A study of hybrid ventilation in an institutional building for predictive control

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Abstract

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This thesis presents a study aimed at thermally massive high-rise buildings equipped with fan-assisted hybrid ventilation through corridors linking controlled motorized inlets on opposing façades and an atrium (solar chimney) consisting possibly of stacked atria. During the cooling season, hybrid ventilation is used when outdoor air conditions satisfy a set of criteria in order to reduce cooling energy consumption, especially at night when the outdoor air temperature drops. Additionally, this reduction can be greater when the system is controlled in a predictive manner by incorporating forecast weather in anticipation of a warm or cool day. Without compromising thermal comfort, the result from this study proposes 8 °C and-12 °C as the lower limit for allowing cool outdoor air during unoccupied and occupied hours respectively. Furthermore, replacing the existing criterion of relative humidity range of outdoor air by its humidity ratio is proposed. Using an institutional building in Montreal as the site for full-scale tests during the cooling season, the cooling potential of using the hybrid ventilation system and considerations for thermal comfort when admitting cool outdoor air are studied. To this effect, a calibrated transient thermal network model, based on the measurements from 4 hours of night ventilation and focusing on the first 10 m of the corridor at one of the motorized inlets, is developed to study the behaviour of the main building thermal mass - the 0.4 m thick concrete floor and how the temperature evolves with distance from the inlets and the resulting effect on thermal comfort. The effect of the outdoor temperature setpoint at which air is admitted into the building on potential energy savings is also studied.

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Nomenclature

Abbreviations and acronyms

ACH	Air change per hour
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BAS	Building Automation System
CFD	Computational fluid dynamics
COP	Coefficient of Performance
CV-RMSE	Coefficient of Variation of the Root Mean Squared Error
EN	European standard
EV	Engineering, Computer Science, and Visual Arts Integrated Complex
HR	Humidity Ratio (g_{water}/kg_{dry_air})
HVAC	Heating, Ventilation, and Air Conditioning
ISO	International Organization for Standardization
MBE	Mean Bias Error
NPL	Neutral Pressure Level
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
RH	Relative Humidity
RMSE	Root Mean Squared Error
RSF	Research support facility of NREL
VFD	Variable Frequency Drive

Greek letters

α	thermal diffusivity (m^2/s)
ΔT	temperature difference(°C)

Δt	simulation timestep (s)
ρ	density (kg/m^3)

Variables

A	Area of contact or cross-sectional area (m^2)
Bi	Biot number
C	thermal capacity (J/K)
COP	coefficient of Performance
c_p	specific heat capacity (J/kg·K)
h	convective heat transfer coefficient (W/m^2·K)
k	thermal conductivity (W/m·K)
L_c	characteristic length (m)
Q	amount of cooling energy consumption reduction (kWh)
q	energy (W)
T	temperature (°C)
t	time elapsed since the start of operating in hybrid ventilation mode (s)
U	thermal conductance or effective heat transfer (W/m^2·K)
v	velocity (m/s)

Subscripts

air	air
air-concr	air to concrete floor
air-sfc	air to surfaces
concr	concrete floor surface or inner node
corridor	corridor

EV	EV building's weather station
i	equation node's number
inlet	inlet (façade opening)
j	nodes' numbers, surrounding node i
m	control volume number (i.e. corridor section number)
n	concrete layer number
sfc	combined surfaces

Superscripts

p	timestep number

Table of Contents

List of Figures

List of Tables

1 Introduction

Aside from providing fresh air in the building through non-mechanical means, buildings that use natural ventilation can also consume less energy than those that do not. In addition, there are often fewer cases of Sick Building Syndrome in buildings with natural ventilation, and evidence of increased productivity in these buildings. [1] The use of natural ventilation in occupied spaces is far from a new concept; however, during the building design and construction phases, it is common to introduce guidelines and standards specifying the indoor conditions considered satisfactory to occupants. These requirements are simpler to meet using mechanically-controlled conditioning systems, than with natural ventilation. Thus, it can be challenging to meet these requirements using natural ventilation which aims at using the least amount of energy possible towards cooling the indoor environment while staying within the suggested conditions.

1.1 Natural ventilation in buildings

Buildings designs are responsive to climate. For temperate climate, where the outdoor conditions vary greatly from summer to winter, buildings would need to cater to both hot summers and cold winters, as well as the shoulder seasons in between. There is a renewed interest in using natural ventilation in buildings in temperate climates during cooling season and between cooling and heating season. These buildings would allow cooler outdoor air into the building in order to cool the indoor environment, as well as provide fresh air to the occupants.

Buildings located in sub-tropical or tropical climates also use natural ventilation and rely on the air movement to provide convective cooling to the occupants, making a higher air temperature in the indoor environment acceptable. Naturally ventilated buildings usually make use of cross-ventilation and buoyancy to create air movement, and larger commercial or institutional buildings often also incorporate atria to enhance the stack effect. Of course, buildings should be oriented in accordance to the local predominant existing wind direction when possible, even though the wind direction may change due to the future development of surrounding buildings.

For example, in Golden, Colorado, the Research Support Facility (RSF), part of the U.S. Department of Energy's National Renewable Energy Laboratory, was designed to allow both single-sided and cross-ventilation through the building [2]. The occupants are placed within 9 m from manually operable windows used for natural ventilation. The RSF having two wings with high length to depth ratio is beneficial for air to freely traverse the short depth of 18 m in addition to allowing deep penetration of daylight [3]. As well, there is internally exposed thermal mass that absorbs heat from the indoor environment during the day and is cooled at night through night ventilation with automatically controlled windows [2].

Natural ventilation in buildings can be inspired from vernacular architectural designs. The Moulmein Rise, a high-rise residential building known for its "Monsoon window" façade, where the windows' design is based on creating openings to draw air from below into the indoor environment for cross-ventilation [4]. Operable perforated air grilles from the window sill allow air to enter from outside while keeping the rain out. Other innovative buildings utilize natural ventilation with other technologies. For instance, The Lanchester Library in Coventry, England, UK uses the light well not only as a means to bring daylight into the building, but also as a means for natural air movement throughout the building [5]. Retrofits can also incorporate natural ventilation; the BCA Academy in Singapore included four solar chimney integrated with the façade and roof to naturally ventilate the building [6], and the GSW Headquarters in Berlin, Germany, was refurbished with a double-skin façade and makes use of cross-ventilation, which can yield up to 40% energy savings [7].

For mid- to high-rise buildings of with atria, there are many typical ventilation patterns that are discussed by Moosavi et al. in their overview of effective natural ventilation designs [8]. In general, the atrium either serves as an exhaust for hot air at the top of the building while cooler air enters it from the bottom or its sides, as an inlet for cool air into the building as it makes its way towards a solar chimney, or as both an entry and exit point for cool and hot air. The authors mention the different general placements of the atrium depending on the local climate: in temperate climates, it is often attached to the building and is highly glazed to allow solar energy in during winter, whereas in hot and humid climates, the atrium would be more centralized or linear within the building. Even given these generalizations, appropriate building design is required to predict if natural ventilation is plausible and if hybrid ventilation and/or fan assistance is required. Yang and Li [9] developed, for stack-based hybrid ventilation in tall buildings, a procedure with a dimensionless performance indicator to choose the appropriate ventilation scheme.

