works independently from the HRV. Obviously, as indicated in the Table 39, the drawback of the exhaust system is the depressurization of the suite that can draw pollutants from far-away areas into the suite, and produce high pressure differentials at the suite enclosure depending on the suite airtightness.

Because the modeling assumes the air is fully mixed in the entire suite, the cooking area in the kitchen and the hood are modelled as separate zones, otherwise, the cooking pollutants would be distributed throughout the entire suite at every time step, which is unrealistic. The performance of the stove hood is calibrated by adjusting a kitchen-cookstove airflow to achieve hood pollutant capture efficiency (CE) values according to the literature (Rojas et al. 2011).

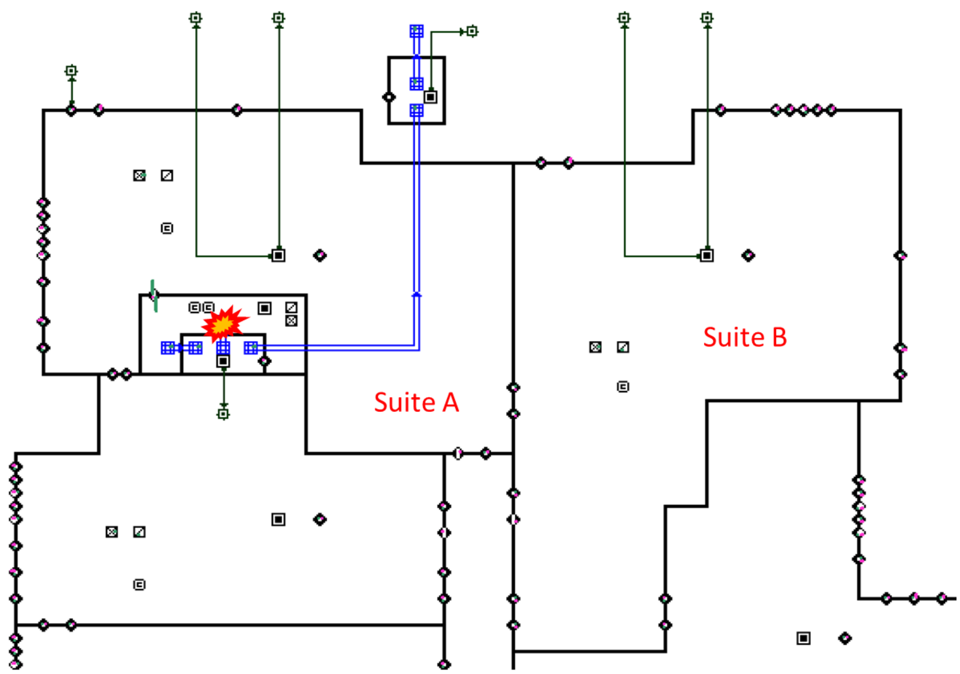


Figure 66. Cooking pollutant source in Suite A. Pollutant migration to suite B beside and suite C right above

For the hood recirculation-filtration scenarios, a MERV8 filter is selected to remove PM2.5, and a carbon filter is selected to remove acrolein with efficiency of 17%. Hood recirculation filters are designed to remove odors from gases, not particles. However, as a side-effect, these filters also have a small particle removal capacity. A supplier mentions that a regular charcoal filter may absorb acrolein at an efficiency of around %10 to %25 of its mass, and provides filtration similar to a MERV8 filter.

<u>Results and discussion</u>:

Figures 67, 68, and 69 below show PM2.5 concentrations in the air during a day. The results for acrolein are not shown here for conciseness, because the patterns observed with acrolein are similar to those reported for PM2.5. The model assumes three cooking meals during the day (breakfast, lunch, dinner). The duration of the cooking is half an hour for breakfast and lunch and one hour for dinner. The Figures below show PM2.5 concentrations in the source suite A, in the adjacent suite B, and in suite C, just above suite A in the 3rd floor.

In Figures 67, 68, and 69 it can be seen that Sc4 and Sc5 provide similar PM2.5 removal in the source suite A. However, Sc5 provides much more effective pollutant migration control to the neighbouring suites. As can also be seen in the Figures below, SC5 is the only scenario that eliminates completely the migration of PM2.5 to the neighbouring suites.

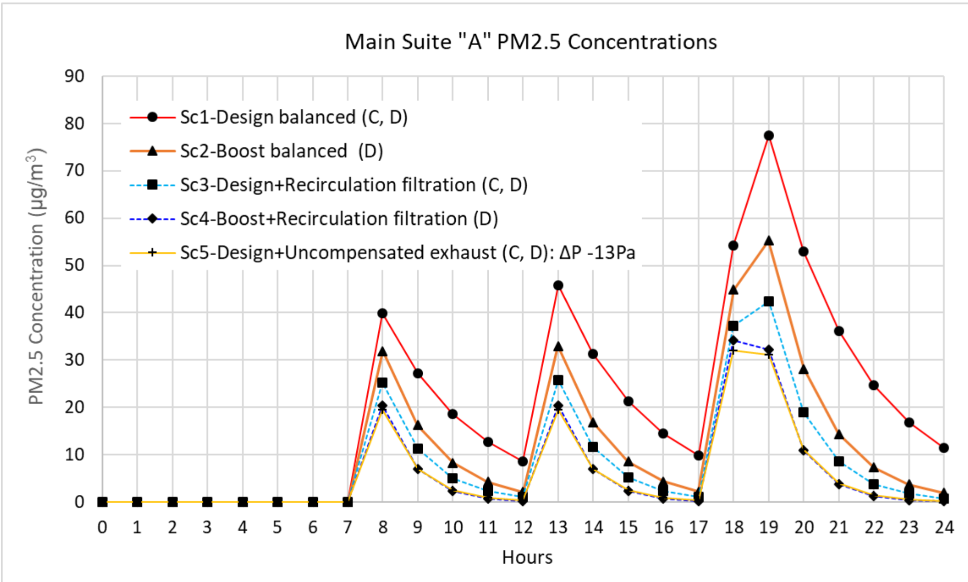


Figure 67. Cooking pollutant source in Suite A. Pollutant migration to suite B beside and suite C right above

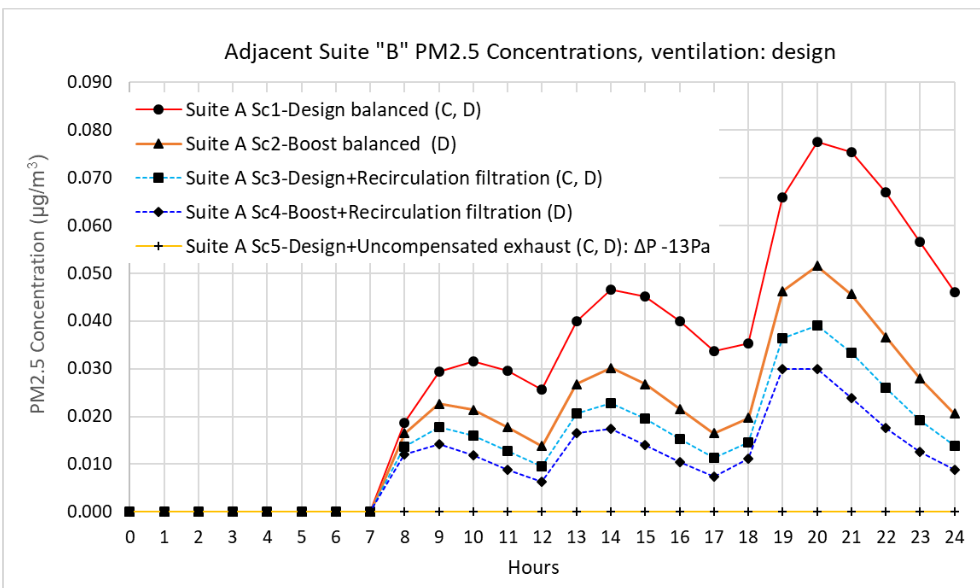


Figure 68. Cooking pollutant source in Suite A. Pollutant migration to suite B beside and suite C right above

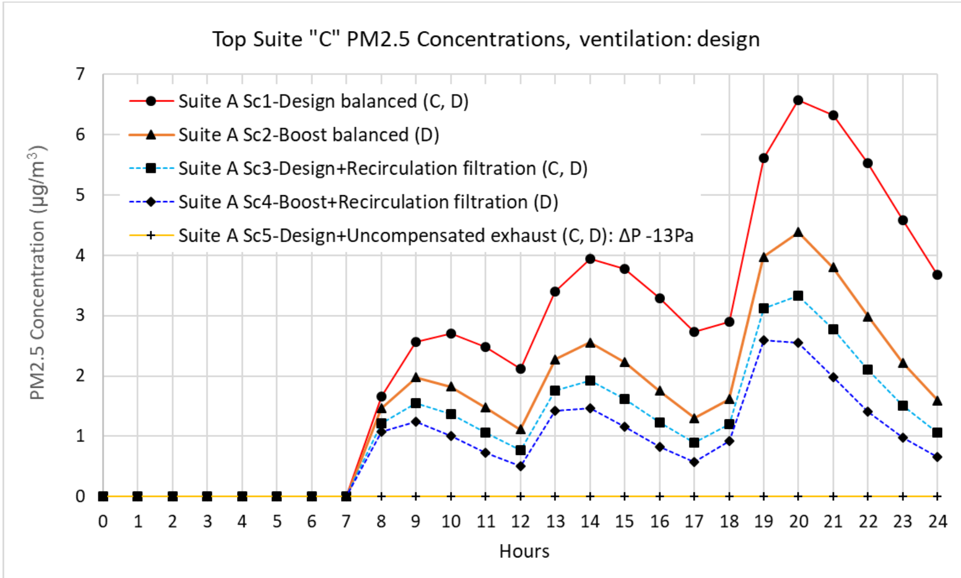


Figure 69. Cooking pollutant source in Suite A. Pollutant migration to suite B beside and suite C right above

Conclusions:

The simulation above shows that Sc5 (HRV at design flow rates + uncompensated cookstove exhaust hood) provides the most effective PM2.5 pollutant removal in the source suite and a 100% effective pollutant migration control to neighbouring suites. However, the uncompensated cookstove exhaust hood depressurizes the suite. Suite depressurization draws pollutants into the suite from near and far-away sources, wastes energy by bypassing the HRV heat recovery and filtration, may cause operational problems to doors and windows if the building is very airtight. Therefore, Scenario 5 is not a viable option for airtight, energy efficient MURB suites. This leaves Scenario 3 (centralized or decentralized) and Scenario 4 (decentralized) as the most effective alternatives to control PM2.5 dispersion and migration to suites in the building.

The simulation results cannot be regarded in an absolute sense. The concentration values can be orders of magnitude higher or lower than the ones reported from the simulations. Multiple sources of uncertainty affect the performance of each system/scenario and the pollutant concentrations, including the type of food being cooked, the type of cooking media, and the cooking temperature. The capture efficiency (CE) of the hoods and the filtration efficiency of the recirculation hood are also variable. The CE depends on the hood design and the location (front/back) of the burner being used (Rojas et al. 2011). The filtration efficiency of the recirculation filter depends on its type and condition. Furthermore, because the model assumes fully-mixed air in the suite, the spatial PM2.5 variations in the suite cannot be observed, for example between kitchen and bedrooms.

Nevertheless, the analysis demonstrates the relative performance of each scenario that enables a comparison between scenarios. In conclusion, Scenario 4 (boosting the HRV while turning on the stove hood recirculation-filtration) provides the highest PM2.5 pollutant removal, and the lowest migration to neighbouring suites. However, it is assumed that boosting the HRV can only be applied to decentralized (in-suite) HRV systems. Aside from the cooking-related factors, the actual pollutant concentrations in a real suite and the migration to other suites, depends on the hood design and its use by the dwellers. Furthermore, achieving proper building/suite compartmentalization is also critical for pollutant migration control. Further simulations can test the effects of different levels of suite airtightness on the pollutant migration to other suites.

10.3 WS-3 Ventilation retrofit of an existing low-rise MURB

Author: Alireza Asharioun, MEng

This study was motivated by complaints from dwellers about second-hand smoke and cooking smells migrating between suites across the building.

<u>The building:</u>

The building is a 4-story building with 3 upper residential floors, and an enclosed parkade at the ground level. The building was built in 1975. The main access lobby to the building is at ground level, along with the parkade, the laundry room, the boiler room, the electrical room, and storage and locker rooms. The three upper residential floors are wood-framed, and the ground floor is concrete-framed.

Number of stories	4-stories: Ground enclosed parking, access, laundry, mechanical, electrical, storage 3 upper residential floors
Structure	Ground floor: concrete, upper 3 floors: wood-frame
Circulation	• One elevator from the ground lobby up to the top floor • One staircase from the lobby to the first residential floor • Two staircases from the ground exterior access/evacuation up to the top floor
Number of suites	14 suites per floor 42, one-bedroom and two-bedroom suites
Heating	Hydronic baseboard heating, boiler room in the ground floor
Cooling	No mechanical cooling
Ventilation	Corridor pressurization: two fan units located at the roof, bathroom exhaust fans intended to pull corridor air into the suites. • 2 diffusers supply: 210 cfm x 2 = 420 cfm per floor • 14 suites per floor: 30 cfm per suite • BCBC 9.32 minimum requirements: 1-bed suite: 30 cfm, 2-bed suite: 45 cfm • BCBC 9.32 per floor supply air requirement ≈ 480 - 500 cfm/floor • Bathroom exhaust fans: 14 x 30 cfm = 420 cfm per floor • Cooking: kitchen stove exhaust hood on-demand: 100 cfm, no makeup air • Boiler combustion gases are exhausted to the roof, the boiler room has a combustion makeup air vent
Parkade ventilation	Induced exhaust ventilation, 1000 cfm fan, intended to work based on a timer
IAQ complaints	• Second-hand tobacco smoke migration between suites, cooking smells migration between suites
IAQ ventilation observed issues	• Suite exhaust fans do not run continuously, in fact, these fans are rarely being used by dwellers. • Parkade ventilation does not operate as intended. • Concerns about shared kitchen and bathroom vents to the roof. • Concerns about the rooftop ventilation units introducing polluted and untreated air into the building. • Building lobby and laundry room do not have mechanical ventilation.
Measurements	• Flow hood: corridor supply airflow • Kitchen and bathroom exhaust at one suite • RH/T, CO_2 monitoring during several weeks in July of 2021

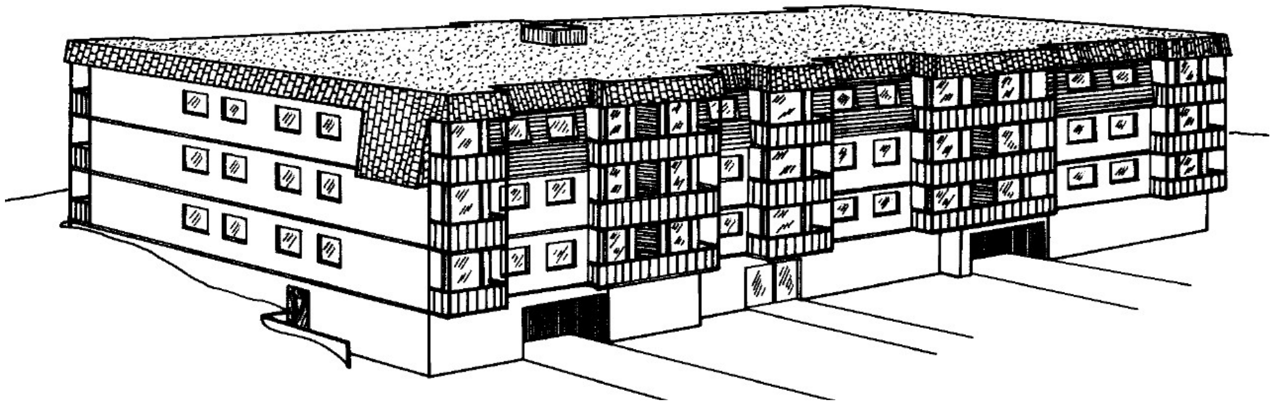


Figure 70. Existing building rendering

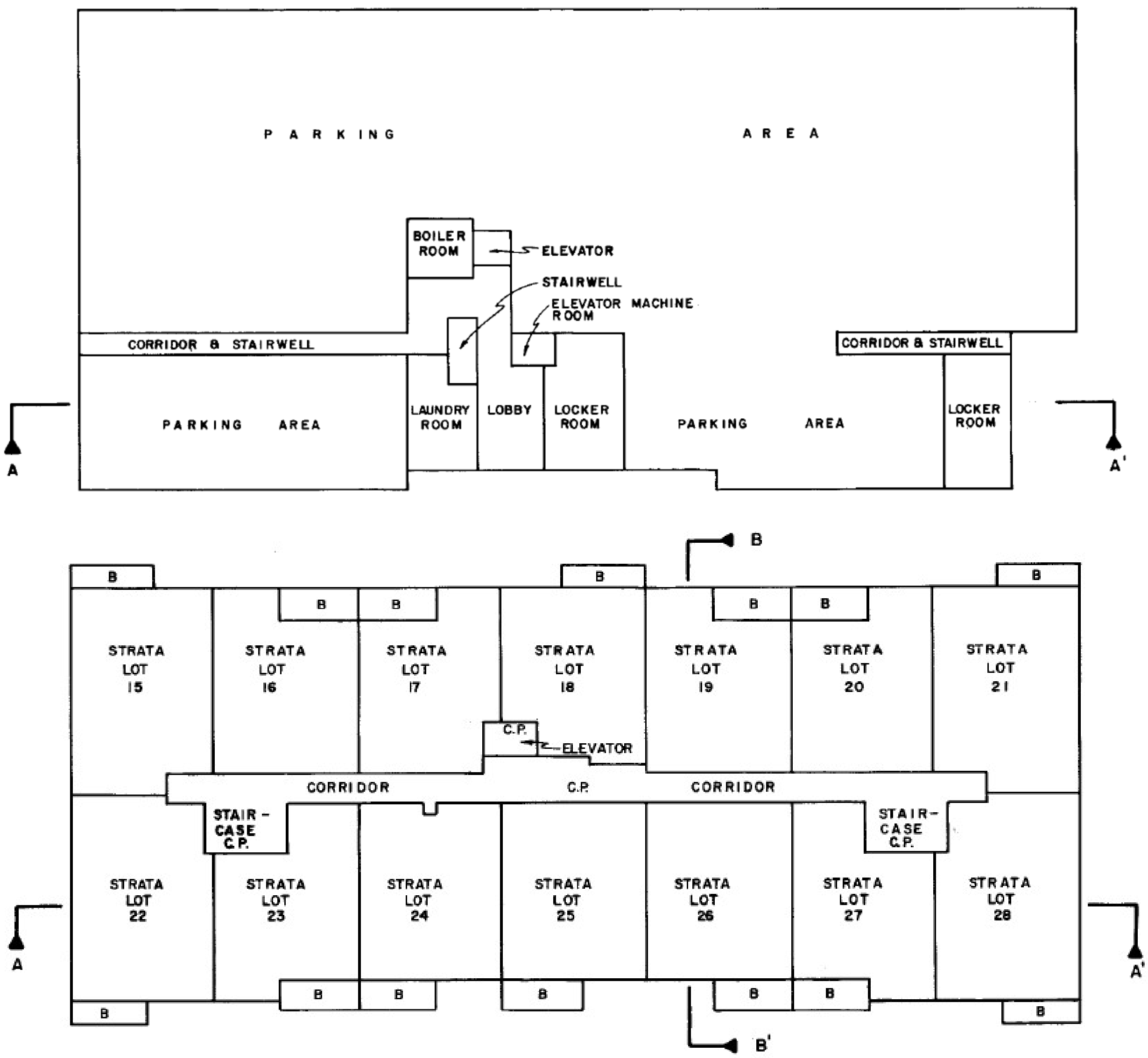


Figure 71. Floor plans. Top: ground floor, Bottom: typical residential floor

Ventilation Observations:

The building ventilation units on the roof look like two boxes with an air intake. When opened, the fan is visible, as well as small filter that is not tightly fitted to the frame, in fact air leakages around the filter were visible. This raises indoor air quality and health concerns as well as concerns about supplying hot untreated air into the building. In summer, roof temperatures can reach more than 50°C, which warm up the surrounding air, and enhance the off-gassing of pollutants from the roof membrane. Supplying hotter than ambient air, and roof-polluted air into the building is counterproductive both, for human health and energy performance.

Figure 72. Rooftop kitchen and bathroom vents, boiler exhaust, and corridor ventilation unit

Figure 73. Two rooftop ventilation units for the entire building

Figure 74. Parkade makeup air and exhaust fan

Each kitchen vent on the roof collects the cooking exhaust air from a stack of 3 suites. Similarly, each bathroom vent on the roof collects bathroom exhaust air from a stack of 3 suites underneath. The sharing of vents among stacks of suites raises concerns about the need for proper venting and duct sealing of the venting stacks, to avoid the leaking of polluted air from the vents into the upper suites. A retrofit study on this building should carefully inspect all the kitchen and bathroom exhaust vents to make sure their integrity has not been compromised after more than 40 years of operation. Most importantly, any performance deterioration of the kitchen exhaust and vents can pose serious fire and health risks. Therefore, it is paramount to inspect, and probably retrofit the kitchen exhaust-vents, to make sure they are safe to operate for many more years.

The enclosed parkade ventilation does not operate as intended. Due to complaints of excessive fan noise by dwellers in suites just above the fan, the fan operates at times only during the day, and at times the fan is turned off for periods, when the parkade doors are left open for ventilation. Also, at the ground level, the lobby and laundry areas do not provide controlled mechanical ventilation. Aside from building compartmentalization and separation between the ground floor and the residential floors, uncontrolled airflows at the ground level can lead to unintended airflows between the ground level and the suites.

Airtightness and Compartmentalization:

Whole-building airtightness and suite compartmentalization measurements were not conducted in this building. However, any whole-building energy building retrofit study should include airtightness and compartmentalization tests in order to improve the building ventilation and air flow control for energy efficiency, well-being, health, and safety of the dwellers to avoid any unintended air flows and pollutants migrating from the parkade or the service areas into the suites.

After a thorough inspection it was observed that the visible piping penetrations at the ground level leading from the mechanical room and parkade to the upper floors are well sealed. However, cracks around mechanical, electrical, staircase, and elevator doors do not seem well sealed. Upon inspection of one suite, cracks around plumbing piping were visible. Large cracks in the suite were also concealed behind bathroom and kitchen cabinets.


Figure 75. Visible and concealed cracks behind kitchen and bathroom cabinets

Ventilation and IAQ measurements:

A flow hood was used to measure supply air at the corridors, as well as at the kitchen and bathroom exhaust fans at one suite. CO_2 was monitored in a bedroom, living room, kitchen, and bathroom in a suite-facing suite in the second floor, in July of 2021. However, the value of the CO_2 measurements is limited because the dwellers opened the windows, crack-open at a minimum, during the summer.

<u>Modeling:</u>

The MZ-AFN/C modeling followed the proposed performance-based methodology. The modeling steps are not described here for conciseness. The existing building is assumed to be leaky, with an airtightness of 3.2 L/s/m^2, which was verified with a virtual whole-building pressurization test. The retrofit is assumed to increase the building airtightness to 1.6 L/s/m^2.

Goal	Evaluate ventilation retrofit alternatives to reduce second-hand-smoke pollutant migration between suites, and improve building resilience against wildfire smoke penetration.
PoC	SHS PM2.5, properties, particle aerodynamic diameter, particle density Wildfire smoke PM2.5, properties: particle aerodynamic diameter, particle density
Modeling	WS: whole building to suite
Airtightness	Existing before retrofit: 3.2 L/s/m^2, After retrofit: 1.6 L/s/m^2 @ 75 Pa
Compartmentalization	Interior cracks reduced to minimal, thermal draft coefficient not calculated. Vestibule added at the building lobby.
Suite airtightness	Suite-level virtual pressurization not tested
Weather	SHS migration: steady-state winter outdoor temperature of 4°C assumed Wildfires smoke: transient hourly weather and outdoor pollution from Burnaby North Station, during late wildfire season in September of 2020, for simplicity wind is not considered
Occupancy	Residential occupancy schedules. Occupancy schedules and activities do not affect simulation outcomes because simulations assume that dwellers do not open/close windows, and do not operate devices that may affect air pressures and flows in the suites
PoC source model	SHS smoke generation: 10 mg/h constant coefficient Penetration factor: 0.8, deposition rate: 1 1/h
Thermal-airflow model	Indoor temperature assumed constant at 20°C SHS: winter outdoor temperature of 4°C assumed Wildfire smoke: outdoor temperature from weather file

<u>Modeling Scenarios:</u>

Twelve modeling scenarios were developed (Table 40) as follows:

- Scenarios 1 and 2 model the existing building. The baseline building, scenario 1a: second-hand-smoke (SHS) and scenario 1b: wildfire smoke (WFS), models the existing building with the bathroom exhaust fans turned off, as observed in the actual building. Scenarios 2a (SHS) and 2b (WFS) model the existing building, but with the bathroom exhaust fans turned on, as intended by design.
- The retrofit scenarios 3 though 7 assume an upgraded central rooftop supply air unit with variable speed, cooling, and enhanced filtration. The central unit is interlocked with the suite bathroom fans, to draw corridor air into all suites during regular operation, and for building pressure control during wildfires. A rooftop AHU/HRV, with return air, does not seem viable for the case study building given that its current corridor-suites ventilation is simply a rooftop box with a supply fan supplying air through ducts to the corridors. However, given that in the case study building bathroom and kitchen exhausts are connected as stacks/risers that vent to the roof, it may still be possible to design roof AHU/HRVs that collect the exhaust air from a set of bathroom stacks for heat recovery.
- Scenario 8 models a hybrid ventilation and cooling alternative proposed in section 8.1.6., without the return air and heat recovery, again due to ducting limitations in the existing building. In this hybrid alternative a central unit provides corridor ventilation that can be boosted in extreme events, with increased cooling capacity, enhanced filtration (MERV16), and building pressurization (Alternative 1 in section 8.1.6); while the suites can have their own mechanical cooling with integrated in-suite HRV ventilation and enhanced MERV13 filtration (Alternative 2b, PTAC-HRV in section 8.1.6).

Table 40. Case study WS-3 modeling scenarios

Scenario		Goal	Weather	Envelope	Compart.	Corridor air supply / floor	Bathroom exhaust	Suite Ventilation Filtration Cooling	Notes
1a	**Existing** Actual Baseline Central supply fan	Second-hand smoke migration: 112 (1)	Steady-state, 2 days $t_o = 4$°C	Leaky 3.2 L/s/m²	Leaky	420 cfm	**OFF Not enabled by occupants**	Corridor pressurization No filtration	Unbalanced Envelope ΔP ≈ 2 Pa
1b		Wildfire smoke penetration (2)	Transient (3) WTH, CTM File						
2a	**Existing** Design Central supply fan	Second-hand smoke migration: 112 (1)	Steady-state, 2 days $t_o = 4$°C	Leaky 3.2 L/s/m²	Leaky	420 cfm	**30 cfm**	Corridor pressurization No filtration	Unbalanced Envelope ΔP ≈ 1 Pa
2b		Wildfire smoke penetration (2)	Transient (3) WTH, CTM file						
3a	**Retrofit Upgraded central supply fan design flow**	Second-hand smoke migration: 112 (1)	Steady-state, 2 days $t_o = 4$°C	**Airtight 1.6 L/s/m²**	**Airtight(4) Vestibule**	**480 cfm**	**30 cfm x 10 45 cfm x 4**	**Corridor pressurization MERV16 Lobby ventilation Cooling**	Balanced Envelope ΔP < 1 Pa
3b		Wildfire smoke penetration (2)	Transient (3) WTH, CTM file						
4	**Retrofit** Upgraded central supply fan design flow	Wildfire smoke penetration (2)	Transient (3) WTH, CTM file	Airtight 1.6 L/s/m²	Airtight (4) vestibule	480 cfm	**OFF During wildfire**	Corridor pressurization MERV16 Lobby ventilation Cooling	Over-pressurized ΔP ≈ +4.5 Pa
5	**Retrofit** Upgraded **high speed**	Wildfire smoke penetration, **cooling**	Transient (3) WTH, CTM file	Airtight 1.6 L/s/m²	Airtight (4) Vestibule	**High speed 800 cfm Cooling**	**50 cfm x 10 75 cfm x 4**	Corridor pressurization MERV16 Lobby ventilation Cooling	Balanced Envelope ΔP < 1.5 Pa
6	**Retrofit** Upgraded **high speed**	Wildfire smoke penetration, **cooling**	Transient (3) WTH, CTM file	Airtight 1.6 L/s/m²	Airtight (4) Vestibule	High speed 800 cfm Cooling	**OFF During wildfire**	Corridor pressurization MERV16 Lobby ventilation Cooling	Over-pressurized ΔP ≈ +11.5 Pa
7	**Retrofit** Upgraded **high speed**	Wildfire smoke penetration, **cooling**	Transient (3) WTH, CTM file	Airtight 1.6 L/s/m²	Airtight (4) Vestibule	High speed 800 cfm Cooling	**30 cfm x 10 45 cfm x 4**	Corridor pressurization MERV16 Lobby ventilation Cooling	Pressurized Envelope ΔP ≈ +1.5 Pa
8a	**Retrofit Hybrid**	Second-hand smoke migration: 112 (1) **cooling**	Steady-state, 2 days $t_o = 4$°C	Airtight 1.6 L/s/m²	Airtight Vestibule	**100+ cfm for corridor ventilation only + enhanced pressurization, cooling, filtration MERV16**	**Humidity-sensitive DCV?**	**In-suite PTAC-HRV Balanced MERV13 Limited ventilation capacity**	Slightly pressurized Envelope ΔP ≈ 1 Pa
8b	**Retrofit hybrid**	Wildfire smoke penetration (2) **Cooling**	Transient (3) WTH, CTM File						

(1) Report peak PM2.5 in the smoker suite 112, in the two adjacent rooms 111, 113 and the ones stacked above 212 312
(2) Report peak PM2.5 in rooms 102, 106, 216, 220, 330, 334
(3) Transient WTH and CTM: run from Sep 1 to Sep 22 of 2020 (fire season in 2020)
(4) Except for suite main door which is the supply "diffuser" for the corridor pressurization air

Table 41 describes characteristics of the ventilation, cooling, and resilience of the different scenarios. In all retrofit scenarios, if the building permits, a central AHU/ERV or a set of rooftop AHU/ERVs can replace the central supply fan air handling unit. To pressurize the building in wildfire events, the central AHU/ERV can run the supply fan at high speed and the return fan at low speed.

Table 41. Characteristics of the different scenarios (see notes below)

Scenario	Characteristics	Envelope Pressurization	Cooling
1	• Existing, corridor pressurization, current operation • Bathroom exhaust fans turned off (they are rarely used)	Yes	No
2	• Existing, corridor pressurization, design operation • Bathroom exhaust fans operated continuously • The building is slightly pressurized because the bathrooms exhaust less air than the central supply fan	Slight	No
3	• Upgraded central corridor pressurization for suites' ventilation according to BCBC 9.32 • Bathroom exhaust fans interlocked with central corridor pressurization for regular operation • Central corridor pressurization and in-suite bathroom exhaust fans are balanced (supply = exhaust) • Airtight, compartmentalized, vestibule at lobby elevators • MERV 16 filtration during wildfires	Balanced	No
4	• **Alternative 3, with bathroom exhaust fans turned off during wildfires for building pressurization**	**Yes**	**No**
5	• Variable speed central supply fan, set to high speed for partial cooling of suites • Interlocked bathroom exhaust fans at increased speed to allow more cool and filtered air into the suites • Central corridor pressurization and in-suite bathroom exhaust fans are balanced (supply = exhaust)	Balanced	Central Partial
6	• Alternative 5, but with bathroom exhaust fans turned off to maximize the building pressurization during wildfires	Yes Over-pressurized	Central Partial
7	• **Alternative 5, but with bathroom fans running at normal speed** • **The building is slightly pressurized (central supply fan > sum of exhaust fans)**	**Slight**	**Central partial**
8	• **Hybrid system with central unit supplying air for corridor ventilation only (100 cfm/floor), and in-suite PTAC-HRVs for in-suite cooling and limited ventilation** • **The corridor ventilation provides slight building pressurization** • **The central corridor unit can increase the air flow for enhanced pressurization, cooling, and filtration during wildfires**	**Corridor slightly pressurized Suites balanced**	**In-suite Room**

***Notes**. Shades group same systems under varied operation scenarios. Bold font indicates best alternatives to reduce wildfire smoke penetration without over-pressurizing the building.*

<u>Second-hand smoke modeling Results:</u>

Figure 76 shows the smoker suite 112, and the adjacent suites tested for smoke migration, suites 111 and 113, and suites 212 and 312 (not shown), above suite 112.

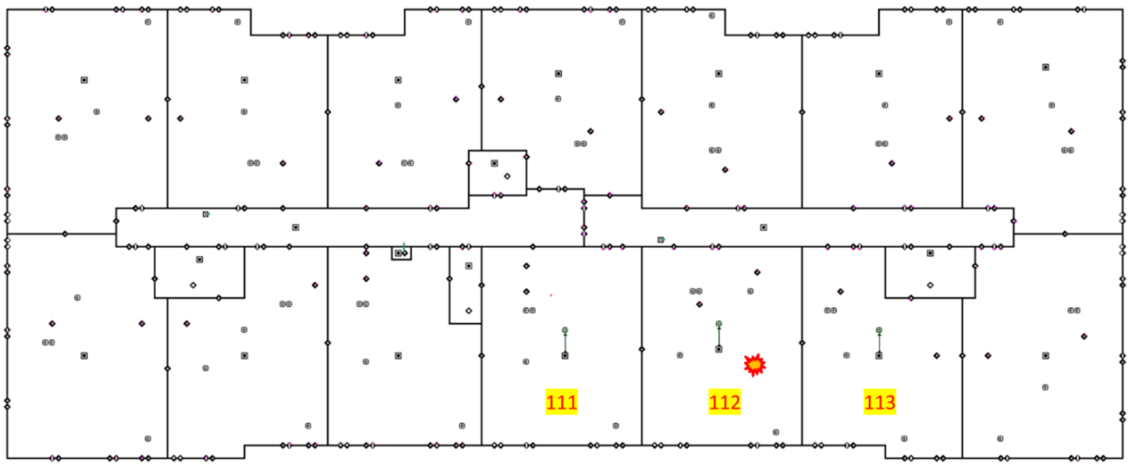
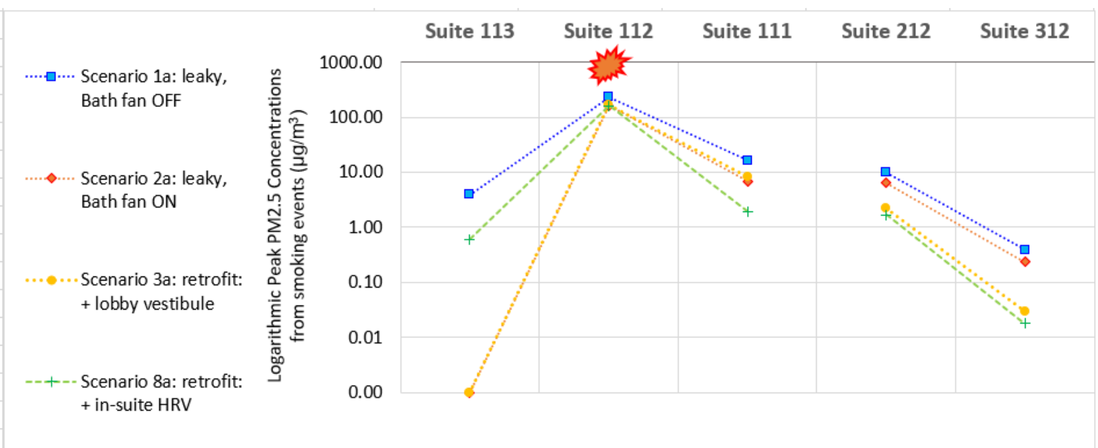


Figure 76. The smoker suite and adjacent suites tested for PM2.5 migration, as well as the suites right above

Figure 77 shows peak PM2.5 concentrations in the suites studied during a smoking event, that illustrate how second-hand-smoke (SHS) from a smoker in suite 112 reaches adjacent suites under alternative ventilation and retrofit scenarios. It is important to mention that the assumed airtightness and compartmentalization levels that can be achieved in this building are moderate, not close to Passive House Standard. The simulations demonstrate that controlling SHS migration between suites is very difficult in a building retrofit due to the inherent constraints to access concealed cracks and avoiding disturbances to dwellers for sealing unconcealed cracks, for example, sealing electrical outlets in partition walls between suites. In Figure 77 The most effective strategy to control SHS migration between suites is Scenario 8. However, this should be coupled with improved compartmentalization



Scenarios	Suite 113	Suite 112	Suite 111	Suite 212	Suite 312
Scenario 1a: leaky, Bath fan OFF	3.91	232.22	16.64	9.81	0.39
Scenario 2a: leaky, Bath fan ON	0.00	160.91	6.94	6.35	0.23
Scenario 3a: retrofit: + lobby vestibule	0.00	167.87	8.32	2.27	0.03
Scenario 8a: retrofit: + in-suite HRV	0.61	161.74	1.94	1.68	0.02

Figure 77. PM2.5 concentrations ($\mu g/m^3$) in suites showing second-Hand-Smoke migration from suite 112 to the neighbouring suites.

<u>Wildfire smoke (WFS) modeling results:</u>

The WFS concentration in the selected suites is shown in Figure 78 below for Scenarios 1b, 2b, 3b, and 4. Scenarios 1b and 2b correspond to the existing building before the retrofits. Scenarios 3b and 4 correspond to a proposed retrofit with balanced ventilation (3b), and the exhaust fans turned off (4).

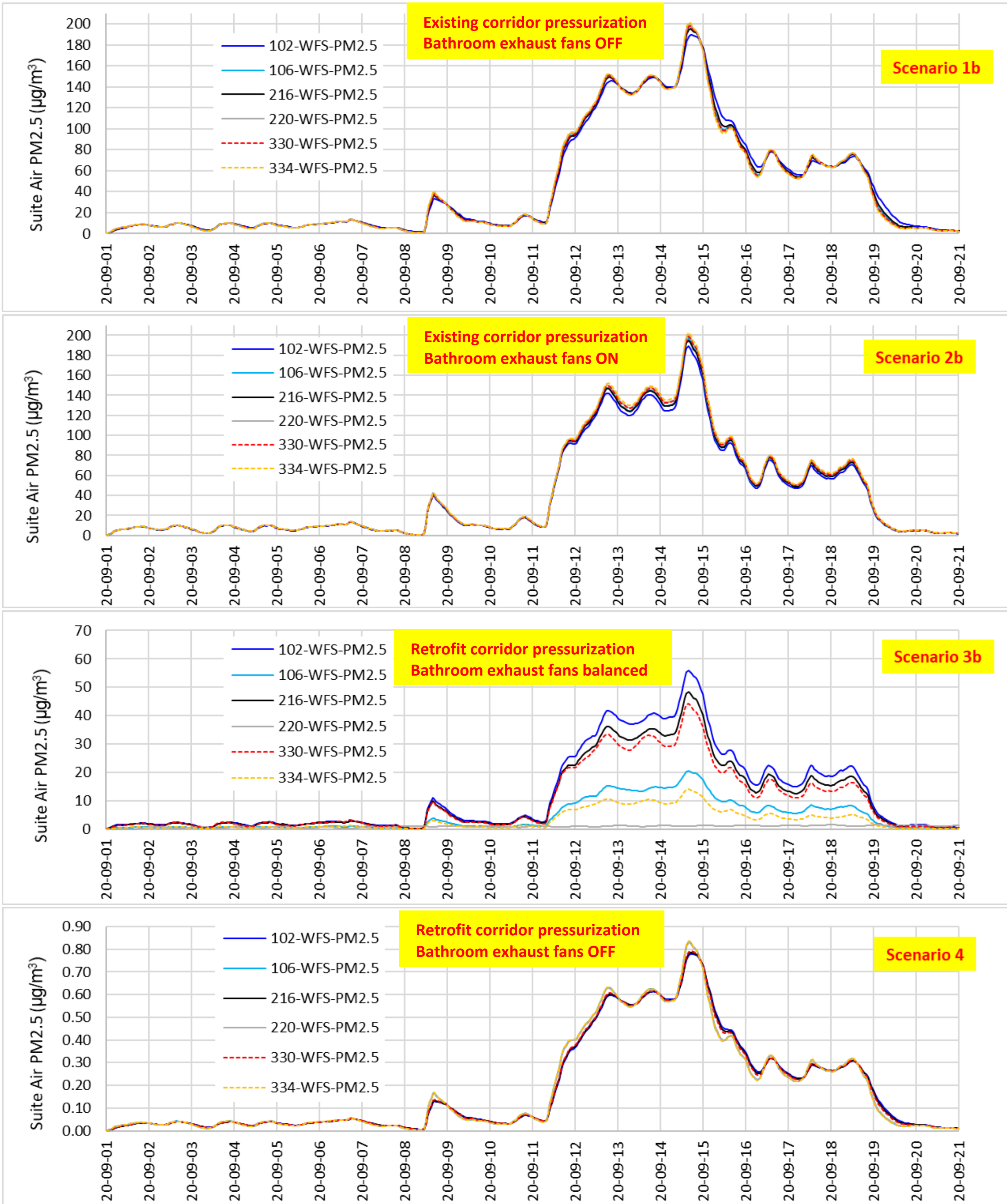


Figure 78. WFS concentration in selected suites for scenarios from top to bottom: 1b, 2b, 3b, and 4

Scenarios 5, 6, and 7 correspond to scenarios with enhanced ventilation for cooling and building pressurization. Scenario 8b corresponds to a hybrid system with a central HRV that supplies corridor ventilation and enhanced cooling, ventilation-filtration, and pressurization; and in-suite HRV with integrated cooling.

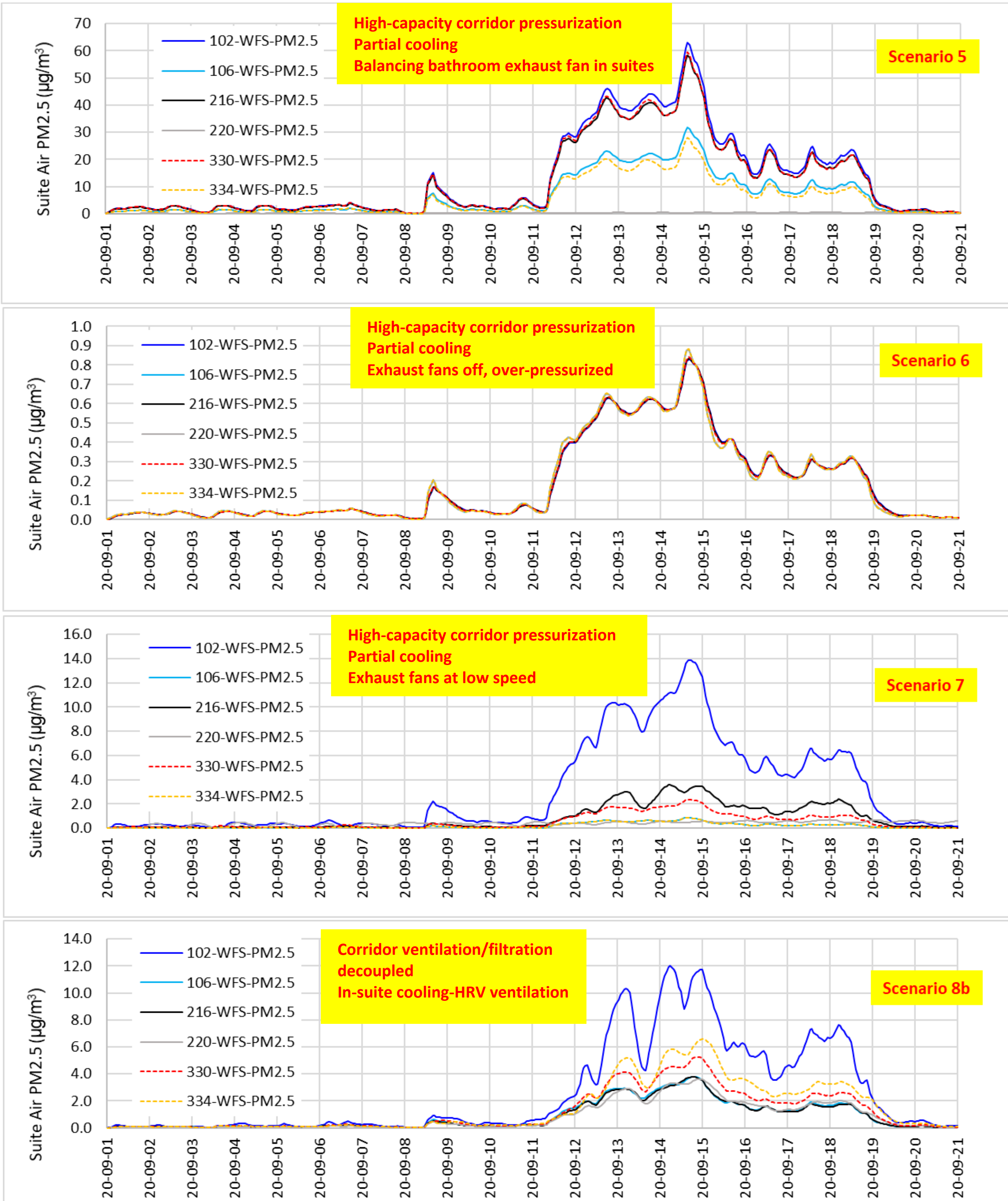


Figure 79. WFS concentration in selected suites for scenarios from top to bottom: 5, 6, 7, and 8b

Figure 78 shows that the current system (Scenarios 1b and 2b) does not mitigate WFS penetration into the suites, mainly because the corridor pressurization supply fan provides no air filtration. Scenario 3b is a retrofit scenario with an air-tightened envelope and a central HRV with MERV16 filtration. Scenario 3b demonstrates the advantages of adding MERV16 filtration to the central HRV. However, the indoor PM2.5 concentrations are still above the 24-hour TLV of 25 μg/m^3, at least for half of the suites selected. This is because Scenario 3b maintains the envelope pressure neutral/balanced. Scenarios 4 and 6 turn the bathroom exhaust fan off during the wildfire event, thus pressurizing the building. Only under such levels of pressurization, effective WFS PM2.5 penetration control is achieved. Scenarios 7 and 8 achieve an acceptable level of PM2.5 penetration control below the 24-hour TLV of 25 μg/m^3. However, the higher variability in PM2.5 between suites indicates that the level of building pressurization is not sufficient to keep the PM2.5 from fully entering through the envelope.