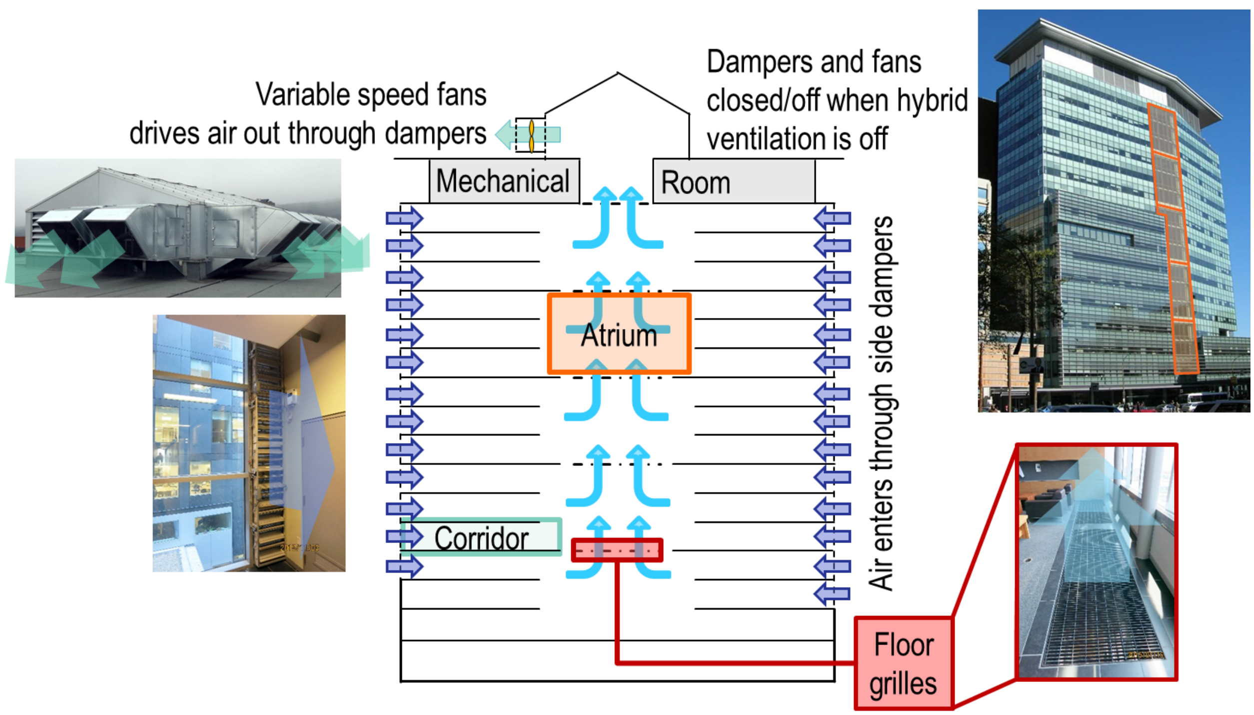

Figure 1-1: Schematic of fan-assisted hybrid ventilation system components in EV building.

The Engineering, Computer Science, and Visual Arts Integrated Complex (EV building) located in Concordia University's downtown campus in Montreal, Canada is a building that is designed and constructed to use fan-assisted hybrid ventilation, as shown in Figure 1-1. In hybrid ventilation systems, natural ventilation is used in parallel with the mechanical heating, ventilation, and air conditioning (HVAC) system, while fans increase air movement throughout the building [10].

Located in the temperate climate of Montreal, the EV building south facing façade is highly glazed, and has five stacked and interconnected atria that form a solar chimney. Motorized dampers on the south-eastern and north-western façades can be opened to allow outdoor air into the building. The air travels through corridors towards the atria and upwards to the roof where it is exhausted. In 2015, the addition of variable speed fans on the roof, at the end of the series of atria, increased the system's capacity to draw air into and out of the building when hybrid ventilation is in operation. As a representative mid- to high-rise institutional building in a temperate climate, the EV building was studied previously [11] and is used as a case study in this thesis to draw conclusions applicable to other similar buildings.

1.2 Motivation

A Natural Resources Canada report on a survey in 2009 states that commercial and institutional buildings in Canada consumed a total of 849.6 PJ, of which Quebec's part is 17% and Ontario's is 44% [12]. In Ontario, the 2002 summer peak profile for energy end use shows that 50% of the energy use in the commercial sector was for space cooling [13]. In addition, Natural Resources Canada's handbook of energy usage from 1990 to 2010 shows that the total growth for the total energy use in the commercial and institutional sector in Canada was 22%, and that the amount of energy used for space heating and cooling ranged from 50% to 59% [14]. It also shows a total growth of 84.2% for space cooling and 1.4% for space heating, indicating that reducing the need for space cooling in commercial and institutional buildings is essential in the pursuit of aggressively reducing energy consumption in buildings.

Commercial and institutional buildings often require cooling not only in summer, but also in shoulder seasons due to high internal gains. Using natural ventilation instead of HVAC systems in new buildings and retrofits can contribute to slowing down the growth of energy consumption for space cooling, and potentially cause a reduction instead. To further reduce the need for space cooling, building designs can include interior thermal mass to store heat during the day, and release it at night through night ventilation, depending on the diurnal temperature range at the building location. The aforementioned Lanchester library is one example of a building that uses night ventilation to cool down the building throughout the night such that the indoor temperature starts off low for the next day [5]. Another example is the EV building which couples exposed interior thermal mass, mainly the concrete floor, with natural night ventilation to cool it down during unoccupied hours.

1.3 Occupant comfort in a building

When designing new energy efficient buildings or retrofitting old buildings, it is important to remember that the purpose of the building is first and foremost to shield occupants from the harsh outdoor conditions that may arise. In other words, they should provide shelter from precipitations, strong winds, extreme heat or cold, and extreme sunlight. In fact, there are standards such as ASHRAE-55 [15], ISO EN 7730 [16] and EN15251 [17] that suggest the ideal indoor conditions such that human occupants are comfortable. Occupants would feel and react differently depending on their personal history and their expectations for indoor conditions. Someone living in the tropics would naturally be more accustomed to stronger heat than another person who lives in a cold climate. The standards attempt to take this into account for naturally ventilated buildings through the inclusion of the idea of adaptive thermal comfort by providing a range of acceptable operative temperature as a function of the monthly mean outdoor temperature [15] [16]. They also acknowledge that higher air movement around occupants leads to a higher acceptable indoor temperature. Clearly, while reducing the amount of energy used for space cooling is important, it is just as essential to ensure that the occupants are not discomforted. These standards, as well as their weaknesses will be discussed later in Chapter 2.

1.4 Objective

This thesis aims to derive insight in terms of thermal comfort from the use of hybrid ventilation coupled with exposed interior thermal mass in a representative mid- to high-rise commercial or institutional building constructed in a temperate climate and to provide guidelines for the use in predictive night cooling of the building. In order to avoid causing discomfort to occupants within the building, the main concern is to determine an adequate lower limit of the acceptable range of measured outdoor air temperature for operating in hybrid ventilation mode. To do so, local thermal comfort considerations are taken into account as well as the average air temperature in a subsection of the building: a corridor where outdoor air comes in. The thesis also looks at the effective thermal mass in this corridor and the heat transfer between the air, concrete floor, and surrounding surfaces.

1.5 Scope of the research and thesis outline

Through full-scale test data from the EV building, a calibrated thermal model of the first 10 m of a corridor adjacent to a motorized opening on the façade is developed to examine the thermal mass behaviour when employing hybrid ventilation. In addition, thermal conditions during and after using hybrid ventilation are strongly considered in order to determine an acceptable lower temperature limit for the admission of outdoor air into the building without causing discomfort to occupants. Moreover, an alternative criterion to a relative humidity range of outdoor air is proposed to increase the range of acceptable outside air conditions when outside air is allowed into the building for hybrid ventilation.

The thesis content is summarized into the following sections:

- Chapter 1, Introduction: provides a general overview of natural and hybrid ventilation in buildings and its significance in terms of the building cooling energy consumption and occupant thermal comfort.
- Chapter 2, Literature Review: presents the EV building and related past works regarding it and reviews different types of models for natural or hybrid ventilation, the parameters used for operating natural or hybrid ventilation, and the prescribed thermal comfort and its limitations for transitional spaces.
- Chapter 3, Thermal model based on full-scale tests in EV building: describes the development of the calibrated thermal network model, followed by the experimental setup and purpose of three different tests performed in the EV building
- Chapter 4 Results and Discussion: presents the measured data from the different tests in EV building with a focus on the thermal comfort implications and the free cooling potential. Results derived from the calibrated thermal model are also discussed to look at the behaviour of the thermal mass, and consider the possibility of implementing heuristic predictive control or model predictive control into the building automation system.
- Chapter 5, Conclusions: summarizes the main research findings of the thesis and presents recommendations.

2 Literature Review

This chapter first provides an overview of the EV building and studies that were conducted on this building, followed by a review of literature related to thermal models for buildings with natural ventilation, their controls and performance indicators, and finally occupant thermal comfort in the indoor environment.

2.1 EV building: a representative high-rise building for fan-assisted hybrid ventilation

One of Concordia University's own building located on the downtown campus was designed and constructed to make use of natural ventilation: the EV building. This 17-storey high-rise institutional building has offices for professors and students, research facilities and studios, as well as meeting rooms and classrooms. The 17th floor serves as the mechanical room of the building. The building has five atria, spanning three floors each, that are stacked one on top of the other, and each measuring 9 m x 12 m x 12 m high, with the façade facing 35° west of South. The openings between the stacked atria have grilles and motorized dampers that close in case of fire to contain smoke propagation. The two main large façades of this building are facing approximately south-east and south-west to favour solar heat gains in winter. Blinds are installed at the atria and in perimeter rooms for occupants to freely operate, but can also be automated. Typically, these should be down in summer to prevent overheating. Overall, the EV building requires cooling during the months of April until October and possibly even in the beginning of November. The high solar gains, coupled with an expected occupancy of 4,000-5,000 people, and a significant amount of plug loads makes for a building that requires cooling even when it is cool outdoors.

The EV building was used as a case study during the design process to simulate various options as a function of window-to-wall ratio, glazing type, shading devices and controls, electric lighting and controls, and hybrid and natural ventilation. The goal was to increase natural daylighting and reduce the need for electrical lighting, while at the same time reducing the peak and overall heating and cooling energy demand for the building, and eliminate the need for perimeter heating [18]. The suggested design in terms of natural ventilation is to have 5 atria interconnected via floor grilles, variable speed fans at the top of the highest atrium capable of extracting air at a total of 30,000 L/s, openings with motorized dampers on opposing ends of the corridor, and small vents in the perimeter offices. Construction for the building was completed in 2005; however, the perimeter office vents were discarded as a design feature and therefore never installed. The variable speed fans were also not installed initially to reduce costs, but their future implementation was taken into account in the design by creating a cabin for their future installation.

The typical floor plan of the EV building features a corridor that runs from the north-western to the south-eastern façade, corridors running from those two ends to the atrium, as well as smaller corridors that branch off from these main corridors. For the purpose of hybrid ventilation, the openings on the south-eastern and north-western façade allow outdoor air to enter and leave the building. The motorized dampers at these openings, along with those at the atrium floor grilles, are controlled by the building automation system (BAS). When hybrid ventilation is in effect, these dampers are opened for natural air movement; however, some rooms are still conditioned with the HVAC system. Due to wind, cross-ventilation within each floor can occur with air travelling from one end of the corridor to the other instead of towards the atrium. With the opening of the dampers at the atrium, air can flow upwards from the bottom atria to the roof exhaust due to buoyancy. The EV building couples hybrid ventilation with exposed thermal mass – which consists mainly of its 0.4 m thick concrete floor. During the day, as the indoor environment is warmed by plug loads, solar heat gains and occupants, the thermally massive components absorb a portion of the heat and slow down the process of heating the space. With natural ventilation, as the cool outdoor air travels from the façade openings towards the atria, shown in Figure 2-1, the building is cooled down, removing heat from the thermally massive concrete floor and allowing it to start the following day at a cool temperature. The interconnected atria form a solar chimney for hot air to exit at the rooftop. With the installation of the 3 sets of 2 variable speed fans at the roof in late 2015, air movement can be enhanced when needed through the BAS. Ultimately, the goal is to incorporate the weather forecast into a model to be written into the control program in order to operate hybrid ventilation in a predictive manner to suit the upcoming cooling demands or lack thereof.

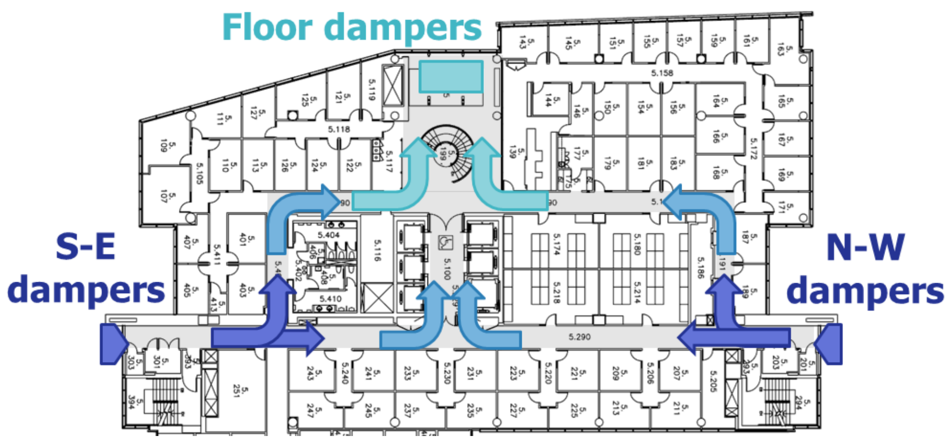

Figure 2-1: Typical floor plan in EV building and expected airflow path from the motorized inlets.

Incorporating hybrid ventilation into the EV building was a means to reduce the need for energy consumption due to space cooling and fresh air provision. As its use is controlled by the BAS, the controls program must have criterion that must be met to activate hybrid ventilation. During the design phase of the building, it was suggested that outdoor air temperature within the range of 12-20 °C and not exceeding 70% relative humidity is acceptable for hybrid ventilation during the time of the year when the building is mostly cooling-dominated [18]. It was also mentioned that, in terms of night ventilation, the temperature range can be extended to 8-22 °C. A later study was done on this building's thermal performance as a typical institutional building with hybrid ventilation [11]. It was shown that for a 30 m long corridor, the amount of heat removed from the concrete floor when the lower limit for inlet air temperature is 12 °C compared to air at 15 or 18 °C can be 2 or 5 times higher respectively. The study estimates that the amount of free cooling that can be achieved is approximately 30% of the total cooling load for the atrium and corridors. Measurements were also taken to verify whether the indoor environment was comfortable. An average temperature difference between the top floor and bottom floor of the atrium of about 2-3 °C was measured, while it is larger near the façade at 3-4 °C. The thermal stratification is at its highest around 16:00, with air temperature reaching 25.5 °C and 28.5 °C in rooms and the lobby area respectively.

2.2 Models for buildings with natural ventilation

At all stages in the design and analysis of buildings, models are useful for purposes such as considering alternative designs or simulating specific situations. Depending on the study, a model of the whole building may be required, and at other times, a model of a specific zone within the building would suffice. Even for a specific building, there can be many methods of modeling the zone of interest. This section gives an overview of the types of models used for natural ventilation in buildings and their benefits.

2.2.1 Physical models

Physical models make use of well-established concepts in physics, such as the continuity equation, the Bernoulli equation, and the conservation of mass and energy law. Also known as white box models, these models are useful so people can understand the reasoning behind the results are as they can examine at the physical properties or assumptions used. As a result, parametric studies with such models are performed easily by modifying specific physical inputs to the model. Building simulation programs use specific physical models which are generally described in detail in the user manual or guide.

A comprehensive study on heat and mass transfer by Santamouris et al. focuses on natural convection through large openings between adjacent zones within a building [19]. The effects of gravitational flow is considered by applying the Bernoulli equation with the continuity equation, and heat transfer equations, whereas the effects of boundary layer flow is considered through applying heat transfer to a resistance network. Their study included a comparative table of different experimental set-up in terms of their proposed systematic classification of convective heat transfer algorithms to natural convection. Meanwhile, Aynsley introduces the airflow resistance approach to analyse natural ventilation as an alternative to computational fluid dynamics [20]. Like in thermal resistance networks, this approach is analogous to an electric circuit, where volumetric airflow rate, airflow resistance, and pressure differences or head losses are the equivalent to current, electrical resistance, and voltage respectively. As equations need to be simultaneously solved, the Hardy Cross method of balancing flows at the network nodes until the error throughout the network is negligible is suggested. On the other hand, Boyer et al. couple thermal and airflow resistance models and explain how they can be included in a simulation software, by detailing the relevant procedure used in the simulation code called CODYRUN [21]. At every iteration, the airflow simulation and heat flow simulation are run consecutively with the air mass flow being the coupling variable. When setting up the network, larger openings would be separated into several smaller openings, and it was stated that even with small pressure differences, there is an important mass flow through a large opening.

With the advancement of technology, many have turned to using simulation software to model an existing building or alternative designs for new buildings. The user can choose from the modelling options made available to them in the specific software. They are expected to have consulted the user manual to understand which physical modeling techniques they can use and the assumptions that the software makes. A variety of simulation software exists, and researchers have used them for the modeling of buildings with natural ventilation as well. For example, Adamu et al. uses IES to perform dynamic thermal simulations and PHOENICS to perform simulations using computational fluid dynamics (CFD) [22]. Their focus was to investigate the performance of four different strategies for natural ventilation in terms of airflow rate and thermal comfort in a healthcare environment. Schulze and Eicker instead use EnergyPlus coupled to an air flow network model to compare the performance of an office building in three different locations with moderate climate [23]. Belleri et al. also use an airflow network with EnergyPlus, but to predict the performance of a naturally ventilated building in California and compare with measured data in order to do identify the parameters with highest uncertainty [24]. They use three metrics which encompass modeling window usage, air change per hour, and determining the number of hours where the minimum ventilation rates detailed in the ASHRAE standard 62.1 is met or exceeded. It was found that the predictions for occupant control of window is most inaccurate, which causes a difficult situation when designing a building without measurements to use as input.

An extensive study is done by Geros et al. using measurements from three different buildings in Athens and creating models using TRNSYS in order to find parameters that affect the efficiency of night ventilation [25]. The resulting three parameters are the relative difference between the indoor and outdoor temperature, the useful air flow rate, and the thermal capacity of the building. Under free-floating conditions, night ventilation can reduce the following day peak indoor temperature by up to 3 °C. Also, their results show that the temperature setpoint during the morning can be lowered by 0.8 °C to 2.5 °C in order to further delay and reduce cooling energy demand. Another parametric study, by Oropeza-Perez and Østergaard using airflow-thermal simulations in EnergyPlus, shows that in temperate climate, the input parameters in order of greatest influence on the energy savings are [26]:

1) the temperature difference between indoors and outdoors,
2) internal heat sources,
3) outdoor temperature,
4) temperature setpoint,
5) wind speed,
6) solar heat gains of the thermal mass.