It is important to note that the corridor pressurization system tends to bypass the main rooms in a suite as shown in Figure 80, which is detrimental for ventilation-IAQ as well as for cooling in scenarios 5, 6, and 7. To minimize this deficiency, increased amounts of corridor air are supplied to the suites. Scenarios 5 and 7 may produce the best suite air distribution, because they provide enhanced central airflow for cooling and pressurization, which is coupled with enhanced bathroom exhaust flow rates (scenario 5) and regular flow rates (scenario 7). Suite air distribution from these two scenarios can be evaluated using the proposed performance-based design approach by conducting suite-room (SR) type of modeling and simulations.

Scenario 8 seems to provide the best compromise between wild-fire smoke penetration, energy efficiency, fire-safety, and in-suite ventilation and cooling control for the following reasons: 1) it maintains indoor PM2.5 penetration from wild-fire within acceptable levels, 2) the central air handling system uses smaller ducts and less fan power energy to filter outdoor air, ventilate the corridors, slightly pressurize the building, 3) it decouples corridor pressurization from in-suite ventilation for fire-safety, 4) it enables in-suite individual control of the cooling and ventilation on-demand. The system could be more energy efficient if return air to the air-handler can be achieved through vertical shafts, to enable heat/energy recovery in the central system.

Figure 80. Corridor pressurization ventilation air bypasses the main rooms in a suite (exhaust fan in bathroom)

Conclusions:

The simulation scenarios demonstrate the complexities in achieving proper ventilation, cooling, and resilience in existing MURBs. Ultimately, the effectiveness of any of these retrofit measures depend on the type, age, size, and space configuration of the existing building.

The second-hand smoke control scenarios demonstrate that it is difficult effectively control the migration of second-hand smoke between suites, unless a high-level of compartmentalization is achieved, which is unlikely in existing building retrofits. For example, proximity of suites to local shafts pulls air from these suites, and draw air and pollutants from far away suites. However, the simulation demonstrates that the most effective system to control SHS migration between suites is the slightly pressurized corridor ventilation and decoupled in-suite HRV balanced ventilation (Scenario 8).

The scenarios demonstrate that increased building pressurization produced with highly filtered makeup air is the most effective measure to achieve wildfire smoke penetration control, as indicated in Figure 47. The case study also demonstrates the application of the ventilation principles illustrated in Figure 12b, where effective ventilation, filtration, and energy efficient cooling of MURB suites can more successfully be achieved in airtight buildings that are compartmentalized, because these enable tighter pressure control. However, the contribution of increased airtightness and compartmentalization to wildfire smoke penetration control is not demonstrated in this case study. Furthermore, as indicated in Figure 47, the stack effect is weak during the wildfire season and therefore envelope airtightness and building compartmentalization become less critical to control the stack effect. However, by laws of physics, controlling air pressures is always more effective and energy efficient in an airtight building.

In summary, the best energy and ventilation retrofit system for the case study building seems to be the hybrid system modeled in Scenario 8. This system enables individual in-suite cooling and ventilation control, seems adequate for wildfire smore penetration control, is most effective in controlling SHS migration between suites, and is the most suitable for fire-safety because it decouples corridor ventilation from suite ventilation. The system is equivalent to the High-Performance Hybrid System proposed in section 8.1.4.

10.4 WS-4 Differential pressures and airflows to suites under stack effect

The case study building is a modern 10-story MURB with corridor-pressurization ventilation for the suites. The building has an underground parkade and commercial spaces in the ground floor. The case study aims to demonstrate how variations in ventilation, airtightness, and compartmentalization result in uneven pressure differentials and ventilation airflows across the suite doors. The simulations are steady-state, under typical Vancouver winter conditions. Scenario 1 models the existing baseline building, and scenarios 2 to 5 simulation various hypothetical retrofit scenarios.

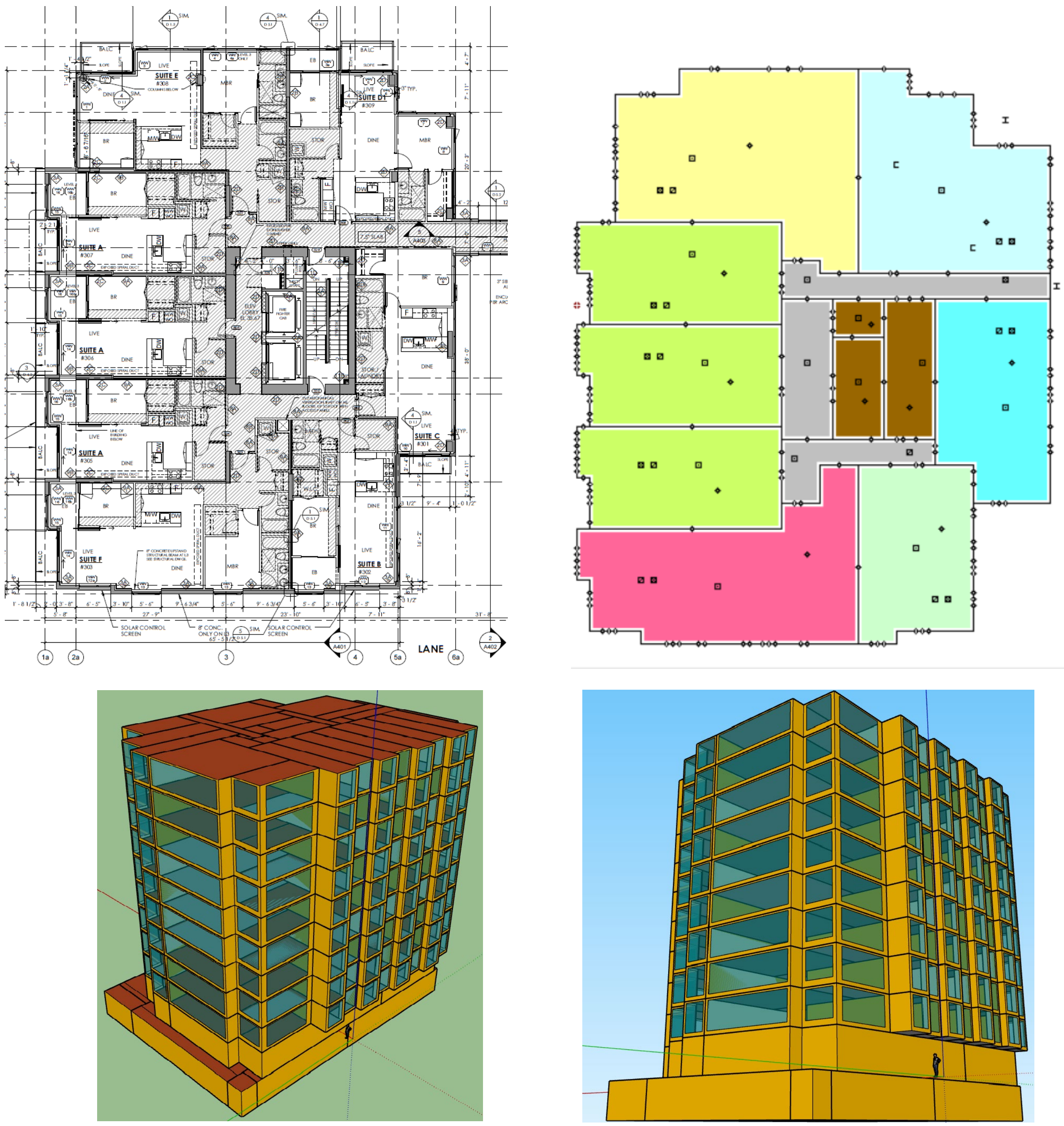


Figure 81. Existing multi-unit residential building typical floor plan and model

Simulation scenarios:

Table 42. Case study WS-4 simulation scenarios

Scenario	Passive Measures - Air tightness / Compartmentalization				Active Measures - HVAC			
	Horizontal Penetrations	Shaft doors	Suite door	Envelope	Underg. Parking	Staircase	Corridor	Suite
1 Baseline	Leaky	Baseline	Leaky	Baseline	Doors: Closed System: OFF	NA	Corridor pressurization (430 cfm/floor)	Exhaust fan (25 cfm)
2 Retrofit	Leaky	Baseline	**Airtight**	Baseline	Doors: Closed System: OFF	NA	**(80 cfm/floor) corridor ventilation**	**Balanced HRV**
3 Retrofit	Airtight	Airtight	Airtight	Airtight	Doors: Closed System: OFF	NA	(80 cfm/floor) corridor ventilation	Balanced HRV
4 Retrofit	Airtight	Airtight	Airtight	Airtight	Doors: Closed System: OFF	Pressurized 900 cfm	(80 cfm/floor) corridor ventilation	Balanced HRV
5 Retrofit	**Airtight**	**Airtight**	**Airtight**	**Airtight**	**Decoupled from building**	**Vestibule @ lobby to elevator & stair**	**(130 cfm/floor) corridor ventilation**	**Balanced HRV**

Notice that given that this is an existing building, the airtightness and compartmentalization levels assumed in the retrofit scenarios in this case study are not comparable to those in a passive house building, such as the building in case studies WS-1 and WS-2. Therefore, this case study demonstrates that consistent levels of differential-pressure and ventilation airflows across the suites in the building are more difficult to achieve in existing buildings.

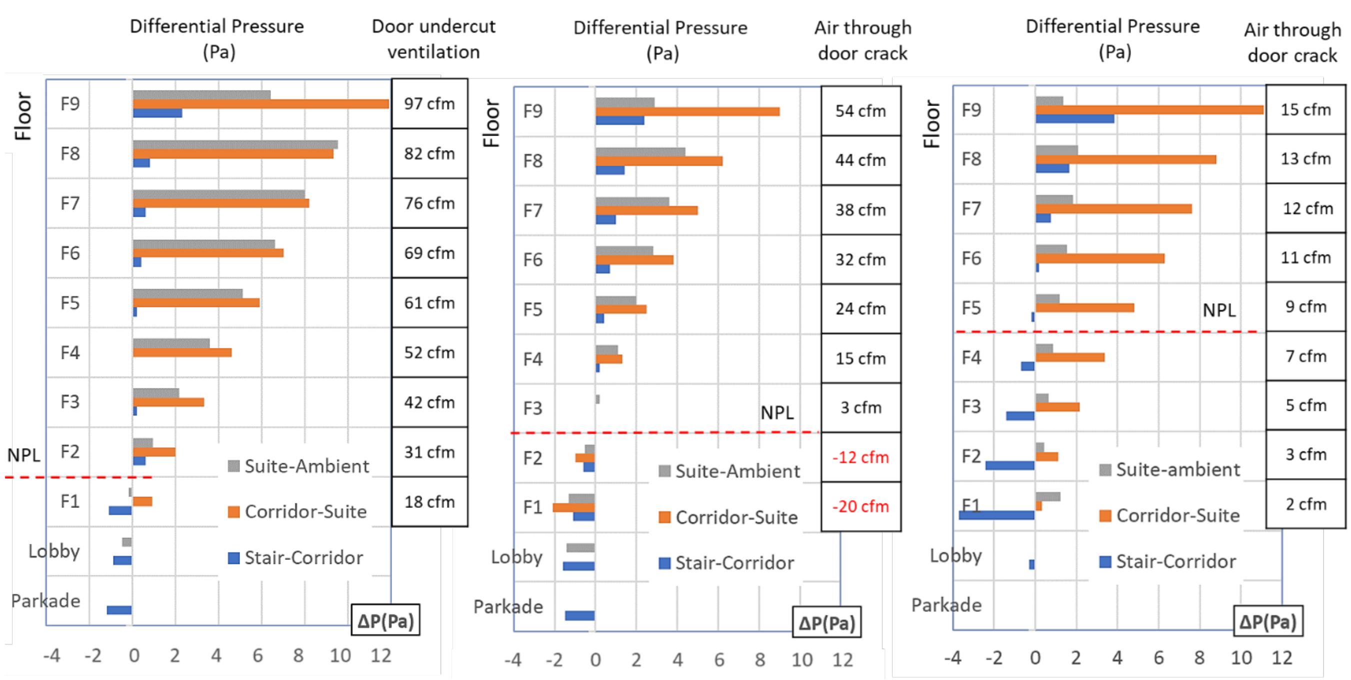
Results:

Figure 82 (a), shows that in the baseline corridor pressurization case 1, the suite ventilation gradually increases from the bottom of the building to the top due to the stack effect, over-ventilating the suites in the upper floors and under-ventilating the suites in the lower floors of the building. The neutral pressure level (NPL) is pushed down due to: 1) the strong corridor pressurization, 2) the uncompartmentalized lobby, and 3) the underground parkade, which is not fully sealed. The pressure differentials in in Figure 82 (a) show that air from the parkade can reach the floors above the NPL. The results are consistent with a study by RDH (2017) on a 13-story residential envelope and energy retrofit with corridor-pressurization ventilation. Differential-pressures, tracer gas, and suite-CO_2 measurements in that building, led to the following conclusions, which are consistent with the WS-4 case-study simulations:

- Lower suites receive order or magnitude less ventilation from the air handler located at the roof.
- Consequently, CO_2 concentration rates in the suites on the lower floors of the building were considerably higher than in suites on the upper floors.
- The ventilation system does not adequately control the migration of contaminants within the building.
- Flow of air from the parking garage into the building was measured to be significant.

Figure 82 (b), shows the retrofit scenario 2, in which central ventilation supplies corridor air, while each suite is provided with an HRV for in-suite balanced ventilation. In this scenario, the suite door undercut is air-tightened because it is no longer needed to supply air for the suites. Because the corridor is only slightly pressurized, the stack effect raises the neutral pressure level. However, the uncompartmentalized lobby and the parkade still pull the NPL downwards. Once again, the stack effect causes the differential pressure and airflows across the suite doors to vary with the building height. Even with airtight suite doors, the top floor suites still receive large amounts of corridor air. However, note that all the suite door and envelope pressures decreased compared to Scenario 1 because less air is being pushed in by the corridor pressurization unit.

Figure 82 (c), shows that air tightening and compartmentalizing the building, including decoupling the parkade and adding a vestibule at the lobby, results in reduced airflows under the suite doors compared with the previous scenarios, thus causing less interference in the suite HRV-balanced ventilation, and lowering the risk of contaminant migration between suites. Notice that in this scenario, the envelope differential pressures are small, and the stair-corridor pressures are high, compared to the other scenarios. This is an outcome of increased compartmentalization, that increases internal resistances to airflow, and is reflected in increased internal differential pressures, and decreased airflows. The differential pressures at the suite doors also increases because they are better air-sealed, and result in reduced airflows under the suite doors.



(a) Scenario 1 (b) Scenario 2 (c) Scenario 5

Figure 82. Existing multi-unit residential building typical floor plan and model

In conclusion, achieving enhanced compartmentalization and balanced ventilation (scenario 5) is critical in existing building retrofits to achieve better differential-pressure and ventilation airflow control across the building, and enable closer to balanced ventilation in the suites. However, uneven corridor airflows to suites throughout the building height seems inevitable in existing building retrofits as shows by the various simulation scenarios. The results can be compared to those in case studies WS-1 and WS-2 on a highly airtight and highly compartmentalized building (Figure 65), in which more even and reduced differential-pressures and minimum airflows are achieved across suite doors.

Nevertheless, slightly pressurized corridor ventilation, combined with increased building compartmentalization, and balanced HRV ventilation in the suites manage to maintain positive differential pressures (corridor-to-suite) at the suite doors, which prevents reverse airflows at the suite doors (from suite to corridor) at the lower floors below the NPL. As a result, contaminant migration between suites at different floors is minimized. However, as demonstrated in case studies WS-2 and WS-3, pollutant migration through partition walls across suites in the same floor, or through penetrations in the floor slabs between adjacent floor suites can still lead to pollutant migrations between suites that bypass the main circulation areas of the building. As indicated in Sections 8.3 and 8.4 of this report, these penetrations are difficult to uncover and seal in existing buildings.

McKeen and Liao (2022) used CONTAM MZ-AFN simulations to demonstrate that exhaust fans with higher exhaust rates in the suites at floors below the NPL combined with air-tighter suites increases the ventilation rate from the corridor to those lower-level suites. However, the authors point out that this approach may significantly reduce the building energy efficiency.

10.5 SR-1 ROOM-BY-ROOM AIR DISTRIBUTION AND VENTILATION ALTERNATIVES

This case study is related to case study WS-4. The case study simulates the ventilation in a 2-bedroom suite of the building of the case study building WS-4. The goal of this case study is to understand the factors that affect the reliability of the corridor pressurization ventilation at the suite level, and the effectiveness of ventilation retrofits.

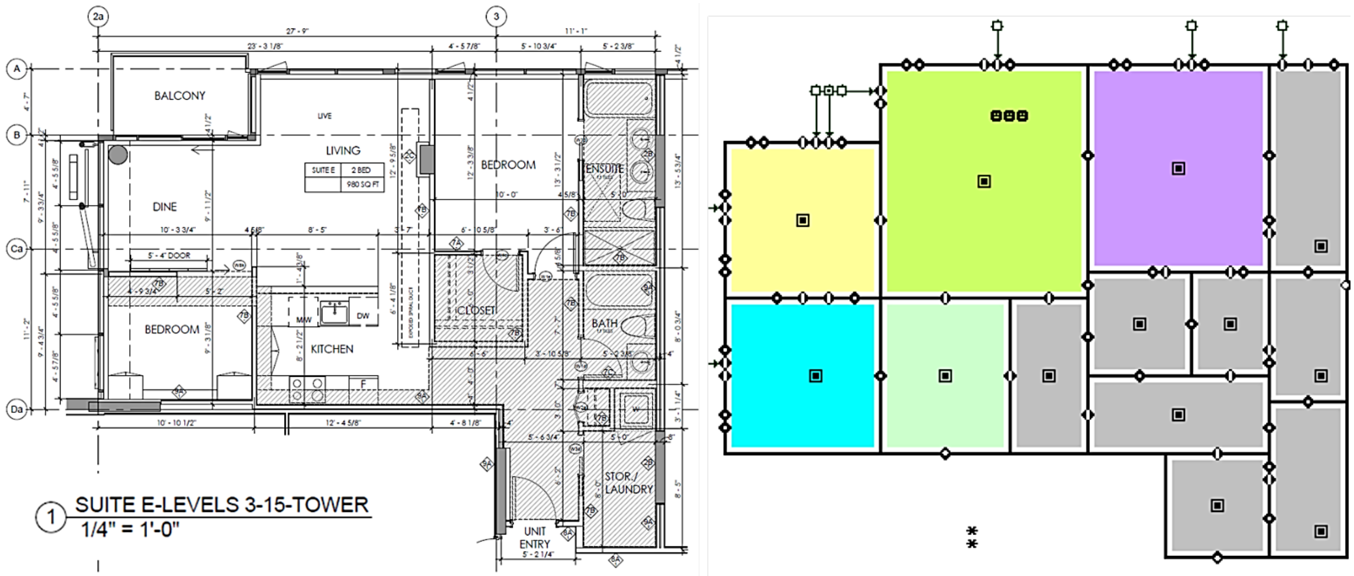


Figure 83. Suite modelled in case study SR-1

The design scenario models room-by-room CO_2 concentrations under corridor pressurization under typical weekend schedules. The BCBC 9.32 ventilation requirement for this suite is 70 cfm. Figure 84 shows that the CO_2 concentrations are in general acceptable, with slightly elvated CO_2 concentrations only in the master bedroom. Figure 84 also shows that having the doors open or closed has no impact on the ventilation airflow distribution, as shown by the CO_2 concentrations.

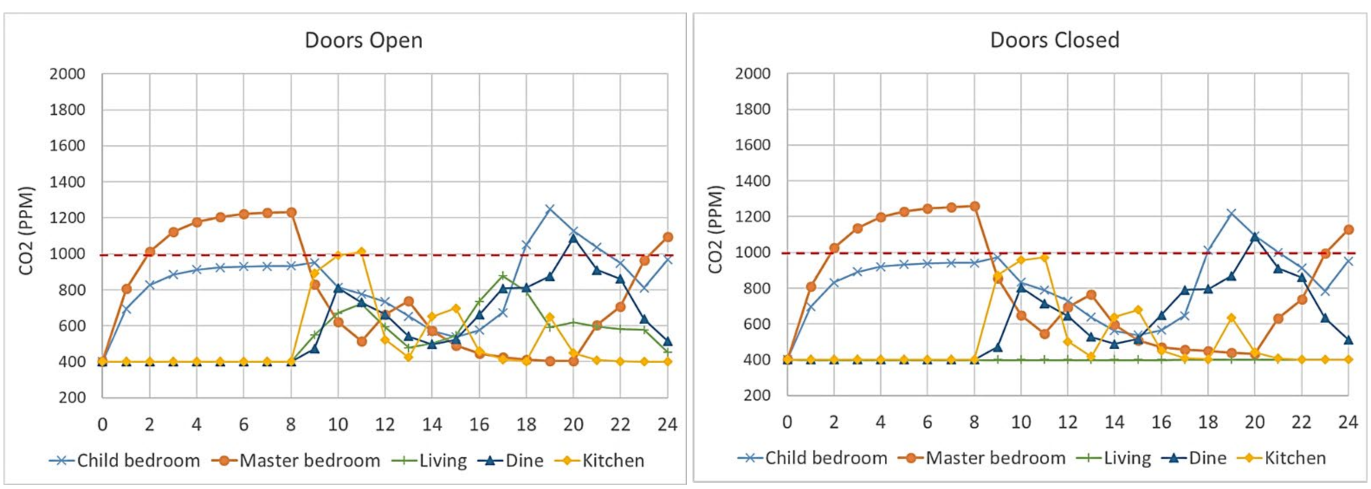


Figure 84. CO_2 concentrations under corridor pressurization with design 70 cfm supply air and 25 cfm bathroom exhaust

Figure 85 shows that a reduction in corridor supply airflow to 50 cfm causes elevated CO_2 concentrations in the rooms. This will be the case of a suite in the 4th floor (F4) of the baseline scenario in case study WS-4, shown in Figure 82 (a). Furthermore, in Figure 82 (a) all floors below F6 would have deficient corridor ventilation, even below 50 cfm, the worst being in F1.

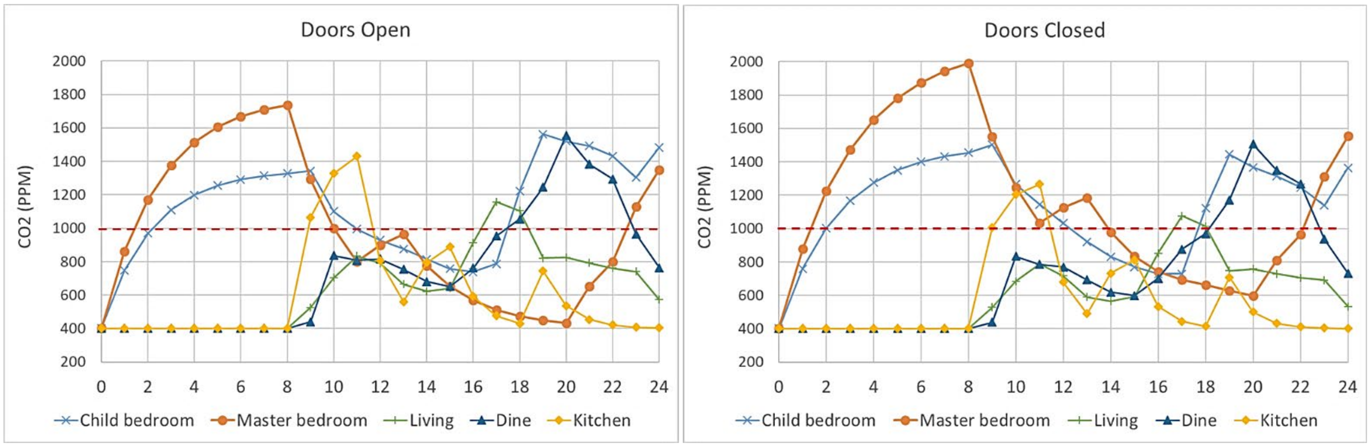


Figure 85. CO_2 concentrations under corridor pressurization with assumed 50 cfm supply air and 25 cfm bathroom exhaust

In Figure 86, an in-suite HRV supplying airflows at the BCBC 9.32 design volume flowrates maintains CO_2 concentrations below 1000 ppm in all rooms.

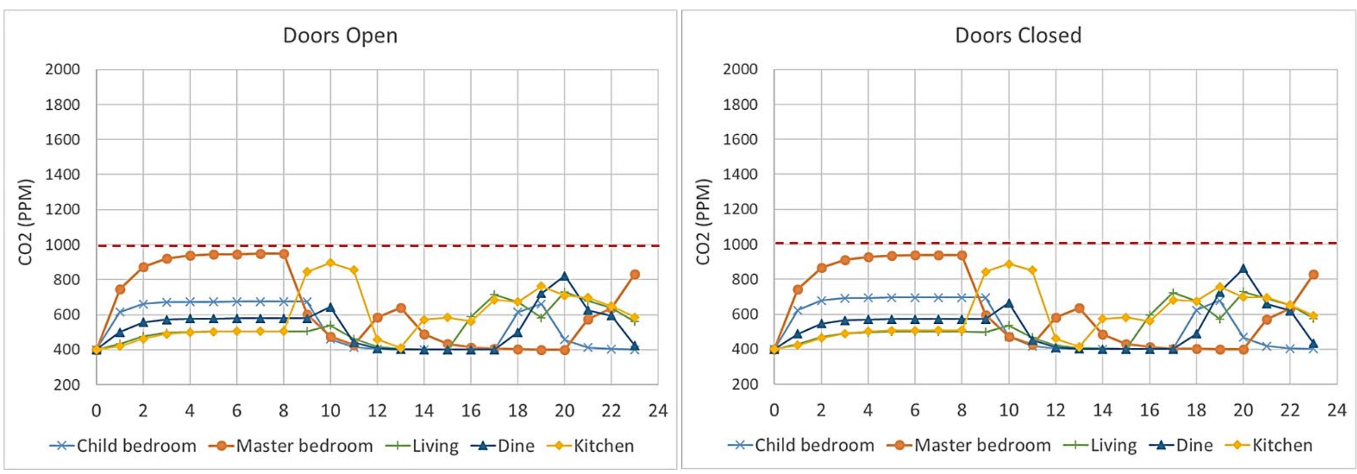


Figure 86. CO_2 concentrations under balanced in-suite HRV ventilation with 70 cfm supply/exhaust volume flow rate

In conclusion, case studies WS-4 and SR-1 demonstrate that robust MURB ventilation retrofits of existing buildings require a detailed compartmentalization and air-tightening of the building, which could be prioritized according to section 8.4. Table 35 of this document. This would permits controlling the corridor airflows under the suite door (Figure 82), and mitigating the migration of pollutants between suites. Un-suite balanced HRV ventilation provides the most reliable ventilation air supply and room-by-room air distribution.

10.6 SR-2 ROOM-BY-ROOM AIR DISTRIBUTION AND VENTILATION OPTIMIZATION

Author: Anoop Vijayakumar Sobha, MASc.

SR-2 includes a series of case studies, that evaluate the ventilation in 3 MURB suites of recently built high-performance buildings in Vancouver. Suites A and B are in a Passive house building. Suite C is in an iconic high-rise Vancouver building.

Case study SR-2-1 - Ventilation and Air Quality analysis of suite A

Suite Description:

Type of building	6-storey Passive House Building Mixed-use, retail-commercial uses on the ground floor and residential market rental units on the five stories above Underground parking
Suite A:	4th floor
• Floor area	383 ft^2 (35.6 m^2)
• Number of bedrooms	Studio (one occupant)
• HRV ventilation	30 cfm (14 L/s), consistent with BCBC 9.32 60 cfm (28 L/s), high-speed
• Heating	500W electric baseboard heating under the window

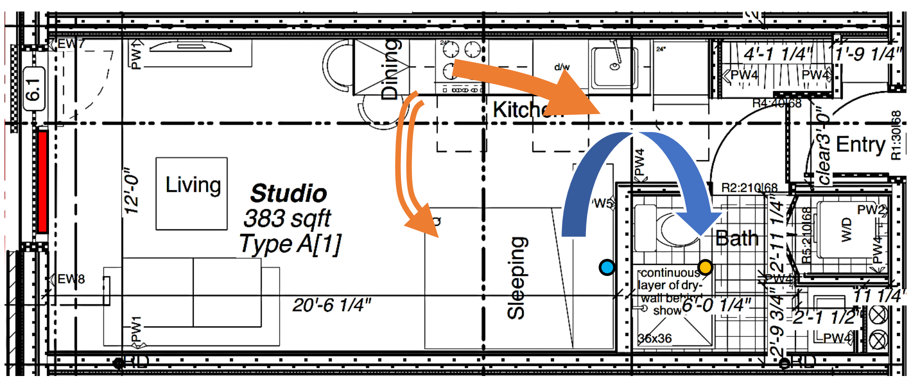


Figure 87. Suite A plan view (blue circle: ventilation supply, yellow circle: ventilation exhaust, red rectangle: electric heater). The curved blue arrow indicates the anticipated ventilation airflow from supply to exhaust, bypassing the living room. The orange arrows indicate the possible cooking pollutant dispersion paths

CO2 Monitoring:

CO_2 was monitored in the suites over a period of one year during post-occupancy. The CO_2 sensor/logger was placed in the living room close to the envelope. Therefore, its data represents CO_2 concentrations in that room only. It is worth to mention that the CO_2 instruments have an accuracy of ± 50 PPM. Before analyzing the data, its trends and patterns were studied. Figures 88 and 89 show data from the month of March only, because the CO_2 concentrations previous winter months shows the suite was unoccupied for long periods (CO_2 readings close to 400 PPM during weeks). Thus, the CO_2 data during those months does not reflect the actual need for ventilation. including those months would not provide reflect the actual relation between occupancy and ventilation.

In Figure 88, it can be seen that the median CO_2 concentration is about 700 PPM, and 75% of the concentration readings are below about 900 PPM (optimal according to table 10, section 3.6). However, 25% of the readings still are between 900 PPM and about 1400 PPM (acceptable according to table 10, section 3.6).

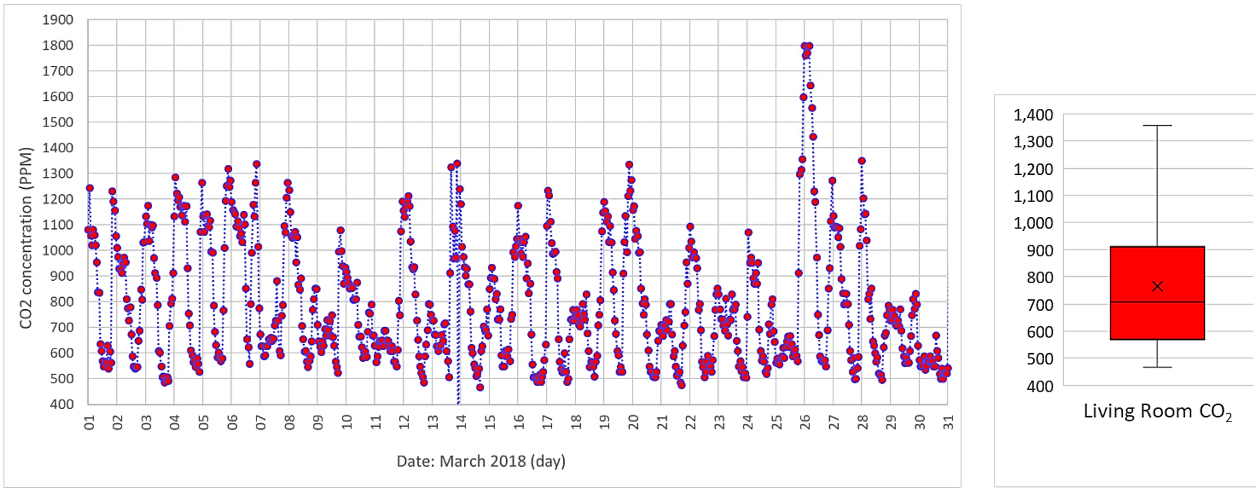


Figure 88. Monitored CO2 concentrations in the living room in March (Suite A)

Figure 89 show CO_2 concentrations during five days in March, including week days and weekends. The CO_2 data follows the daily occupancy cycles of the suite.

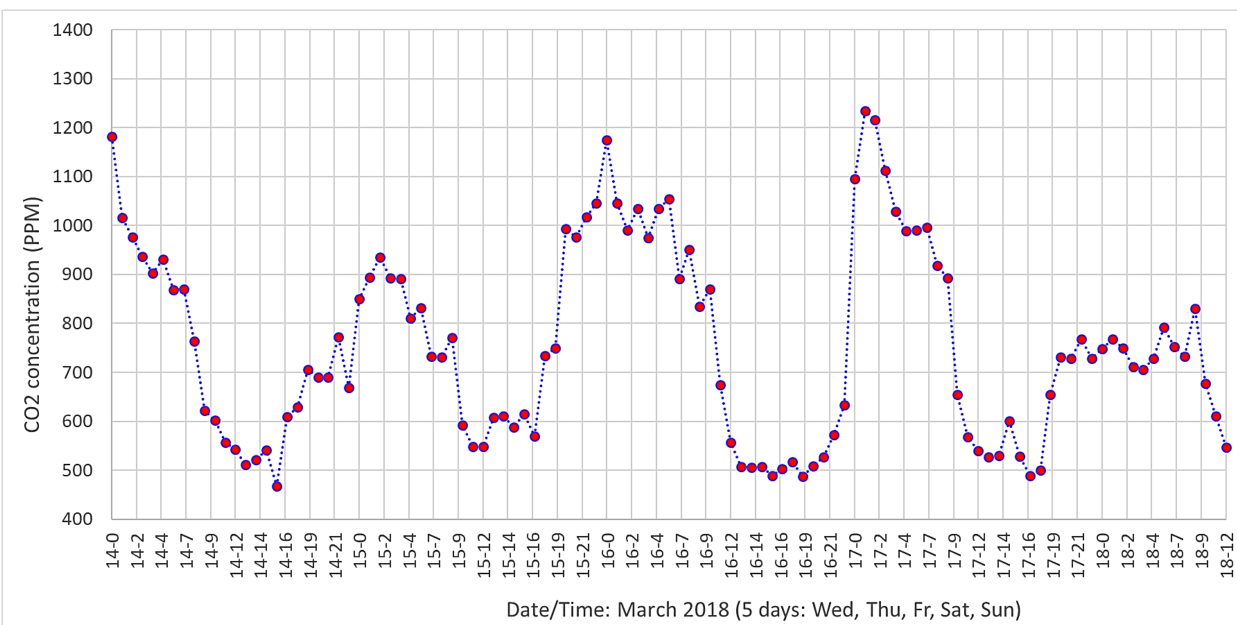


Figure 89. Monitored CO2 Concentrations in the living room during five days (Suite A)

<u>MZ-AFN Simulations (HRV ventilation according to BCBC 9.32)</u>:

- Inputs:
  - Envelope cracks equally distributed along the walls
  - No leakage between neighbouring units or floors
  - Balanced HRV ventilation: as designed according to BCBC 9.32

- Calibration:
    - Envelope cracks adjusted to obtain simulated pressurization test ≈ 0.6 ACH50
    - CO2 verification: air leakage cracks adjusted for results to match CO2 measurements
- Boundary conditions:
    - Steady-state, ambient temperature = 0°C, suite temperature = 20°C
    - Background ambient CO2 concentration = 450 PPM
    - Airflow driving forces: stack effect, wind is not considered
    - Room by room occupancy schedules: weekdays and weekend
    - HRV ventilation: BCBC 9.32
    - Bedroom doors open

CO2 verification:

The simulations were calibrated using occupancy patterns and tuning the envelope porosity to obtain CO_2 concentrations in the living room within the same range as the measured CO_2 concentrations. The model calibration by CO_2 comparison against measurements does not seek to match the simulated CO_2 concentration with the measurements, although a tighter match could be achieved using data-driven inverse modeling techniques and would involve carefully fine-tuning the room by room occupancy, which is out of the scope of this project.

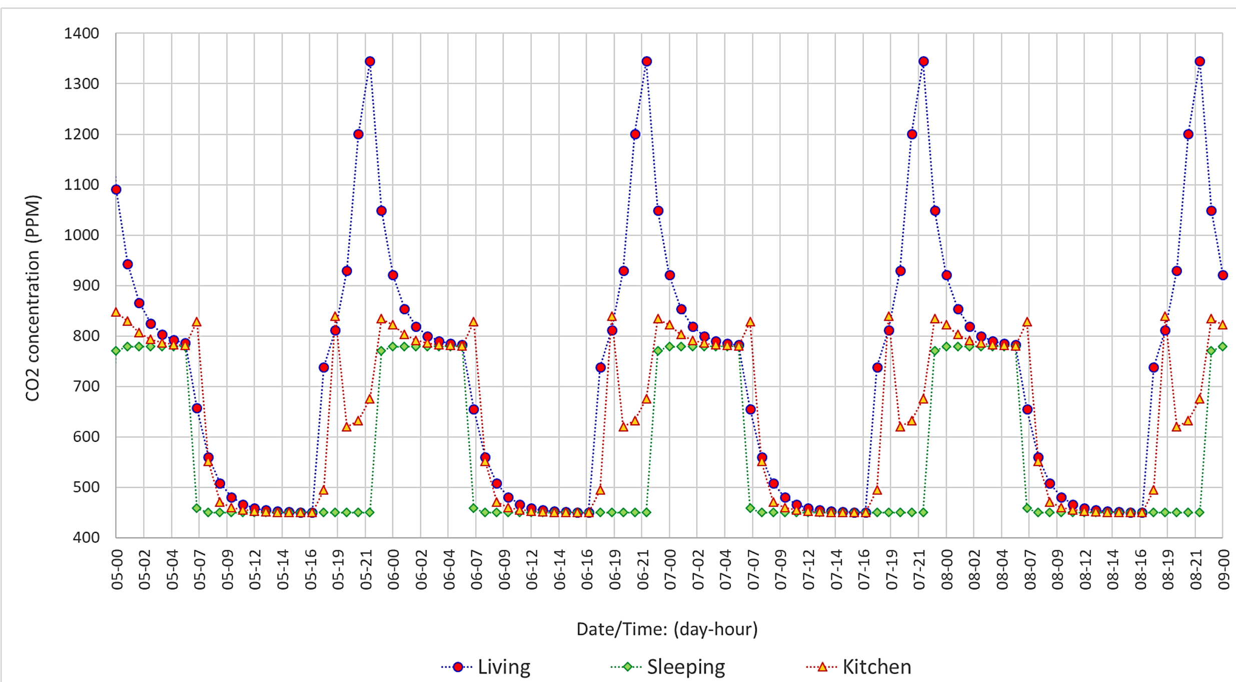


Figure 90. Simulated CO2 Concentrations in the spaces of the studio suite during five days (Suite A)

The CO_2 simulations in Figure 90 show that the CO_2 concentration in the living room rises to up to almost 1400 PPM when the occupant is at the living room, according to the room-by-room occupancy schedule, and drops fast as soon as the occupant leaves the living room. By contrast, the CO_2 level reaches a steady-state value of about 700 PPM at the bed, when the occupant is sleeping, and rises to about 800 PPM when the occupant is in the kitchen. Therefore, the simulation clearly shows that the ventilation bypasses the living room. Also notice that the

CO_2 concentration can keep rising above 1400 PPM if the occupant spends more time in the living room because there is no supply diffuser in this room.

The CO2 concentrations in the living room are high because, as indicated in Figure 87, the supply air at the bedroom space will circulate directly towards the bathroom drawn by the exhaust fan, while likely bypassing the living room. However, the simulation may over predict the CO_2 concentrations in the living room because air circulations caused by the buoyant air from the heater are not considered. The heater buoyant air rises up to the ceiling and expands towards the other spaces, thus drawing makeup air from the other spaces into the living room. The strength and pattern of these air circulations depends on the temperature of the window. However, given that this is a passive house building, the interior window temperature is expected to be higher than 17°C, in which case the heater may not operate that frequently. Well calibrated CFD thermal-fluid simulations can overcome this modeling limitation. Interestingl, Figure 15 in Section 4.2 shows monitored data in a Passive House dorm with a study desk near the envelope, with elevated CO_2 concentrations in the study area. The results are not surprising because the room uses a fan-coil unit for heating that recirculates room air away from the study area, and unlike the baseboard heater in this case study, there are no indoor pressure gradients inducing air into the study area.

Simulation of cooking pollutants' concentration under HRV ventilation:

- Heating source: electric
- Simulation scenario: Baseline (no range hood exhaust ventilation, HRV ventilation only)

Pollutant: Acrolein

- Molecular mass : 56.05 kg/kmol, background ambient concentration: 0
- Emission rate: 0.72 mg/h constant emission during cooking time (Seaman et al. 2007)

Figure 91 shows the concentrations of acrolein in each suite space during a 1-hour cooking event that takes place between 18:00 and 19:00 hours. Figure 91 shows acrolein migration from the kitchen through the entry and into the bathroom. Figure 91 also shows that acrolein does not reach the living room and the sleeping area, both having zero concentration of acrolein. These concentrations are consistent with the anticipated airflow directions indicated in Figure 87.

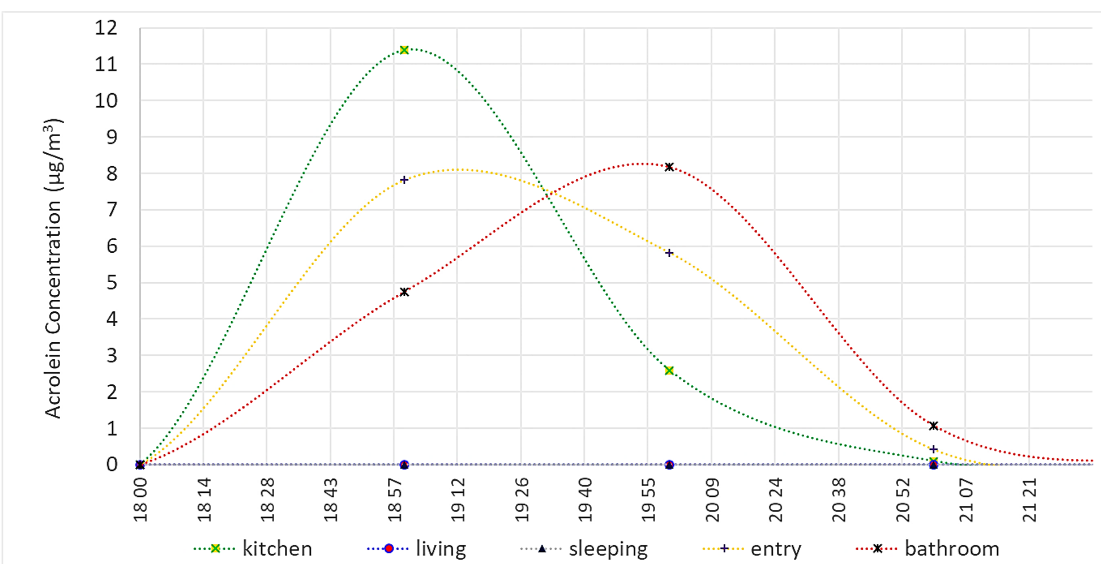


Figure 91. Simulated Acrolein Concentrations during a 1-hour cooking event between 18:00 and 19:00 hours (Suite A)

The acrolein concentrations in Figure 91 are below the recommended short-term (1-h) exposure limits established by Health Canada (Table 9).