2.2.2 Data-driven models

On the other end of the models spectrum, there are data-driven models or black box models. These require historical data in order to predict the outcome given a new set of conditions. Unlike physical models, the relationship between the various inputs and outputs have no physical meaning, and is thus case specific; however, the methodology for creating these models can be applied to different buildings.

Spindler and Norford propose a data driven linear thermal model for buildings using natural or hybrid ventilation [27]. The model handles several thermal zones as well as different operating modes. A list of features (model inputs), which can include linearization of nonlinear functions, are selected along with an initial number of lag terms associated with them, creating a dependence on the values of previous time steps. The amount of lag terms are then increased or decreased in accordance to forward/backward selection. The coefficients to the linear equations in the model are then determined through the training set of data. From there, the model undergoes testing and validation using the data for each purpose. Their model has been successfully applied to two complex buildings with hybrid ventilation.

Mahdavi and Pröglhöf created two models that predict both the air change rate and mean indoor air flow speed based on the window opening position, the exterior air speed, and the temperature difference between the indoor and outdoor conditions, for controls purposes with natural ventilation [28]. The first is a statistical model based on in-situ measurements, while the second is a calibrated multi-zone airflow model built using the simulation program BACH. The models had a similar deviation range in their predictions; however, some of the error is attributed to the inputs that are used, such as weather conditions, and leakage through cracks. They suggested that a deviation range of less than 40% for air change rate and air flow speed s practical enough for the control system with natural ventilation.

2.2.3 Modelling thermal mass in naturally ventilated buildings

For buildings located in climates with large diurnal temperature variations, the use of natural ventilation is especially useful when coupled with thermal mass. By retaining heat during the day, the exposed thermal mass contributes to a reduction in the peak indoor temperature by delaying this peak. A study by Yam aims to predict the time lag in thermally massive buildings and found that a delay of 6 h is possible without controlling outdoor air supply [29]. Through night ventilation, when the outdoor air temperature is cooler, the accumulated heat within the thermal mass is released as cool air flushes the building. A study done by Shaviv et al. for a thermally massive building involves simulating it in four different locations in a hot and humid climate, and using night ventilation [30]. Their simulated results show that a thermally massive building's indoor temperature can be reduced by 3-6 °C, and that there is an effective plateau when the air change rate reaches 20 ACH.

Parametric studies can be executed for thermally massive naturally ventilated buildings; they can be especially useful during the design stage. For example, Zhou et al. use the harmonic response method of modeling thermal mass in a building coupled with natural ventilation. Their goal was to estimate not only the average indoor air temperature, but also the time constant, and heat transfer number depending on the size of the internal thermal mass, the construction of the thermally massive external walls, local climate, and internal heat source [31]. Different combinations of construction and internal mass were compared to find a case where the indoor air temperature fluctuation and mean are acceptable for comfort.

2.3 Parameters used for control

Buildings that use natural ventilation depend on single-sided and/or cross-ventilation, and stack effect [32]. Strategic placement of openings, such as doors and windows, in the building is essential to ensure adequate airflow in and out of the building. As well, having effective blinds can limit the amount of solar heat gain through the glazing and avoid high indoor temperature. More importantly, how the occupants operate the openings, and shades will greatly affect the effectiveness of natural ventilation. In hybrid ventilation, where HVAC systems are in use simultaneously, or with fan-assisted natural/hybrid ventilation where fans are installed to enhance air movement, occupant control or the BAS control sequence over the HVAC and/or fans also play a crucial role. A study relating thermal comfort and occupant control of doors, windows, blinds, fans, and lights was done by Raja et al. using surveys at fifteen buildings in the UK [33]. They found that as indoor temperature rises above 20 °C, there is a surge of occupants opening windows, with almost all windows open once it reaches 27 °C. Similarly occupants start using fans when the indoor and outdoor temperatures are at 20 °C and 15 °C respectively. Findings that allow generalization of their operation are particularly useful for buildings that include window, shade, and fan controls in their BAS, not only to reduce the need of human input, but also for unoccupied hours. In fact, Mahdavi and Pröglhöf suggest using model-based control schemes, where the control system periodically checks for any action required from it based on a simulated future state of indoor environment [28]. Based on a chosen performance indicator that can be simulated, the BAS will compare simulation results of different courses of action; for example, compare the indoor temperature setpoint with the predicted temperature depending on whether windows are open or not. For such type of controls, a simple model is preferred, such that computation time stays reasonable. Table 2-1 compares parameters used in various studies concerning the control sequence used in buildings with natural ventilation and their performance indicators.

Table 2-1: Variables used when controlling the use of natural ventilation in a building and performance indicators.

Study	Model or Software	Day/Night scheme	Specified schedule	Outdoor temperature	Outdoor dewpoint temperature	Outdoor relative humidity	Indoor temperature	Operative temperature	Wind speed/Inlet velocity	ACH	CO_2 concentration	predictive control	Performance criteria
Kolokotroni and Aronis [34]	BRE's 3TC (thermal), CIBSE's AM10 (ventilation)		√	√									
Pfafferott et al. [35]	ESP-r and parametric model	√								√			reducing room temperature and heat dissipation
Artmann et al. [36]	HELIOS		√	√				√					operative temperature, and overheating degree hours above 26 °C
Spindler and Norford [37]	linear model for each control mode		√				√					√	indoor temperature range, use minimal electric energy to operate the fan
Prajongsan and Sharples [38]	CFD package in DesignBuilder, EnergyPlus (thermal)							√	√				percentage of hours within comfortable operative temperature
Karava et al. [11]	semi-empirical model	√		√		√							cooling of concrete slab, indoor temperature at atria
Schulze and Eicker [23]	EnergyPlus, airflow network model			√			√	√			√		cumulative number of hours with temperature outside of setpoint to a limiting value
Hu and Karava [39]	MATLAB with Particle Swarm Optimization	√			√		√	√	√			√	hourly mean energy consumption, peak demand, and operative temperature deviation

2.4 Thermal comfort in indoor environment

Even with a main focus on reducing energy consumption in buildings, it must not be forgotten that ultimately, buildings were made to shelter occupants from the harsh outdoor conditions. Expectations for a thermally comfortable environment led to the creation of standards and design guidelines, which are updated regularly to incorporate new research findings. For example, the ASHRAE standard 55 was revised to include adaptive thermal comfort for naturally ventilated buildings [40]. The following sections briefly describe reviews on standards ASHRAE standard 55, ISO 7730, and EN15251, followed by a review on thermal comfort in transition spaces.

2.4.1 Existing standards

The ASHRAE standard 55 for thermal environmental conditions for human occupation uses a 7 point scale for predicting the mean vote for thermal comfort. This is then related to a predicted percent dissatisfied (PPD) and is used for setting the limits of indoor conditions. For example, the standard prescribes temperature ranges or limits for the floor temperature, and thermal stratification from 0.1 m to 1.7 m off the ground. For naturally ventilated buildings, an adaptive thermal model is used, where the indoor operative temperature is prescribed depending on the monthly mean outdoor temperature. In addition, increasing the air velocity is equivalent to increasing the upper limit of the acceptable indoor operative temperature range, in order to take into account convective cooling.

With regards to the seven-point scale used by ASHRAE 55, Humphrey and Hancock conducted experiments that asks not only how the occupant felt thermally, but also what they wanted to feel [41]. To that effect, a positive correlation is found in the range from cool to warm and a negative correlation at the extreme feelings of hot and cold, where they would rather feel slightly cool or slightly warm respectively. Generally, results showed that occupants wanted to feel neutral or slightly warm and an adjusted ASHRAE scale that takes into account the difference between actual thermal sensation and desired sensation was proposed; however, since the study was conducted in the UK, the findings are expected to differ in other climate.

Five naturally ventilated low-rise thermally massive office buildings in France were studied by Moujalled et al. to evaluate the thermal comfort algorithms detailed in ISO 7730, EN15251, and ASHRAE standard 55 [42]. The first is based on a static model, whereas the two latter include adaptive thermal comfort algorithms for naturally ventilated buildings. Despite occupants feeling warm and wanting more air movement during the warm season, over 90% of occupants were accepting of the interior conditions during cool season. They found that the ISO standard overestimates the predicted percent dissatisfied, whereas the adaptive thermal comfort algorithm predicts thermal comfort well.