Pollutant: fine particulate matter

- PM2.5 : diameter 2.5 µm, effective density: 1.18 g/cm3, background ambient concentration 0
- Emission rate : 0.4 mg/min constant emission during cooking time (Hu et al. 2012)
- Deposition velocity: 1E-03 cm/s (Lai and Nazaroff 2000)

In Figure 92 PM2.5 shows the same dispersion pattern as acrolein. The deposition velocity is very low and therefore its effect in PM2.5 concentration is negligible; fine particles are very small and tend to behave in the air like gases.

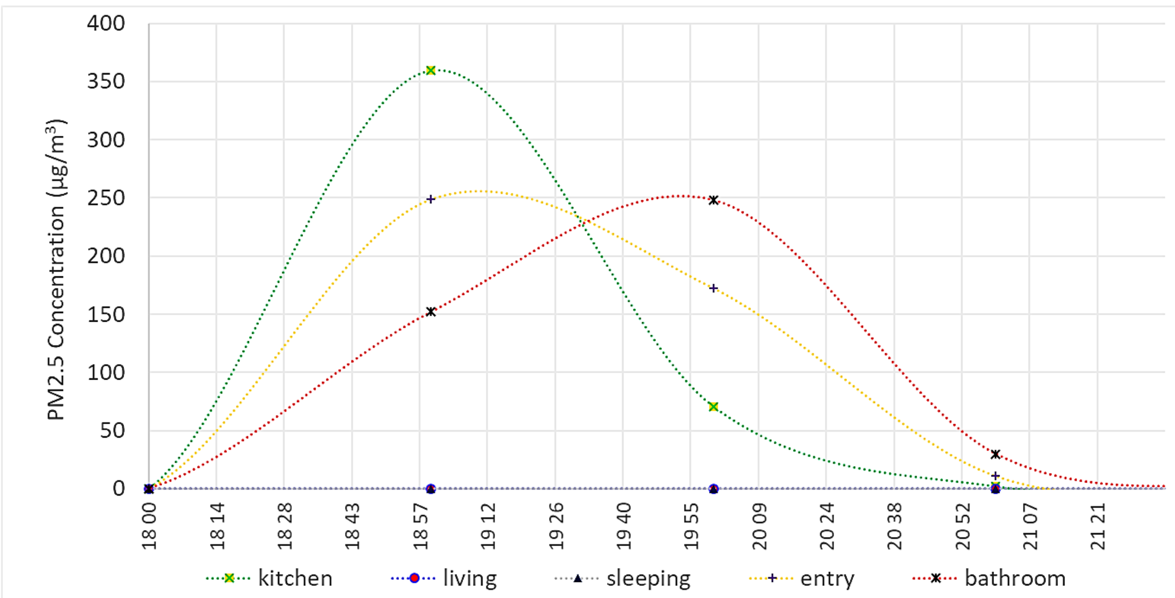


Figure 92. Simulated PM2.5 Concentrations during a 1-hour cooking event between 18:00 and 19:00 hours (Suite A)

Contrary to acrolein, the PM2.5 concentrations in Figure 92 are excessive but in the same order of magnitude as those in the literature, without range hood source control ventilation (e.g. Figure 8). Similar to the baseboard heater, because thermal-fluid air circulations generated by buoyant cooking air and its pollutants are not considered, the dispersion of air and its cooking pollutants and their concentration in the suite spaces will depart to some degree from the simulated values. Just like with the heater, the cooking air and its pollutants will rise to the ceiling and expand at the ceiling level towards other spaces, including the living room and the sleeping area. Therefore, the pollutant movement from the kitchen towards the bathroom exhaust may not be that direct, and the concentration of cooking pollutants in the living room and the sleeping area will likely not be zero. Furthermore, cooking pollutants are wet and sticky, and will tend to attach to surfaces and react chemically, which will decrease their peak concentration in the rooms but will extend their presence and smell for longer periods. Therefore, the simulations will over predict cooking pollutant concentrations in the kitchen, but under predict these concentrations in the living and sleeping areas, as well as the duration of their presence. Particularly, due to the proximity of the kitchen to the sleeping space it would be expected to have cooking pollutants migrate towards the bedroom area. The location of the supply diffuser may counter this migration to some degree, or may even enhance it as indicated by the empty orange arrow in Figure 87. However, MZ-AFN simulations cannot verify this phenomenon without modeling the buoyancy effect from the pollutant-laden cooking air. A workaround to model the thermal air exchanges between the kitchen and the sleeping area would be to model the kitchen air artificially warmer than the air in the sleeping area. However, CFD is a more reliable approach.

<u>Modeling workaround to simulate thermal-fluid interactions between spaces:</u>

From the cooking pollutant simulations results in Figures 91 and 92 we can conclude that cooking pollutants are efficiently dispersed by the mechanical ventilation towards the bathroom exhaust, and do not migrate into the living room or the sleeping area in the suite. However, as indicated before, buoyant cooking fumes rise and create thermal stratification in the kitchen that drive warm pollutant laden air from the kitchen into the living room and the sleeping area, and draws back cooler and cleaner air from those areas into the kitchen as indicated in Figure 93.

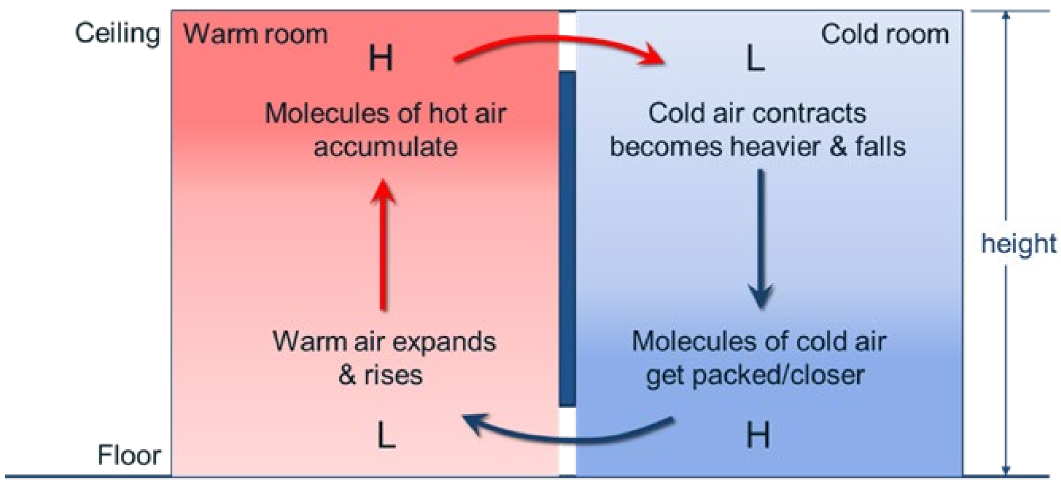


Figure 93. Illustration of buoyant cooking plumes migrating towards other rooms and drawing cooler air towards the kitchen

To simulate this phenomenon, a temperature differential will be assumed between the kitchen, the sleeping area, and the living room, being the living room the coldest room because it is exterior. The room temperatures below simulate air circulations between rooms driven by $1K$ temperature difference between the rooms (Chapter 2 Building Airflow Principles).

- Inputs:
  - Kitchen temperature = 23℃
  - Sleeping area temperature = 22℃
  - Living room temperature = 21℃

The results in Figures 94 and 95 show the equalization in pollutant concentrations between rooms leading to more uniform concentrations across the suite, and low concentrations in the kitchen. The results seem to more realistically represent the actual migration of cooking pollutants from the kitchen into the adjacent, open areas. Such cooking pollutant migration will inevitably lead to unpleasant cooking smells reaching the living room and the sleeping area.

The acrolein concentrations in Figure 94 are about half of those in Figure 91, without considering the thermal stratification of the air in the kitchen and the temperature differences between the rooms. The PM2.5 concentrations are also much lower than those in the model without room temperature differentials. However, the PM2.5 concentrations are still extremely high compared to the normal background outdoor concentrations that range from about 5 $\mu g/m^3$ to about 20 $\mu g/m^3$ in Vancouver.

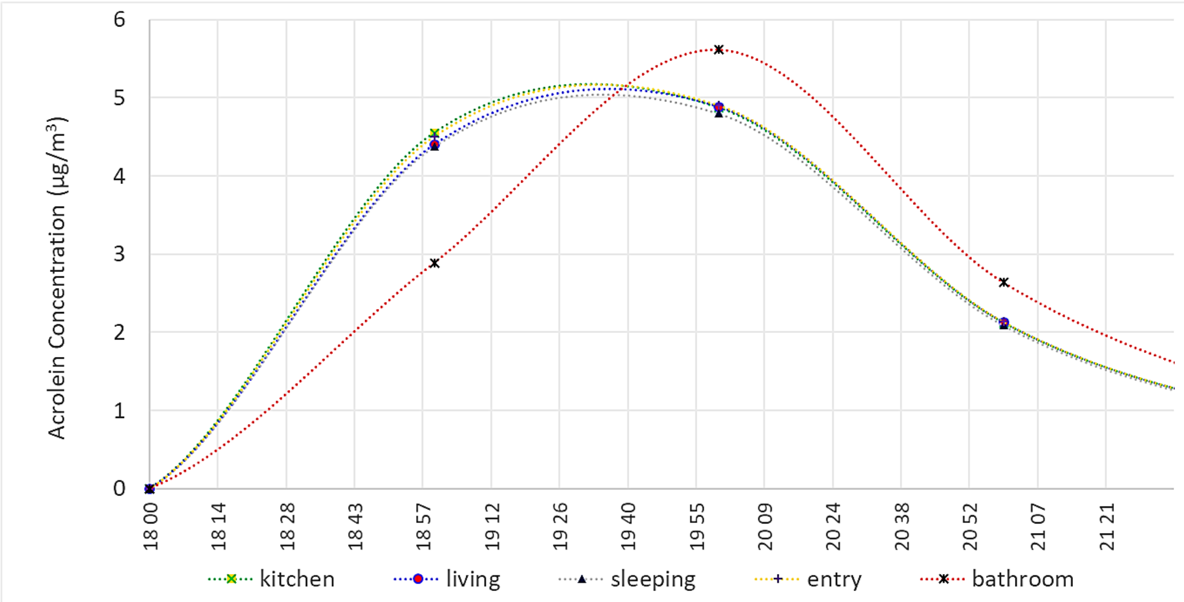


Figure 94. Simulated Acrolein Concentrations during a 1-hour cooking event between 18:00 and 19:00 hours (Suite A), under 1K temperature difference between rooms

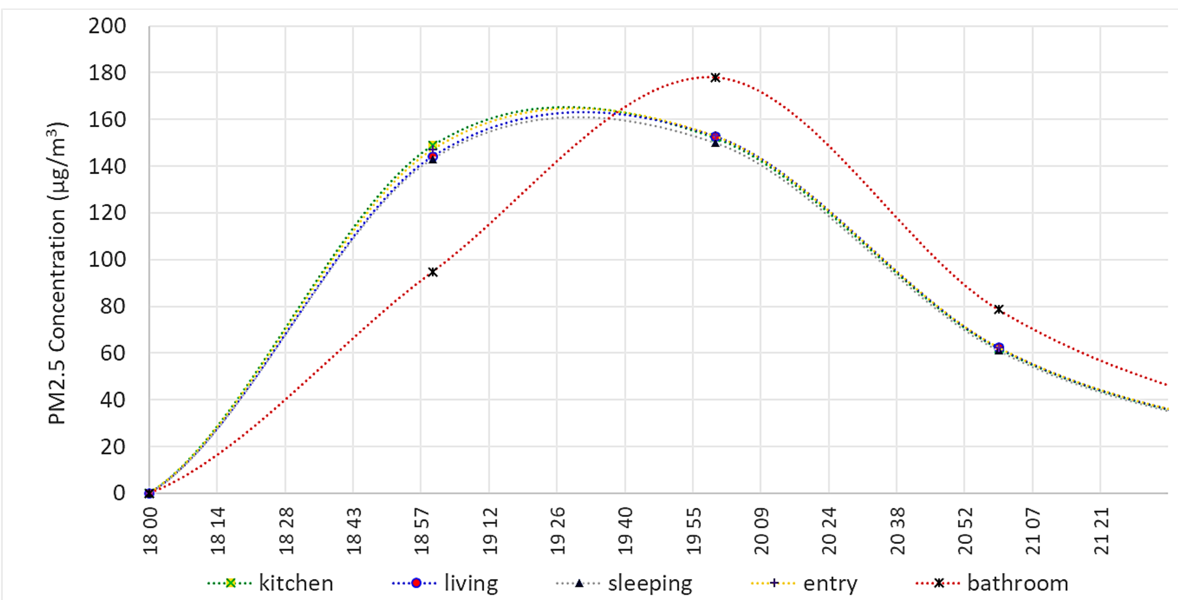


Figure 95. Simulated PM2.5 Concentrations during a 1-hour cooking event between 18:00 and 19:00 hours (Suite A), under 1K temperature difference between rooms

Case study SR-2-2 - Ventilation and Air Quality analysis of suite B

Suite Description:

Type of building	6-storey Passive House Building Mixed-use, retail-commercial uses on the ground floor and residential market rental units on the five stories above Underground parking
Suite B:	4th floor
• Floor area	776 ft^2 (72.1 m^2)
• Number of bedrooms	2 bedrooms (3 occupants: one in one bedroom, and two in the master bedroom)
• HRV ventilation	45 cfm (21 L/s), consistent with BCBC 9.32 (supply: 22.5 cfm/bedroom, exhaust: 22.5 cfm living, 22.5 cfm bathroom) 72 cfm (34 L/s), high-speed (supply: 36 cfm/bedroom, exhaust: 36 cfm living, 36 cfm bathroom)
• Heating	500W electric baseboard heaters under the windows

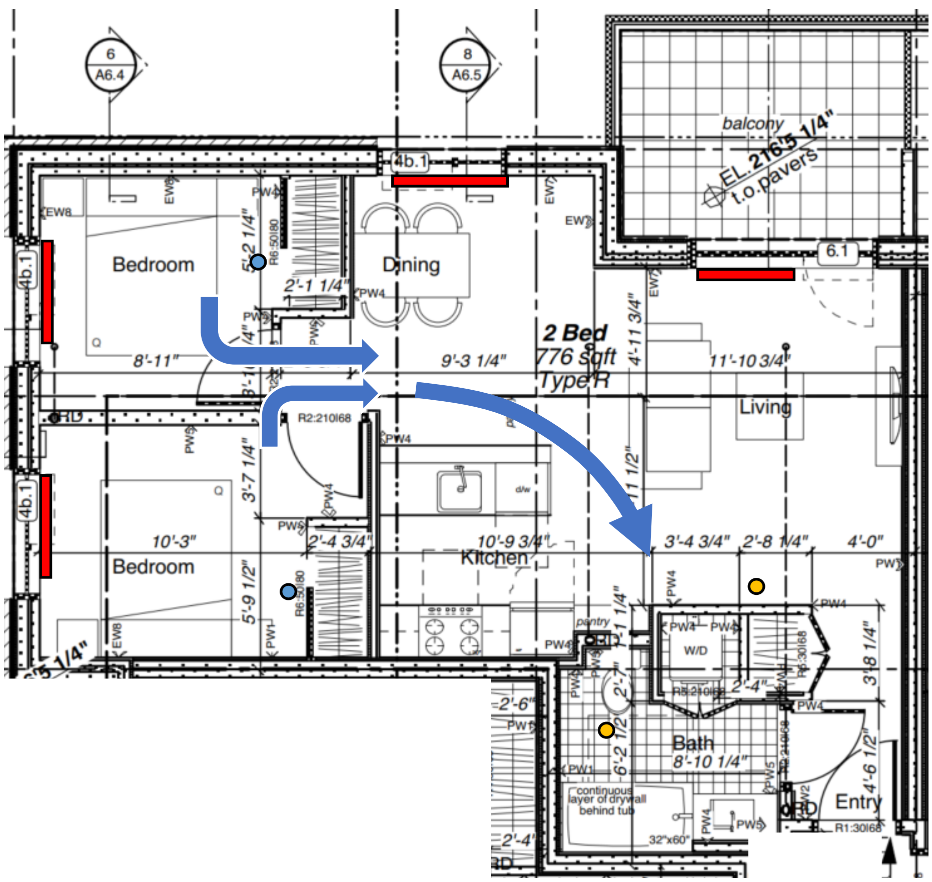
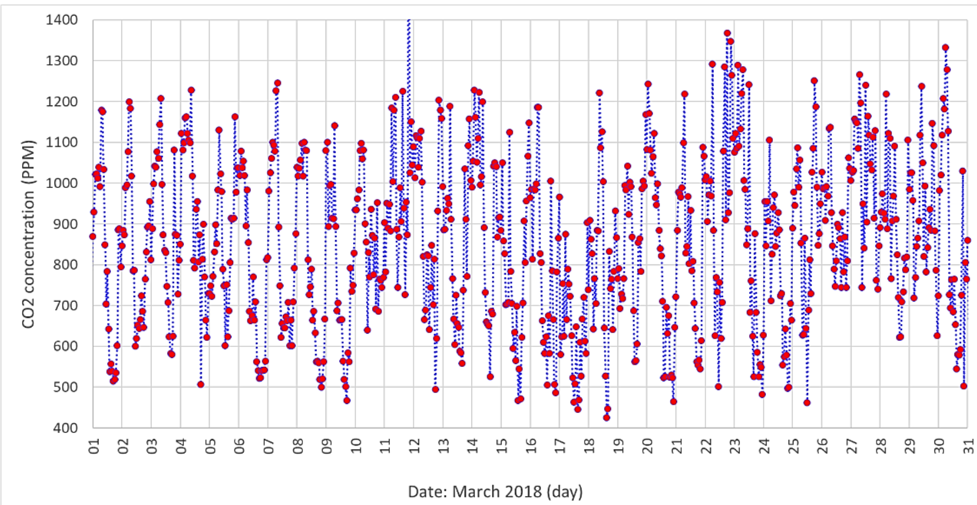


Figure 96. Suite B plan view (blue circles: ventilation supply, yellow circles: ventilation exhaust, red rectangles electric heaters). The curved arrow indicates the anticipated ventilation airflow from supply to exhaust, bypassing the living room.

CO2 Monitoring:

Similar to Suite A, CO_2 was monitored in the suites over a period of one year during post-occupancy. Also similar to Suite A, the CO_2 sensor/logger was placed in the living room close to the envelope. Again, for some reason the CO2 patterns during winter were highly irregular with long unoccupied periods. Therefore, the month of march was again selected for the analysis as illustrated in Figures 97 and 98.

Figure 97 shows the median CO_2 concentration is about 850 PPM, and 75% of the concentration readings lie below about 1000 PPM (optimal according to table 10). However, 25% of the readings still lies between 1000 PPM and about 1400 PPM (acceptable according to table 10).



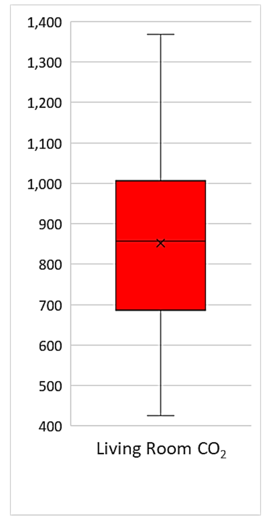


Figure 97. Monitored CO2 concentrations in the living room in March (Suite B)

Figure 98 shows CO_2 concentrations during five days in March, including week days and weekends. The CO_2 data shows the daily occupancy cycles of the suite.

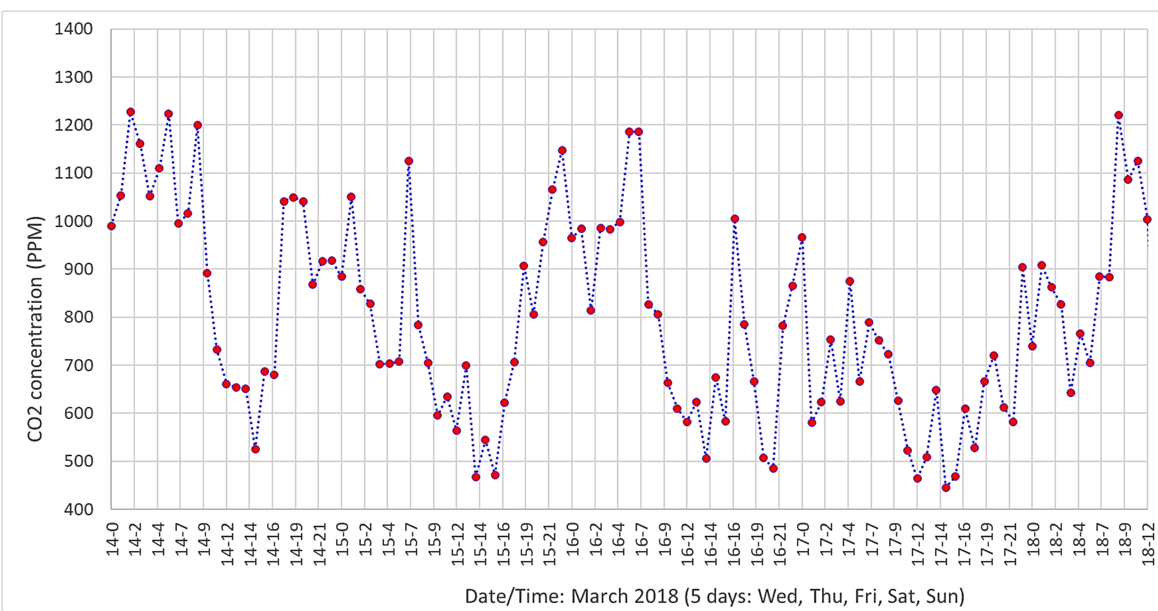


Figure 98. Monitored CO2 Concentrations in the living room during five days (Suite B)

<u>MZ-AFN Simulations (HRV ventilation according to BCBC 9.32)</u>:

- Inputs:
  - Envelope cracks equally distributed along the walls
  - No leakage between neighbouring units or floors
  - Balanced HRV ventilation: as designed according to BCBC 9.32
- Calibration:
  - Envelope cracks adjusted to obtain simulated pressurization test ≈ 0.6 ACH50
  - CO2 verification: air leakage cracks adjusted for results to match CO2 measurements
- Boundary conditions:
  - Steady-state, ambient temperature = 0°C, suite temperature = 20°C
  - Background ambient CO2 concentration = 450 PPM
  - Airflow driving forces: stack effect, wind is not considered
  - Room by room occupancy schedules: weekdays and weekend
  - HRV ventilation: BCBC 9.32
  - Bedroom doors open
- Limitations:
  - The air is modelled to be fully mixed in each room.
  - Thermal-fluid indoor airflows caused buoyant air from the electric heater are not considered.
  - Thermal-fluid air circulations generated by buoyant cooking air and its pollutants are not considered.

CO2 verification:

The simulations were calibrated using occupancy patterns and tuning the envelope porosity to obtain CO2 concentrations in the living room within the same range as the measured CO2 concentrations, as illustrated in Figure 99.

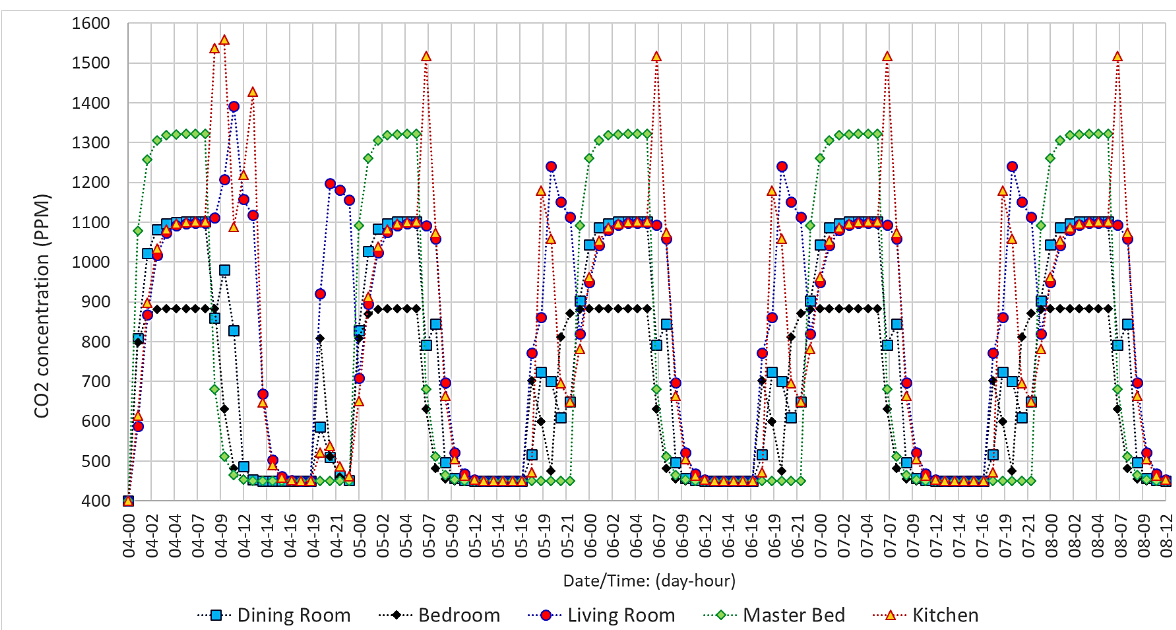


Figure 99. Simulated CO2 Concentrations during five days (Suite B)

In Figure 99, the kitchen CO2 concentration peaks correspond to relatively short periods of time when the three occupants are in the kitchen, a similar pattern is seen in the living room. Just like in suite A, the bedrooms show a more steady-state CO2 concentration pattern reflective of the time when people are sleeping. The master bedroom shows a high, but still acceptable CO2 concentration. This is due to the assumption of this being a master bedroom with two occupants. Given that the air from the bedrooms migrates into the dining room, the dining room air CO2 concentrations shows a more-or-less steady-state CO2 concentration pattern with magnitude in between that of the two bedrooms. The elevated CO2 concentration in the master bedroom may be of concern given the amount of time people spend sleeping. Furthermore, the layout of the supply diffusers in the bedrooms raises further concerns about the ventilation air bypassing the occupants' breathing zone while sleeping. However, because this issue cannot be verified using MZ-AFN simulation, CFD modeling needs to be used.

Simulation of cooking pollutants' concentration under HRV ventilation:

The heating source and cooking pollutant characteristics in this simulation are the same as those assumed in suite A. Figure 100 shows the concentrations of acrolein in each suite space during a 1-hour cooking event that takes place between 18:00 and 19:00 hours. Driven by the ventilation air, the pollutant migrates from the kitchen to the living room and then to the bathroom. Just like in suite A, the pollutant concentration is zero in the rooms that are not in the path of the ventilation air.

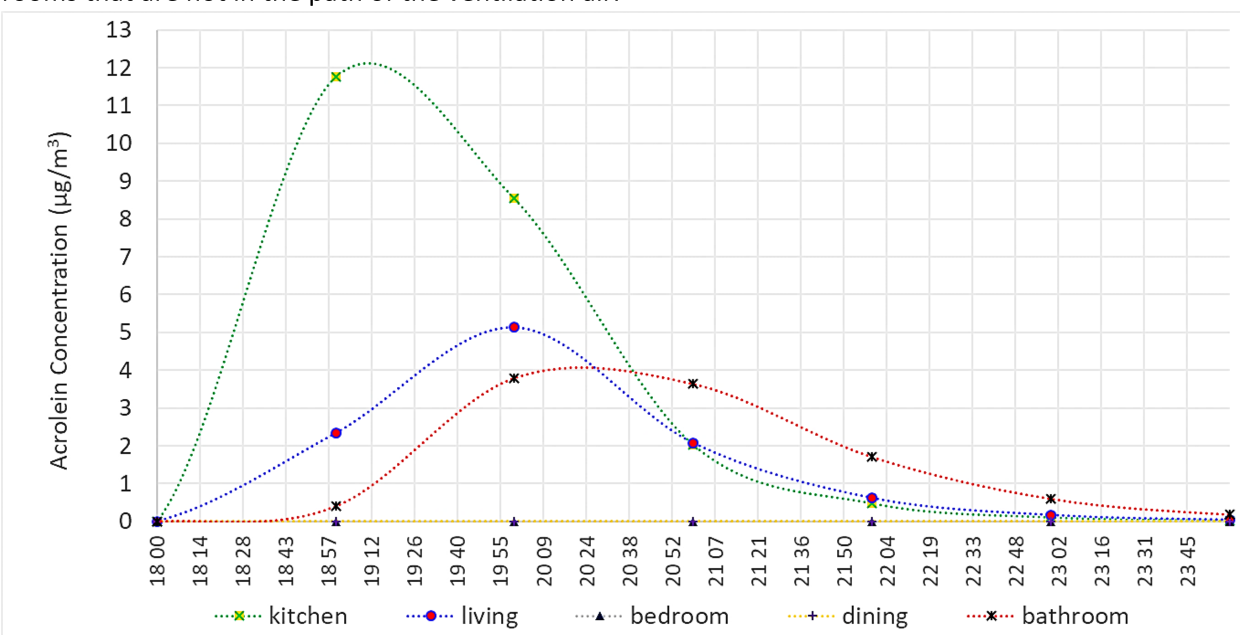


Figure 100. Simulated Acrolein Concentrations during a 1-hour cooking event between 18:00 and 19:00 hours (Suite B)

Figure 101 shows the concentrations of PM2.5 in each suite space during a 1-hour cooking event that takes place between 18:00 and 19:00 hours. The pollutant concentration shows the same pattern as that of acrolein.

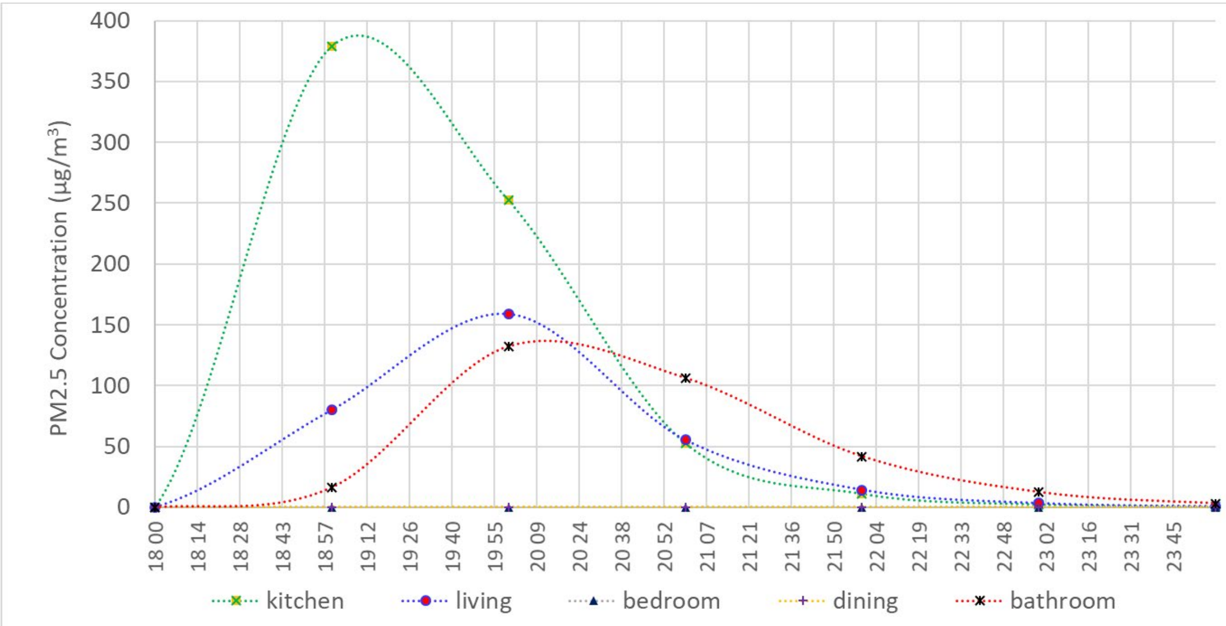


Figure 101. Simulated PM2.5 Concentrations during a 1-hour cooking event between 18:00 and 19:00 hours (Suite B)

Figures 100 and 101 in Case Study 1, Suite B illustrate the cascading ventilation principle “cascade ventilation” principle, directing airflows from clean habitable rooms (bedrooms and living room) where people spend more time, towards more transient and polluted rooms.

The same modeling limitations outlined in suite A apply to suite B, regarding the air assumed to be fully mixed, and the impossibility to model buoyant airflows driven by the baseboard heaters and the pollutant-laden cooking air. However, due to the well-defined ventilation patterns from the bedrooms into the living area in suite B, it is very likely that the kitchen pollutants will not reach the bedrooms.

Modeling workaround to simulate thermal-fluid interactions between spaces:

Similar to suite A, the results in Figures 102 and 103 show the equalization in pollutant concentrations between rooms leading to more uniform concentrations across the suite, and low concentrations in the kitchen. The results seem to more realistically represent the actual migration of cooking pollutants from the kitchen into the adjacent, open areas. Such cooking pollutant migration will inevitably lead to unpleasant cooking smells reaching the living room and the dining room.

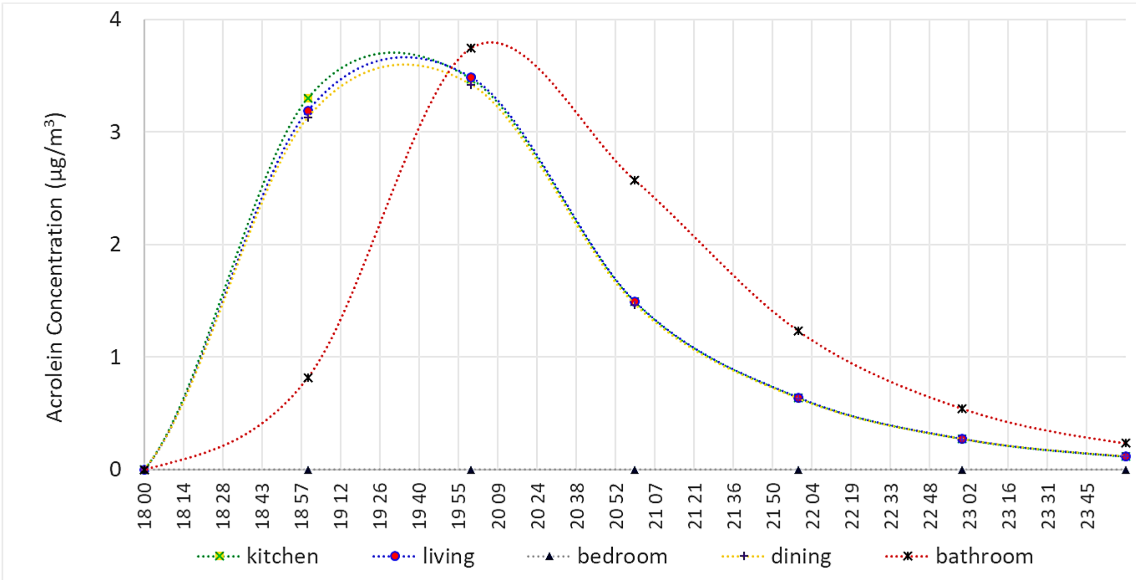


Figure 102. Simulated Acrolein Concentrations during a 1-hour cooking event between 18:00 and 19:00 hours (Suite B), under 1K temperature difference between rooms

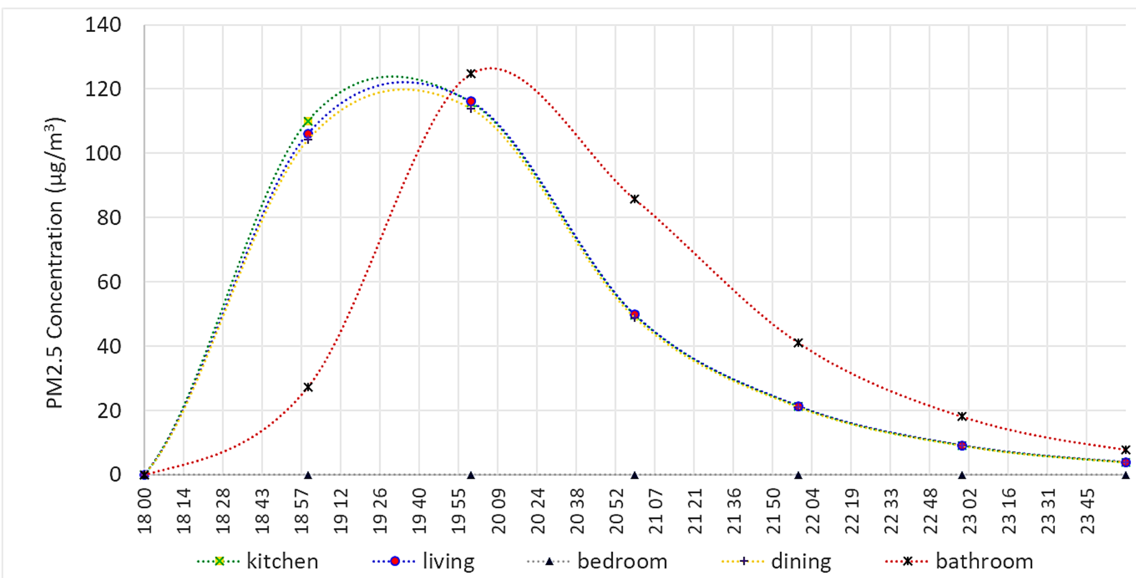


Figure 103. Simulated PM2.5 Concentrations during a 1-hour cooking event between 18:00 and 19:00 hours (Suite A), under 1K temperature difference between rooms

Case study SR-2-3 - Ventilation and Air Quality analysis of suite C

Type of building	49-storey high-rise building Mostly residential Underground parking
Suite A:	46th floor
• Floor area	1075 ft^2 (100 m^2)
• Number of bedrooms	3 (three occupants)
• HRV ventilation	**Scenario 1** (design): 50 cfm (25.5 L/s), consistent with BCBC 9.32 ○ master: 20 cfm, bedroom: 10 cfm, living: 10 cfm, dining: 10 cfm **Scenario 2** (actual balanced/measured): 86 cfm (40 L/s) ○ boost mode up to 105 cfm (50 L/s) ○ flow Balanced/Measured (used in model calibration): ○ master: 25 cfm, bedroom: 15 cfm, living: 21 cfm, dining: 25 cfm **Scenario 3** (adjusted): adjusted to improve air distribution: ○ master: 30 cfm, bedroom: 20 cfm, living: 20 cfm, dining: 16 cfm
• Heating	hydronic baseboard heating and cooling under the perimeter windows
• Suite airtightness	Suite blower door test: 4.6 ACH50

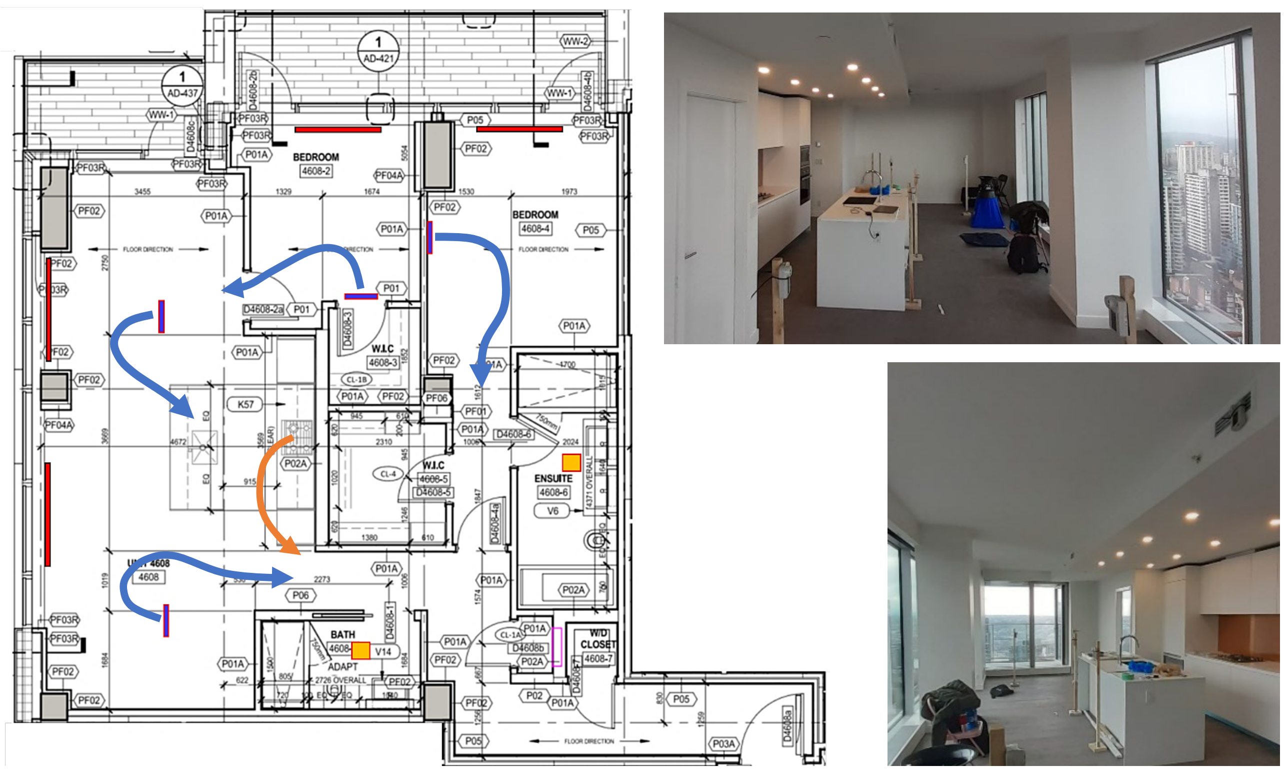


Figure 104. Left. Suite C: baseboard heaters shown in red, anticipated cascading ventilation shown with blue arrows, return diffusers shown in yellow, kitchen pollutant shown with yellow arrow. Right. CO2 monitoring loggers placed in the rooms

The building was under construction during the time of our study. We conducted a pressurization-depressurization blower door test to the unit and obtained suite airtightness of 4.6 ACH50. The blower door was placed at the suite entry door. Which means that the 50 Pa differential pressure was between the corridor and the suite. To overcome this limitation, the entry doors and windows of the two neighbouring suites were left fully open during the test (i.e. to try to equalize the corridor pressure to the ambient pressure). However, the air tightness result from the blower door test will inevitably include air leakages with the neighbouring suites as well as with the suites in the floors above or below. Therefore, the actual envelope airtightness of the suite is expected to be smaller.

<u>CO2 Monitoring</u>:

CO2 was not monitored because the building was under construction during the time of our study. However, we conducted a 1-hour transient CO2 experiment instead. First, in each room, we placed a grid of CO2 sensors at 1.1 m from the floor. Then, before beginning the experiment, we opened all the windows to ventilate the suite and reach close to outdoor CO2 levels. Next, we closed the bedroom doors and four of us, three students and myself, took positions as follows: two people in the master bedroom, one person in the second bedroom, one person in the living room. We spent 1 hour in our positions and finalized the experiment. The resulting CO2 concentrations are in Figure 105.