Nicol and Wilson critiques the European Standard EN 15251, saying that it was written with the undertone that buildings are by default mechanically ventilated buildings and that naturally ventilated buildings make for subpar indoor environment [43]. Unlike the ISO 7730 and ASHRAE Standard 55, the EN 15251 do not take local discomfort into account, meaning that air drafts, radiant temperature asymmetry, vertical air temperature difference and floor surface temperature is not considered. For hybrid or naturally cooled buildings, the comfort temperature varies linearly with the running mean of the outdoor temperature, which is a better variable to use than the monthly mean of the outdoor temperature. The predicted comfort temperature, however, doesn't produce a range of temperature for any value of running mean of the outdoor temperature; hence, many instances of the environment at the prescribed temperature would differ from the occupants' actual preferred temperature.

Ning et al. did a study on the thermal comfort of students in their university dormitories from September to May in Harbin, China [44]. During the transition season, occupants were adapting themselves to the gradually colder environment and 90% of the acceptable temperature went as low as 18.9 °C. Once heating season started, the indoor environment was heated to 23 °C, the students felt that it was warm and even actively opened windows. The sudden increase in indoor temperature in the heating season counteracts their adaptation to the cold and leads to a waste of energy. As a result, the study argued that the lower limit of indoor temperature in ASHRAE Standard 55 should be lowered due to occupants' adaptability to the cold. After having adapted to the cold by the end of autumn, once the occupants are more inclined to be indoors due to the harsh coldness of winter, their thermal comfort zone will also shift towards the indoor temperature setpoint. The students' neutral temperature is then shifted higher, when it should be lower from acclimatization to the outdoors. Their thermal sensation and comfort thus varied with the season even though the conditions were similar.

2.4.2 Transition spaces

Usually in buildings, there are spaces that serve as connectors or circulation areas between occupied spaces. In these transient spaces where occupants are merely passing by, it can be argued whether expectations of thermal comfort can be less stringent, such that less energy is required to condition their environment.

The literature review by Chun et al. demonstrates that there is ambiguity in the term "transition space" as it differs between authors [45]. This term can be defined as exterior spaces such as balconies, courts, arcades, and verandas, and/or interior spaces such as underground shopping malls or metro stations, building entrances, atria and corridors. The authors categorized the transition spaces in terms of how the space is affected by outdoor conditions, including a category for detached exterior spaces such as a bus shelter. Their study shows that the PMV in the latter type of transition space would not be applicable as it would be out of the range from -2 to +2, whereas a sensation of warmth is possible in enclosed interior transition spaces where occupants are expected to be moving through and have a higher metabolic rate. This finding is confirmed by a study performed by Pitts and Saleh who considered transition spaces as buffer spaces and physical links between the outdoor and indoor environment [46]. Taking into account the expected higher air velocity and metabolic rate of occupants as they walk through the spaces, they found that the lower limit of acceptable temperature within the indoor environment can be at least 2 °C lower in transition spaces. They performed an analysis of potential energy savings for four types of configuration for transition spaces in all orientations and the configurations with the highest potential were those where the transition zones span across the façade. Their results show that by allowing the temperature setpoint to be at 16 °C, savings in heating energy can be up to 35% for these configurations when considering only the transition spaces. Pitts and Saleh also found that different orientation of these spaces modestly affect the energy consumption in heating season, but is significant in terms of cooling energy requirements. They concluded by stressing the importance of transition spaces when designing a building in terms of energy consumption.

In a later study, Pitts separates transition spaces into three categories: entrance, circulation, and longer-term occupancy zones [47]. These are described based on the typical stay period, clothing insulation, and metabolic rates. Of the three, circulation zones encompass spaces where occupants are expected to be walking or standing in, for 5-10 minutes, and with varying clothing insulation. Pitts found that in these area, the PMV range can be increased from ±0.5 to ±1.5, even when accounting for the varying clothing insulation and physical activities of the occupants in the study. On the other hand, the PMV range for other indoor spaces can potentially be extended from ±0.5 to ±0.7. Having a wider range is consistent with the lower thermal expectation from occupants in transition spaces.

An interesting study by Wu and Mahdavi examined the difference in thermal comfort votes of occupants subjected to different temperature changes from one room to another [48]. The concept of an effective temperature difference is proposed relating the temperatures between the two rooms to a comfort temperature. An equation for the difference in thermal comfort votes was then made as a function of clothing insulation and the effective temperature difference. It maybe be possible to apply these concepts to transition spaces adjacent to an entrance to a building, as it is generally where the greatest temperature difference occurs in mechanically ventilated buildings.

2.5 Conclusions

Studies of Concordia University's EV building were presented dating from its design phase to building occupation. This building is emphasized as it is representative for the following building archetype: a thermally massive mid- to high- rise commercial or institutional building with openings on multiple façades and a solar chimney with fans at the top and for fan-assisted hybrid ventilation. Hybrid ventilation, whether fan-assisted or not, was shown to have a great potential for reducing cooling energy consumption in buildings, but research is needed better understand its effect on the building, both in terms of the thermal response and thermal comfort for occupants and to use this knowledge in the form of guidelines or models for its predictive control.

A variety of models, either physics based or data-driven, were presented to show different methods of modeling buildings with natural ventilation, with the goal of gaining a better understanding of the building behaviour with response to the exterior environment and the employment of natural ventilation. From the presented studies, the goal of implementing predictive controls for operating natural ventilation in buildings to match the upcoming cooling loads was sought out in order to further the reduction in cooling energy consumption. In terms of controls, different parameters that are used either to control when to operate in natural ventilation mode or as a target for gauging the performance of using natural ventilation given the indoor and outdoor environment conditions were listed. The most common criterion was related to the outdoor and/or indoor air temperature. Undeniably, saving on cooling energy consumption would be meaningless if it significantly increased occupant dissatisfaction due to discomfort. The ASHRAE Standard 55 and ISO 7730 are briefly described for how they provide guidelines for occupant thermal comfort. Moreover, their limitation was mentioned, especially regarding its lack of regulation for transitional spaces where occupants are not staying for prolonged periods of time and are more accepting of deviation from the ideal prescribed interior environment. This paves way for the research that will be presented as it deals with not only the cooling potential by employing hybrid ventilation and the effects of varying the criteria for its operation, but also considers occupant thermal comfort in the transitional space that is the corridor which is the critical region for developing guidelines for the lowest ambient temperature at which the hybrid ventilation system can be operated.

3 Thermal model based on full-scale tests in EV building

Buildings with high level of thermal mass can benefit from natural ventilation, especially night ventilation, during cooling season given a large diurnal temperature difference. Free cooling reduces the need for mechanical conditioning of the indoor environment and helps circulate air throughout the building. In mid- and high-rise buildings, the potential savings can be substantial. Therefore, being able to model the thermal behaviour of such a thermally massive building subject to natural or hybrid ventilation will provide insight on the amount of cooling that can be achieved. This chapter presents the methodology used for the development of a calibrated finite difference thermal model of a subzone in a building designed and constructed for natural or hybrid ventilation. The EV building in Concordia University's downtown campus is used as a full-scale case study and the on-site measurements are used to calibrate the thermal model.

3.1 Model description

A thermal model can vary greatly in complexity. As opposed to a CFD model or a detailed thermal network model, the model that is developed is a simple model keeping in mind that it would be ideally integrated into the BAS control sequence. In fact, due to many uncertainties in a building, caused by, for example, wind effects, the building geometry and even the number of floors and rooms, the model inevitably will need to be calibrated to take these factors into account. The more calibration is required, the more possible combinations there are to a solution, which can bring about more error in the model. To this effect, simplification of the model in terms of building geometries should be made when possible, and reasonable assumptions should be used. Ultimately, the developed model is a grey box model, since although it uses the explicit scheme of finite difference equations, it is calibrated using the collected data from the full-scale test. In this thesis, the developed model is based on the EV building, but the general procedure can be applied to other buildings as well:

1) Geometry and discretization
2) Thermal network
3) Properties and calibration factors
4) Timestep

3.1.1 Geometry and Discretization

The developed model does not encompass the building as a whole. Instead, it emphasises the first space that cool air enters from the motorized openings on the façade since it is where the most heat exchange between the cool incoming air and the corridor surfaces is expected. Cool outdoor air enters the EV building through openings on opposing sides of the façade for cross-ventilation and a roof exhaust draws warm air out with the stack effect. The region of interest is therefore the first 10 meters of the corridor starting from the South-East façade, which runs until near the intersection with other corridors. Aside from an electrical room at roughly 3 m from the façade, and the access to the emergency staircase at approximately 7 m from the façade, the corridor's only occupied space would be the meeting room that is located around 12 m from the façade. There are a few simplifications in the developed model in terms of geometry. First, the corridor is assumed to be a 1.8 m x 3 m x 10 m rectangular prism on top of a 0.4 m thick concrete slab, and the whole façade is considered as the opening inlet for air. In reality the corridor is wider at the glass façade, and the motorized dampers are placed on the side that widens, as shown in Figure 3-1, in order to keep the motorized dampers somewhat out of sight to occupants. In addition, the corridor has suspended ceiling consisting of acoustic tiles and luminaires; the space above the suspended ceiling is not considered in the model since this space essentially does not interact with the cool incoming air.