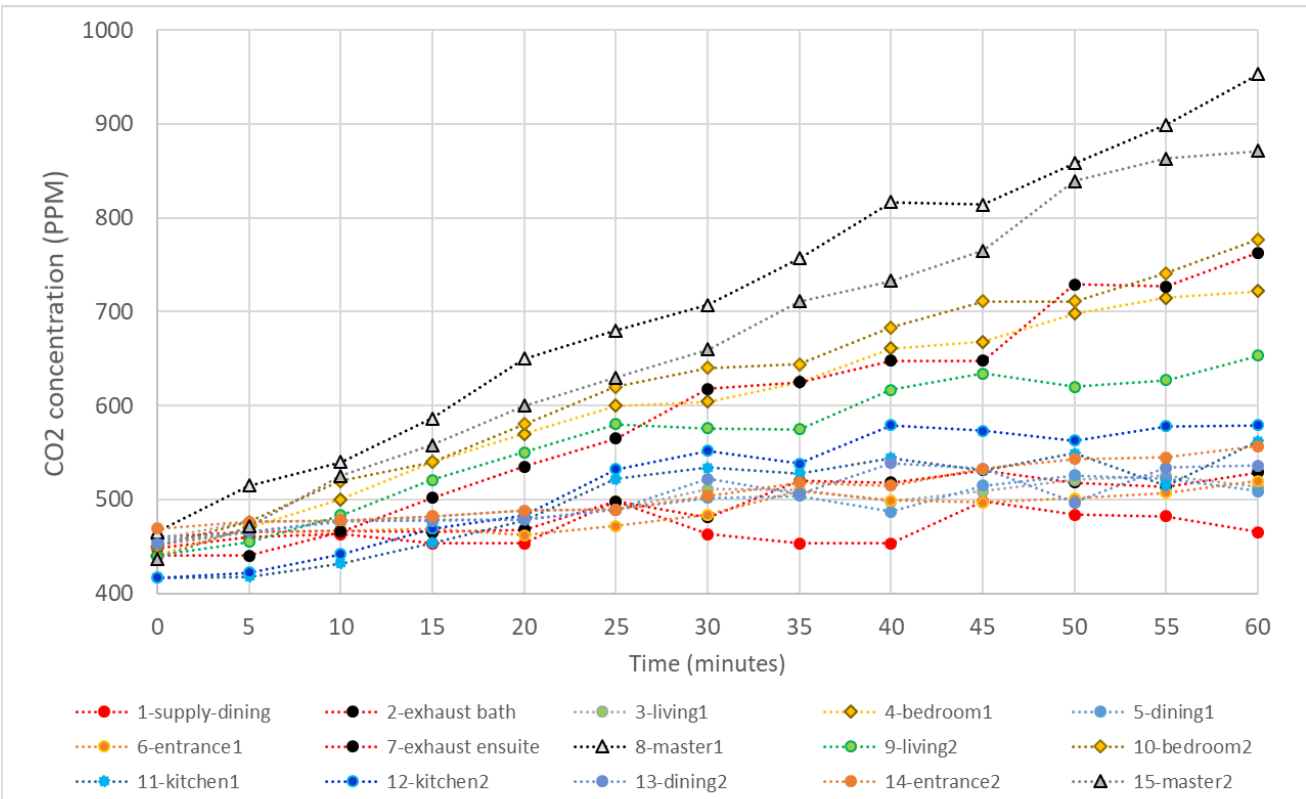


Figure 105. Measured transient room by room CO2 concentrations (suite C). HRV ventilation according to flow measurements

The results in Figure 105 show that the CO2 readings do not reach steady-state concentrations within the hour, as expected. The two master bedroom sensors, with two people, show the highest increase in CO2, followed by the second bedroom, the bathroom exhaust, the living room and the kitchen. The results confirm the airflow circulations indicated in Figure 104.

Scenario 1 - MZ-AFN Simulations (HRV ventilation according to BCBC 9.32):

In this scenario the HRV volume flow rate is according to the BCBC 9.32, which are below the measured values. Results from the actual/measured HRV flow rates are simulated in Scenario 2.

- Inputs:
  - Envelope cracks equally distributed along the walls
  - No leakage between neighbouring units or floors
  - Balanced HRV ventilation: according to BCBC 9.32 (below measured values)
  - Number of occupants: 4 (one more than the code to match the experiment)
- Calibration:
  - Envelope cracks adjusted to obtain simulated pressurization test ≈ 4.6 ACH50
  - CO2 verification: air leakage cracks adjusted for results to match CO2 measurements
- Boundary conditions:
  - Steady-state, ambient temperature = 0°C, suite temperature = 20°C
  - Background ambient CO2 concentration = 450 PPM
  - Airflow driving forces: stack effect, wind is not considered
  - Room by room occupancy schedules: weekdays and weekend
  - Bedroom doors open
- Limitations:
  - The air is modelled to be fully mixed in each room.
  - Thermal-fluid indoor airflows caused buoyant air from the electric heater are not considered.
  - Thermal-fluid air circulations generated by buoyant cooking air and its pollutants are not considered.

Figures 106, 107, 108, and 109 show the simulation results from using ventilation rates according to BCBC 9.32. Note that the CO_2 concentrations are expected to be higher than the measured ones (Figure 105). Scenario 2 shows simulation results at the boosted HRV speed, which correspond to the measured speed. Comparing these to those of scenario 2, we can see how the BCBC 9.32 ventilation results in increased CO_2 levels in all rooms. The bedrooms in particular experience a high steady-state increase in CO_2 concentrations while sleeping.

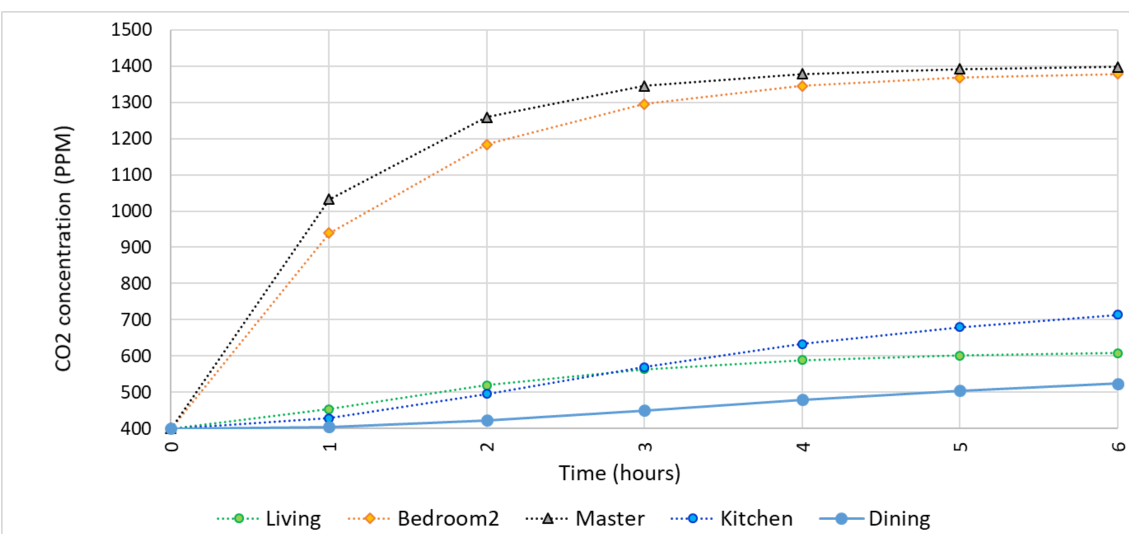


Figure 106. Simulated transient room by room CO2 concentrations (suite C). HRV ventilation according to BCBC 9.32

Figure 107 shows that the CO2 level in the living room rises up to 2500 PPM. The reason for this steep rise is because the occupancy schedules were slightly adjusted to show the effect of having family gather in the evenings the living room before going to bed, for example to watch television.

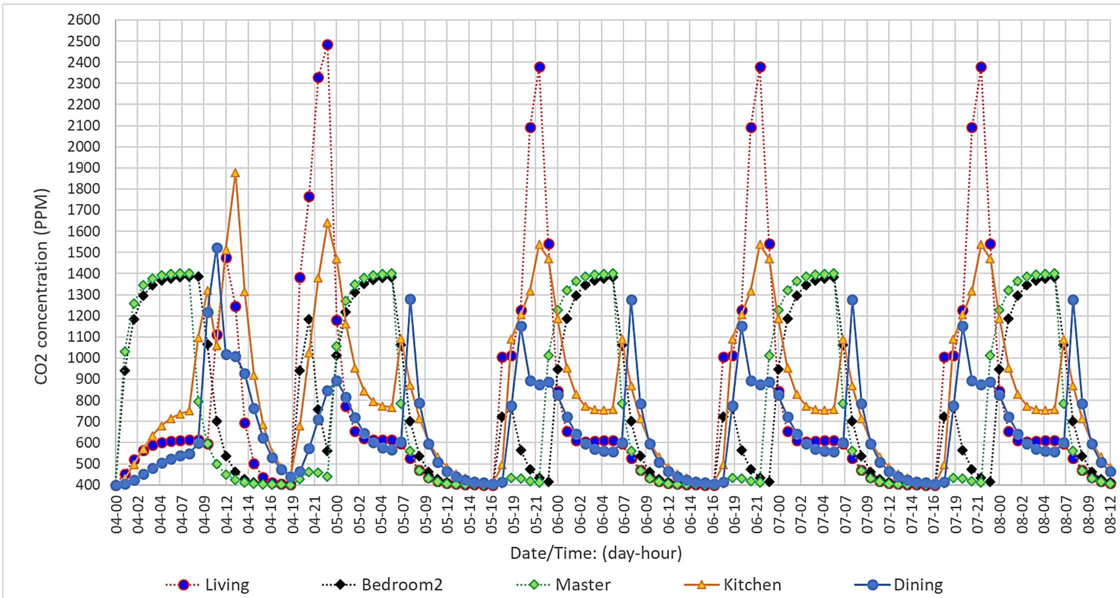


Figure 107. Simulated CO2 Concentrations during five days (Suite C). Ventilation according to BCBC 9.32

Figures 108 and 109 show the increase in air pollution from cooking contaminants (acrolein and PM2.5) compared to the high flow ventilation, as well as the ventilation cascade principle from the kitchen, to the dining room and then to the bathroom. However, part of the kitchen air bypasses the dining room (Figure 104), which results in a lower pollutant concentration in the dining room.

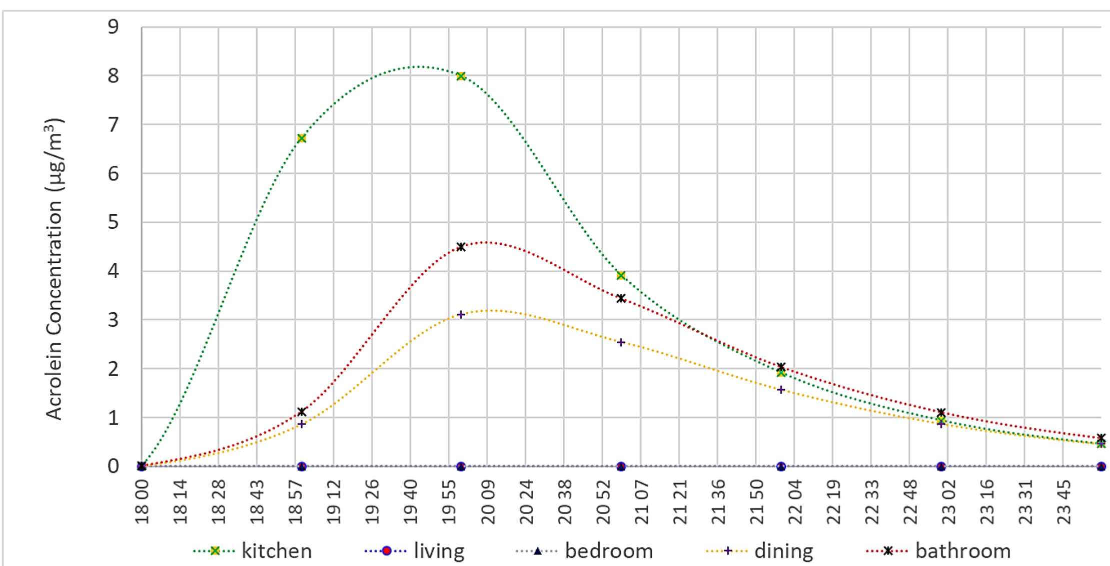


Figure 108. Simulated Acrolein Concentrations during a 1-hour cooking event between 18:00 and 19:00 hours (Suite C). HRV ventilation according to BCBC 9.32

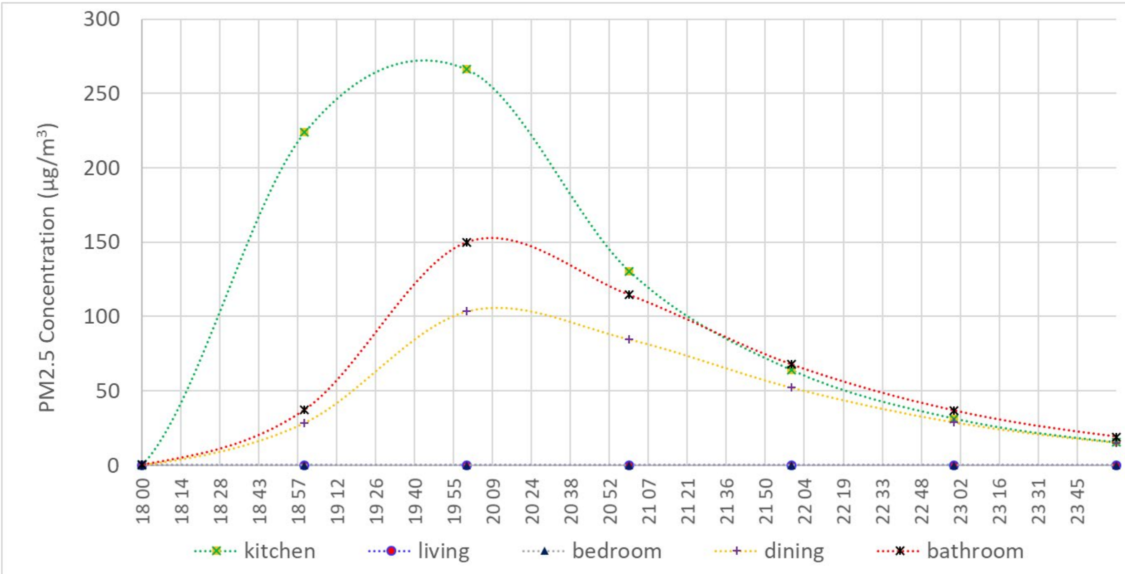


Figure 109. Simulated PM2.5 Concentrations during a 1-hour cooking event between 18:00 and 19:00 hours (Suite C). HRV ventilation according to BCBC 9.32

<u>Scenario 2 - MZ-AFN Simulations (HRV ventilation according to flow balancing and measurements)</u>:

CO2 verification:

The simulations were calibrated tuning the envelope and interior wall porosities to obtain transient CO2 concentrations in the rooms close to those of the experiment. The results are illustrated in Figure 110.

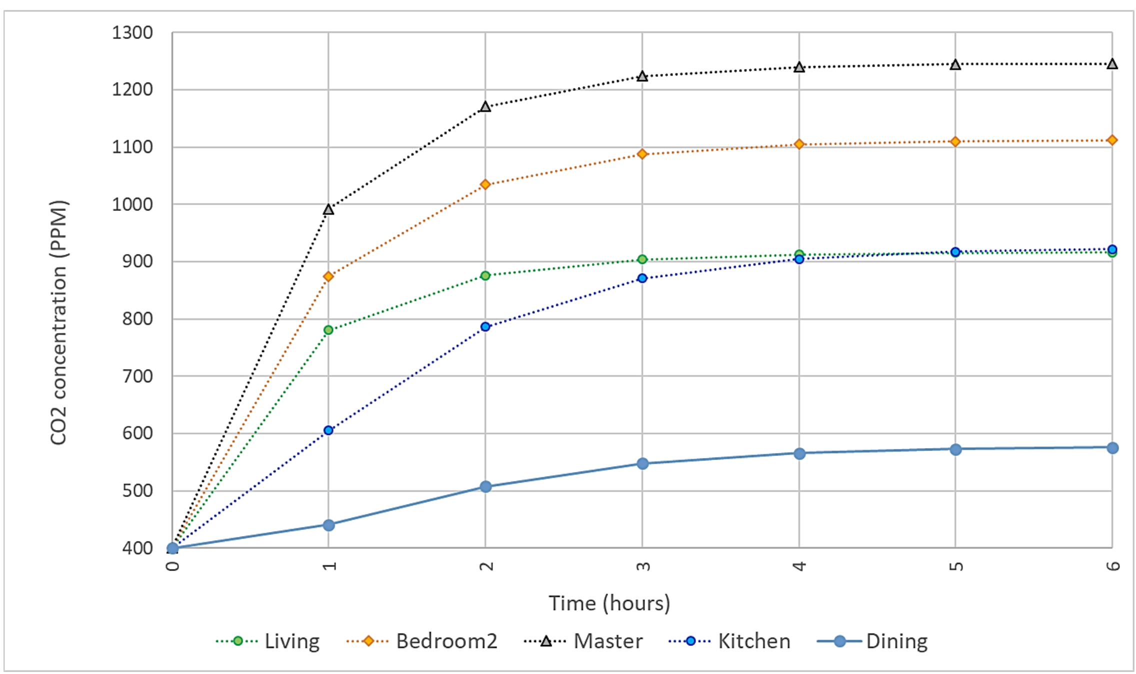


Figure 110. Simulated transient room by room CO2 concentrations (suite C). HRV ventilation according to flow measurements

To compare the transient simulated CO2 concentrations versus the measured ones, only the first hour of simulations needs to be considered. Notice that the simulation time-step is 5 minutes, but the results are reported every hour, which could also be 5 minutes. Comparing the room-by-room CO2 results for the first-hour in Figure 105 versus the results in Figure 110, it can be seen that they are close.

Figure 110 also shows that the CO2 concentration in the bedroom is acceptable but not optimal because it reaches steady-state levels above 1000 PPM. Furthermore, the same issue seems to take place in the bedrooms of this suite as in Suite B, where the ventilation bypasses the breathing zone of the occupants while sleeping. However, this issue needs to be verified using CFD modeling.

Simulation of cooking pollutants' concentration under HRV ventilation:

The electric heating source and cooking pollutant characteristics in this simulation are the same as those assumed in suites A and B. Figure 111 shows the concentrations of acrolein in each suite space during a 1-hour cooking event that takes place between 18:00 and 19:00 hours. Driven by the ventilation air, the pollutant migrates from the kitchen to the dining room and then to the bathroom. Just like in suites A and B, the pollutant concentration is zero in the rooms that are not in the path of the ventilation air. In Figure 111, even though the pollutant reaches the dining room, part of it bypasses the dining room because it is not directly in the path from the kitchen to the bathroom exhaust.

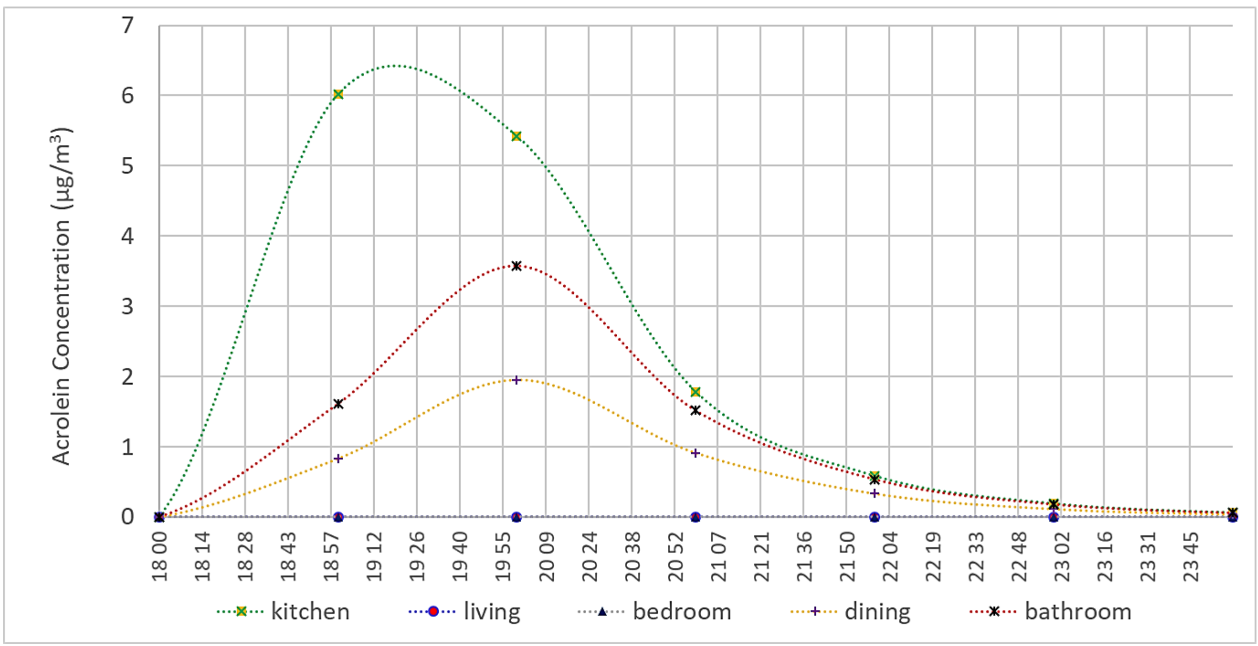


Figure 111. Simulated Acrolein Concentrations during a 1-hour cooking event between 18:00 and 19:00 hours (Suite C). HRV ventilation according to flow measurements

Figure 112 shows the concentrations of PM2.5 in each suite space during a 1-hour cooking event that takes place between 18:00 and 19:00 hours. The pollutant concentration shows the same pattern as that of acrolein.

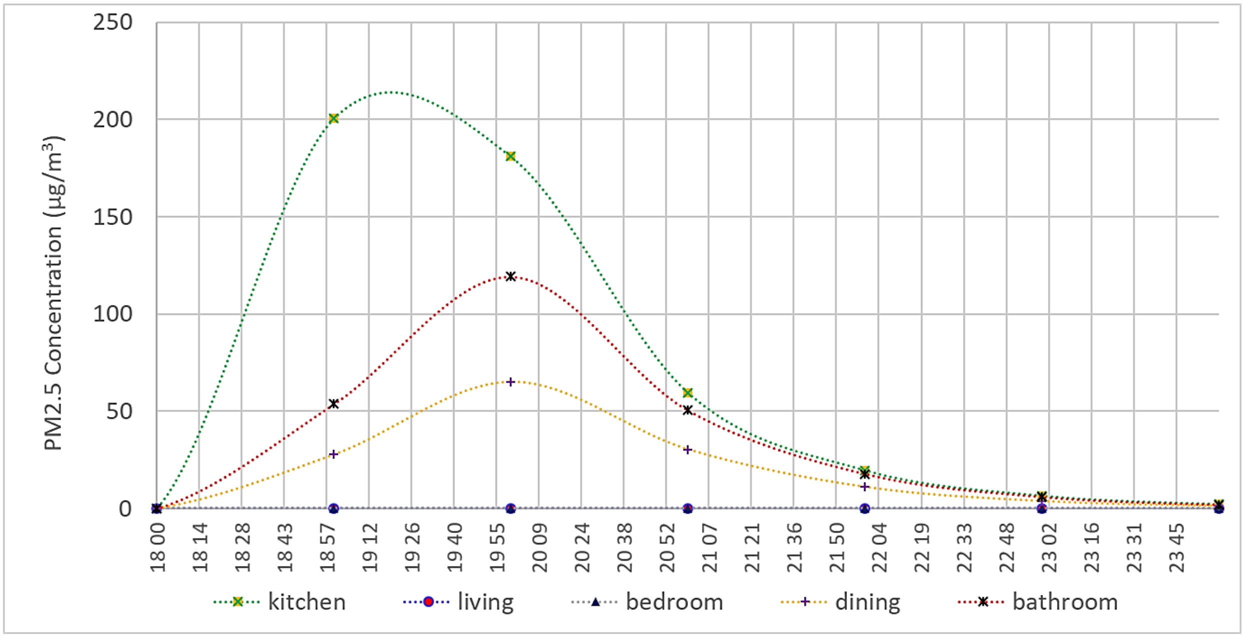


Figure 112. Simulated PM2.5 Concentrations during a 1-hour cooking event between 18:00 and 19:00 hours (Suite C). HRV ventilation according to flow measurements

Figures 111 and 112 in Suite C clearly illustrate the proper application of the cascading ventilation principle "cascade ventilation" principle, directing airflows from clean habitable rooms (bedrooms and living room) where people spend more time, towards more transient and polluted rooms.

The same modeling limitations outlined in suites A and B, apply to suite C, regarding the air assumed to be fully mixed, and the impossibility to model buoyant airflows driven by the baseboard heaters and the pollutant-laden cooking air. However, due to the well-defined ventilation patterns from the bedrooms into the living area, and to the kitchen in suite C, it is very likely that the kitchen pollutants will not reach the bedrooms.

Scenario 3 - MZ-AFN Simulations (HRV ventilation at high speed adjusting flows to improve air distribution):

Figures 113, 114, 115, and 116 show the room by room contaminant concentrations under high-speed ventilation with improved air distribution. Compared to Scenario 2, the reduction in pollutants' concentrations seem small, but since the supply airflows implementing cascade ventilation are better tuned, the concentration of CO2 in rooms is smaller.

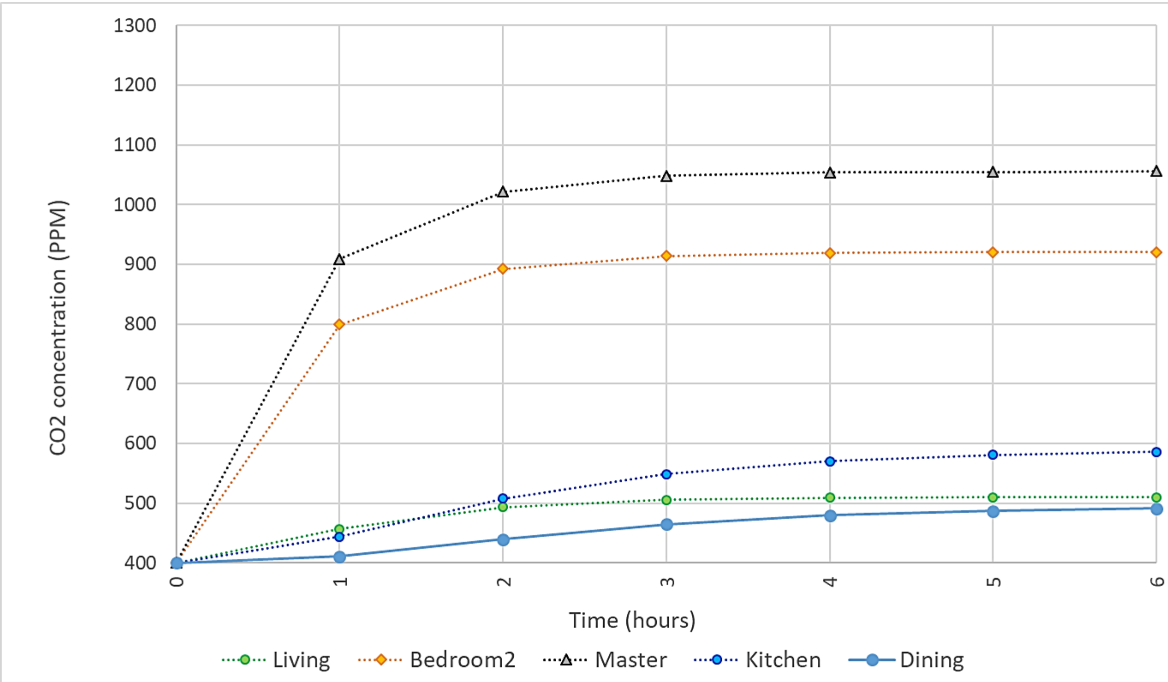


Figure 113. Simulated CO2 concentrations (suite C). HRV ventilation high-speed improved air distribution

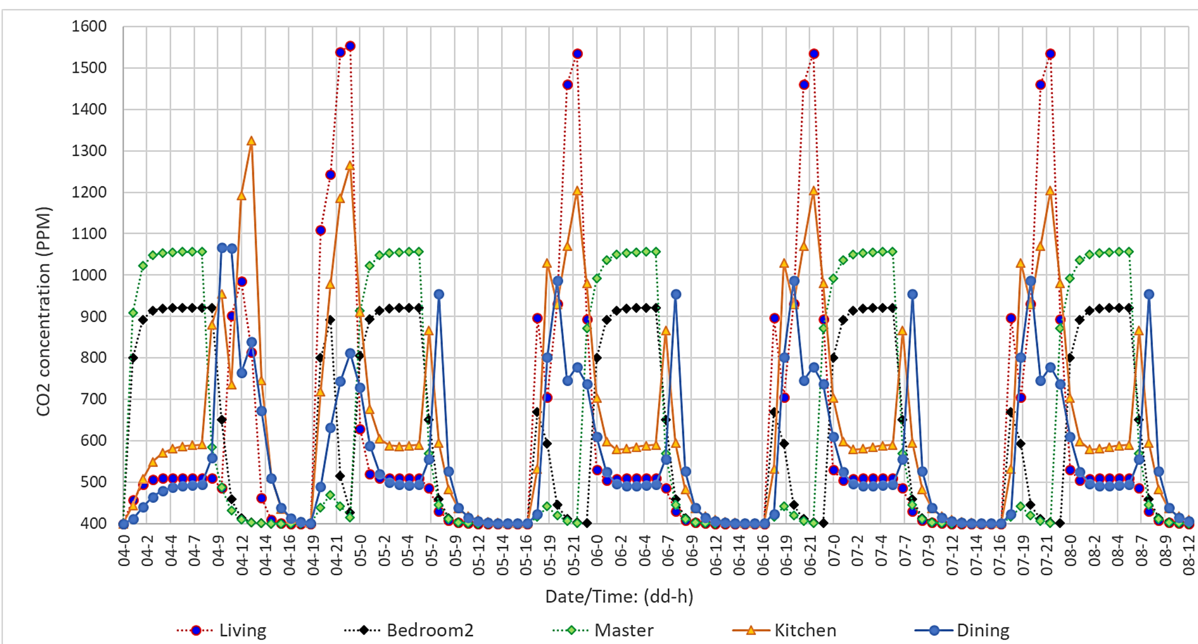


Figure 114. Simulated CO2 Concentrations during five days (Suite C). HRV ventilation high-speed improved air distribution

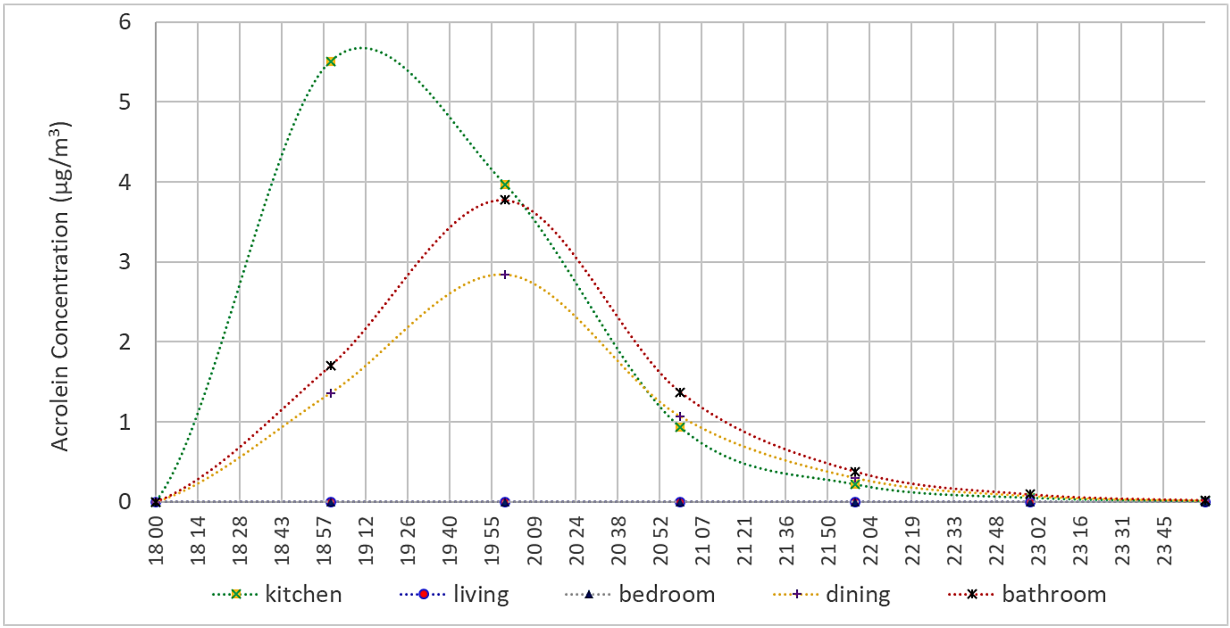


Figure 115. Simulated Acrolein Concentrations during a 1-hour cooking event between 18:00 and 19:00 hours (Suite C). HRV ventilation high-speed improved air distribution

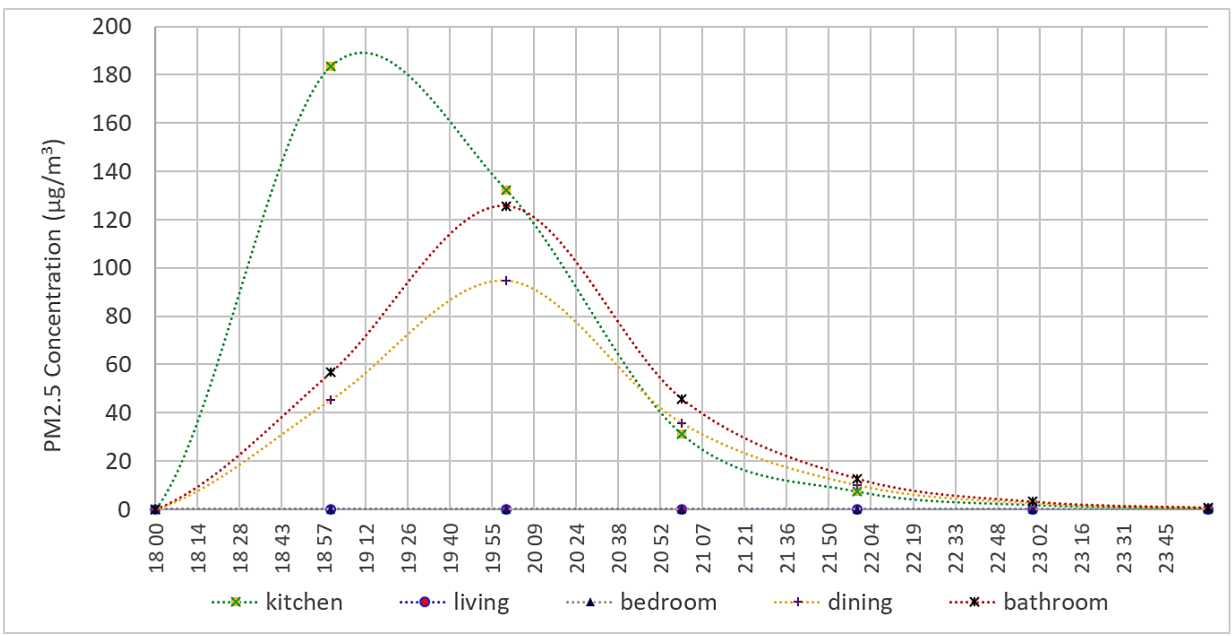


Figure 116. Simulated PM2.5 Concentrations during a 1-hour cooking event between 18:00 and 19:00 hours (Suite C). HRV ventilation high-speed improved air distribution

Scenario 4 - MZ-AFN Simulations (HRV ventilation at high speed adjusting flows to improve air distribution + range hood exhaust fan at 100 cfm with own makeup air):

This scenario adds a range hood exhaust fan at 100 cfm with its own make up air, to capture cooking pollutants at the source. In this case, the cooking pollutant concentrations are reduced significantly as illustrated in Figures 117 and 118. However, the MZ-AFC oversimplifies the pollutant transport in the kitchen because it assumes that the air is fully mixed. To overcome this limitation, similar to case study WS-2, the cookstove and hood can be modeled as a separate small zone. To better capture the thermal-fluid and pollutant transport physics, CFD modeling is recommended as presented in section 10.9 of this document. However, regardless of the modeling method, it is important to remember that the results cannot be regarded in as absolute values. Instead, they can be used to compare the advantages and disadvantages of different cooking ventilation source-control alternatives.

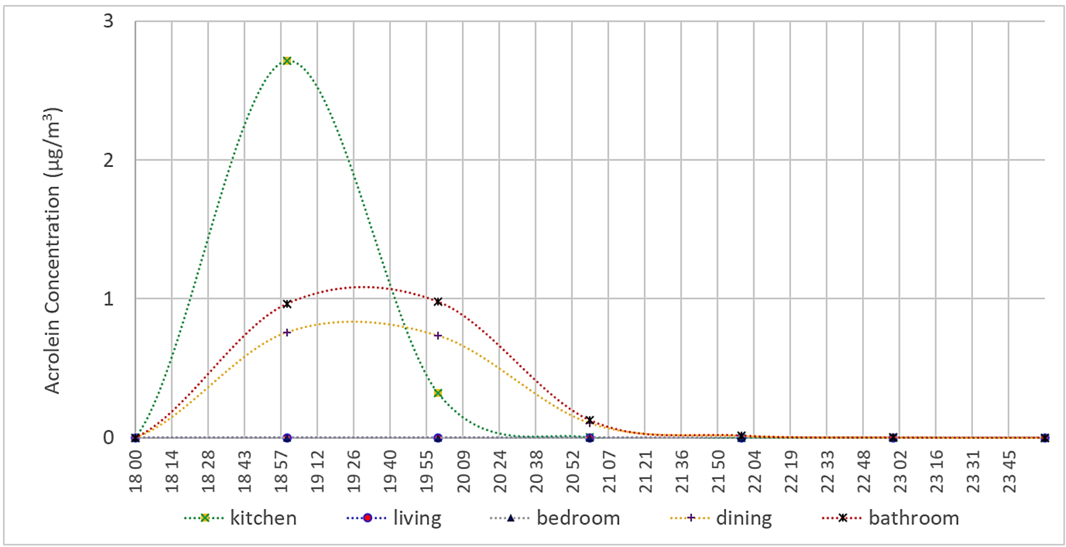


Figure 117. Simulated Acrolein Concentrations during a 1-hour cooking event between 18:00 and 19:00 hours (Suite C). HRV ventilation high-speed improved air distribution plus range hood exhaust with makeup air

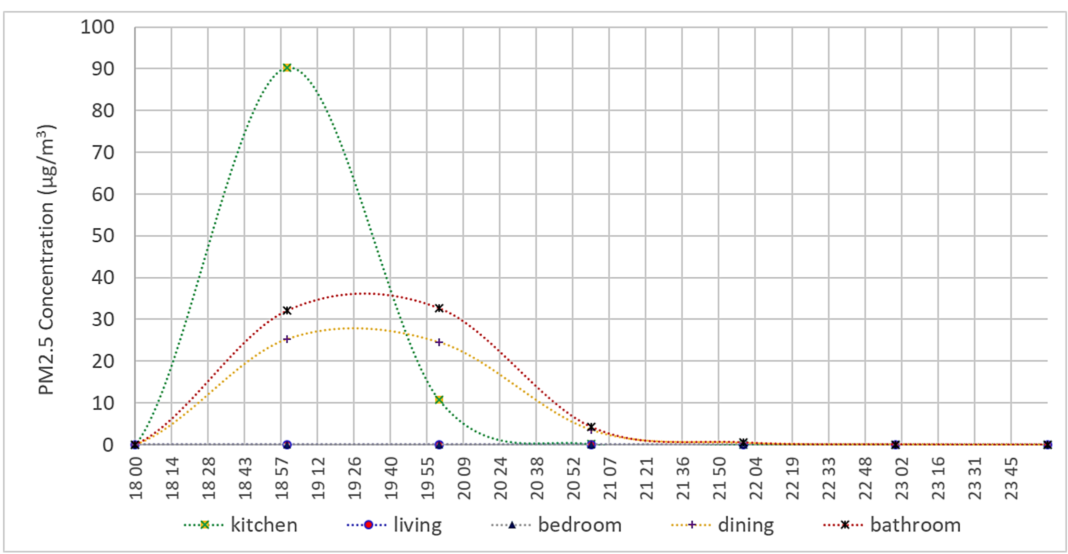


Figure 118. Simulated PM2.5 Concentrations during a 1-hour cooking event between 18:00 and 19:00 hours (Suite C). HRV ventilation high-speed improved air distribution plus range hood exhaust with makeup air

Enhanced ventilation rates

MZ-AFN simulations demonstrate that the enhanced ventilation rates in Table 43 below can maintain CO2 concentrations below 1000 PPM in all rooms, and help reduce the concentrations and dispersal of cooking pollutants. In the table the main ventilation improvements consist in supplying ventilation to the living room, exhausting air from the kitchen, better attributing ventilation to the rooms for cascading airflow, and adding more ventilation to the master bedroom. The results from the simulations are not shown here to avoid presenting repetitive sets of figures with similar pollutant concentration patterns. However, adding more diffusers to the suite may defeat the enhanced ventilation purpose and increase the risk for producing short-circuiting airflows, as can be observed if the more diffusers are laid out in the drawings. Furthermore, it is acknowledged that implementing enhanced ventilation is not always feasible because it results in added ducting branches, larger ducts, and bigger HRV units, all of which are critical factors affecting the design and the energy efficiency of MURBs. Therefore, space limitations and economies of scale in MURBs, and energy efficiency considerations result in compromises in ventilation system design for acceptable indoor air quality, rather than optimal.

Table 43. Case study suites with design ventilation rates and enhanced ventilation rates for improved IAQ

Room	Suite A (cfm)			Suite B (cfm)			Suite C (cfm)		
	BCBC	high	enhanced	BCBC	high	enhanced	BCBC	High	enhanced
Master bed	+30	+60	+30	+23	+36	+45	+20	+30	+40
Bedroom 2				+22	+36	+23	+10	+20	+20
Living room			+30	-23	-36	+22	+10	+20	+45
Dining							+10	+16	+15
Kitchen			-30			-45			-35
Bathroom 1	-30	-60	-30	-22	-36	-45	-25	-43	-40
Bathroom 2							-25	-43	-45
Total (cfm)	30	60	60	45	72	90	50	86	120

Conclusions from the MZ-AFN/C air distribution optimization from the three case studies

MZ-AFN simulation in the three case study suites demonstrate the importance of understanding how the occupancy of rooms, the occupant activities (cooking), the ventilation rates, and the air circulation between the rooms in a suite (Section 4.2. Elements of Ventilation) affect the air quality and the indoor pollutant concentrations.

The rooms where people spend more time are the bedrooms, which is where pollutant levels can reach steady-state and where occupants are more exposed to potential air pollutants (Section 3.5 Health Effects, Figure 9: duration of exposure), such as human bioeffluents, bioaerosols (mould spores), chemicals in bedding and furniture, chemicals from laundry detergents, accumulated dust, etc. The living room (or family room in MURB suites), which is a space for family gathering, for example to watch television, is also a space of potential high exposure to air pollutants. Simulations show that these spaces are in need for higher amounts of ventilation.

Cooking gases and particulates concentrate for short periods of time (about 1 to 2 hours), but can reach high levels in the kitchen and in adjacent rooms, beyond the prescribed TLVs during these periods. The simulations show that

HRV suite ventilation is not effective in removing cooking related pollutants even at high speeds. Source control (Section 4.1 Ventilation Principles) is required during cooking time using a range hood exhaust fan. The source control approach implemented as a MZ-AFN model oversimplifies the range hood exhaust and therefore over predicts the resulting cooking pollutant concentrations with range hood exhaust "source control". CFD simulations can better represent the range hood exhaust mechanism and the cooking pollutant removal.

The simulations illustrate the importance of implementing the cascade ventilation principle (Section 4.1 Ventilation Principles) where ventilation air is supplied to the bedrooms and possibly at the living room and cascades down to the exhaust at the bathrooms, after passing through the kitchen. The effectiveness in the implementation of this principle depends on how the spaces are laid out in a suite in the path of the cascading airflow.

In conclusion, based on the simulation results the designed ventilation rates result in acceptable CO2 concentrations in the occupied rooms, with a few exceedances, which indicate that the ventilation in those rooms is acceptable. However, increased ventilation rates, beyond the minimal code rates, can maintain more optimal air quality conditions particularly in rooms with high occupancy such as the master bedroom and possibly the living room, and minimize the exceedance risks over TLVs. Furthermore, locating a supply diffuser in each major occupied room, including the living room, and attributing adequate ventilation rates according to intended occupancies, further reduces the risks of having poor ventilation conditions in these rooms if they are occupied for longer periods of time. Finally, it is recommended to implement cooking range hood ventilation as a source control measure to remove cooking pollutants at the source and minimize the risk of migration of these pollutants into adjacent rooms.

There are multiple practical limitations to increase ventilation rates beyond the code prescribed rates (energy efficiency), to locate a supply diffuser in each major occupied room such as the living room (extended ducting), and to provide source control range hood ventilation for cooking pollutants. Space limitations and economies of scale in MURBs, and energy efficiency considerations result in compromises in ventilation system design for acceptable indoor air quality, rather than optimal.

10.7 SR-3 WILDFIRE PM2.5 POLLUTANT PENETRATION – A SUITE-LEVEL ANALYSIS

Author: Amir Salehi, MEng

The analysis is similar to that in case study WS-1. However, WS-1 modeled a whole building, while SR-3 models a single suite. The goal it to demonstrate that while the magnitude of the results is obviously different, the conclusions from the simulations are essentially the same. A multi-zone airflow network (MZ-AFN/C) model was developed of a single MURB suite to compare the effects of various levels of air filtration and airtightness on pollutant PM2.5 penetration through the envelope and the mechanical system. The model considers the suite as a single zone because the focus of the case study is on wildfire pollutant penetration through the envelope, not on room by room air distribution. The modeling inputs and assumptions are presented below.

Suite floor area	90 m2
Suite floor to ceiling height	2.5 metres (stack effect height H)
Occupancy	3 occupants
Indoor temperature	22℃
Mechanical ventilation	HRV, balanced, BCBC 9.32 ventilation: 21 L/s (45 cfm)
Mechanical filtration	MERV8, MERV13, MERV16
Suite air tightness	0.6 ACH50, 1 ACH50, 3 ACH50, 5 ACH50, 8 ACH50
Monitoring period	September 1 to September 21, 2020
Pollutant of concern	PM2.5 concentration ($\mu g/m^3$), modelled mean diameter 0.3 µm (worse-case scenario) hourly data collected from nearby station
PM2.5 deposition rate	$0.1\ h^{-1}$ (Lai et al. 2020)
Pollutant penetration factor (P)	P = 0.2 @ 0.6 ACH50, P = 0.4 @ 1 ACH50, P = 0.6 @ 3 ACH50, P = 0.8 @ 5 ACH50, P = 1 @ 8 ACH50
Ambient temperature	Hourly data collected from nearby station
Natural forces for airflow	Stack effect only, wind is not considered
Internal airflows across spaces: suite-suites and suite-corridor	Assumes there are no airflows between the suite and the rest of the building (i.e. the building is well compartmentalized and the internal pressures are balanced)
limitations	The simulation is limited to one suite, which implies that the pollutants that penetrate through the envelope fill the suite volume rapidly, thus ignoring the delay caused by pollutants migrating across floors and across suites in an non-compartmentalized building.

Indoor concentrations of airborne contaminants can be estimated by basic principles, where concentrations are a function of penetration efficiency, air exchange rate (AER), decay and deposition rate, indoor source strength and unit volume" (Long et al., 2001). There are other potential parameters that have a lower impact to indoor air quality. Researchers (Branis et al., 2005; Hahn et al., 2009; Lopez-Aparicio et al., 2011) have proven that the impact of indoor coagulation, chemical reaction and resuspension on indoor PM2.5 mass concentration can be ignored since they do not have a noticeable impact on the indoor concentration. The key parameters values taken from literature are therefore air exchange rate, the penetration factor, and the deposition rate. There have been many studies that attempt to quantify these parameters, but there is high variance between the studies. Due to this large variance, attempts to determine lower and upper bounds as well as the average value have been made.

Deposition Rate

The deposition rate is the rate at which particulate matter settles and is deposited on surfaces. Any deposited particles have the potential to re-suspend themselves and eventually an equilibrium balance is met between deposition and resuspension. Deposition rate values vary significantly between studies. As can be seen by Figure 37 below, deposition rates vary based on the particle size.

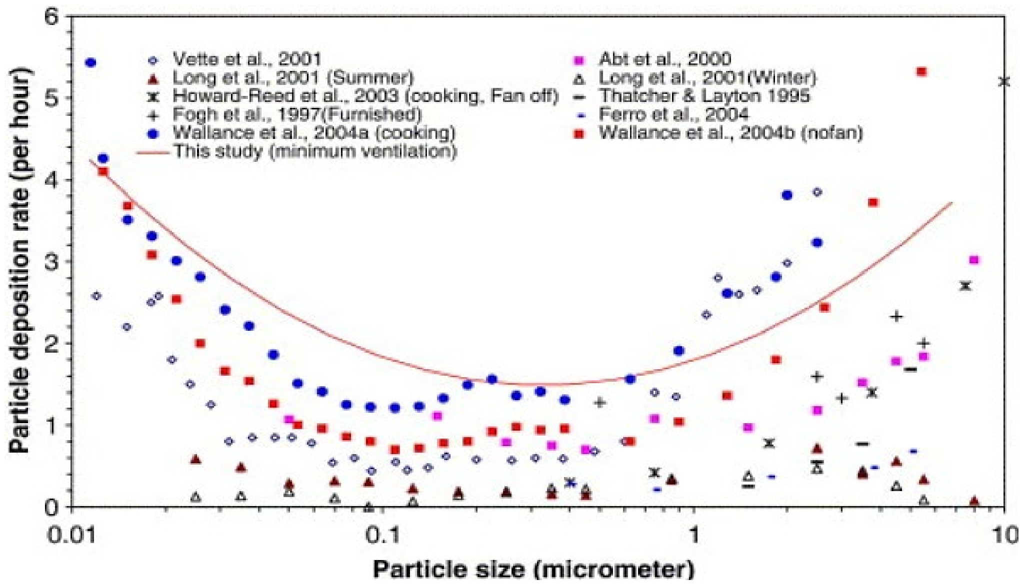


Figure 119. Deposition Rate relation to Particle Size. Source: Is Remaining indoors an effective way of reducing exposure to fine particulate matter during biomass burning events? (He et al. 2005)

Figure 119 and Figure 120 demonstrate the great variability in deposition rates between different studies. The median deposition rate value of the studies evaluated is at 0.6 (hr^{-1}). One study found that the AER was an important factor affecting deposition rates for particles in the size range from 0.08 to 1.0 µm, but not for particles smaller than 0.08 µm or larger than 1.0 µm (He et al., 2005). The difference in deposition rates are thought to be caused by differences in the surface-to-volume ratio, turbulent mixing patterns, and the types of house and internal surfaces (Abadie et al., 2001; Long et al., 2001; Thatcher et al., 2002). The lowest deposition rates found for PM2.5 particles by Long et al. were around 0.2 (hr^{-1}) (Long et al., 2001).

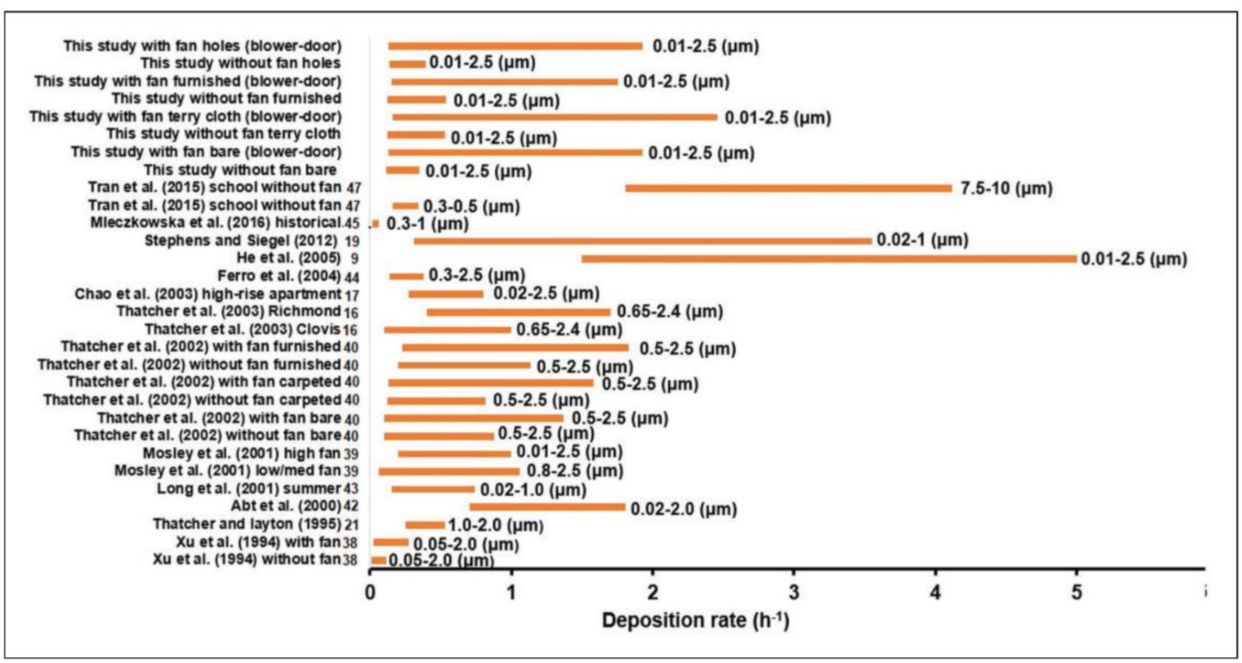


Figure 120. Deposition Rates study Comparison. Source: Blower-door estimates of PM2.5 deposition rate and penetration factors in an idealized room, (Yonghang Lai, 2020, Hong Kong SAR).

Penetration Factor

The penetration factor is a number between 0 and 1 that indicates what fraction of particles penetrate the building envelope where there is leakage. Larger particles tend to have lower penetration factors. This first study found that the penetration factors ranged from 0.7 to 0.86 depending on the building and particle size (Mleczkowska et al., 2016). The average penetration factor for PM2.5 particles was found to be between 0.79 and 0.94 in an idealized room study (Lai et al., 2020). Another paper puts the penetration factor at 0.79 ± 0.20 for particles of size 0.852-1.382 µm (Chao et al., 2003). While conducting experimental research in 1999, Tung et al found particulate penetration factors of 0.69 to 0.86 (Tung et al, 1999). The worst-case scenario would be a penetration factor of 1 indicating that all contaminants penetrated through the building envelope.

Hourly Temperatures

Figure 121 shows the hourly ambient temperature from the nearby ambient station during the monitored period. The yellow line indicates the constant indoor temperature used in the simulations.

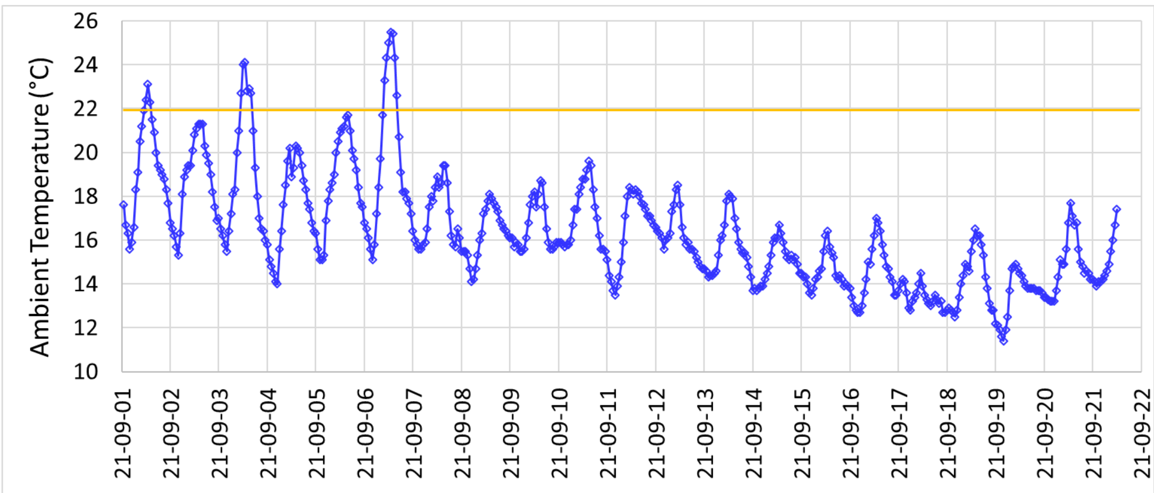


Figure 121. Ambient temperature measured hourly during the wildfire event, and the indoor temperature used in the modeling

Simulated Suite CO2 Concentrations

Figure 122 shows the simulated indoor CO_2 concentrations for 5 suite air-tightness levels. From Figure 122 it can be noticed that when the suite airtightness is 0.6 ACH50 (top curve), the indoor CO_2 concentration is almost constant at about 1100 PPM, i.e. less affected by the stack effect. This CO_2 concentration is maintained by the mechanical ventilation for three occupants, according to the BCBC section 9.32. As the suite airtightness decreases, the CO_2 concentration decreases and also becomes more variable, which reflects the stronger effects of the outdoor temperature variations and the background CO_2 concentration. In the top five curves, the stack effect takes place at the suite level only, because the building is assumed to be well compartmentalized and the internal pressures between suites and common areas are balanced. The lowest curve represents a suite in a 10-storey building that is not compartmentalized.

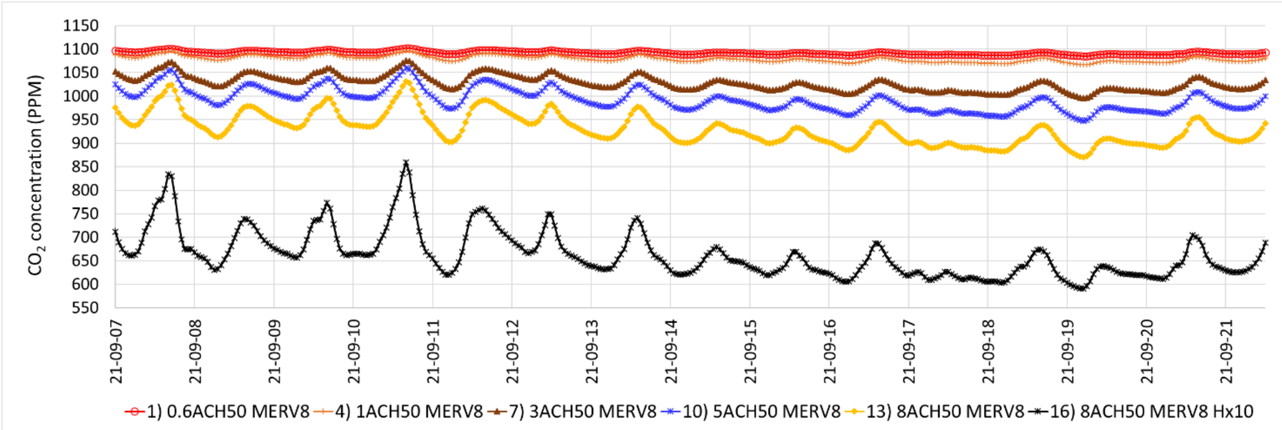


Figure 122. Simulated indoor CO2 concentrations during the wildfire event

Simulated Suite PM2.5 Concentrations

Figure 123 shows outdoor PM2.5 data from the nearby ambient station, and resulting indoor PM2.5 from 15 simulated combinations of filtration and air-tightness under the assumption of fully compartmentalized and balanced internal building pressures.

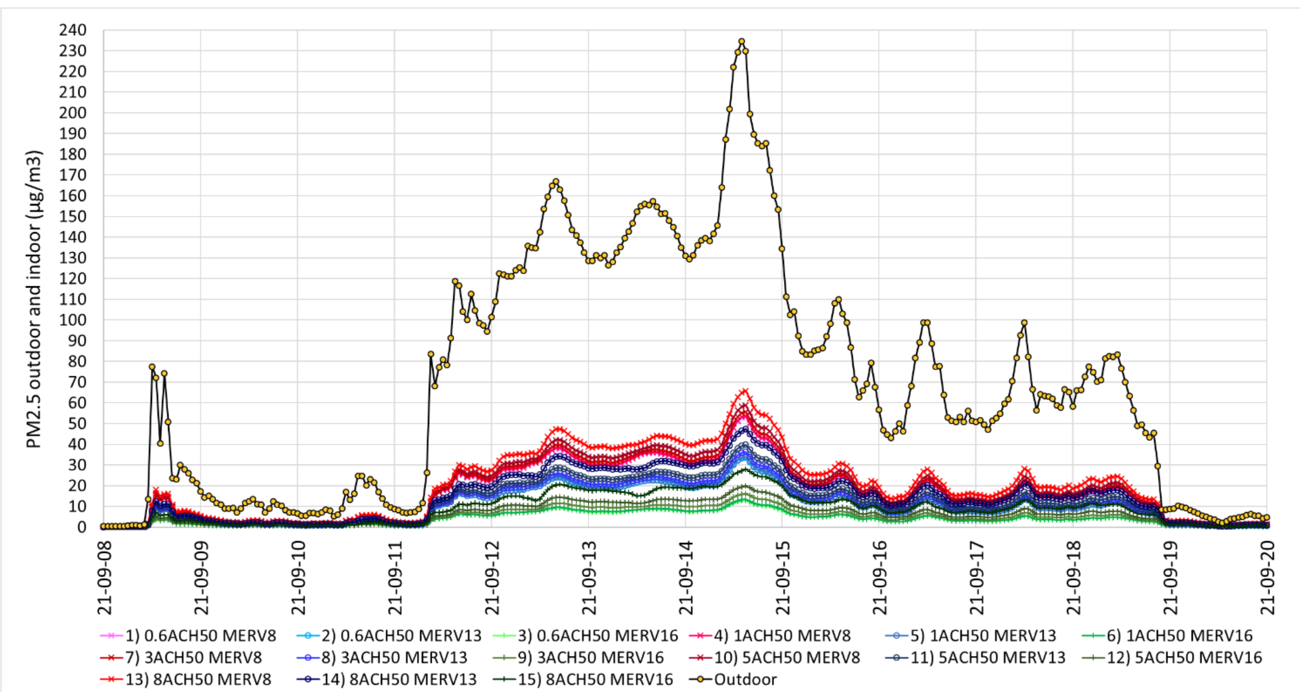


Figure 123. Ambient PM2.5 from nearby station and simulated indoor PM2.5 scenarios

Figures 124, 125, and 126 break down Figure 123 by the type of filtration, for the same five airtightness levels for a suite in a well compartmentalized building, i.e. with a minimal floor-level stack effect.

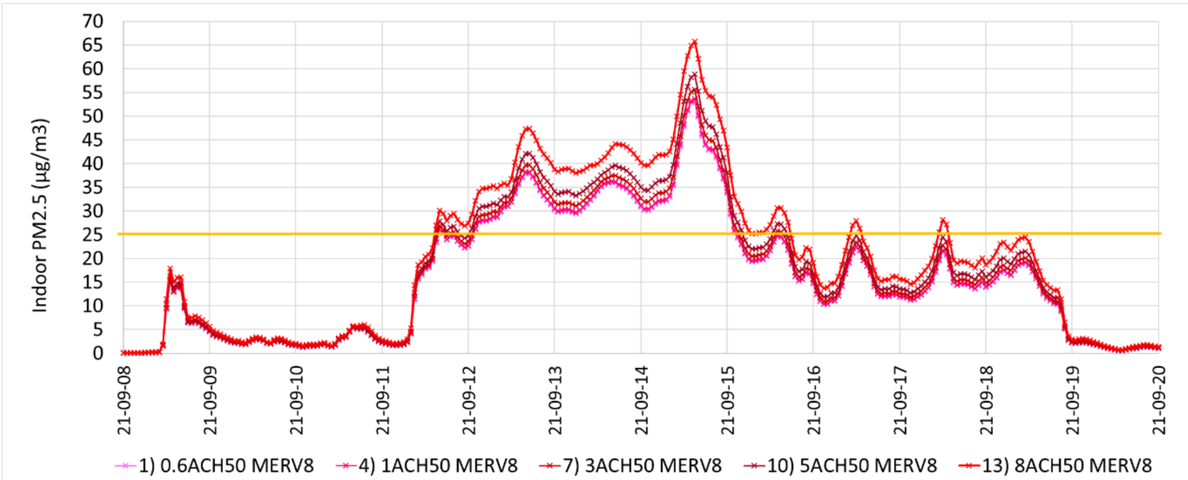


Figure 124. Simulated indoor PM2.5 with HRV **MERV 8** filter and five airtightness levels

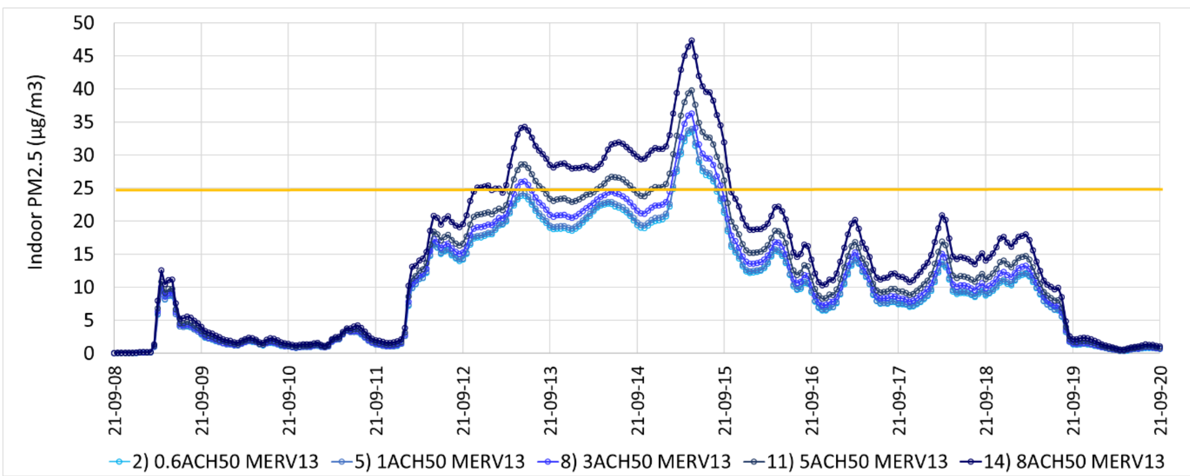


Figure 125. Simulated indoor PM2.5 with HRV **MERV 13** filter and five airtightness levels

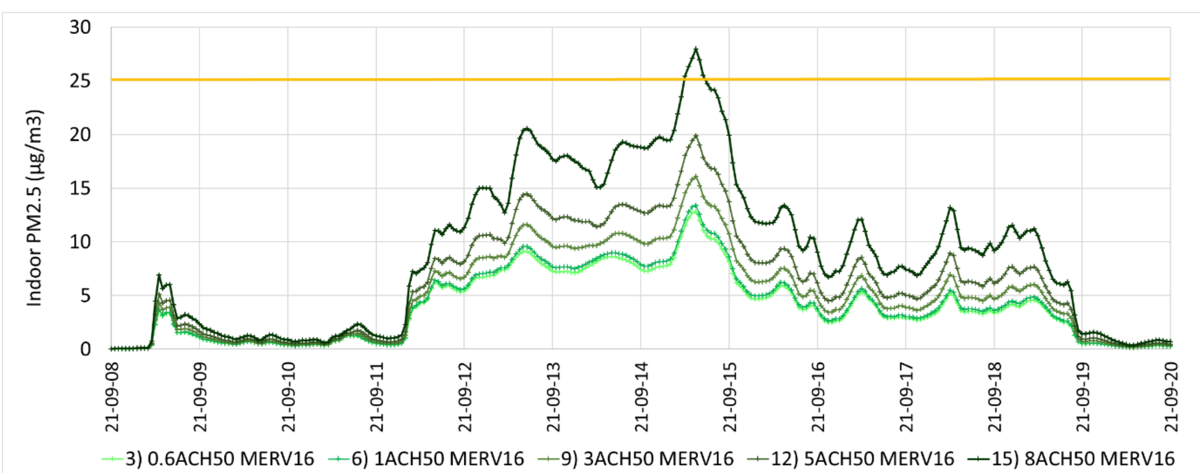


Figure 126. Simulated indoor PM2.5 with HRV **MERV 16** filter and five airtightness levels

Figures 124, 125, and 126 demonstrate the benefits of adequate air filtration in the ventilation system. These figures also demonstrate that air filtration is more effective in airtight buildings. Notice that for this wildfire event, only MERV 16 filters were able to reduce the indoor PM2.5 concentrations to a value below the 24-hour averaging time exposure limiting value of 25 μg/m^3. However, MERV 16 filters can only be implemented in MURB buildings with centralized ventilation.

Figure 127 shows peak indoor PM2.5 concentrations from 12 simulation scenarios. The first 5 scenarios are the ones shown in Figures 123 through 126. Again, they demonstrate that in a well compartmentalized building, ventilation-filtration has the biggest impact in reducing indoor PM2.5 concentrations during wildfire events. Scenarios 6 and 7 are also well-compartmentalized (i.e. stack effect at the floor level only), but pressurize the suite by shutting off the HRV exhaust fan, and leaving running only the supply fan at low flow (21 L/s). However, scenario 6 shows that in a very air-tight suite, such low flow suite pressurization leads to a very high envelope pressure differential of 22 Pa, compared to 0.5 Pa for a leaky suite scenario 7. It is important to realize that a suite pressurization scenario would have to be applied at the whole building level using a centralized ventilation system, otherwise it will unbalance the pressure differentials across suites and with the common areas, and create pressure differentials that will enhance pollutant migration across suites. Scenario 8 provides balanced ventilation and enhances the stack effect height to 10 floors. Comparing scenarios 6 and 7, it can be appreciated that the suite pressurization strategy works well for the leaky suite 8 ACH50 (scenario 7), but makes no difference for the air-tight suite at 0.6 ACH50 (scenario 6). The result makes sense because in the airtight suite most of the PM2.5 penetration is through the mechanical ventilation. Scenarios 6 and 8, demonstrate that an airtight building (0.6 ACH50) with balanced ventilation can effectively control the penetration of PM2.5 even if the building is not well-compartmentalized (i.e. 0.6 ACH50 airtightness practically eliminates the stack effect). Scenarios 9 and 10 show that in leaky and non-compartmentalized buildings, with balanced ventilation (9) or pressurized (10), ventilation-filtration is ineffective in reducing PM2.5 penetration indoors because the stack effect, enhanced by a tall stack, brings large amounts of PM2.5 through the leaky envelope. Scenarios 11 and 12 demonstrate that portable air cleaners/purifiers (PAC) can reduce PM2.5 concentrations to acceptable levels, even in an non-compartmentalized building. Scenario 12 again demonstrates that building pressurization is unnecessary as long as the building is airtight.

In conclusion, the analysis demonstrates the effects of applying the cascading control measures 1, 2, 3, 4, and 5 in Figure 47. Note that in all the simulated scenarios, a minimum BCBC-9.32 code-prescribed ventilation rate of 21 L/s is maintained. Therefore, considering internal air contaminant sources, indoor air quality is not compromised. In theory, according to the simulations, whether the building is airtight but not compartmentalized, or vice versa, are equally effective measures in reducing the stack effect, and therefore the penetration of PM2.5 through the building envelope. While envelope airtightness minimizes the envelope openings (the air entering and leaving flow paths), compartmentalization minimizes the channeling of air along interior building paths (i.e. the Paths in Figure 3). Therefore, using a multistory shaft analogy, if the shaft enclosure is sealed, then no air will come in or out of it; and if the shaft enclosure is not sealed but its floors are sealed at each level instead, then the stack effect is also minimal, i.e. only floor level. However, in practice, both measures should be addressed to provide more reliable airflow control in MURBs, including added redundancy in case one measure is breached (e.g. some occupants decide to open windows). Building pressurization help reduce PM2.5 penetration indoors, but its effectiveness decreases, and becomes unnecessary, as the building is more airtight and compartmentalized (scenarios 6, 7, and 10 versus 1). Furthermore, building pressurization can only be implemented reliably at a centralized whole-building level.

From Figure 127, it can be concluded that the most effective strategy to minimize PM2.5 concentration from smoke during wildfire events is represented by scenario 12 (which is airtight but non-compartmentalized). However, for better reliability and redundancy, both airtightness and compartmentalization are necessary. Therefore, the best strategy to minimize PM2.5 from wildfire smoke in buildings combines the following measures:

1. Good envelope airtightness 1.0 ACH50 (0.6 ACH50 would be even better)
2. Good building compartmentalization
3. Balanced ventilation
4. MERV 13 filtration (in-suite), MERV 16 filtration (centralized)
5. Supplement ventilation with portable air cleaners (PAC)

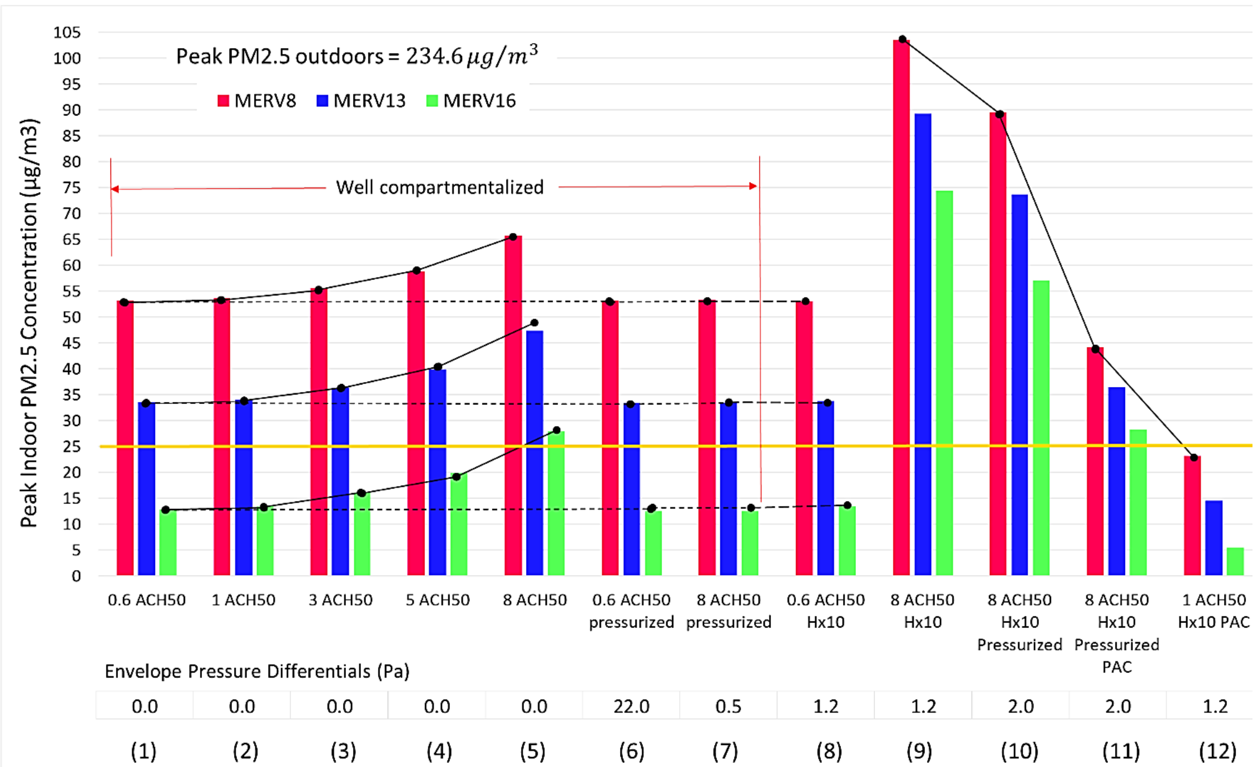


Figure 127. Peak indoor PM2.5 concentrations from various simulation scenarios

For existing buildings that are not airtight and not compartmentalized, do not have adequate ventilation, and cannot afford an envelope retrofit, then shelter in place may not be the most suitable option when air pollution becomes extreme (Table 28). Old buildings with corridor-pressurization ventilation and in need for retrofits may require enhancing the level of centralized filtration, as well as increasing the air-handler fan speed, and therefore the level of pressurization, provided that the system has the capacity to do implement those measures. Las but not least, wildfires also emit toxic gases (Table 27), which are not removed through mechanical (MERV) filtration. Therefore, gas-phase filtration is recommended, which can only be applied to centralized ventilation systems. Finally, the peak concentration delay in the simulations ranged between 35 minutes for a 0.6 ACH50 suite and 65 minutes for a 8 ACH50 suite. However, these peak delays need to be computed using a whole-building simulation to account for the delays caused by pollutant laden air driven by stack effect across floors and across suites.

10.8 SR-4 Ventilation and moisture control

This case study uses the same studio suite of case study SR-2-1. The CO2 levels at the living room are in the same range as the measured ones in Figure 88 and Figure 89. The simulation assumes two occupants in the suite. The same room by room model of case study SR-2-1 is used. In this case an ERV (with moisture recovery) is the ventilation unit modeled. Schedules are created for the suite occupancy (weekdays and weekend), shower (5 minutes per person), laundry (3 hours once a week), and cooking (breakfast and dinner only for half an hour each). The modeling uses 3-mointh weather Vancouver data from January 1 to March 30. The scenarios assume that occupants do not open the windows in the winter, and that room temperature is maintained at 22°C. Lowering the room air temperature will produce higher room relative humidity results.

Table 44. Case study SR-4 Ventilation and moisture control simulation scenarios

Scenario	Moisture generation		Ventilation	Buffer			
	Shower Laundry	Cooking Dishwash		Level	Mass transfer coefficient	Partition coefficient	Surface mass
1 baseline	2 occupants: 25 g/m, 20-m/day 100 g/h 3-h/week	No cooking	Design 30 cfm	Low	0.72 m/h	6	Low mass
2	2 occupants: 25 g/m, 20-m/day 100 g/h 3-h/week	Low 9 g/m x 60 m/C+D	Design 30 cfm	Low	0.72 m/h	6	Low mass
3	2 occupants: 25 g/m, 20-m/day 100 g/h 3-h/week	Moderate 12 g/m x 60 m/C+D	Design 30 cfm	Low	0.72 m/h	6	Low mass
4	2 occupants: 25 g/m, 20-m/day 100 g/h 3-h/week	Moderate 12 g/m x 60 m/C+D	High speed 60 cfm While cooking	Low	0.72 m/h	6	Low mass
5	2 occupants: 25 g/m, 20-m/day 100 g/h 3-h/week	Moderate 12 g/m x 60m/C+D	High speed 60 cfm While cooking	Medium	5 m/h	6	Medium mass

All scenarios assume two occupants producing moisture according to Table 44. The shower and laundry moisture loads are the same for all five scenarios. The changes between scenarios are due to cooking, ventilation, and the moisture buffering of materials. The baseline scenario 1 assumes a continuous design ventilation rate, and no cooking taking place. In Scenario 2 the cooking moisture load is the lowest from Table 44, assuming that cooking activities (steaming and boiling) are consistent with the size of the suite and its occupancy. Scenarios 3 to 5 assume a higher cooking moisture load, two times the amount of the lowest one, which is still below the typical values proposed by reference (1) in Table 44. Scenarios 4 and 5 double the ventilation airflow during cooking. Finally, to assess the effect of moisture buffering on indoor relative humidity, Scenario 5 increases the moisture buffering effect of interior materials.

In general, the scenarios show that the relative humidity remains moderate to low for most of the time, except during cooking, as seen in Figures 18 to 133. In all scenarios, 75% of the time, the relative humidity is maintained below 70% as shown in Figure 133. Scenario 3 results in the highest relative humidity levels. However, in Scenario 3, only 2.2% of the time the relative humidity is above 80%. In general, cooking, increases the suite relative humidity for a period of less than 1 hour, which span cooking time and about half an hour for the humidity to gradually recede. In the morning, cooking and showering produce the highest moisture loads of the day.

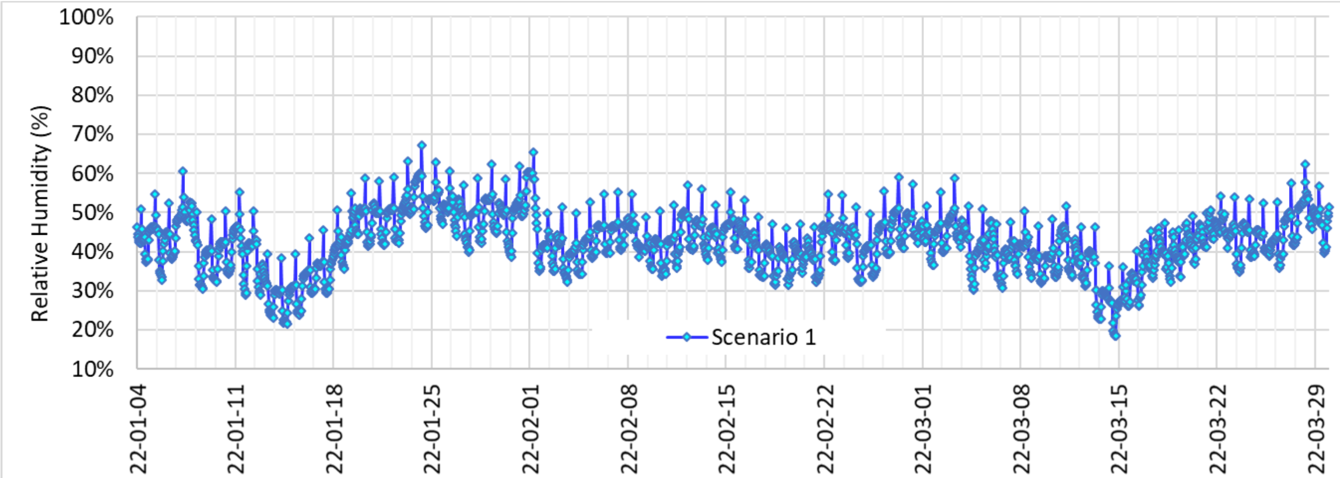


Figure 128. Indoor relative humidity, Scenario 1 (no cooking)

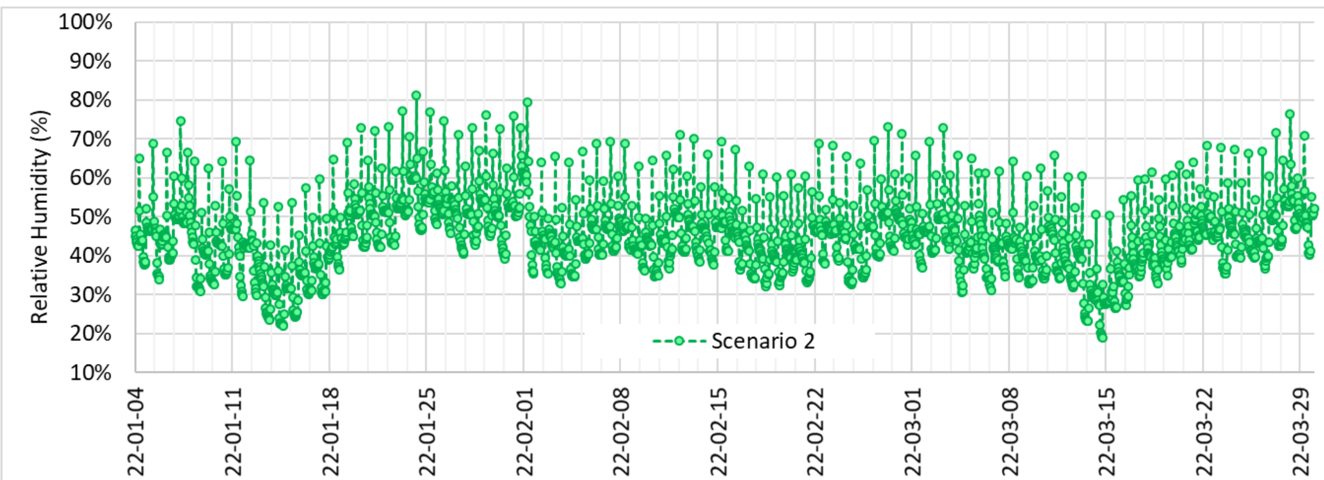


Figure 129. Indoor relative humidity, Scenario 2

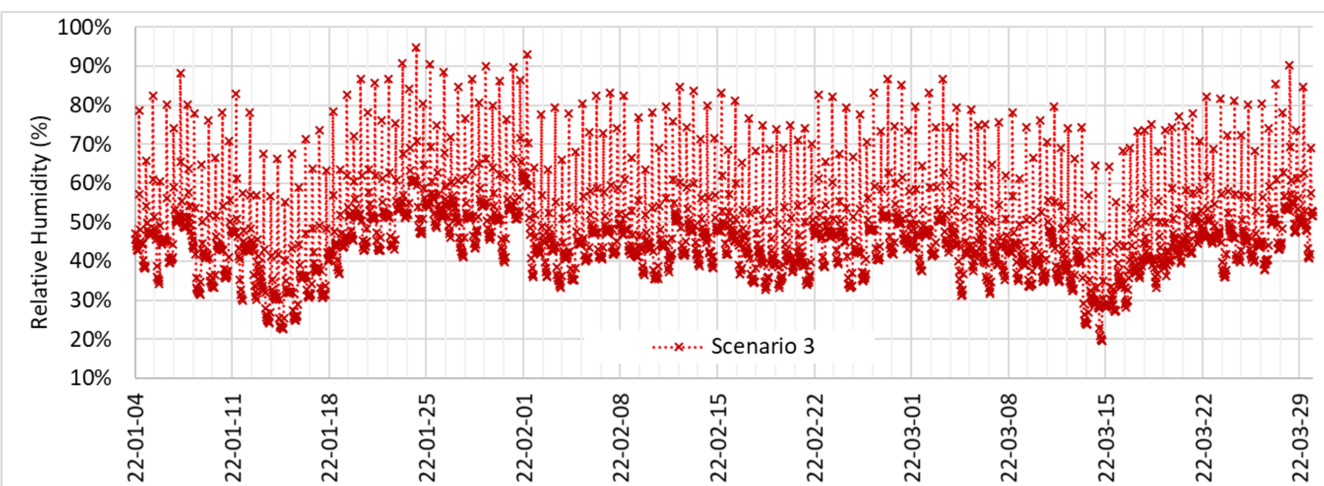


Figure 130. Indoor relative humidity, Scenario 3

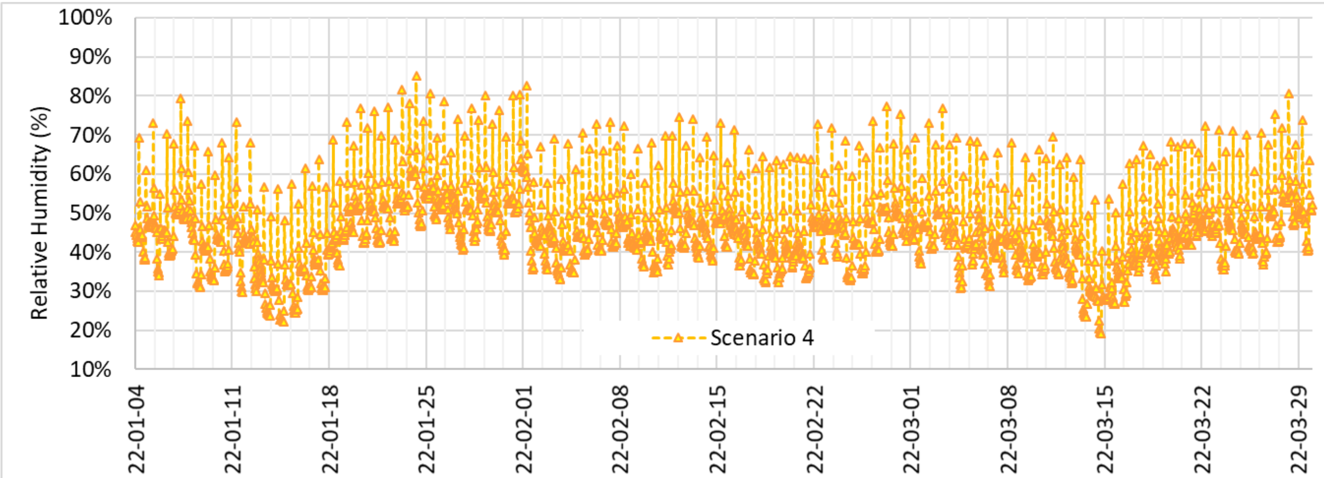


Figure 131. Indoor relative humidity, Scenario 4

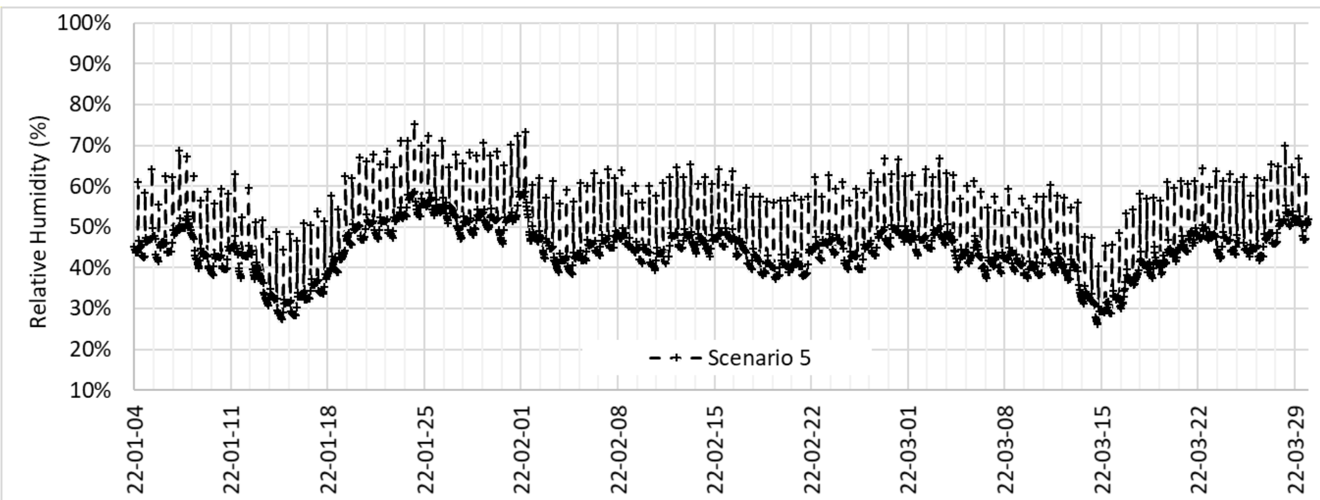


Figure 132. Indoor relative humidity, Scenario 5

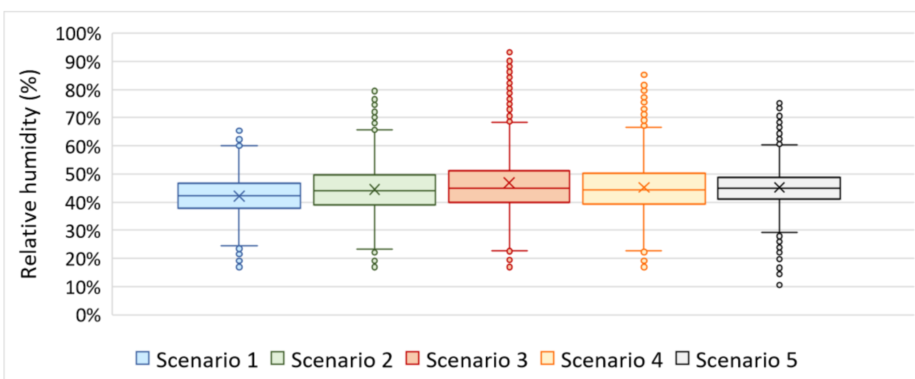


Figure 133. Peak Indoor relative humidity median and variability, all scenarios

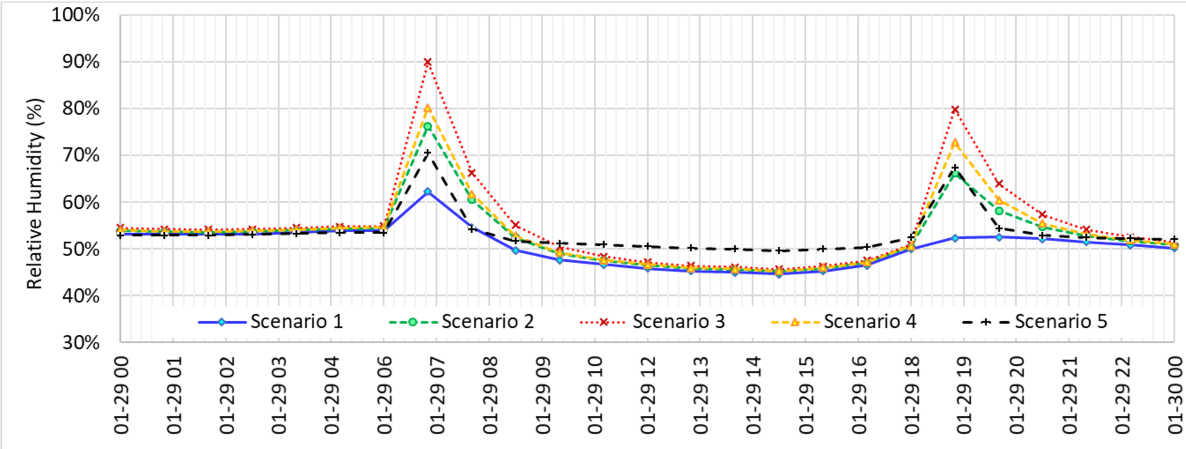


Figure 134. Typical day 1, relative humidity, all scenarios

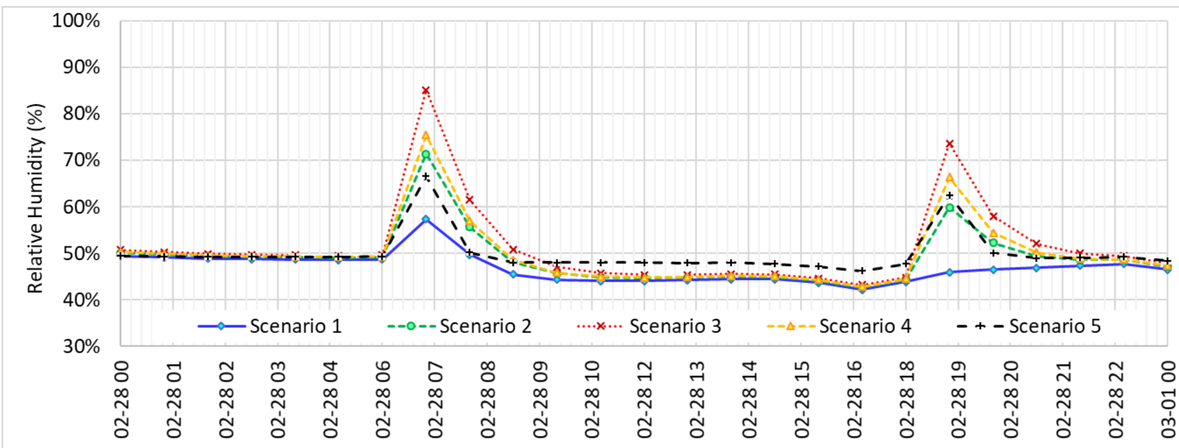


Figure 135. Typical day 2, relative humidity, all scenarios

Controlled mechanical ventilation with moisture recovery (ERV) maintains moderate humidity levels in the suite, indicating that the baseline design ventilation is adequate for the suite moisture load produced by two occupants. Increasing the baseline ventilation is not necessary for humidity control, and would dry the air excessively. In general, in all scenarios, the risk of condensation is low. A simple psychrometric analysis, shows that at 80% indoor relative humidity condensation takes place at about 18.5°C (i.e. the dew-point temperature of the indoor air), and at 70% about condensation takes place at 16°C. High-performance windows can maintain their indoor surface temperatures above 18°C in cold climates. However, even if indoor humidity levels are not excessive, defective air and vapor control layers in the walls, coupled with thermal bridges, could produce serious moisture damage problems inside the walls.