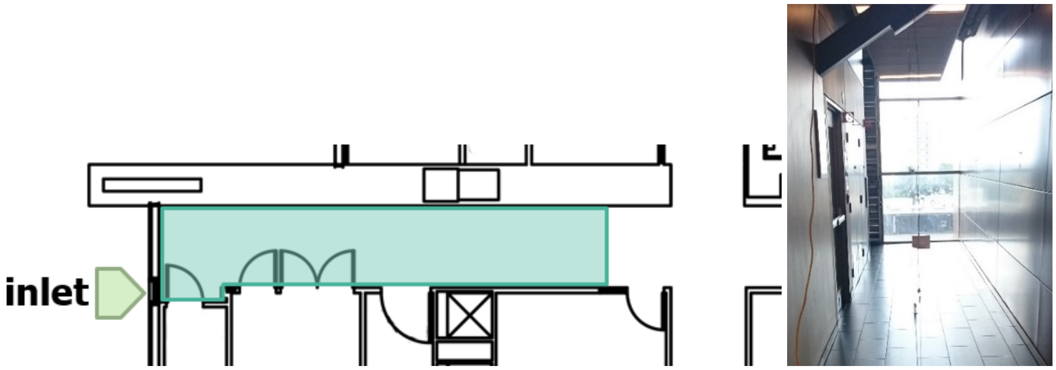

Figure 3-1: Actual corridor geometry (left) and photo of the corridor with the inlet on the façade (right)

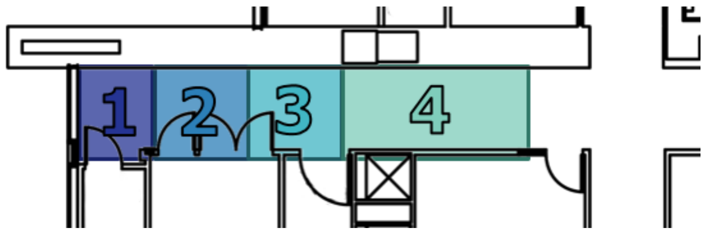

Figure 3-2: Discretizing the corridor along the corridor.

The geometry settled, the corridor must be discretized in a way that can describe the main heat transfer between the incoming stream of air and concrete floor surface adequately, but with the least amount of sections in order to reduce the amount of calibration required. The corridor is separated into 4 sections along its length as shown in Figure 3-2. Each section length is as follows: 1.5 m, 3 m, 3 m, and 2.5 m. As most of the heat exchange between the cool air and the indoor environment is expected to occur close to the façade opening, the regions near the façade are much smaller. On the other hand, the 0.4 m thick concrete floor is discretized along its depth such that it is symmetrical along the mid-depth plane with the thicknesses 0.5 cm, 1.5 cm, 3 cm, 5 cm, and 10 cm in a manner that the layers are thinner near the exposed surfaces and thicker at the center, as shown in Figure 3-3. This was done so that the exposed layers can be approximated as a lumped solid by verifying their Biot number [49] using Eq. 1, where Bi is the Biot number, h is the convective heat transfer coefficient (W/m^2·K), k is the thermal conductivity (W/m·K), and L_c is the characteristic length (m). When this dimensionless number, which compares the resistive forces of convection at the surface and of conduction within the solid, is less than or equal to 0.1, the lumped solid assumption can be applied.

$$Bi = \frac{h * L_c}{k} \leq 0.1 \qquad \text{Eq. 1}$$

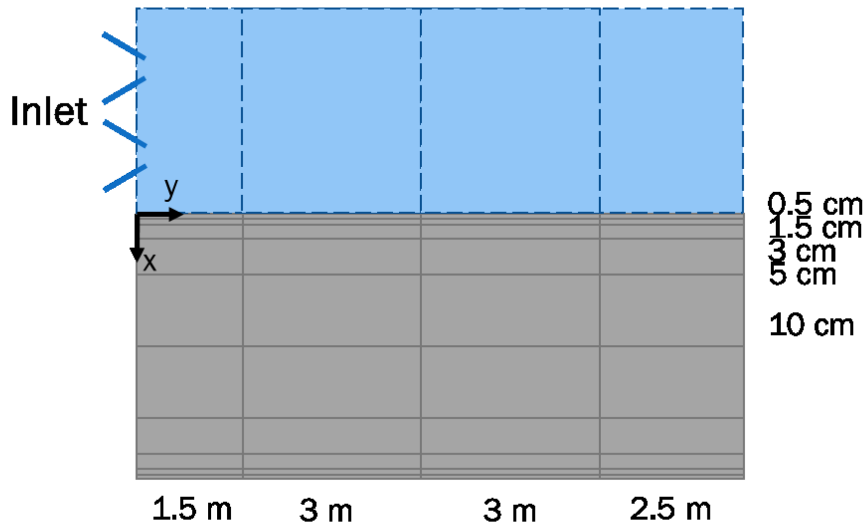

Figure 3-3: Discretized corridor into 44 control volumes; 4 for air (blue) and 40 for concrete (grey).

3.1.1 Thermal network and equations

The developed thermal network model uses the explicit scheme of the finite difference method and is calibrated using on-site measurements during a test described in section 3.2.1. It represents a numerical solution of the two-dimensional transient heat diffusion equation shown as Eq. 2 with convective boundary condition between the floor surface and air shown as Eq. 3 (combined convective-radiative coefficients are assumed). The air node, in turn, has heat transfer with the surrounding surfaces. At the bottom surface of the concrete floor, the boundary condition with the air below it also uses a combined film coefficient, but the air temperature is considered to be constant at the setpoint temperature, since the air below the concrete slab is the stagnant air above the suspended ceiling of the floor below. In fact, due to the lack of air circulation below the slab, the majority of heat exchange with the concrete floor is with the incoming rolling air stream of outdoor air. In this model, the corridor is separated into 4 control volumes as numbered in Figure 3-2 with y=0 representing the inlet and x=0 representing the surface of the concrete floor.

$$\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)=\frac{\partial T}{\partial t} \qquad \text{Eq. 2}$$

where thermal diffusivity $\alpha = \frac{k}{\rho c_p}$

$$q_{x=0} = h[T_{air}(y) - T_s(y)] \qquad \text{Eq. 3}$$

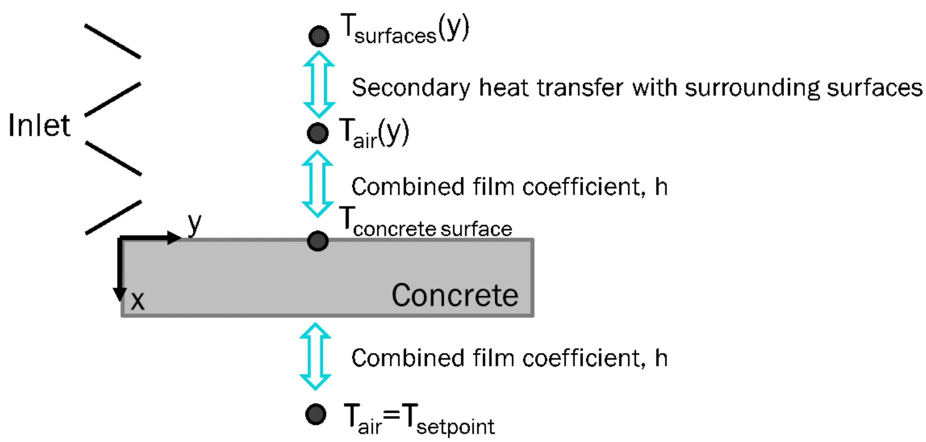

Figure 3-4: Schematic for 2-D transient heat diffusion equation with convective boundary condition at the concrete floor surface.

The thermal network shown in Figure 3-5 is used to represent the building components' interaction with incoming cool outdoor air. In order to keep the number of control volumes and nodes at a minimum (since this is a calibrated model), the wall and ceiling temperatures are combined and called "surfaces" temperature henceforth. Moreover, although each surface temperature was measured during the night ventilation test, having visible sensors in the corridor is unwanted. As a result, the combined surfaces temperature is calculated in the model using linear correlations for each control volume along the corridor, based on its location, the concrete floor temperature, and inlet air temperature. By doing so, the need for sensors on the walls and ceiling is avoided. With these simplifications to the thermal network, the amount of calibration factors are lessened to 4 per corridor section; 3 effective heat transfer coefficient and 1 air velocity calibration factor per corridor section.