As illustrated in Scenario 4 and Scenario 5, and observed in Figures 134 and 135, humidity-sensitive demand-controlled ventilation (DCV) can further minimize the risk for condensation. For example, DCV can enable enhanced ventilation when the relative humidity reaches 70%. However, implementing DCV at the suite level requires decentralized, in-suite, ERV units. Materials' moisture buffering in Scenario 5 can further help maintain moderate indoor humidity levels by reducing the peaks and releasing back moisture into the air when indoor levels are low. Increased moisture buffering can be achieved using typical porous finishing materials such a drywall in ceilings and walls, or wood finishing products, as well as carpet, and furniture.

10.9 SR-5 CFD STUDY OF VENTILATION AND IAQ IN MURB SUITES

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In this section, CFD simulation models are developed to study the effectiveness of suite ventilation strategies to maintain the acceptable indoor air quality in the rooms where occupants spend more time and remove selected cooking pollutants. Inherent boundary condition uncertainties are same as the MZ-AFN model. The analysis uses CO_2 as the surrogate contaminant to predict the whole suite ventilation effectiveness and PM2.5 as the selected contaminant for studying cooking ventilation system performance. The MZ-AFN and CFD models set to the same boundary conditions to understand the accuracy of the results. The ventilation boundary conditions are the same as the actual design conditions. CFD modeling parameters are obtained from the calibrated laboratory model and from the literature review. Electric baseboard heaters are added to the CFD models to simulate the strong thermal fluid airflows driven by the heaters. However, the modelling of cooking pollutants and ventilation involves a higher level of complexity and uncertainty, and cannot be validated, without having a realistic set-up with controlled boundary conditions, a stove, food, a hood, and sensors. To overcome this limitation, the literature was used to inform the modelling inputs and assumptions of pollutants emissions and transport, as well as the local temperature-driven airflows between the stove and the hood. In section 10.9.1, CO_2 simulations are developed for two purposes: 1) to test the suite ventilation effectiveness and 2) to obtain adequate boundary conditions for the cooking pollutant simulations.

10.9.1 CO_2 ANALYSIS OF SUITES A, B, AND C UNDER ENHANCED VENTILATION RATES

The CFD models were created of the suites A, B, and C, simulated using MZ-AFN boundary conditions and assumptions in the previous chapter. A base model was created, and adequate thermal indoor environmental conditions were created for occupants with adjusting the baseboard heaters. The suite ventilation parameters are described in table 45 below. The human sleeping condition is tested in the CFD and analysed the CO_2 emission and behaviour in the indoor environment. In all the CO_2 analyses, the bedroom and bathroom doors are kept closed but air is allowed to move by resulting pressure differentials through the doors' undercut.

Table 45. High HRV ventilation rates in boost mode used for the 3 suites.

Room	Suite A	Suite B	Suite C
	CFM	CFM	CFM
Master bed	+60	+36	+30
Bedroom 2		+36	+20
Living room		-36	+20
Dining			+16
Kitchen			
Bathroom 1	-60	-36	-43
Bathroom 2			-43
Total(cfm)	**60**	**72**	**86**

Assumptions

1. Bedroom and bathroom doors are kept closed during sleeping time.
2. Ventilation rates in the suites are in boost mode (high rate)
3. HRV supply air temperature = 20°C.
4. The k-ε model was used to simulate the steady-state airflow distribution in the suite.
5. In this 3D space, the air was incompressible, air density is constant, the Boussinesq approximation is applicable, and the airflow was steadily turbulent with a high Reynolds number. A no-slip (smooth) wall boundary condition is assumed.
6. The supply diffusers supply the air radially with 25% flow in a downward direction and 75% flow in a lateral direction to enable achieving the coanda effect.
7. Adiabatic thermal boundaries are assigned to the interior walls, exterior wall, ceiling, and floor. Humans are present as heat sources. The window temperature is considered 18 degrees Celsius, as it represents colder outside condition.
8. Steady State residential environment is considered.
9. To simplify the analysis, leakage from the space is considered negligible. But the door undercut has been set with a zero-pressure balance condition.
10. Each internal door has a crack at floor level to simulate real-life conditions.
11. The diffusion coefficient for CO_2 determines how the species gets diffused in a medium. The medium in this simulation is air, and the diffusive element is CO_2. The diffusion coefficient assumed is 0.16 cm2/s.
12. The background concentration in the room has been assigned to the Domain Cuboid based on the values measured when no human sources were present in the room.
13. Sleeping human is the CO2 source CO2 generation is the concentration per second, the amount of pollutants generated and added to the air per second from the human mouth.
14. The human respiration rate at rest is about 8 L/min and which produces 0.3L/m of CO2.
15. The baseboard heaters conditioned the indoor air and created a buoyancy current in the room. The baseboard heaters are adjusted to maintain realistic indoor thermal boundary condition and to create the buoyancy air current in the suite.
16. The heat sources in the suites are the human body and baseboards heaters. They arranged to maintain the indoor temperature in the range of 20-22 degrees Celsius. Heaters are placed under the cold window as similar to the real apartment suite.

Meshing Details

Table 46. Details of Meshing

Meshing Type	Detailed
Method of Gridding	Rough grids and detailed mesh
Standard length	50 mm
Geometric Ratio	1.0
Threshold Size	X – 0.1 mm, Y – 0.1 mm, Z – 0.0001 mm.
CFD simulated cycles	500 or until reach steady state

CO2 analysis result from CFD

Suite A (high ventilation rate)

In suite A air is supplied above the bed and exhausted in the bathroom. The air movement in the suite is created by the mechanical supply inlet and exhaust outlet, as well as by the buoyancy produced by the baseboards heater under the window, and to a smaller extent by the occupant (Figure 137, top). The contaminant concentration in the plane 1 m above the floor (about 10 cm to 20 cm above the sleeping occupant's face) is considered a critical plane for the analysis and CO2 concentration (Figure 137). The analysis shows that CO2 concentrations are maintained at acceptable levels near the occupant (Figure 137, bottom-left). The HRV-High supply air of 60 CFM (high-speed) is adequate to keep the CO2 concentration under an acceptable level. Overall indoor air quality is acceptable. The age of air at the sleeping occupant level (Figure 137, bottom-right) demonstrates adequate air distribution: the "young" supply air effectively reaches the opposite side of the suite, at the window, and migrates towards the bathroom where the "old" air is exhausted. However, the air at the occupant's head turns "older" as it migrates towards the bathroom. Overall the both the age of air and the CO2 results show that the ventilation is able to provide satisfactory air distribution and CO2 dilution capability.

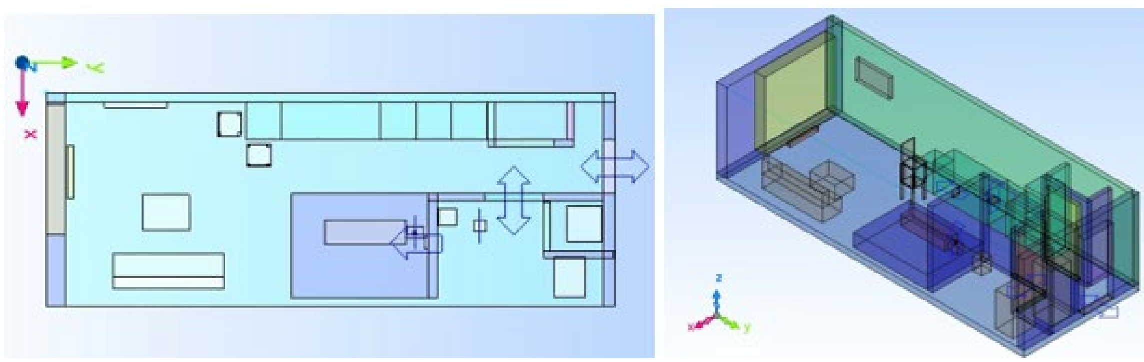

Figure 136. Suite A: Z plane section at 1m above the floor Showing the CFD model (left) and the 3D model (Right)

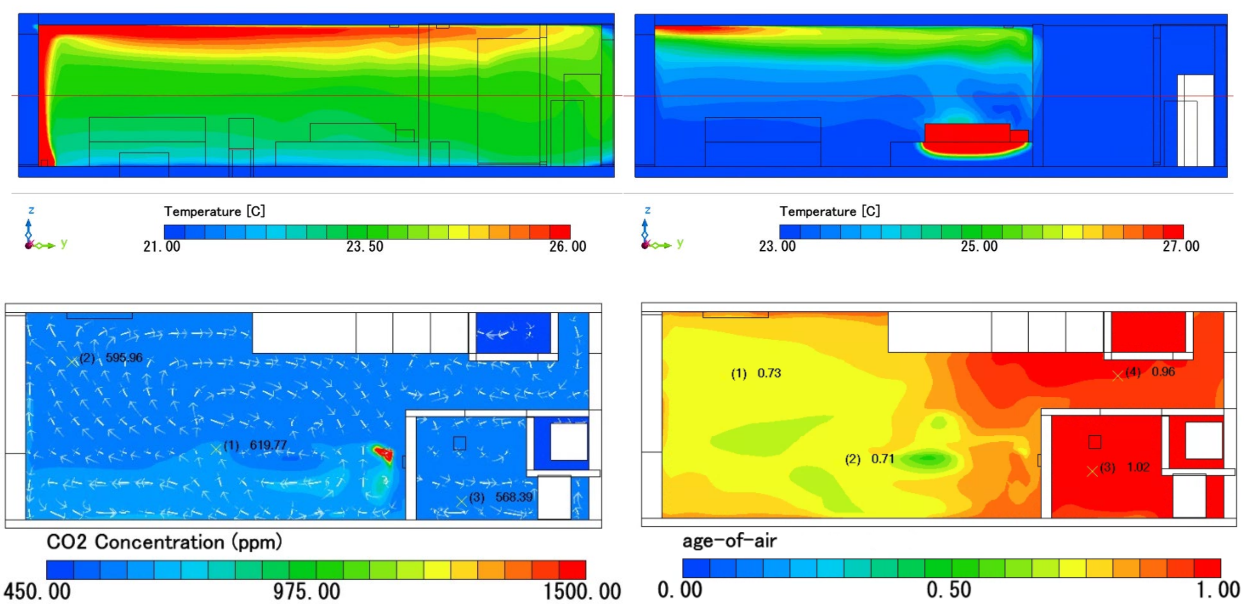

Figure 137. Top: thermal stratification at baseboard heater and at the sleeping occupant sections. Bottom: CO2 concentration and age of air at the Z = 1 m above the floor (arrows indicate the airflow pattern).

Suite B (high ventilation rate)

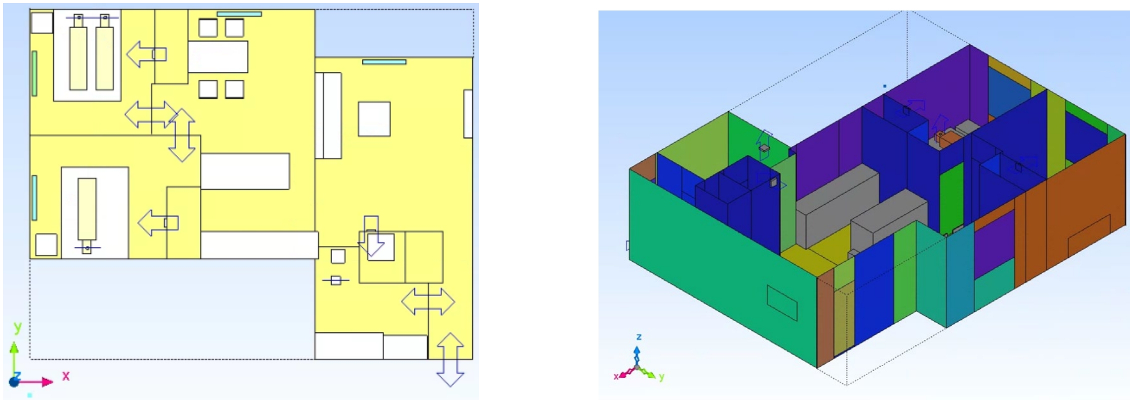

Figure 138. CFD model in the Z plane section (left) and the 3D model of the suite-B(right)

As shown in Figure 138, the HRV supplies air to the bedrooms, and exhausts air from the living room and the bathroom. AS shown in Figure 139-left the master bedroom reaches a contaminant concentration higher than 1250 ppm 20 cm above the sleeping occupants, which is not satisfactory. CO2 levels are acceptable in all the other rooms. The age of air metric (Figure 139-right) shows adequate air distribution from the bedrooms towards the living room and bathroom exhausts. Furthermore, the age of air shows that the master badroom has better ventilation ("younger" air) than the adjacent bedroom. However, the high CO2 concentration in the master bedroom is due to increased CO2 production by the two sleeping occupants, which indicates that even boosted ventilation is insufficient to effectively dilute the CO2 produced by the two room occupants. Therefore, the enhanced ventilation proposed in table 45, based on MZ-AFN, would be prefered to achieve more uniform and acceptable air quality across the suite.

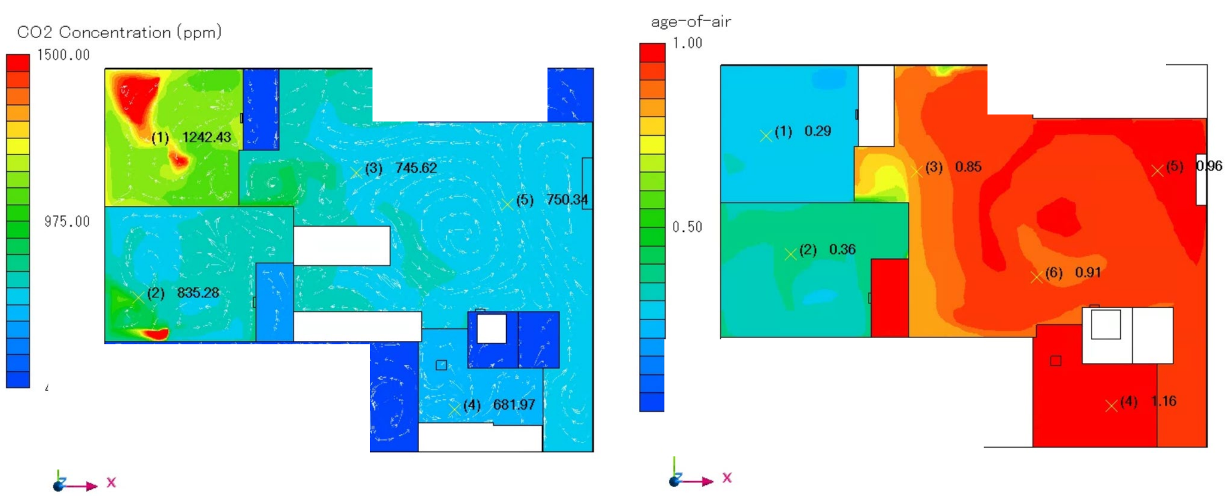

Figure 139. CO2 concentration in ppm (Left), and age of air (Right) at Z plane at 1m above the floor

Suite C (high ventilation rate)

As indicated in Figure 140, the HRV air is supplied in the bedrooms and living room area and the HRV air is exhausted from the two washrooms. In 141, Suite C shows similar CO2 and age of air results as those in Suite B. In general, the ventilation is adequate, except for the master bedroom, where the ventilation rate is not sufficient to effectively dilute the CO2 from the two sleeping occupants.

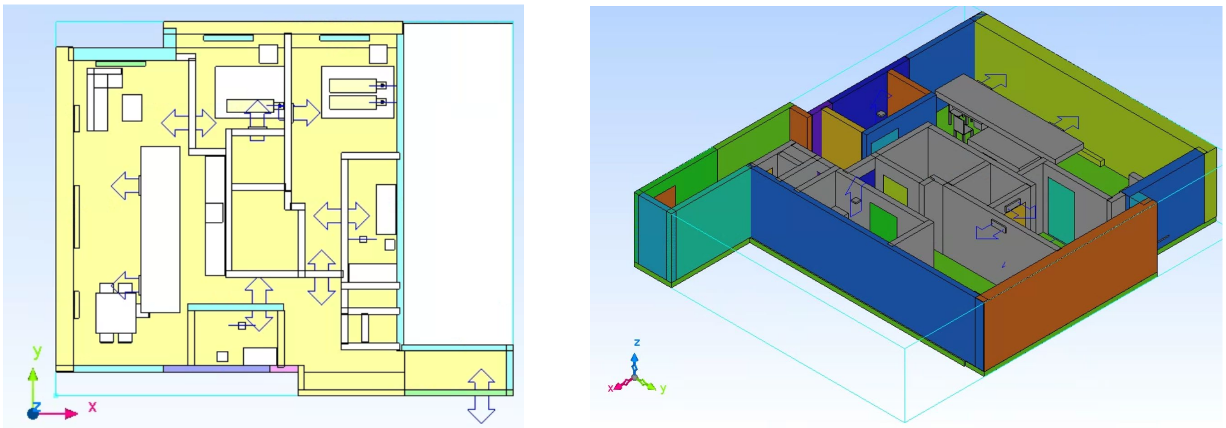

Figure 140. CFD model in the Z plane section (left) and the 3D model of the suite-C (Right)

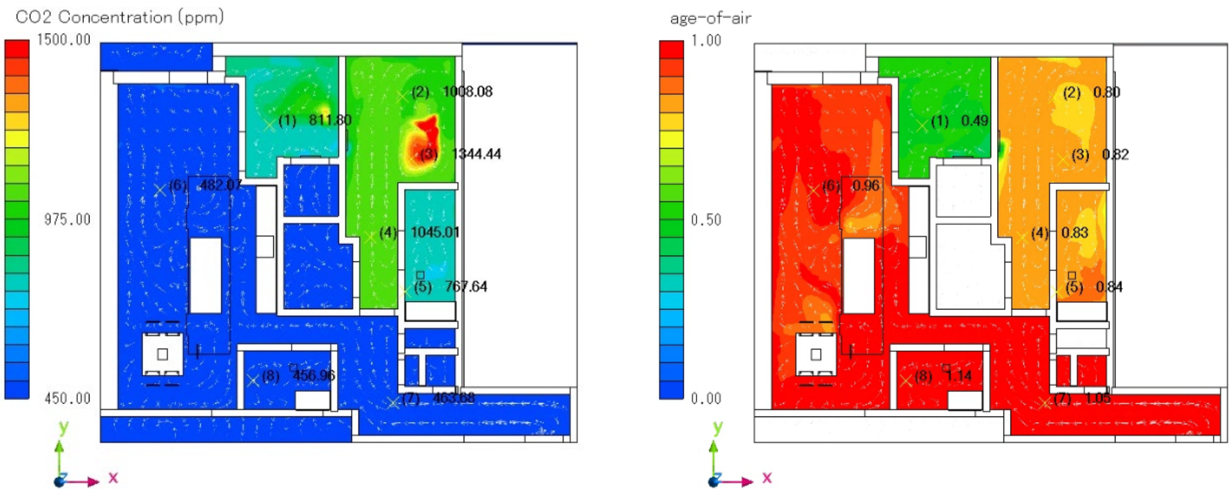

Figure 141. CO2 concentration in ppm (Left), age of air (Right) at Z plane at 1m above the floor

Figure 141-left shows that the CO2 concentration in the ensuite is not high, and Figure 141-right shows that the air in the bathroom is not old. Both of these results are counterintuitive because the bathroom exhausts "old" air that is drawn from the master bedroom. However, because the ensuite exhaust fan runs at 43 cfm, and the master bedroom supply fan runs at 30 cfm, the exhaust fan depressurizes the entire master bedroom area, and causes makeup air to enter from the corridor, which is older air but with very low CO2 concentration.

The age of air analyses of the three suites demonstrates adequate cascading ventilation from the cleaner areas where people spend more time to the areas where people spend less time. The CO_2 analysis in suites B and C shows that despite having enhanced ventilation, master bedrooms result in higher CO_2 concentrations because of an increased pollutant load, i.e. two people assumed to be sleeping in the master bedroom. Contrary to suites B and C, suite A does not show the same increase in CO_2 concentration (only up to 700 ppm above the bed) because, being a studio suite with one single space, it assumes only one occupant. However, with two occupants, the concentration may reach 1000 ppm. This scenario needs to be tested. Furthermore, the CFD results confirm the MZ-AFN findings (Table 45) that indicate the need for providing enhanced ventilation for suites B and C, particularly at the master bedrooms.

10.9.2 Cooking pollutant analysis of suites B and C

CFD models of suites B and C are created to analyze the behavior of cooking pollutants in the suites under selected types of cooking range hood exhaust systems. The analysis does not include a recirculation-filtration system because there is insufficient data on the filtration efficiency of these systems. Therefore, the baseline simulation strategy (Strategy 1) represents the case where the range hood ventilation, exhaust or recirculation-filtration, is not used, even if it is present. As such, Strategy 1 is the worst-case scenario which is very real as indicated by a passive house designer and member of the Board of Directors of Passive House Canada: "*... exhaust range hoods are noisy and therefore are rarely used by occupants, so what is the point of having them if they are not used".*

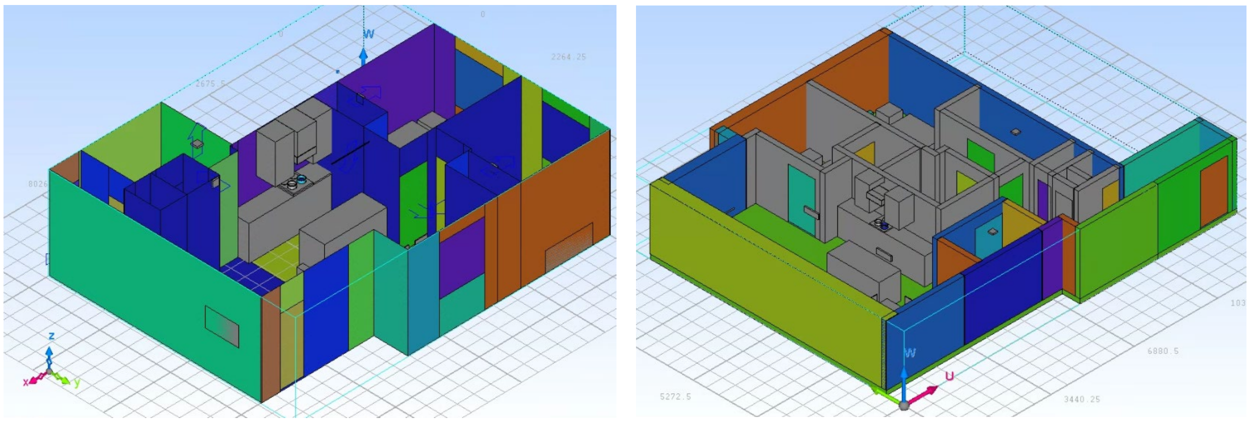

Figure 142. CFD Model Geometry for Suite B (Left) and Suite C (Right)

The details of the CFD solver are listed in below table:

Table 47. CFD – PM2.5 simulation details

Space	3D
Flow Analysis	Solve
Flow Type	Turbulent Flow
Turbulence Model	Standard k-eps model
Heat	Solve
Radiation	Ignore
Solar Radiation	Ignore
Analysis Type	Ventilation Efficiency and Diffusion
Algorithm	Steady State – detailed setting
Gravity	Considered
Fluid	Incompressible air
No. of Iterations	500 cycles

Assumptions

1. Bedroom and bathroom doors are kept open during cooking time.
2. Ventilation rates in the suites are in boost mode (high rate).
3. HRV supply air temperature = 20°C.
4. The k-ε model was used to simulate the steady-state airflow distribution of an HRV system.
5. In this 3D space, the air was incompressible, air density is constant, the Boussinesq approximation was applicable, and the airflow is steadily turbulent with a high Reynolds number. No-slip (smooth) wall boundary condition is assumed.
6. The supply diffusers supply radial flow with 25% flow in the downward direction and 75% flow in the sideways direction, in order to achieve the coanda effect.
7. Adiabatic thermal boundaries are assigned to the interior walls, exterior wall, ceiling and floor. Humans are present as heat sources.
8. Steady State environment is considered.
9. To simplify the analysis, leakage from the space is considered negligible. But the doors have been set with a pressure balance condition with zero pressure difference between indoor and outdoor.
10. Each internal door has a crack at floor level to simulate real-life conditions.
11. Flow near the cooktop is turbulent in nature, and the turbulent diffusion is automatically considered in the software even though the diffusion coefficient is not specified for the cooking pollutant diffusion. The turbulent diffusion has more influence than the mass diffusivity in the turbulent flow field.
12. Pollutants (particles) from the cooking, simulated as the diffusion specified in CFD, and simulating millions of particles from cooking is not realistic and take a significant amount of time to run the simulation.
13. The particles property is considered in the simulation, and the particles sedimentation velocity has been applied to have the effect of sedimentation for the mass particles.
14. The background concentration in the room has been neglected as the indoor particle concentration compared to cooking pollutants is negligible.
15. The emission rate of PM2.5 is 0.4mg/min (O'Leary et al. 2019) is taken in this analysis. The emission rate has a strong influence on cooking parameters. In modelling, this amount of PM 2.5 is emitted from the pan as a smoke or diffusive component.
16. The heat sources are the cooktop and radiant heaters. The heaters are adjusted to maintain the comfortable suite temperature of the occupant before the cooking experiment is conducted to ensure actual apartment conditions
17. Selected contaminant, PM2.5 is simulated as the diffusive component in the CFD simulation and assumed that the mass of the particle is very minute, and dispersion is similar to gas particles. The sedimentation velocity is applied to the particle incorporate the influence of the mass of the particle in the dispersion (gravitational effect). The sedimentation velocity is assumed to be $-1e^{-05}$ m/s in the direction.

Following are the simulated Scenarios for Suites B and C, using the cooking source control ventilation systems described in Section 4.3.9 of this document. The simulation assumes PM2.5 as the source cooking pollutant. Strategy 1 is the baseline strategy, which assumes that System 4 is operated with the recirculation range hood switched off. This is consistent with the discussion with a passive house designer that indicated that range hood systems (wither exhaust or recirculation) are seldom used because they arer noisy. Therefore, strategy 1 tests a typical operating scenario for these systems.

Simulated ventilation Conditions for Suite C (Section 2.6 Cooking stove hood ventilation)

i. Strategy 1 – HRV Boost mode (Baseline: system 4 with range hood switched off).

i. Strategy 2 – HRV exhaust off, replaced with cooking range hood (proposed system 6).

ii. Strategy 3 - HRV + makeup kitchen ceiling supply and range hood exhaust (system 3, makeup air).

iii. Strategy 4 - HRV + makeup kitchen floor supply and range hood exhaust (system 3, makeup air).

10.9.3 SUITE B COOKING POLLUTANT BEHAVIOR ANALYSIS

Figure 143 shows the suite plan, Figure 144 shows a section through the cook stove and figures from 145 and 146 plan view sections that were selected to present the pollutant removal and dispersion simulation results. Subsequent figures show the simulation results at these sections for the different strategies, followed by an interpretation and discussion of these results.

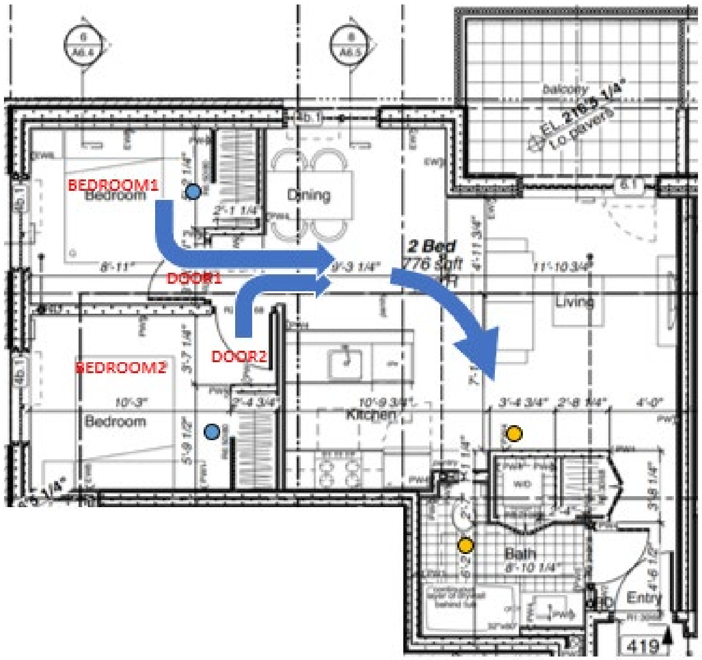

Figure 143. Floor plan of suite B.Yellow and blue circles represent the HRV exhaust and supply, respectively.

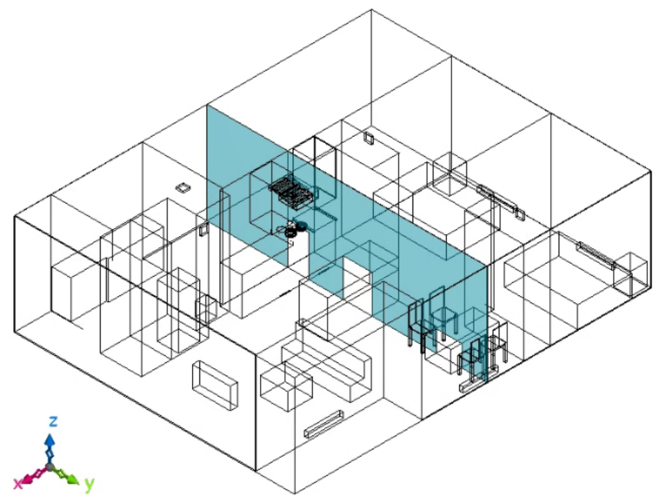

Figure 144. section 1: The plane section across the cooktop in the X-axis.

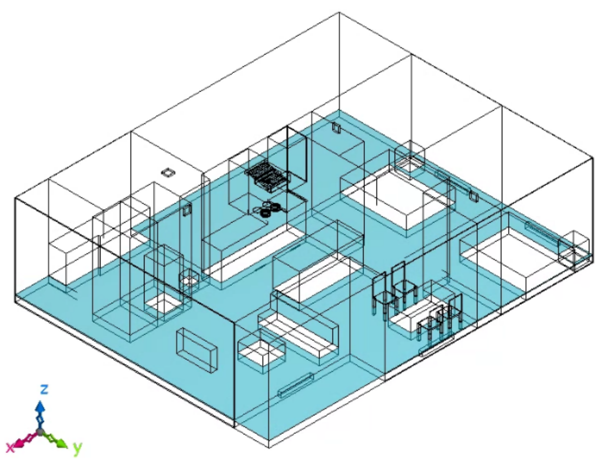

Figure 145. Plan 1: The plane section showing in the Z plane at 0.2 m

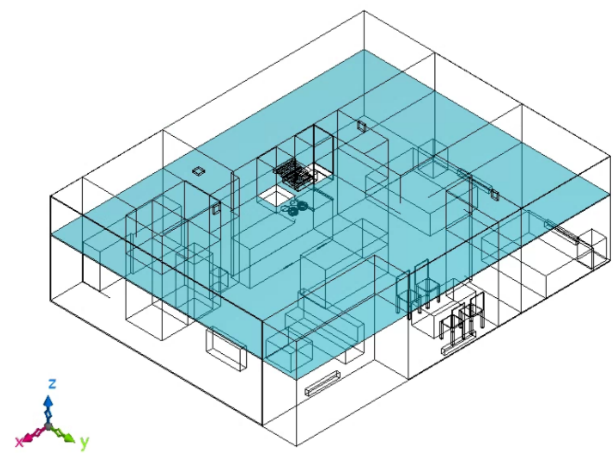

Figure 146. Plan 2: The plane at Z plane at 1.8 m from the floor.

<u>Baseline: HRV Boost mode, range hood ventilation switched off</u>.

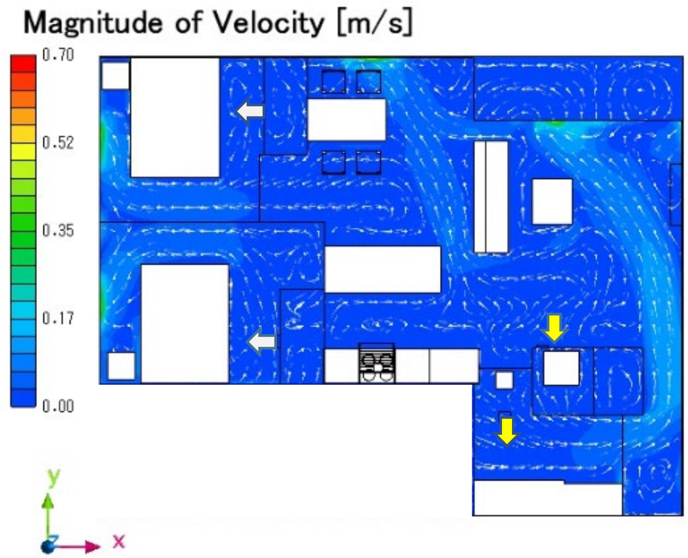

Figure 147. Plan 1, z = 0.2 m, magnitude of velocity and velocity vector.

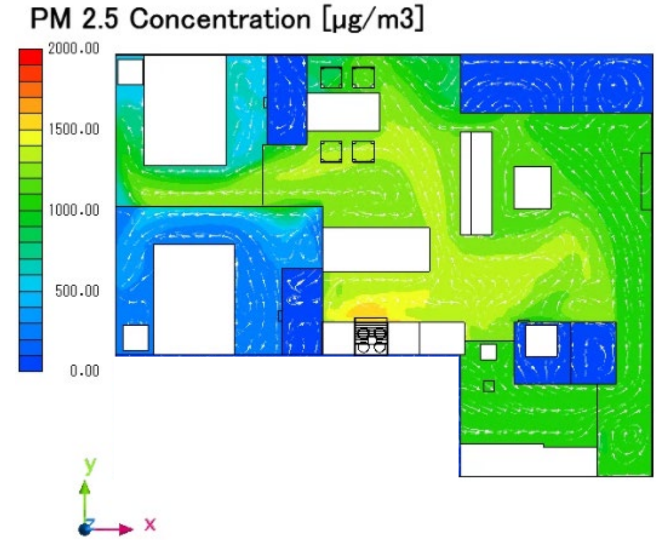

Figure 148. Plan 1, z = 0.2 m, contaminant concentration and velocity vector.

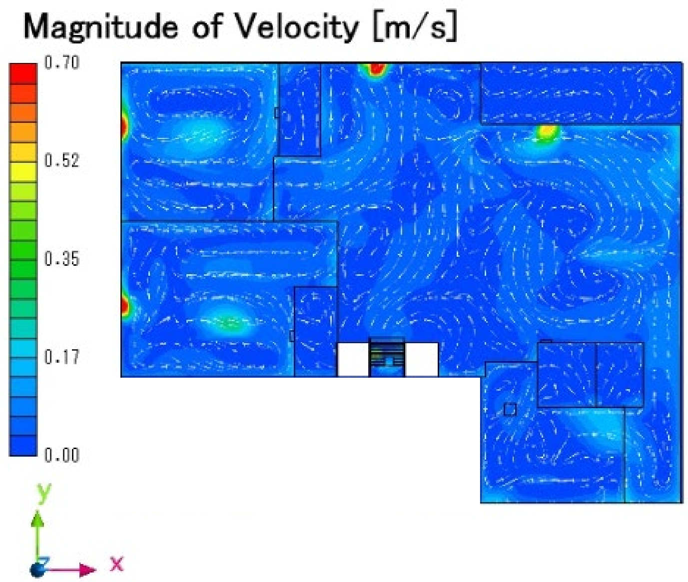

Figure 149. Plan 2, z = 1.8 m, with magnitude of velocity and velocity vector.

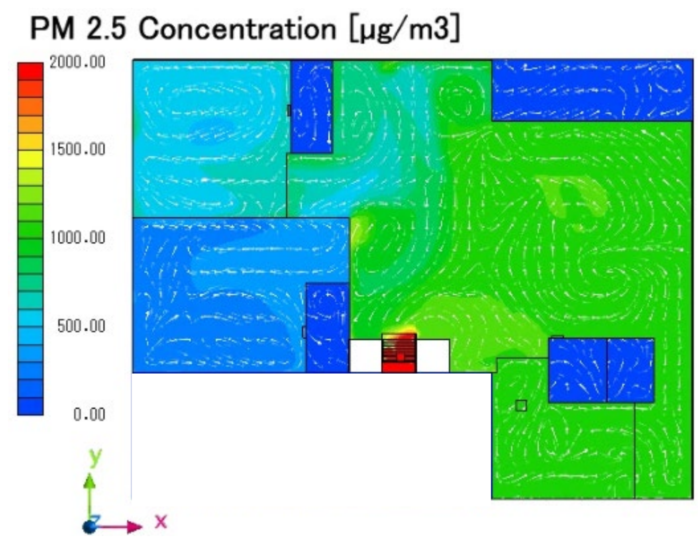

Figure 150. Plan 2, z = 1.8 m, contaminant concentration and velocity vector.

Strategy 1 – Baseline: HRV Boost mode, range hood ventilation switched off.

Figures 148 and 150 show that the PM21.5 concentrations throughout the suite are unacceptably high. From Figures 147 and 149 the airflow at the lower plane causes the pollutants migration towards the bedroom. Meanwhile, the airflow from the dining and kitchen area to bedroom 2 is not dominant compared to bedroom 1, which results in lower pollutants present in bedroom 2. The bedroom one door is in the same direction as the dining room air current, while the bedroom-2 entrance is perpendicular to the airflow. A higher contaminant concentration of 1400 µg/m^3 is visible near the cooktop area and close to the living room HRV exhaust. The baseboard heaters produce buoyancy air current, which creates a strong air movement in bedrooms—the bedroom one baseboard heaters create a buoyancy airflow, causing air circulation near the bed. The circulating airflow in bedroom one is in the same direction as the airflow from the dining area, which increases the pollutants migration from the dining area to this bedroom, which is visible in Figure 147 near the door—causing more migration of contaminated air from the dining area to the bedroom. The contaminant concentration in bedroom 2 is in the range of 500 µg/m3, which is a very high level of concentration than the threshold limiting value (TLV) of 25µg/m^3. At the same time, the concentration in bedroom 1 is significantly higher, which is like the contaminant concentration in the kitchen area. The high pollutant concentration in the bedrooms indicates that cascading ventilation is ineffective in stopping cooking pollutants from migrating into the bedrooms.

Moreover, the bedroom doors and furniture location also have a significant influence on the room air movement. Figures 149 and 150 shows that in the higher plane (1.8 m) from the floor, the airflow pattern is different than the lower plane, bedroom two shows a strong airflow towards the dining area, and bedroom one has a similar airflow pattern at the door. Still, a higher magnitude of velocity is visible in the higher plane due to the proximity of the HRV air supply. The pollutants' migration at this plane towards the bedrooms is lower. In section 3, it is evident that the HRV Supply air from two bedrooms diluted the contaminant concentration in the dining area. The contaminant concentration in the dining area is in the range of 1000 µg/m^3. The washroom and corridor areas have the same contaminant concentration as the lower plane. The pollutant concentration is significantly higher in the cooktop area, and comparatively, low contaminant concentration is visible in bedroom two. The accumulation of higher contaminants in the lower plane (near the floor) due to inadequate air movement, as visible in the section 2 contaminant concentration plot. While analysing the results from the two sections, sections 2 and 3 indicate the buoyancy current significantly impacts the air movement and mixing. These results demonstrate the lower efficiency of the ventilation system in managing the cooking contaminants; overall, a source control mechanism (range hood) is necessary to prevent the dispersion of pollutants.

Strategy 2 – HRV exhaust disabled and replaced with cooking range hood.