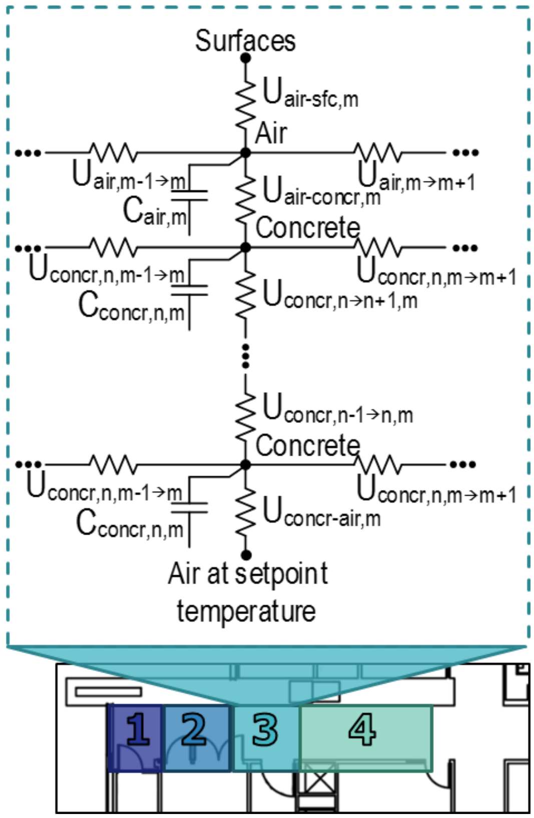

Figure 3-5: Thermal network of modeled corridor (typical subnetwork of section 3 is displayed showing air and concrete control volumes).

$$\begin{aligned} T_{air}{}_m^{p+1} = T_{air}{}_m^{p} & \\ & + \frac{\Delta t}{C_{air_m}} \Big[\rho_{air} c_{p_{air}} v_{air_m}{}^{p} \, A_{corridor} \left(T_{m-1}^{p} - T_{air}{}_m^{p} \right) \\ & + UA_{air-sfc_m} \left(T_{sfc}{}_m^{p} - T_{air}{}_m^{p} \right) + UA_{air-concr_m} \left(T_{concr}{}_{n,m}^{p} - T_{air}{}_m^{p} \right) \\ & + \rho_{air} c_{p_{air}} v_{air_m}{}^{p} A_{corridor} \left(T_{air}{}_{m+1}^{p} - T_{air}{}_m^{p} \right) \Big] \end{aligned} \qquad \text{Eq. 4}$$

$$\begin{aligned} T_{concr}{}_{n,m}^{p+1} = T_{concr}{}_{n,m}^{p} & \\ & + \frac{\Delta t}{C_{concr_{n,m}}} \Big[UA_{concr_{n,m-1\to m}} \left(T_{concr}{}_{n,m-1}^{p} - T_{concr}{}_{n,m}^{p} \right) \\ & + UA_{concr_{n,m\to m+1}} \left(Tc_{n,m+1}^{p} - Tc_{n,m}^{p} \right) \\ & + UA_{concr_{n\to n+1,m}} \left(T_{concr}{}_{n+1,m}^{p} - T_{concr}{}_{n,m}^{p} \right) \\ & + UA_{air-concr_2} \left(T_{air}{}_m^{p} - T_{concr}{}_{n,m}^{p} \right) \Big] \end{aligned} \qquad \text{Eq. 5}$$

where $A_{air\text{-}concr}$: area of contact between air and concrete (m^2)

$A_{air\text{-}sfc}$: area of contact between air and surfaces (walls and ceiling) (m^2)

A_{concr}: area of contact between two layers of concrete within and/or in different control volumes (m^2)

$A_{corridor}$: cross-sectional area of the corridor (m^2)

Δt: timestep (s)

C_{air}, C_{concr}: thermal capacity of air and concrete respectively (J/K)

c_{p_air}: specific heat capacity (J/kg·K)

k: thermal conductivity (W/m·K)

$_{air}$: air density (kg/m^3)

T_{air}, T_{concr}, T_{inlet}, T_{sfc} : temperature of air in the corridor, concrete floor surface, inlet air, and combined surfaces respectively (°C)

T_{concr} : concrete floor surface temperature (°C)

U: thermal conductance or effective heat transfer coefficient (W/m^2·K)

v_{air}: air velocity perpendicular to the inlet (m/s)

superscripts p and $p+1$: the current timestep number and the following one

subscripts n, and m: concrete layer number (from top to bottom), and control volume numbers respectively

The equations Eq. 4 and Eq. 5, used in this thermal model represent the typical equations used to simulate air, and concrete temperature respectively with time. The model is used for night ventilation simulations. As a result, the term for solar radiation is omitted in these equations; however, it can simply be added when considering daytime natural or hybrid ventilation. Care would then be needed in order to calculate the depth of the building to which direct solar radiation impinges incident, such that the term is only included in the affected floor control volumes. The effective heat transfer coefficients, shown in Table 3-1, are calibrated and fairly large since they incorporate radiative and convective heat transfer, and encompass other elements such as heat gain due to air infiltration, lighting and plug loads. These coefficients are especially high between the air and floor surface since the cold outdoor air is denser and will go towards the floor and make its way along the natural flow path towards the atrium due to the design of the building. In other words, the most heat transfer occurs near the floor. The heat transfer between the air at the corridor and the surfaces, on the other hand, is mostly due to vertical air movement due to buoyancy, which is a natural process. Finally, the air between the bottom surface of the concrete floor and the suspended ceiling of the floor below experiences little movement, the effective heat transfer coefficients between those two nodes are a lot smaller.

Table 3-1: Effective heat transfer coefficient used in the thermal model

Effective heat transfer coefficient ($W/m^2 \cdot K$)				
Corridor section	1	2	3	4
Air – surfaces	4	4	3	2
Air – concrete	9	12	9	8
Concrete – air (floor below)	2	2	2	2

Table 3-2: Air velocity calibration factors used for calibration in the thermal model.

Air velocity calibration factors				
Between corridor section	inlet ↔ 1	1 ↔ 2	2 ↔ 3	3 ↔ 4
velocity calibration factor	1	0.6	0.2	0.2

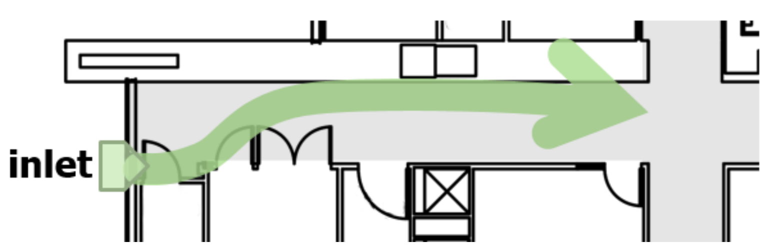

Figure 3-6: Expected airflow path in the corridor.

Due to the actual geometry of the corridor, the air is expected to flow from the inlet into the corridor as depicted in Figure 3-6. The empty space near the façade, where the first corridor section is located is assumed to be a region with air recirculation. The area along the wall, opposite of the expected airflow path is also assumed to be a recirculation area. A CFD model of the corridor section was developed in FLUENT by a colleague and confirmed these assumptions. As such, air is expected to move freely back and forth between each corridor section and calibration factors, listed in Table 3-2, are attached to the air velocity in order to take the potential backflow into consideration. The summation of the calibration factors along the corridor is equal to 1, indicating that all-in-all the amount of air that enters from the inlet is equal to the amount of air leaving the end of the corridor. These values were adjusted manually based on the on-site measurements.

The equation for the air node, Eq. 4, takes into account the convective heat transfer due to forced air movement along the corridor length caused by wind, and the vertical air movement due to buoyancy. As for the concrete surface node equation, Eq. 5, the top concrete layer interacts with air through mainly forced convection due to wind and partly due to natural convection by buoyancy. It also has conductive heat transfer laterally with the control volume of the top layer at the previous and next corridor section, and along its depth with the control volume of concrete layer right below.

The physical properties of both concrete and air are needed for the thermal model. Typical values of density, specific heat capacity, and thermal conductivity of concrete that are used in the model are assumed to be constant. The floor is assumed to be concrete with a density, ρ, of 1,700 kg/m^3, specific heat capacity, c_p, of 800 J/kg·K, and thermal conductivity, k, of 1.7 W/m·K. The properties of air are assumed to be constant despite the changes in outdoor conditions with regards to pressure and temperature; its density is 1.2 kg/m^3 and specific heat capacity is 1,005 J/kg·K.