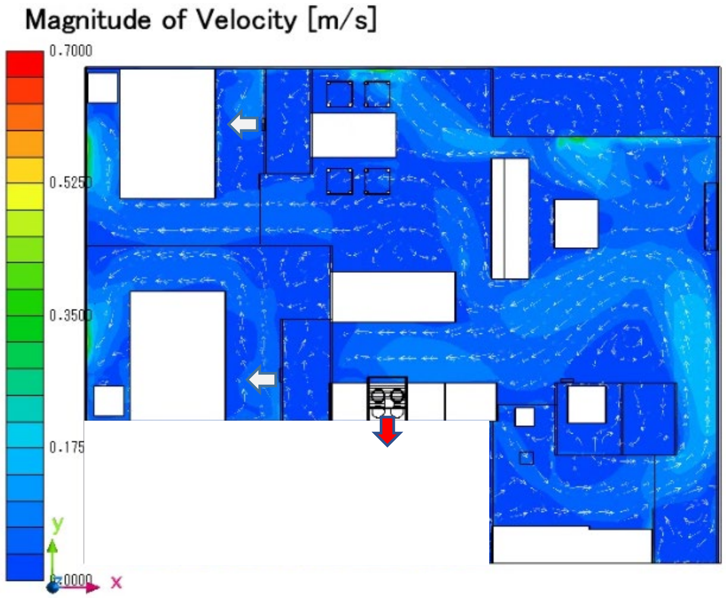

Figure 151. Plan 1 with Magnitude of velocity and velocity vector.

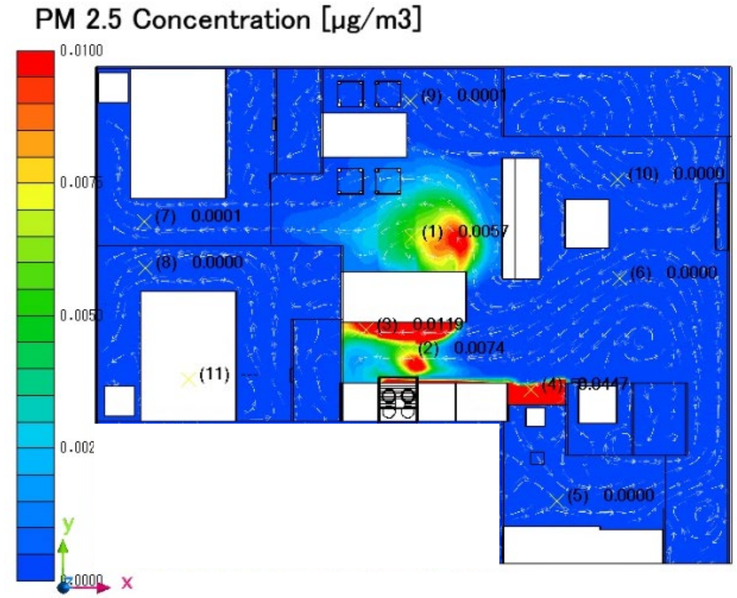

Figure 152. Plan 1 with contaminant concentration and velocity vector.

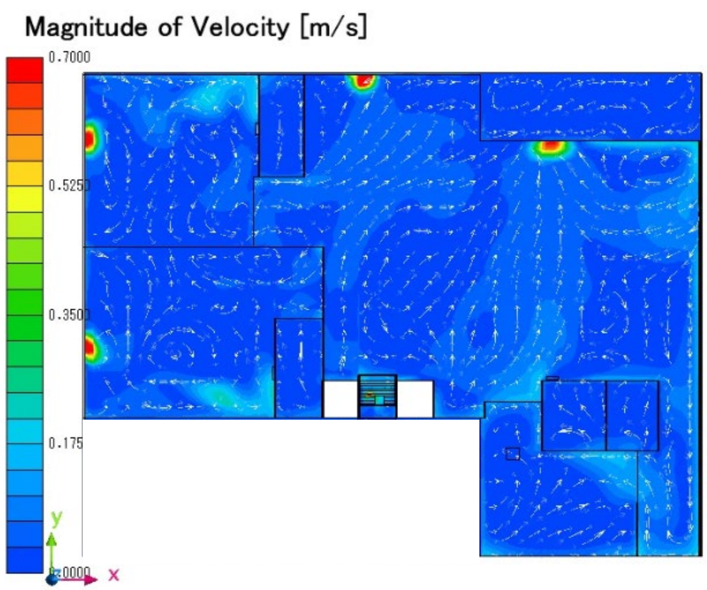

Figure 153. Plan 2 with Magnitude of velocity and velocity vector.

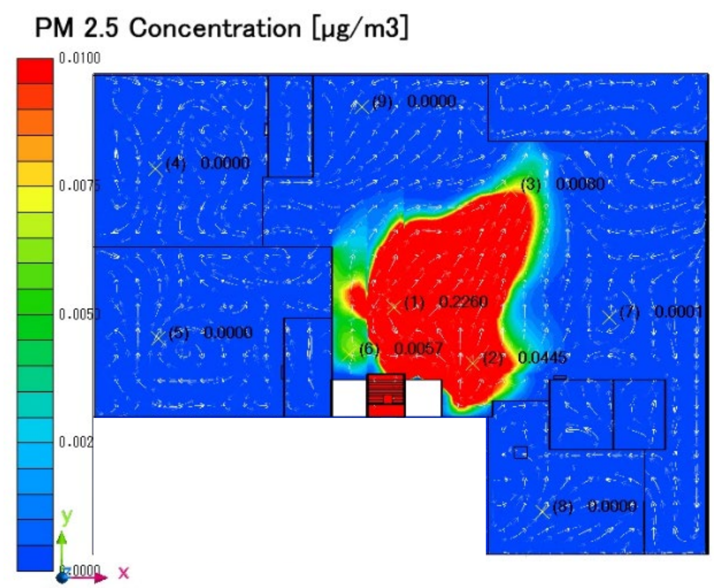

Figure 154. Plan 2 with contaminant concentration and velocity vector.

Strategy 2 – HRV exhaust disabled and replaced with cooking range hood.

Figures 152 and 154 show the contaminant concentrations throughout the suite are acceptable. In this strategy, the HRV exhaust is switched off, and the airflow equal to the HRV supply is exhausted by the cooking range hood to balance the suite pressure. This strategy couples cooking source control with cascade ventilation principle.

From Figures 152 and 154, it is evident that strategy two effectively eliminates contaminants from the cooking. The contaminant is diluted by the supply air when it reaches the dining area, and the remaining portion of contaminants is exhausted by the cooking range hood. The range hood balances the suite pressure. The highest contaminant concentration detected is 19 μg/m^3, closer to the cooktop, but the concentration near the dining area is very minimum, ranging from 1-2 μg/m^3. Bedrooms do not show any contaminant presence. The magnitude of velocity plots in section 2 and 3 shows similar air movements in the bedrooms. The buoyancy created airflow near the baseboard heaters shows a similar pattern compared to strategy 1. The remaining area of the suite shows different airflow patterns. The airflow pattern from the dining areas and washroom area directed towards the kitchen exhaust is the only drawback of this strategy, which causes migration of contaminants from other parts of the suite to the kitchen area, which is only visible in the lower plane (Plan 1).

On the other hand, the airflow in section 3 (higher plane) shows the air movement away from the cooktop, which causes a minute contaminant dispersion towards the living area. The buoyancy current and the kitchen exhaust caused the difference in air movements in the living and kitchen area sections, which created a circulating airflow in the vertical plane. But in this strategy, the effect of Rangehood (Source control) significantly improved indoor air quality, the pollutants concentration in the breathing zone and bedrooms reduced to the very minute. The bedrooms air showed good air quality because no contaminant migrated from the kitchen area towards the bedroom. The contaminant presence in the higher plane (Plan 2) only reaches up to the range of 0.2 μg/m^3, which is lower than the threshold limiting value of 25 μg/m^3, indicating safe indoor air quality. Section 3 also showing a contaminant concentration of 0.2 μg/m^3 in the breathing zone, and the dispersion is limited in the area closer to the kitchen cooktop. The strategy two results indicating the effect of the source control and the impact of lower disturbing airflow near the kitchen cooktop area, the significant share of contaminants exhausted by the range hood, the small concentration of pollutants seen in the floor area near the cooktop area due to the sedimented pollutants, and lower air movement in the floor area.

Strategy 3 - HRV + kitchen makeup air ceiling supply and range hood exhaust.

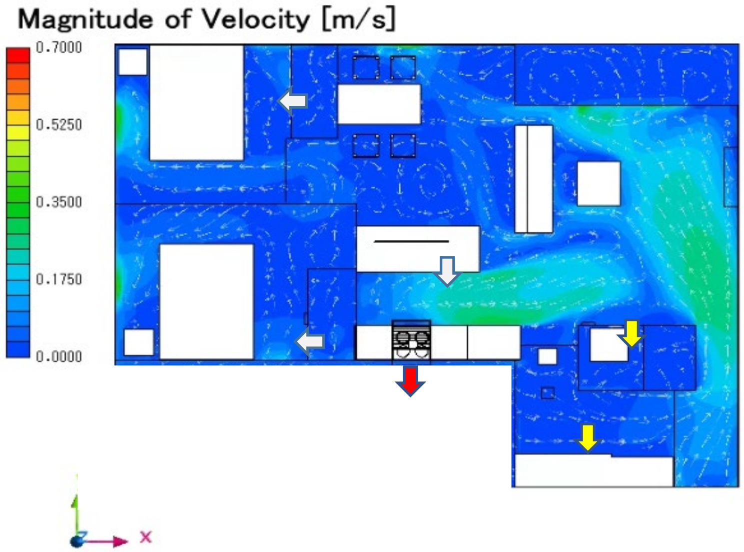

Figure 155. Plan 1 with Magnitude of velocity and velocity vector.

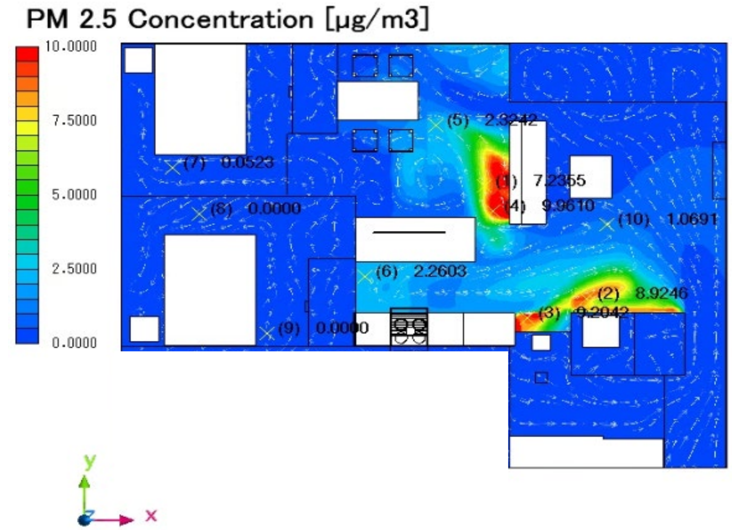

Figure 156. Plan 1 with contaminant concentration and velocity vector.

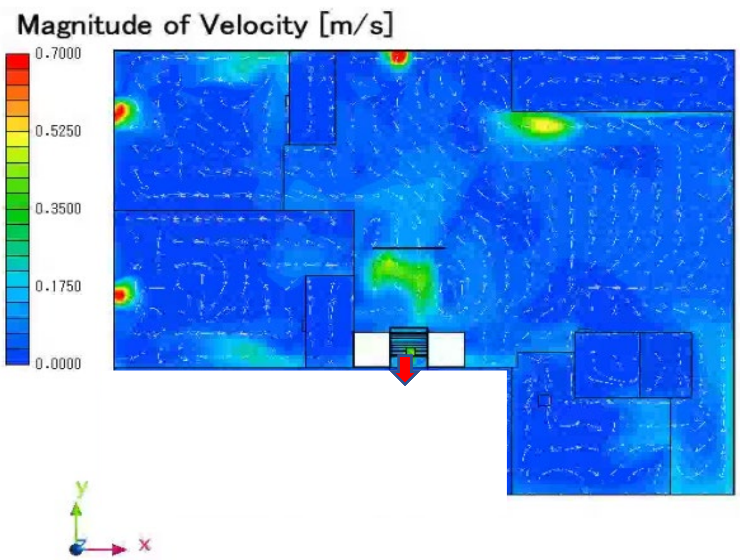

Figure 157. Plan 2 with Magnitude of velocity and velocity vector.

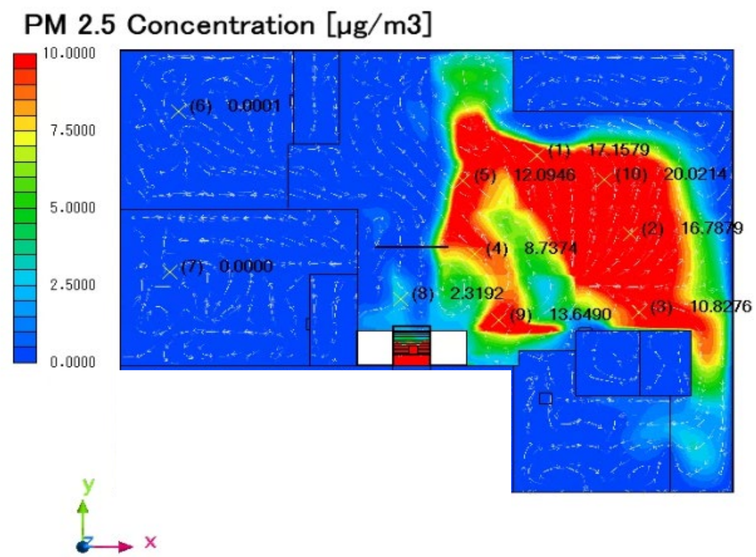

Figure 158. Plan 2 with contaminant concentration and velocity vector.

Strategy 3 - HRV + kitchen makeup air ceiling supply and range hood exhaust.

From figures 156 and 158, it is clear that pollutants concentrations in all section planes are lower than the TLV of PM2.5. The HRV and range hood were decoupled and operating continuously under this strategy. The white arrows in the figure show HRV supply diffusers' location, and yellow and red arrows indicate the HRV return and the RH above the cooktop, respectively. The airflow from the linear diffuser at the ceiling near the kitchen cooktop acts as an air curtain and supplies air equal to range hood exhaust air to balance the suite pressure. This strategy helps to eliminate contaminants with the Rangehood and the HRV ventilation system. The Ceiling diffuser supplies air at 100 CFM and range hood exhausting air at the same airflow rate. The ceiling diffuser was placed at 1.5 m after testing various distances from the cooktop to act as an air curtain. The closer location of the linear diffuser with the cooktop creates a disturbing airflow for the kitchen range hood, which consequently affects the range hood efficiency as per previous studies done by Kim et al., Moreover, if the location of the linear diffuser is far from the cooktop region, the purpose of an air curtain cannot be achieved. The efficiency of the air curtain is analysed in this strategy—the ceiling diffuser supplies fresh outdoor air, which dilutes the indoor contaminants, which improves the IAQ. The airflow pattern in the lower and higher planes (Plans 1 and 2) indicates a different pattern than strategies 1 and 2. In the lower plane, closer to the floor, the air flows towards bedroom one from bedroom two. There is no air current in the direction towards bedrooms from the dining room area like in previous strategies; meanwhile, the air leaving from bedroom two moves towards bedroom one. The air from the polluted dining area is not reaching the bedroom doors. The high airflow rate created by the linear diffuser caused a positive pressure in that region, preventing the air movements towards the bedroom area. Meantime, the ceiling diffuser and HRV exhaust in the living room and the thermal buoyancy created a 0.35m/s airflow towards the suite's living area, which caused the migration of contaminants towards that region. There is more air circulation near the floor and avoid the stagnant contaminant pockets. In the higher plane, air flowing towards the kitchen area from bedroom-1 due to the negative pressure caused by the air curtain and the RH. Contaminant concentration in section one (lower plane) reaches a higher level of 10.2 $\mu g/m^3$ and in section 3 reaching 20 $\mu g/m^3$. The contaminant concentration in this strategy is lesser than the threshold limiting value of 25$\mu g/m^3$. Still, compared to strategy two, the contaminant concentration is higher in the suite's living area. Overall, this strategy is acceptable, and the RH with makeup air can improve indoor air quality and act as source control for the kitchen only. Whereas the RH in strategy 2 is only an air exhausting mechanism for the entire suite.

Strategy 4 HRV + kitchen makeup air floor supply and range hood exhaust

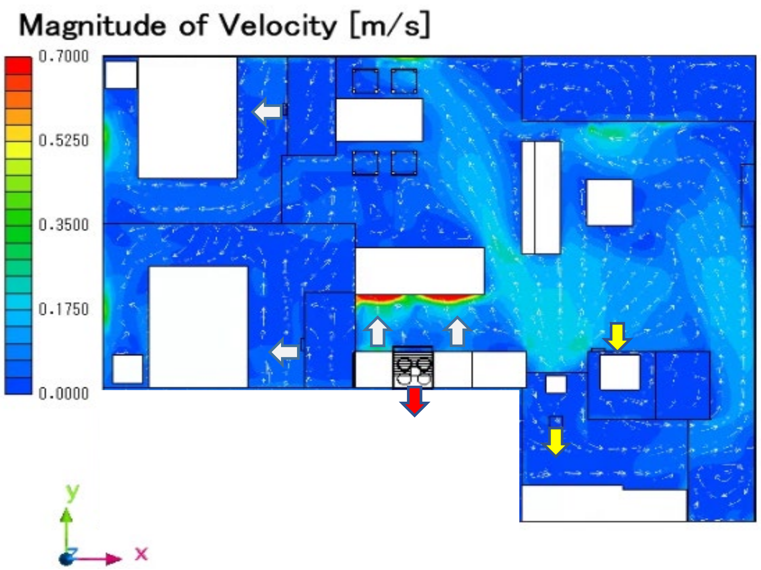

Figure 159. Plan 1 with Magnitude of velocity and velocity vector.

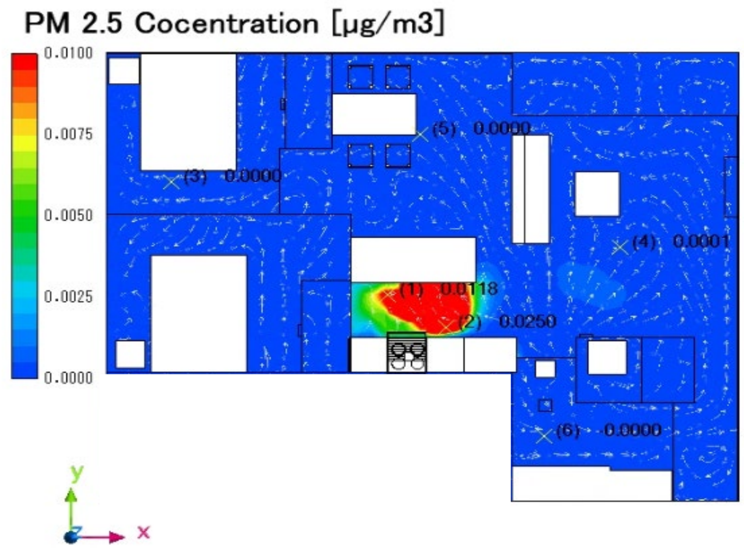

Figure 160. Plan 1 with contaminant concentration and velocity vector.

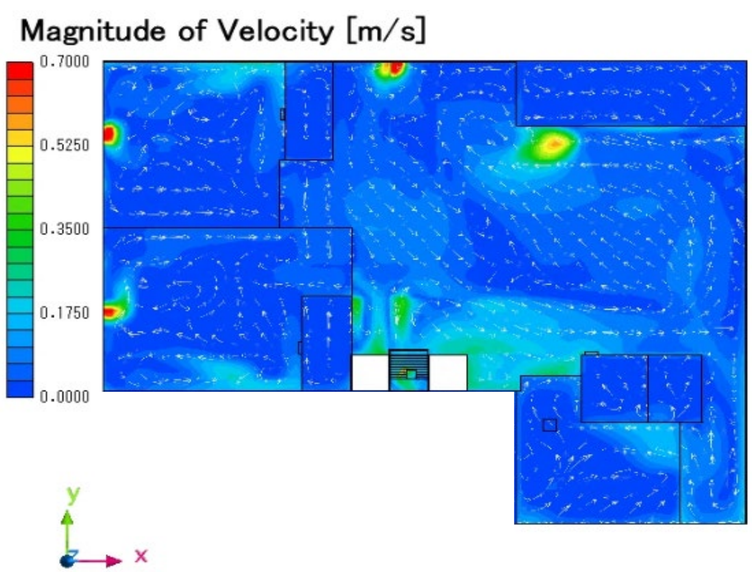

Figure 161. Plan 2 with Magnitude of velocity and velocity vector.

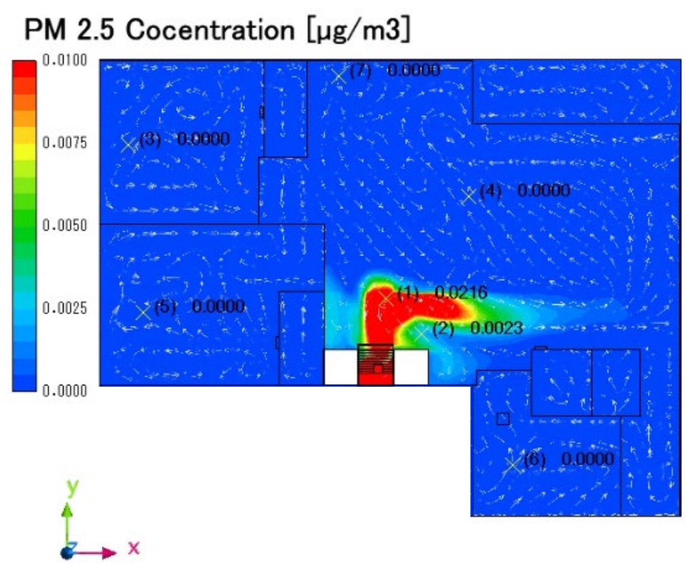

Figure 162. Plan 2 with contaminant concentration and velocity vector.

Strategy 4 HRV + kitchen makeup air floor supply and range hood exhaust

Figures 159 to 162 show the different section views of strategy 4. In this strategy, the ceiling diffuser location shifted to the floor to understand the efficiency of the ventilation system. In strategy 3, the ceiling diffuser created a disturbing airflow in the cooktop area, which caused the dispersion of contaminants from cooking, rather than exhausted by the range hood. Under this strategy, the RH operating efficiently, and the contaminants concentration reduced to 0.02 $\mu g/m^3$ in the breathing zone and lower floor area. While in the previous strategy, the contaminant concentration was 10-20 $\mu g/m^3$ in the breathing zone. These results indicate the highest efficiency of the source control mechanism when it operated with kitchen floor supply. The contaminants concentration in the bedroom is zero, and there is no contaminant transport from the kitchen area to bedrooms. The airflow pattern in bedrooms one and two in lower and higher planes looks similar to the previous strategy. The air current in bedrooms is strongly connected to the buoyancy air current, HRV supply, bedroom walls and furniture orientation. In this strategy, the airflow from the dining room is not reaching the bedrooms, and a higher magnitude of velocity in the living room area due to the HRV exhaust in the living and washroom and buoyancy created air current in that region due to the baseboard heaters. Range hood exhausts a significant portion of contaminants, and the floor supply replaced the exhausted air with fresh outdoor air. The cascade ventilation principle is acting on this strategy. The fresh air from bedrooms flows towards the dining and living area and dilutes the contaminants in that region. The air moves from a cleaner place to a polluted area; in this case, the cooking created contaminants and range hood acting as a source control mechanism.

Contaminant dispersion in Section 1 (across the stove) to understand the pollutants movement towards the front of the kitchen by the air movement.

Strategy 1 – Baseline: HRV Boost mode, no range hood ventilation.

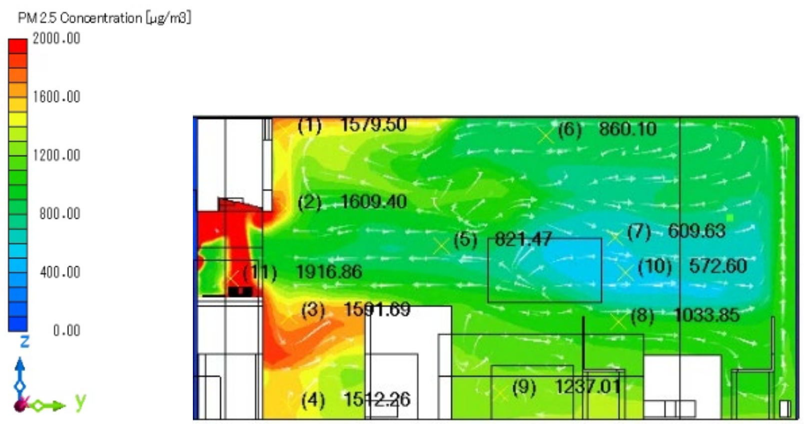

Figure 163. Section 1 with contaminant concentration and velocity vector.

Strategy 2 – HRV exhaust disabled and replaced with cooking range hood.

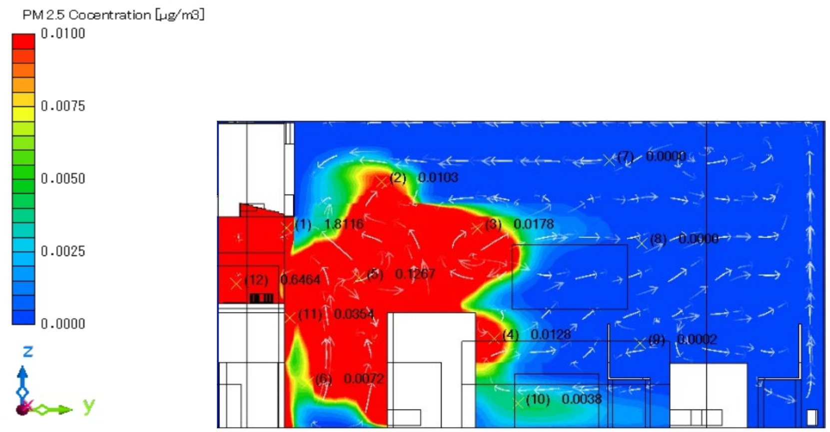

Figure 164. Section 1 with contaminant concentration and velocity vector.

Strategy 3 - HRV + kitchen makeup air ceiling supply and range hood exhaust.

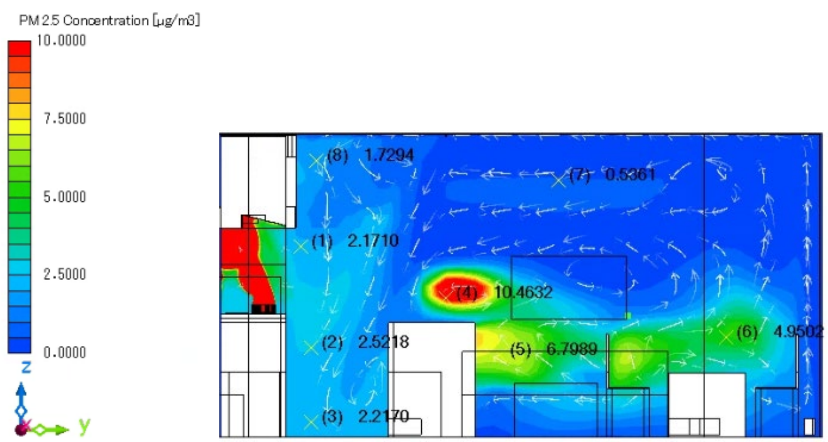

Figure 165. Section 1 with contaminant concentration and velocity vector.

Strategy 4 HRV + kitchen makeup air floor supply and range hood exhaust

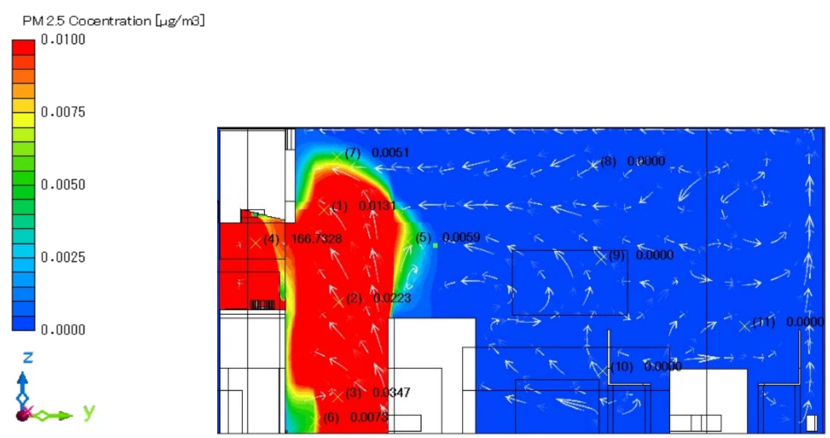

Figure 166. Section 1 with contaminant concentration and velocity vector.

STRATEGIES 1 – 4 COMPARISONS FROM SECTION 1 VIEWS

Strategy 1 – HRV Boost mode.

Figure 163 depicts the contaminant migration from the kitchen towards the front of the cooktop. Under strategy one, the source control system is disabled, and the only source control mechanism is the range hood. From section 1 in figure 163, a portion of contaminants raised with the buoyancy from the hot pan since there is no range hood operating. Part of the contaminants flows downwards due to the air current in that area and sedimentation. The suite baseboard heater and HRV supply air created an air movement in the kitchen area. A small area above the dining area shows lower contaminant concentration due to the inadequate mixing of suite air. The contaminant concentration in the breathing zone reached a significantly higher level, which is not acceptable for safe indoor air quality. The pollutants raised from the cooktop diffused with the indoor air reached all areas of the suite. The results indicating the necessity of an efficient source control mechanism. HRV ventilation system, even in boost mode, cannot manage the indoor cooking contaminants. Overall, the suite air quality is not acceptable.

Strategy 2 – HRV exhaust disabled and replaced with cooking range hood.

Figure 164 shows the airflow pattern and contaminant dispersion in front of the cooktop under strategy 3. The contaminant concentration reached significantly lower than strategy one and threshold limiting value of 25 µg/m^3 for PM2.5. The indoor air quality is safe and acceptable. Contaminated air from near the cooktop flowing towards the kitchen range hood and avoided spreading to other zones. The source control mechanism showed a tremendous impact on indoor air quality. Meantime there is no disturbing air movement in front of the kitchen cooktop other than a hot thermal plume from the hot surfaces.

Strategy 3 - HRV + kitchen ceiling supply and range hood exhaust.

Figure 165 shows the sectional view of strategy 3. Strategy 3 has more contaminant dispersion than strategy 2, but the pollutants' concentration is under TLV. The air from the ceiling diffuser acts as an air curtain and pushes the contaminants towards the wall back of the cooktop. The strong airflow from the ceiling diffuser caused a disturbing air movement near the cooktop and caused the pollutants dispersion at a minute level. But the contaminant concentration in the breathing zone near the dining area and other regions is at an acceptable indoor level and lower than the threshold limiting value of PM2.5. Moreover, air from the ceiling area near the range hood carrying contaminants down to the floor area and mixing with cleaner air of the suite. It is worth noticing the range hood's impact in eliminating the significant amount of contaminants from the cooking. Overall indoor air quality is safe, and the strategy is very acceptable in maintaining adequate indoor air quality.

Strategy 4 HRV + kitchen floor supply and range hood exhaust

It is evident from figure 166 is that the kitchen floor supply increased the efficiency of the ventilation system as compared to the kitchen ceiling supply. The indoor contaminant concentration lowered to the range of 0.01 to 0.035μg/m^3, which is a minimal number compared to TLV of 25μg/m^3. The velocity vector indicates air movement from other regions of the suite to the range hood, which shows the active cascade ventilation system. Strategy 4 showed a similar result as strategy 2 with better indoor air quality. The floor supply supplied fresh outdoor air and improved the Rangehood's effectiveness by eliminating air disturbance in front of the cooktop. Among the four strategies, strategy 4 showed the highest efficiency.

10.9.4 Suite C Cooking pollutant behavior analysis

The same 4 cooking pollutant removal strategies as those in Suite B are tested in Suite C. Similarly, PM2.5 is selected as the representative cooking pollutant. Figures 167 to 170 shows the sections selected for CFD analysis: one vertical section across the stove, and two horizontal plan view sections at 0.2 m and 1.8 m from the floor respectively. The blue arrows in the plan indicate the HRV supply diffuser locations, and the yellow arrow shows the HRV return diffuser locations. The CFD results for each range hood ventilation strategy are presented in figures showing the selected planes, and the results from each strategy are discussed after the corresponding figures.

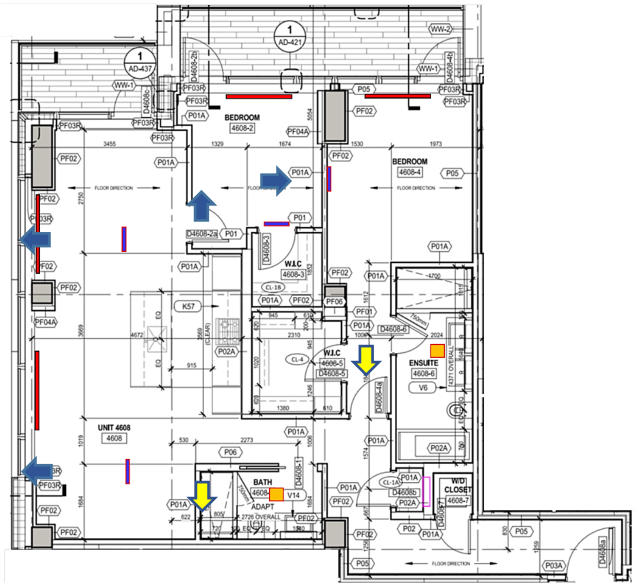

Figure 167. Floor plan of suite. Yellow and blue arrows represent the HRV exhaust and supply respectively.

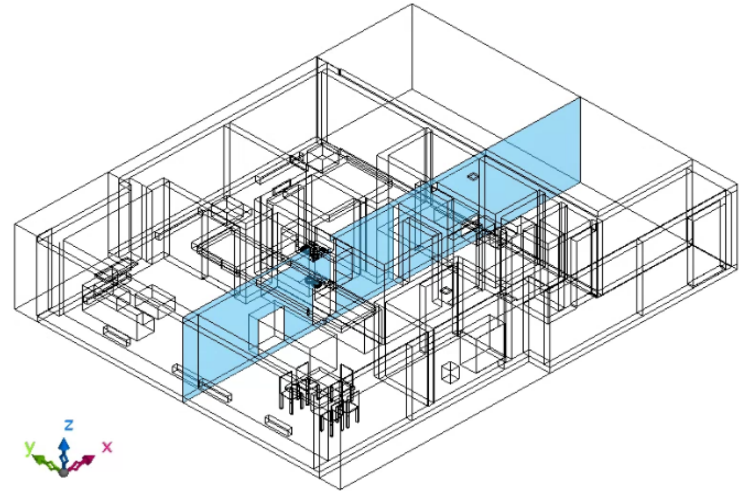

Figure 168. Section 1: The plane section across the cooktop in the Y axis

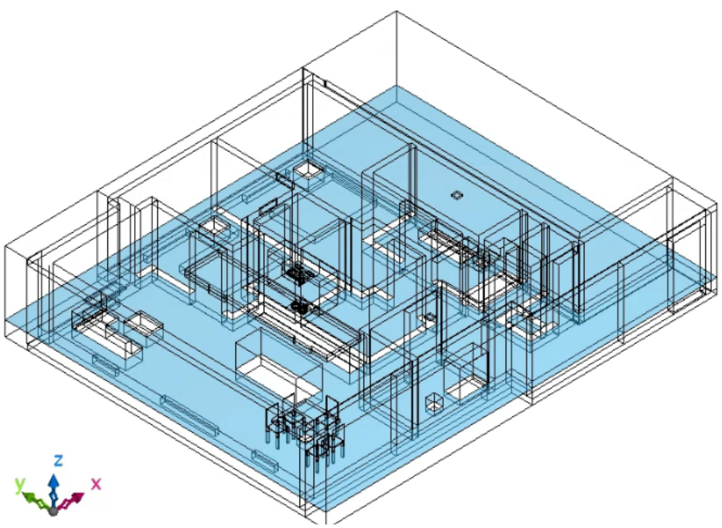

Figure 169. Plan 1: The plane section showing in the Z plane at 0.2 m

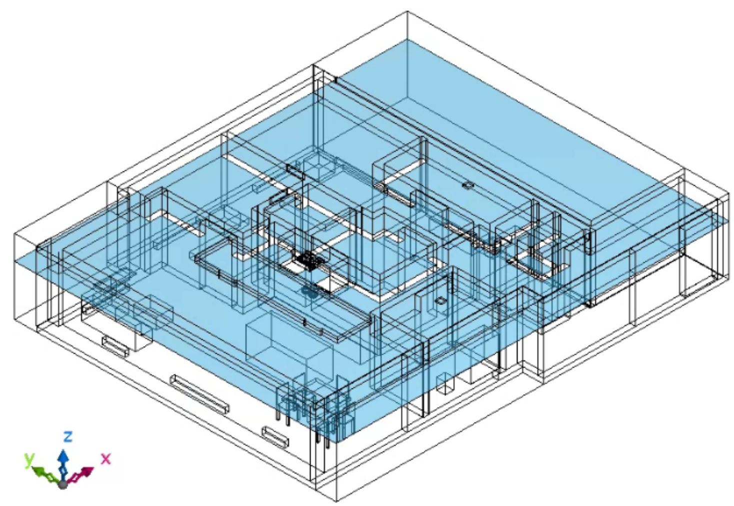

Figure 170. Plan 2: The plane at Z plane at 1.8 m from the floor.

Strategy 1 – Baseline: HRV Boost mode, range hood ventilation switched off.

Figure 171. Plan 1 with Magnitude of velocity and velocity vector.

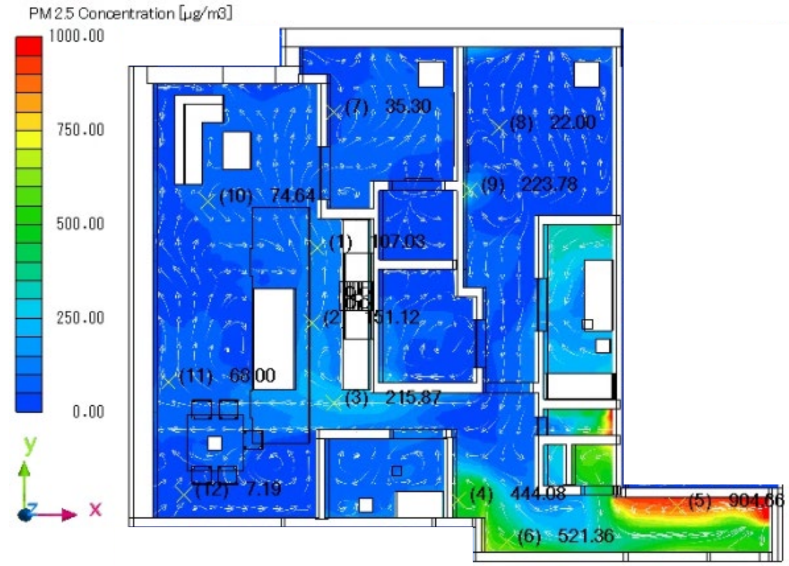

Figure 172. Plan 1 with contaminant concentration and velocity vector.

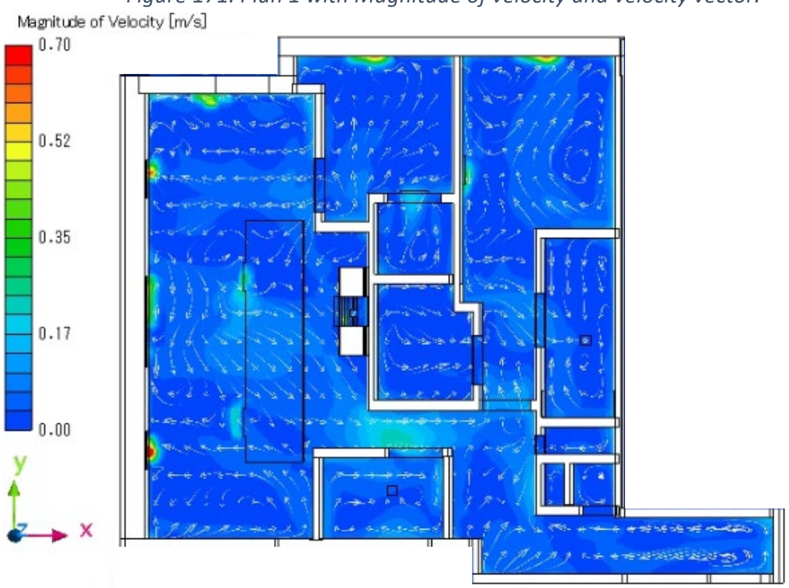

Figure 173. Plan 2 with Magnitude of velocity and velocity vector.

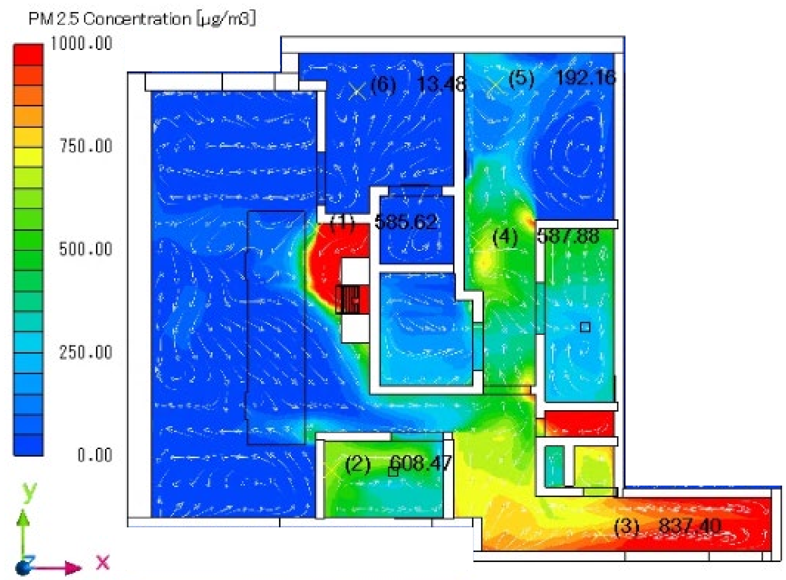

Figure 174. Plan 2 with contaminant concentration and velocity vector.

Strategy 1 is testing the ventilation efficiency in maintaining good indoor air quality with HRV boost mode. Figures 171 to 174 show the contaminant concentrations and velocity magnitude in different suite areas in the sectional planes. The contaminant concentration in the lower plane (Plan 1-near floor) and higher plane (Plan 2-near breathing zone) shows a higher contaminant concentration level. In Plan 1, the contaminant concentration in the master bedroom reached 223 $\mu g/m^3$. And in Plan 2, it reached 1000 $\mu g/m^3$ in the master bedroom. The contaminant concentration in the second bedroom, near the floor area, reached 35 $\mu g/m^3$, which was slightly higher than the TLV of 25 $\mu g/m^3$ for PM2.5.

On the other hand, the pollutant concentration in the breathing level (Plan 2) was reduced to 13 $\mu g/m^3$. The HRV boost mode supplied a total fresh air of 86 CFM and exhausted the same amount of air from the washrooms. The higher rate of a new outdoor air supply in the bedrooms reduced the contaminant concentration by diluting the contaminants. The buoyancy airflow of heaters and the HRV supply air created a circulating air movement in the suite. The heaters and HRV supply outlet significantly impacted airflow in the higher plane. That air current induces an air movement in the lower plane and near the floor regions. The airflow pattern and magnitude of velocity indicate some areas with negligible air movements and some regions with higher air movements. The overall indoor air quality is unacceptable in the suite in terms of contaminant concentration.

Strategy 2 – HRV exhaust disabled and replaced with cooking range hood.

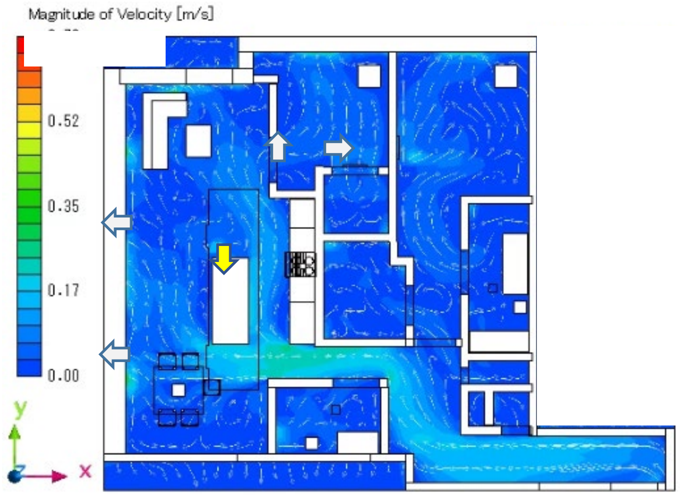

Figure 175. Plan 1 with Magnitude of velocity and velocity vector.

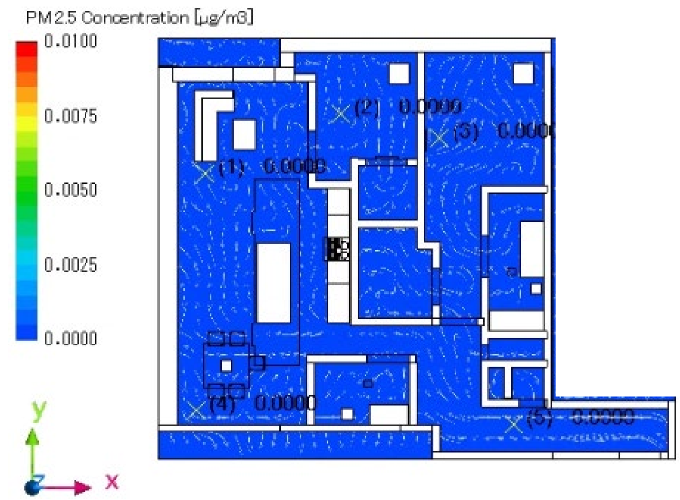

Figure 176. Plan 1 with contaminant concentration and velocity vector.

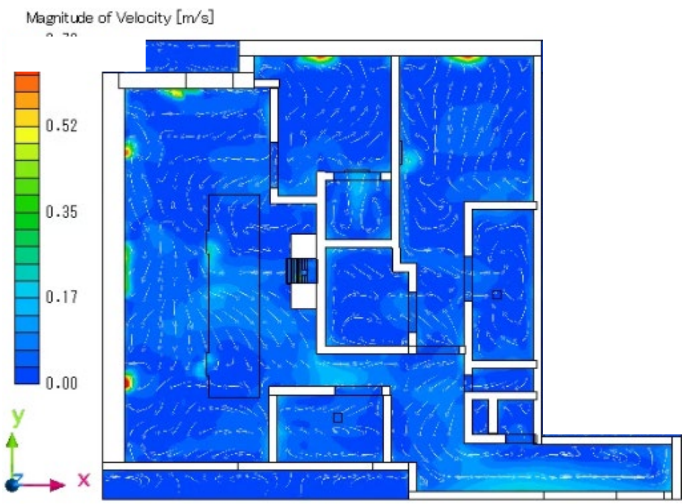

Figure 177. Plan 2 with Magnitude of velocity and velocity vector.

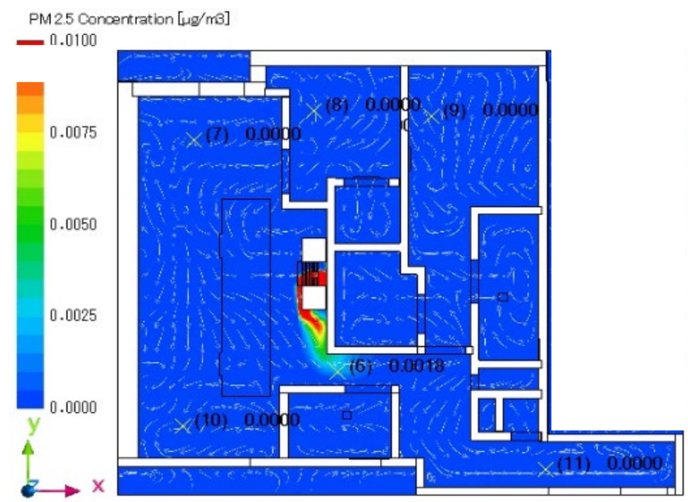

Figure 178. Plan 2 with contaminant concentration and velocity vector.

Figures 175 to 178 show the CFD analysis result of strategy 2. Strategy two have a source control mechanism, Rangehood, which replaced the operation of the HRV exhausts. The range hood is operating at the same rate as the HRV supply of 86CFM. The overall indoor air quality improved significantly as compared to strategy 1. The contaminant dispersion from the cooktop to other regions reduced when the source control operated at an 86CFM, lower than the conventional range hood exhaust rate. Even though there is an airflow between the living room and second bedroom, the contaminant concentration is zero. Which indicating a lower emission of pollutants and significant amount of pollutants exhausted by the source control mechanism. In the lower plane (Plan 1), the contaminant concentration is negligible in most of the regions of the suite, even though there is sufficient air movement and mixing can be identified. In the open-door scenario, the air from the washroom is moving towards other regions of the suite in the lower plane and in the higher plane because the washroom exhausts are disabled in this strategy. In Plan 2, a small number of contaminants moved towards the corridor area carried by the air current between that region. The indoor air quality is excellent, and the contaminant presence is negligible compared to the threshold limiting value of 25 $\mu g/m^3$.

Strategy 3 - HRV + kitchen ceiling supply and range hood exhaust.

Figure 179. Plan 1 with Magnitude of velocity and velocity vector.

Figure 180. Plan 1 with contaminant concentration and velocity vector.

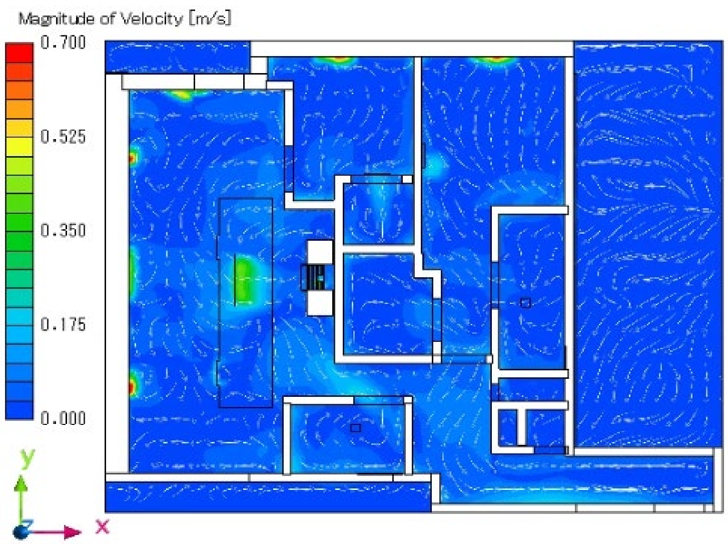

Figure 181. Plan 2 with Magnitude of velocity and velocity vector.

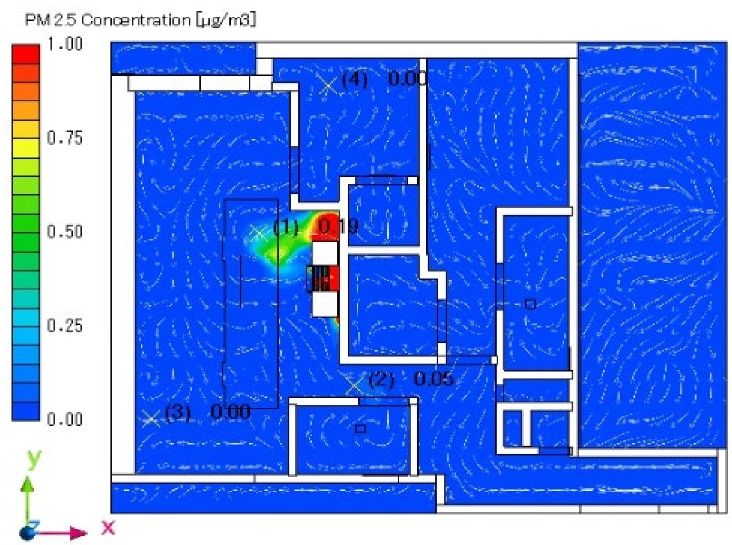

Figure 182. Plan 2 with contaminant concentration and velocity vector.

Figures 179 to 182 present velocities and concentrations in Plan 1, 0.2 m above the floor, and Plan 2, 1.8 m above the floor. The figures depict a strong air movement in the suite's lower and upper planes when the HRV system is decoupled with the cooking ventilation system. The baseboard heaters and the ventilation system created an air flow in the suite. More fresh air was introduced to the suite with the ventilation system and diluted the contaminant concentration. Bedrooms does not show any contaminant present in the lower and upper plane. An air movement towards the washroom exhausts offers a better air cleaning in Plans 1 and 2. Lower bypass of contaminant air from the washroom exhaust indicating the better efficiency of strategy 3. The indoor air quality is acceptable, and the ventilation system efficiently deals with the cooking contaminants

Strategy 4 - HRV + kitchen floor supply and range hood exhaust.

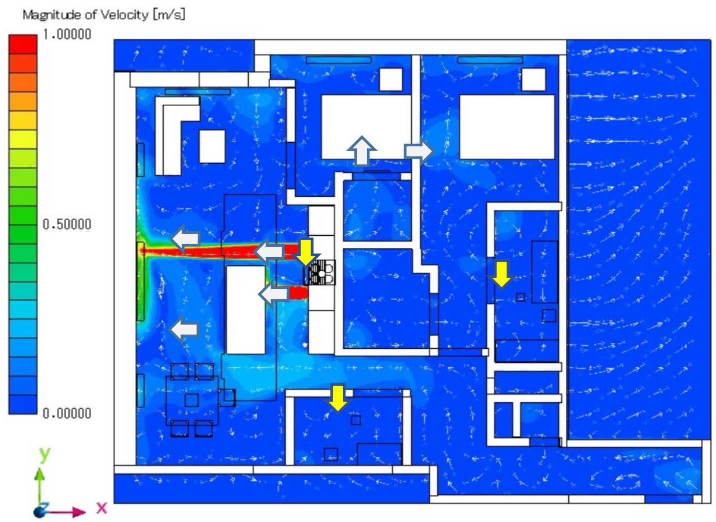

Figure 183. Plan 1 with Magnitude of velocity and velocity vector.

Figure 184. Plan 1 with contaminant concentration and velocity vector.

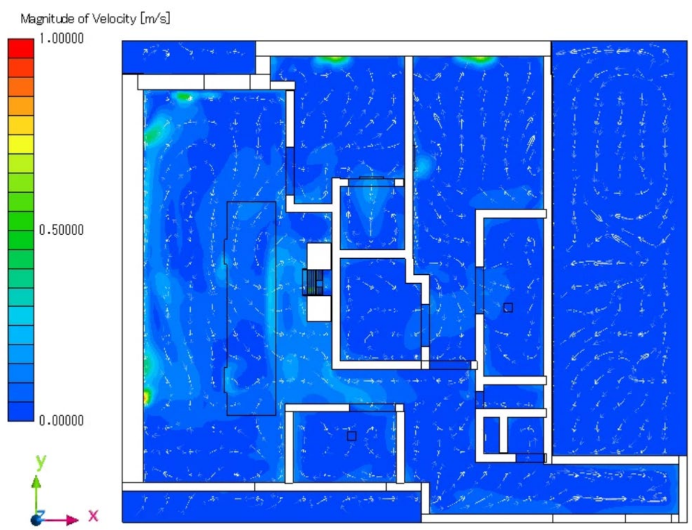

Figure 185. Plan 2 with Magnitude of velocity and velocity vector.

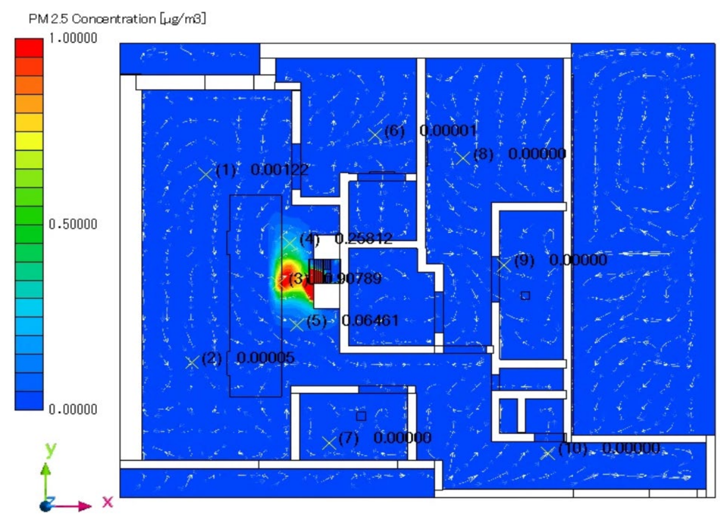

Figure 186. Plan 2 with contaminant concentration and velocity vector.

Figures 183 to 186 show velocities and concentrations in Plan 1 near the floor and Plan 2 at the breathing zone. The figures depict a strong air movement in the suite's lower and upper planes when the HRV system is decoupled with the cooking ventilation system. The baseboard heaters and the ventilation system created an air flow in the suite. More fresh air was introduced to the suite with the ventilation system and diluted the contaminant concentration. Bedrooms does not show any contaminant present in the lower and upper plane. An air movement towards the washroom exhausts shows a better air cleaning in Plans 1 and 2. The indoor air quality is acceptable, and the ventilation system efficiently deals with the cooking contaminants. Compared to strategies 2 and 3 the pollutants dispersion is higher in front of the cooktop in the lower and higher plane. The dispersion is caused due to the air disturbance near the cooktop due to the floor kitchen supply. The kitchen counter in front of the cooktop causing a circulating air movement in that region and carrying the contaminants to other kitchen areas. The increased air supply dilutes the concentration of the pollutants, and IAQ is high. The contaminant concentration in the breathing zone is much lower than the threshold limiting value of 25 µg/m3. Strategy 3 showed negligible contaminant presence in the lower plane as compared to this strategy. Overall, this strategy is acceptable and efficient in dealing with cooking pollutants.

comparing the pollutants behavior in section1

Strategy 1 – Baseline: HRV Boost mode, range hood ventilation switched off.

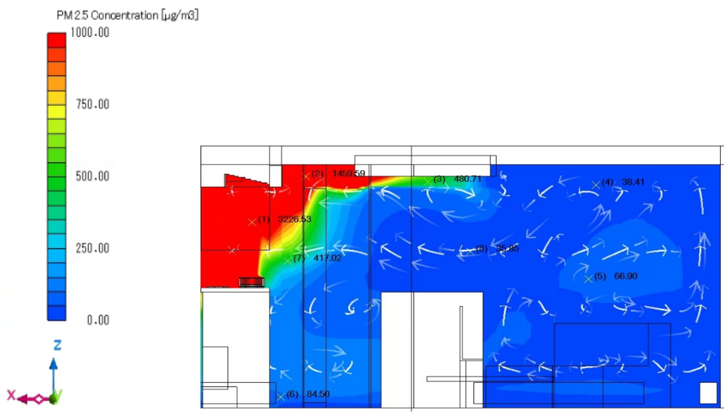

Figure 187. Section 1 with contaminant concentration and velocity vector.

Strategy 2 – HRV exhaust disabled and replaced with

Figure 188. Section 1 with contaminant concentration and velocity vector.

Strategy 3 - HRV + kitchen ceiling supply and range hood exhaust.

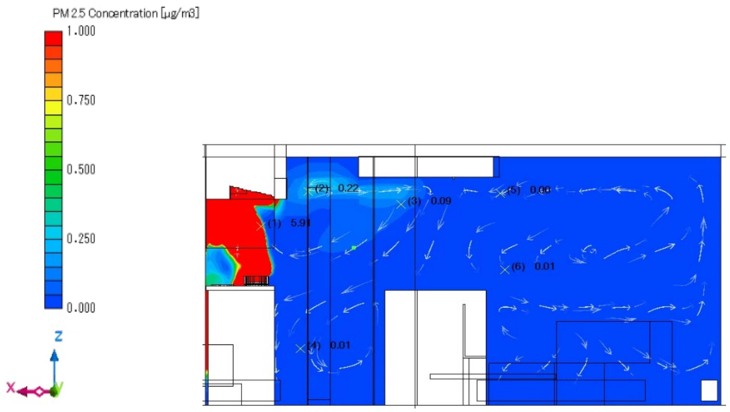

Figure 189. Section 1 with contaminant concentration and velocity vector.

Strategy 4 - HRV + kitchen floor supply and range hood exhaust

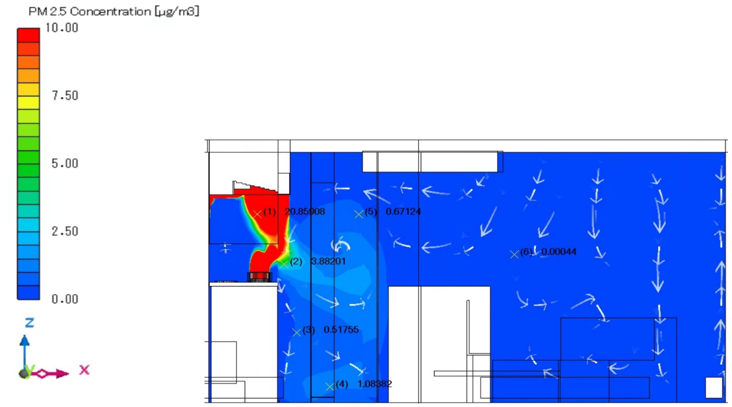

Figure 190. Section 1 with contaminant concentration and velocity vector.

Strategy 1 – Baseline: HRV Boost mode, range hood ventilation switched off.

Strategy one does not have a source control mechanism. Figure 187 indicates PM2.5 concentrations at section 1 across the stove. The pollutants emitted from the pan is flowing up with the thermal buoyancy and air movement in front of the cooktop. The pollutants reached the ceiling in a higher concentration. They diffused to other regions with the help of air current created by the HRV supply and buoyancy from the electric baseboard heater. Contaminant concentration reached in a range of 66 to 450 μg/m^3, which shows unacceptable indoor air quality as compared to the TLV for PM2.5. Results indicating the necessity of a source control mechanism to further preventing the pollutants dispersion to the cleaner region of the suite. HRV ventilation system, even in the boost mode, cannot handle the pollutants from the cooking.

Strategy 2 – HRV exhaust disabled and replaced with cooking range hood.

Section-1 of strategy two depicts the movement of the contaminants from the cooktop. Figure 188 shows PM2.5 concentrations at section 1 across the stove. The air from the living room region moving toward the range hood exhaust because the other washroom exhausts of HRV is disabled. The air disturbance in front of the cooktop is not visible, which increases the rangehood efficiency. The contaminants present in front of the cooktop area is negligible. The only higher contaminant concentration is contained in the region between cooktop and range hood, indicating the influence of the source control mechanism. The air quality is acceptable, and the ventilation system is efficient in maintaining good indoor air quality.

Strategy 3 - HRV + kitchen ceiling supply and range hood exhaust.

Figure 189 shows PM2.5 concentrations across the stove. Strategy three decoupled the HRV ventilation system with the cooking ventilation system to better eliminate the cooking contaminants. The pollutants are eliminated through the HRV exhaust and the range hood exhaust. The range hood is coupled with a linear ceiling diffuser to supply equal air to maintain the suite air pressure. The ceiling supply also acts as an air curtain to prevent contaminant dispersion to other regions of the suite. Section 1 across the cooktop indicates that the linear ceiling diffuser was assisting the range hood in better-eliminating contaminants. The air from the ceiling diffuser separates the cooking area with other regions of the suite on one side opposite the cooktop, which helps avoid the pollutants mixing with the air in front of the cooktop. The pollutants moving closer to the wall with the help of supply air current from the ceiling diffuser and prevented the dispersion to the front of the cooktop. A very minute contaminant concentration can see in front of the cooktop, which indicates the higher efficiency of strategy 3.

Strategy 4 - HRV + kitchen floor supply and range hood exhaust

It is worthwhile to notice that the contaminant dispersion is higher than strategy 3. It is due to the disturbing airflow in front of the cooktop. The kitchen counter diverted the floor supply air towards the cooktop and disturbed that area, which carried the cooking pollutants. Overall, the indoor air quality is excellent and safe for humans. The concentration in the breathing zone is significantly lower than the TLV for PM2.5. Strategy 4 can maintain satisfactory IAQ.

11 FINAL DISCUSSION AND CONCLUSIONS

This study has presented a holistic approach to address indoor air quality and ventilation in multiunit residential buildings (MURBs). The study has addressed all relevant aspects affecting ventilation performance, uncovering complexities from the multiple uncertainties affecting ventilation performance and air quality. However, it is acknowledged that various subjects are treated only superficially because they require more extensive studies, out of the scope of this research. Many practical considerations are left out of this study with the hope that they can be incorporated in future versions after relevant industry feedback is received. The modeling does not consider energy performance. Including thermal aspects more accurately and energy performance requires the coupling of multi-zone airflow networks with building energy simulation tools, which is straightforward but demands significantly more time involvement. Despite the limitations, the study is a first step in the holistic treatment of ventilation and indoor air quality in MURBS. The study lays out a solid foundation to be built upon by more focused studies on specific topics exposed in this research, to enable the optimization of effective ventilation systems for MURBs.

An important contribution of this research is the development of a set of generic ventilation performance requirements for MURBs. The performance requirements are holistic, incorporating ventilation requirements as well as resiliency, and integration with other systems. However, these performance-requirements are only implicitly used in the evaluation of simulation case study alternatives. Further versions of this report will evolve these ventilation requirements into a more robust requirements framework, that can be used to support the comparison of ventilation systems during design, using the proposed performance-based ventilation-IAQ approach, as well as the measurement and verification (M&V) of these systems during operation.

Ventilation and airborne pollutant exposure control principles control indicate that transient and short-term occupancy areas are less critical in terms of human exposure to airborne pollutants. Circulations areas such as elevators and corridors are inherently transient and therefore the concentration and exposure of pollutants is limited compared to areas such as amenities, and service areas. Circulation areas, elevators, and shafts can be seen more like pollutant transport zones that can potentially disperse pollutants across long distances within the building. Undoubtedly, the most critical spaces for airborne pollutant exposure are the dwelling units. For this reason, the proposed performance-based ventilation-IAQ design approach focuses on achieving satisfactory, reliable, and resilient ventilation in the dwelling units.

The proposed performance-based design approach for satisfactory IAQ, can support ventilation design for ventilation-IAQ resilience, as well as ventilation and other systems integration, such as the envelope, energy, heating, and cooling. The simulation case studies demonstrate the application of the performance-based ventilation-IAQ design approach. The models and methods supporting the approach are robust. Using CO_2 to calibrate models is justified because it relates directly occupancy and ventilation, and the uncertainties associated with CO_2 emissions are reduced. Other pollutants present much higher uncertainties in their emissions, such as cooking pollutants or VOCs. However, simulations of high-uncertainty pollutants can be used comparatively, to evaluate the performance of ventilation alternatives.

The simulation case studies provided important insights on the performance of alternative ventilation systems for new and existing building retrofits. Based on the simulations, more reliable and resilient ventilation systems for new buildings and existing building retrofits are proposed.

12 FURTHER WORK

To consolidate the methods and proposals from this study to achieve effective, reliable and resilient, ventilation in MURBs the following research areas have been identified:

1. Develop Ventilation and IAQ Measurement and Verification (M&V) protocols for MURBs. Undertake ventilation-IAQ measurement and verification campaigns of MURB systems at all levels:
    a. Post-occupancy surveys on dwellers' satisfaction with the indoor environment and feedback to improve future designs. Surprisingly, the current focus of post-occupancy evaluations is on energy. Post-occupancy surveys on dwellers are rare. The author has asked passive house designers about occupants' surveys and the response is limited to anecdotal evidence.
    b. Assemble databases with normalized data on airtightness and compartmentalization testing of buildings, suites, assemblies, and components. These databases can help better inform the topology characterization of dwellings to prioritize airtightness and compartmentalization efforts, and improve the accuracy of the modeling.
    c. Conduct M&V of ventilation systems coupled with the indoor air quality monitoring of priority pollutants of concern.
    d. Obtain field evidence on the operation of cookstove recirculation hoods and the performance of cooking filtration systems.
2. Develop a generalized ontology of dwellers' archetypes, and conduct a survey campaign to help identify and characterize dwellers' archetypes in the Province of British Columbia.
3. Investigate smart ventilation in the context of MURBs, to help understand to what extent can human and climate responsive ventilation systems be practically implemented in MURBs, i.e. cooking, humidity, VOCs, windows operation, wildfires' smoke, mechanical cooling?
4. Assemble databases of pollutants with indoor emissions and model coefficients to be used in multi-zone airflow network modeling.
5. Implement data-driven uncertainty in the modeling including a stochastic modeling of dwellers and pollutants, to be able to associate a level of confidence to the modeling results. Parametric studies of differential pressures and airflows under selected airtightness, compartmentalization, and ventilation scenarios can shed light on the most suitable mechanisms to control building air flows.
6. Raise awareness and educate dwellers on the effects on indoor air quality on health, and the impacts of their behaviors on ventilation and indoor air quality.
7. Investigate the synergies between low-energy cooling and effective ventilation in the context of climate change. Given that buildings are for people, socio-technical studies are required to investigate how to design smart technical cooling solutions that consider humans as active enablers/disablers of cooling and ventilation. Inadvertently habituating humans to mechanical cooling may be counterproductive in the long term.
8. The simulation case studies uncovered numerous opportunities to optimize ventilation systems at the whole-building level, as well as at the suite level. For example, at the suite level, data from a Passive House dorm shown in Figure 15, section 4.4, and case study SR-2, section 10.6, show that even for a small studio suite, ventilation can bypass the living/study suite area close to the envelope. Suite CFD simulations can demonstrate how the suite heating system can make a difference in inducing ventilation air into the living/study area near the envelope, thus improving the effectiveness of the ventilation, i.e. ventilation elements 3 and 4 in Table 12. CFD case study SR-5, section 10.9.1, can be used for this purpose, by placing the occupant in the living/study area instead of assuming that the occupant laying on the bed (sleeping area).

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APPENDIX A

Multi-Zone Airflow Network (MZ-AFN) Modeling

MZ-AFN models are suitable to simulate airflow circulations between rooms: Ventilation Element 4, section 1.5, Table 2. idealize a building as a collection of zones, such as rooms, hallways, & duct junctions, joined by flow paths representing doors, windows, fans, ducts, etc. MZ-AFN assumes that the airflow system is made up of pressure nodes, which have relatively low internal resistance to airflow. Pressure nodes are connected by orifices, which have a relatively high resistance to airflow. Differential pressure at each orifice is governed by the Bernoulli equation, which accounts for static pressure on each side of the flow path (Figure A1).

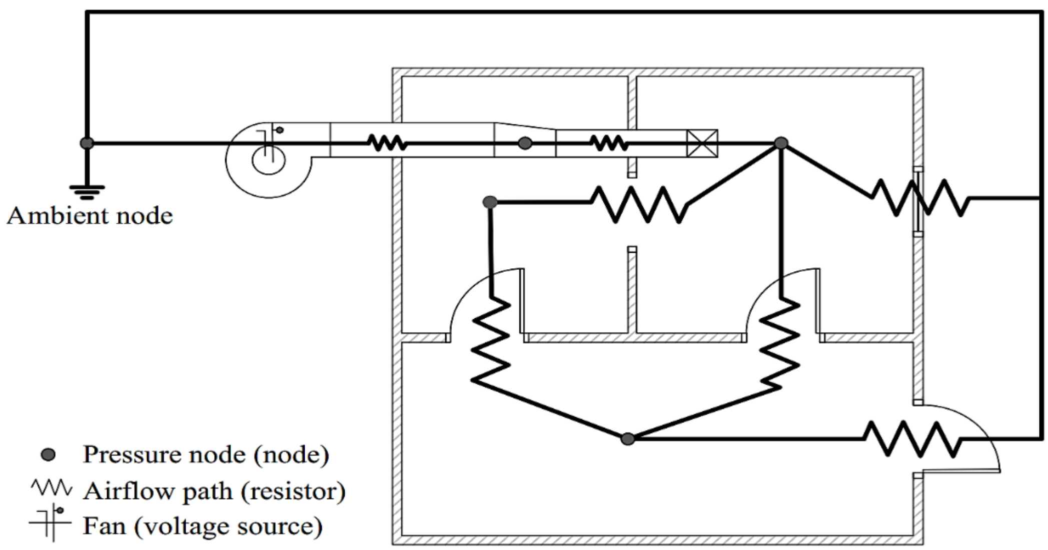

Figure A1. Multi-Zone Airflow Network (MZ-AFN) Modeling

The governing equations of MZ-AFN models are the following:

Conservation of mass:

MZ-AFN enforces conservation of mass as each zone:

$$\sum_{i=1}^{N_{zones}} \dot{m}_{ij} = 0 \qquad \text{Equation (A1)}$$

Where,

$\dot{m}_{ij}$: *air mass flow between zones i and j*

Flow characterization:

The air mass flow rate between zones is driven by pressure differentials between zones, and the resistance of the airflow paths between zones:

$$\dot{m}_{ij} = f(\Delta P_{ij}) \ ; \ \ driving\ forces: \rho_i, \rho_j, \Delta C_{p_{ij}}, \Delta P_{fan_{ij}} \qquad \text{Equation (A2)}$$

Where,

ΔP_{ij}: $pressure\ drop\ at\ the\ path\ connecting\ zones\ i\ and\ j, which\ is\ in\ turn\ a\ function\ of\ the\ driving\ forces\ and\ the\ flow\ path\ characteristics$

ρ_i, ρ_j: $thermal\ flow\ driving\ air\ densities\ in\ zones\ i\ and\ j$

$\Delta C_{p_{ij}}$: $wind\ flow\ driving\ coefficient\ of\ pressure\ differential\ between\ zones\ i\ and\ j$

$\Delta P_{fan_{i,j}}$: $pressure\ differential\ cause\ by\ mechanical\ fans\ at\ zones\ i\ and\ j$

Pressure differences through the flow path caused by temperature/density, height, and wind changes. AFN simulations dynamically balance the flow through multiple openings, which is driven by hydrostatic pressure forces across each opening, through enforcing conservation of mass at each zone, at each time step. Therefore, AFN simulations are coupled dynamically with building energy models, to compute the effects of thermal forces on airflows and vice versa using hourly dynamic simulations. These simulations rely on hourly meteorological boundary conditions from standard weather files that produce airflow-driving forces in the building represented as indoor-outdoor temperature differentials and wind surface-averaged wind-pressure coefficients on the building envelope. AFN modeling is typically supplemented with other types of models in certain specific conditions. For example, single-sided ventilation is typically modelled using semi-empirical models that are coupled with AFN.

Three fundamental AFN modeling assumptions are: 1) it assumes that the resistance to airflow of a flow-limiting path between building zones is much greater than the resistance to airflow of the zones themselves. 2) The airflow within a zone is zero, which means that the pressure varies only hydrostatically within a building zone. 3) The temperatures within a given zone are uniform. Implicit in these assumptions is the assumption that the air in a room (pressure node) is fully mixed and characterized with a single air pressure, temperature, and concentration of pollutants in the air.

Modeling airflow and contaminant transport in the air requires the coupling of airflow, thermal, and even moisture transport models because these three are interdependent, i.e. energy drives airflow and moisture, and vice versa as indicated in Figure A2.

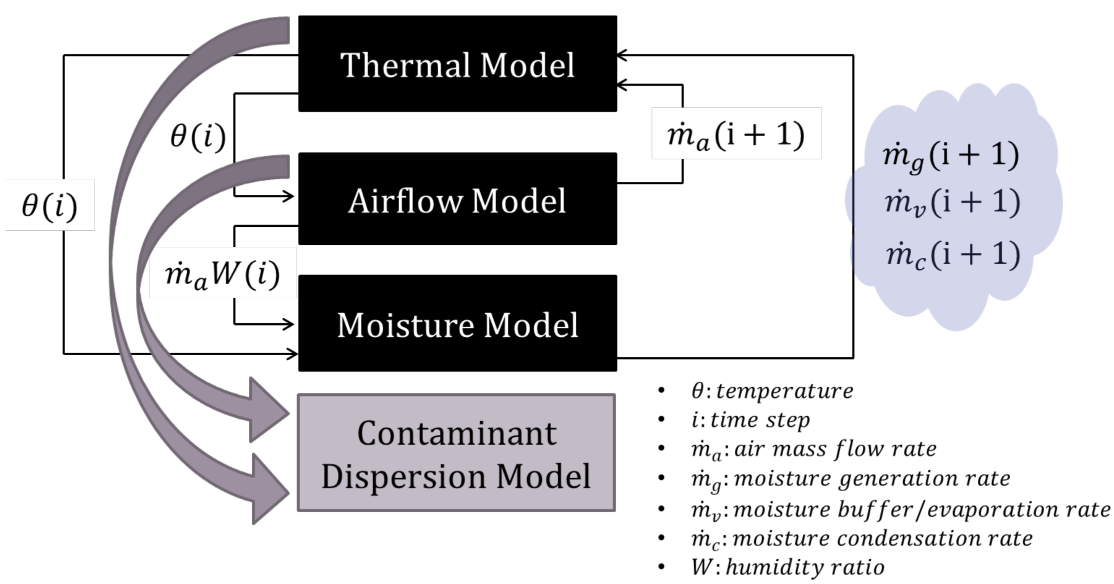

Figure A2. The coupling of thermal, airflow, and moisture models

In Figure A2, contaminant dispersion models are driven by the thermal, airflow, and moisture models, but they do not affect these models in turn, i.e. the models assume that contaminants are driven by the air and affected by thermal forces and the moisture in the air. However, the models assume that contaminants do not affect air temperatures, airflows or air moisture.

APPENDIX B

Room air Contaminant Mass Balance Models

Characterizing indoor air contaminants is complex because indoor air contaminants are multiple, and each of these presents its own complex behaviours. Figure B1 describes the physical and chemical phenomena that drive contaminant emission, transport, and control in the air.

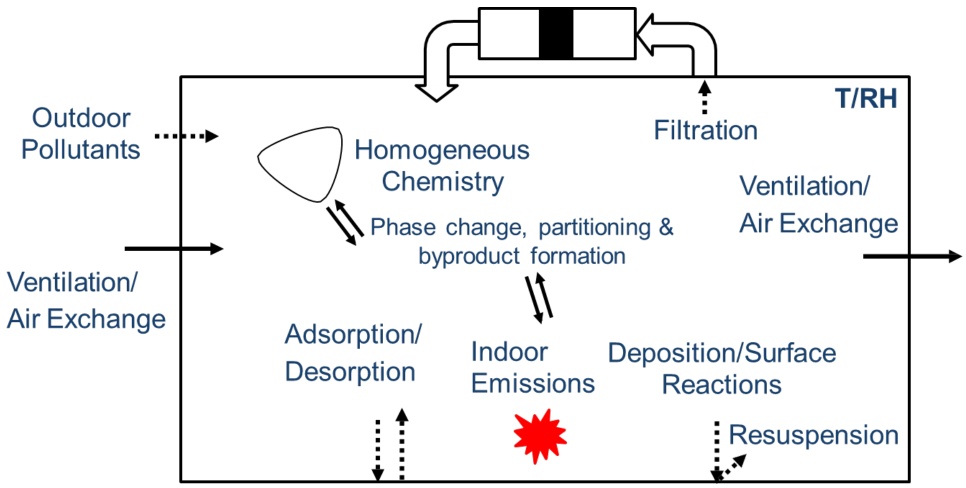

Figure B1. Physical and chemical contaminant behaviours in the air

The room contaminant mass balance model (Figure A2) is described by equation (B1). Given that it is a fully-mixed room air and contaminant balance model, it assumes a well-mixed room air where the pollutants are instantaneously and evenly distributed in a space

$$\frac{dm_{\alpha,i}}{dt} = \dot{E}_{\alpha,i} + m_i \sum_\beta k_{\alpha,\beta} C_{\beta,i} + \sum_j \dot{m}_{i,j}(1-\eta_{\alpha,j,i})C_{\alpha,j} - \sum_j \dot{m}_{i,j} C_{\alpha,i} - R_{\alpha,i} C_{\alpha,i} \qquad \text{Equation (B1)}$$

Where,

$m_{\alpha,i}: mass\ of\ contaminant\ \alpha\ in\ zone\ (kg_\alpha)$
$\dot{E}_{\alpha,i}: emission\ rate\ of\ contaminant\ \alpha\ in\ zone\ i\ (kg_\alpha/s)$
$m_i: mass\ of\ air\ in\ zone\ i\ (kg_{air})$
$k_{\alpha,\beta}: kinetic\ reaction\ coefficient\ in\ zone\ i\ between\ species\ \alpha\ and\ \beta\ (1/s)$
$C_{\beta,i}: concentration\ mass\ fraction\ of\ contaminant\ \beta\ in\ zone\ i\ (kg_\alpha/kg_{air})$
$\dot{m}_{i,j}: rate\ of\ airflow\ from\ zone\ i\ to\ zone\ j\ (kg_{air}/s)$
$\eta_{\alpha,j,i}: filter\ efficiency\ in\ the\ path\ from\ zone\ j\ to\ zone\ i\ (\%)$
$C_{\alpha,j}: concentration\ mass\ fraction\ of\ contaminant\ \alpha\ in\ zone\ i\ (kg_\alpha/kg_{air})$
$R_{\alpha,i}: removal\ coefficient\ for\ contaminant\ \alpha\ in\ zone\ i\ (kg_\alpha/s)$

The removal coefficient represents deposition, adsorption, and other physical or chemical removal mechanisms that may be present.

APPENDIX C

Computational Fluid Dynamics (CFD) Modeling

MZ-AFN and CFD modeling have become widely accepted tools for indoor environmental and ventilation performance predictions (Srebric 2011, ASHRAE-HCh13 2017). MZ-AFN models consider the room air is fully, aggregating the entire room air as a node with air mass, air pressure, air temperature, air humidity, and contaminant mass. Therefore, MZ-AFN cannot be used to simulate the airflow within a room. Computational Fluid Dynamics (CFD) offers a higher level of airflow modeling granularity, down to the room local microclimatic level: Ventilation Element 3, section 1.5, Table 2. Therefore, this research will combine both MZ-AFN and CFD models to simulate indoor airflows and contaminant transport.

A CFD model subdivides the interior space into a number of cells (Figure 16). The accuracy of the CFD solution is governed by the number of cells in the grid or mesh. For each cell, the conservation of mass is satisfied so that the sum of mass flows into or out of a cell from all its neighbours is balanced to zero. Similarly the exchange of momentum from the flow into or out of a cell must be balanced in each direction with pressure, gravity, viscous shear, and energy transport by turbulent eddies (Srebric 2011). CFD involves solving a coupled set of partial differential equations at each cell, which must be worked simultaneously or successively (ASHRAE HCh13 2017). Optimal meshes are non-uniform: finer in areas where large flow variations occur from point to point, and coarser in regions with relatively little change.

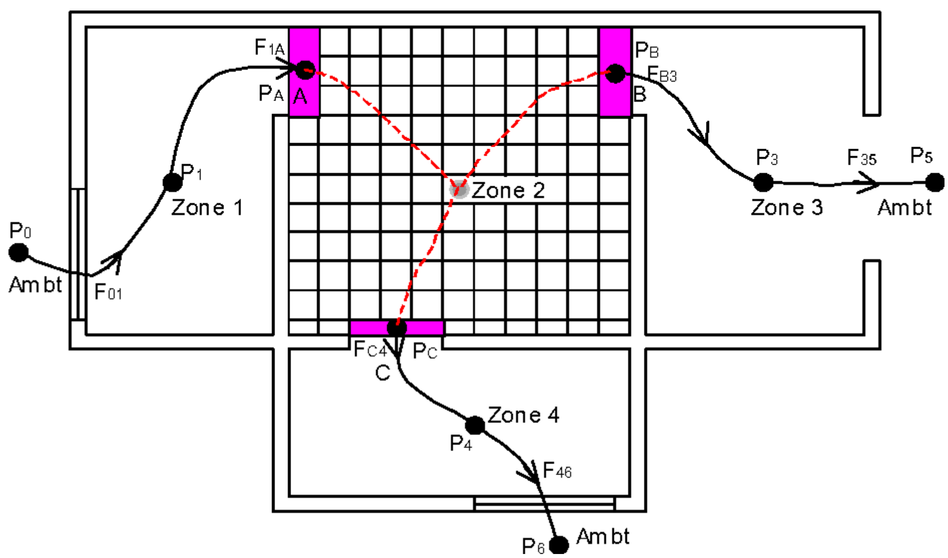

Figure C1. CFD (zone 2) and MZ-AFN (zones 1, 3, and 4) modeling

The governing equations remain the same for all indoor environment applications of airflow and heat transfer, but boundary conditions change for each specific problem: room layout, surface temperatures, location and strength of indoor thermal sources, airflows entering and leaving the space, etc. Indoor airflow, convective heat transfer, and species dispersion are controlled by the governing equations for mass, momentum in each flow direction, energy (Navier-Stokes equation), and contaminant distribution. A generic form is presented in Equation (13), relating the change in time of a variable at a location to the amount of variable flux (e.g., momentum, mass, thermal energy). Essentially, transient changes plus convection equals diffusion plus sources: the rate of increase of ϕ in the fluid element equals the net rate of flow of ϕ out of fluid element (convection term), plus the rate of increase of ϕ due to diffusion into the fluid element (diffusion term), plus the rate of increase of ϕ due to sources in the fluid element (source term).

$$\frac{\partial(\rho\phi)}{\partial t} + div(\rho\phi\boldsymbol{u}) = div\big(\Gamma_\phi\ grad\phi\big) + S_\phi \qquad \text{Equation (C1)}$$

Where,

t = time, s
*ρ = density, **(**kg/m^3**)***
φ = transport property (e.g., air velocity, temperature, species concentration) at any point
$\boldsymbol{u}$** = velocity vector, **(**m/s**)
Γ_ϕ = generalized diffusion coefficient or transport property of fluid flow
S_ϕ = source or sink

The equation above can completely describe the flow in the laminar regime (at low Reynolds numbers). However, for most practical engineering applications, flows are fluctuating and unstable, i.e. turbulent (at large Reynolds numbers). Local turbulence is expressed as a variable diffusion coefficient called the turbulent viscosity, often calculated from the equations for turbulent kinetic energy and its dissipation rate (ASHRAE-HCh13 2017). The total description of flow, therefore, consists of eight differential equations for each cell: 1 conservation of mass, 3 conservation of momentum equations, 1 conservation of energy, 2 turbulence models/equations, and 1 contaminant transport equation. Direct solution of differential equations for the room's flow regime is not possible, but a numerical method can be applied. The differential equations are transformed into finite-volume equations formulated around each grid point. Convection and diffusion terms are developed for all six surfaces around the control volume, and the source term is formulated for the volume

Airflow in natural and built environments is predominantly turbulent, characterized by randomness, diffusivity, dissipation, and relatively large Reynolds numbers (ASHRAE-Ch13 2017). In this research, the modeling of ventilation and indoor air quality in residential suites considers winter boundary conditions, in which the suite is fully enclosed (windows closed) and the airflows are confined by the enclosure. Figure C2 illustrates the airflow boundary conditions in a fully enclosed space.

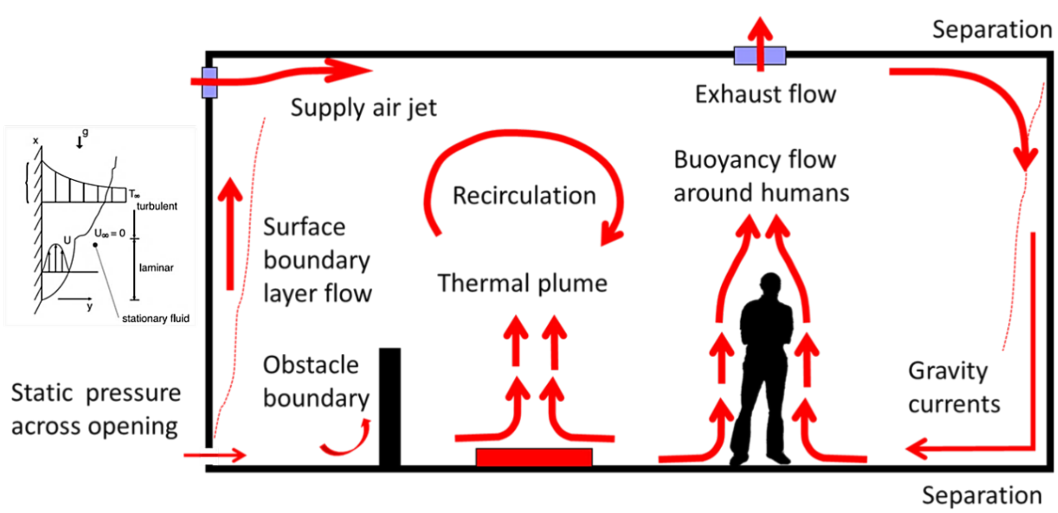

Figure C2. CFD airflow boundary conditions in a fully enclosed space

The indoor air flows in residential buildings are three-dimensional, low-speed (less than 0.2 m/s) and turbulent. Because the flow is fully confined, the modeling can be fairly easily described by the CFD equations and models. However, modeling complexities can arise when conflicting airflows and thermal sources are present due to high solar gains, ceiling fans, local high-temperature heaters, etc. Cooking and the cooking exhaust hood can also create modeling complexities because the cook stove is a high thermal source, pollutant emissions are temperature-driven (i.e. strong buoyancy), moisture generation can be high and interfere with the pollutant emissions and dispersal, and the local airflows are also relatively high. However, researchers (Kim et al. 2020) have already conducted and validated CFD models to simulate of cooking pollutant dispersal. These models are used as a reference for creating the CFD models in this research.