Because the thermal model uses the explicit scheme, it is essential that the timestep used in the simulations is small enough to ensure stability. In other words, the timestep must be less or equal to the smallest timestep calculated from Eq. 6, where Δt is the critical timestep at node i, C_i is the thermal capacity at node *i*, and U_{ij} is the thermal conductance between node *i* and surrounding nodes *j*.

$$\Delta t \leq \frac{C_i}{\sum_j U_{ij}} \qquad \text{Eq. 6}$$

In order to proceed with the thermal model to simulate concrete and air temperatures, initial conditions are required. The on-site data measured right after starting hybrid ventilation is used as initial conditions for air, surrounding surface, and concrete surface temperatures. The interior nodes of the concrete floor, on the other hand, are linearly interpolated between the measured floor surface temperature and the setpoint temperature for the floor below.

3.2 Full scale tests in EV building

Although many buildings have included natural or hybrid ventilation in their design, more research is needed to elucidate ways to systematically integrate this concept to increase energy savings without compromising occupant comfort. This thesis focuses on the building archetype of a mid- to high- rise building with high level of thermal mass, and openings on two opposite façades with common corridors leading to a solar chimney with or without fan-assistance. To this end, it is fortunate that Concordia University's building engineering researchers contributed to the design of the EV building so that it was constructed to fit this archetype. As a result, the whole building became a living laboratory. In addition, with the assistance and approval of the building managers, it was possible to research the possible criteria for operating the building in hybrid ventilation mode by directly modifying the program within the BAS. Several tests were performed in this building including on-site measurements with night hybrid ventilation and temperature measurements along the exposed staircase in the atrium to observe thermal stratification during the day. Finally, with the installation of the three pairs of variable speed fans at the top of the highest atrium near the end of 2015, preliminary tests were performed to obtain a general idea of its effect on the building's interior environment.

3.2.1 Corridor region

The region where outside air first enters the building from the façade openings is investigated, as it is where the most heat removal is anticipated and the evolution of air temperature by the time it reaches the end of the corridor is expected to be sufficient to gauge occupant comfort. The first 10 m of the corridor with the motorized inlet is considered to gain information on the changes in the air temperature along the corridor and the behaviour of the main thermal mass of the building. In order to determine an appropriate temperature lower limit at which outside air is admitted into the building, a test is conducted on the night of October 8th, 2015 between 22:00 and 6:00. During the day, the air temperature at the Dorval airport weather station ranged from a high of 12.1 °C in the late afternoon to a low of 8.1 °C by 2:00 (October 9th) and then decreasing to 5.4 °C by morning at 7:00. For the test at the corridor, hybrid ventilation is only employed from 22:00 to 2:00, with forecasted air temperature around 8-9 °C and relative humidity between 54-63%, after which the motorized dampers are closed for the following 4 hours. Having outside air at this low air temperature enter the building represents an ideal scenario for night cooling, since even lower air temperatures can lead to discomfort for the few occupants in the building at these hours. As well, it is representative of the months of shoulder seasons (April to June and September to October and possibly November) when outdoor conditions can reach this low air temperature at night, and precooling the building is still beneficial towards reducing the EV building energy consumption for cooling during the day. In addition, the large temperature differential between the inside and outside air creates a temperature gradient that is expected to be significant for the heat transfer processes as it promotes airflow into the building and renders modelling errors less significant.

The measurements are taken on the 5th floor of the EV building at the end of the south-eastern corridor. Since this test was performed before the installation of the exhaust fans for fan-assistance, the results are for hybrid ventilation only. The neutral pressure level is expected to be at a height within the fourth atrium (floors 11-14), making the 5th floor an appropriate choice for taking measurements, since it is both at the bottom floor of the 3-storey atrium and is farthest from the supposed neutral pressure level so that there is a higher driving force for air to enter the building and that can be captured by the instruments.

For this test, detailed measurements of the local outside air environment are taken at the weather station installed in 2015 on the rooftop of the EV building. This rooftop weather station has probes to measure air temperature and relative humidity, ultrasonic wind sensors, and a double dome pyranometer. An additional wind sensor and pyranometers are installed as backup, and a laser precipitation monitor for other research purposes. For this test, the relative humidity and air temperature data are compared to the measured indoor air temperature.

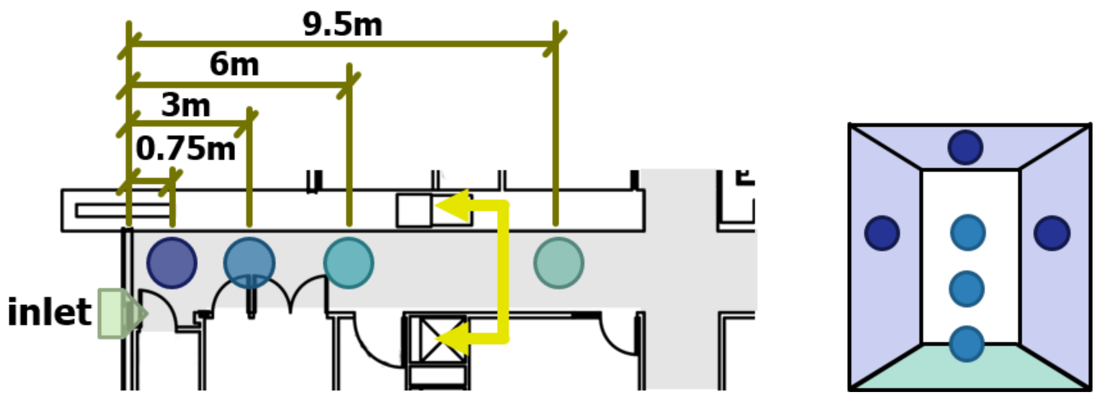

Figure 3-7: Measurement locations with typical set-up (left) and its and cross-sectional view (right).

Sensors on the inside of the building consists of an anemometer for measuring air velocity, thermocouples for air, walls, and ceiling temperature, and infrared sensors for the floor surface temperature. On the inside of the motorized dampers, 0.4 m above the floor, the inlet temperature is measured with a thermocouple (accuracy: ± 0.5 °C), whereas the inlet velocity parallel to the ground is measured with a one-directional anemometer, SENSOR HT-415, (repeatability: 0.03 m/s ±1 % of readings in the range of 0.15 to 1.5 m/s or ± 3 % of readings in the range of 1.5 to 10 m/s). Along the corridor, thermocouples and infrared sensors are installed as a typical setup at 4 locations, as shown in Figure 3-7. This setup consists of a thermocouple on each of the vertical walls and on the suspended acoustic tile ceiling for surface surrounding temperatures, and three thermocouples suspended at 0.1 m, 1.1 m and 1.7 m off the ground measuring the air temperature. The floor surface temperature is measured using infrared sensors OMEGA OS151-LT and OS301-LT (both models accuracy: ±1 % of reading or ±1 °C, whichever is greater) suspended between the acoustic tiles. Only at 3 m from the façade is the infrared sensor OMEGA OS301-LT used.

3.2.2 Thermal stratification in the atria

The stacked atria form a solar chimney for air to rise up and exit the building due to buoyancy; however, when hybrid ventilation is not in use, the motorized openings on the floor between atria are closed, preventing the natural exhaust of hot air from the building. There is an interest in the air temperature gradient within each atrium to have an indication as to whether an acceptable level of thermal comfort is achieved without hybrid ventilation, since these spaces are often occupied during the day by students. In addition, there are different plug loads associated to each floor, and variable incoming solar radiation due to occupant controlled blinds at the glazed façade. It would be interesting to note whether a specific set of 3 floors within an atrium are in the warmer or cooler side in comparison to the other atria. Nonetheless, measurements are taken along a spiral staircase that connects the three floors of each atrium, but not between each atrium. A handheld thermometer and an infrared camera were used to measure the air temperature and the floor surface temperature, respectively, between 14:00-15:00 on November 10th, 2015. At that time, it was a sunny day with an average temperature of 11 °C. While most of the atria had blinds partially closed at the time the measurements were taken, it is unknown when they were last adjusted. Thus, the amount of solar radiation absorbed and stored as heat within the concrete floor and affecting in turn its surface temperature. This test provides a first order assessment of the temperature distribution that can be expected when hybrid ventilation is not in use.

3.2.3 Preliminary test with fan-assistance

The EV building was designed to accept the potential installation of a series of variable speed fans at the roof on top of the highest atrium for an estimated flow rate of 45,000 L/s [18]. After a few years' delay, six variable speed fans are installed and commissioned in the end of 2015, just before winter. Controls related to these fans can be found in the Appendix. A preliminary test was performed using different handheld anemometers to measure the air temperature as well as its velocity and whether it is entering or leaving the motorized inlets on both the south-eastern and north-western façades on all floors, and at the atrium floor grilles. These measurements were taken on May 12th, 2016 at 0%, 25%, 40%, 60%, and 80% of the motors' maximum frequency. From this test, the effects of adding fan-assistance to hybrid ventilation can be observed. Of particular interest is whether outside air is coming into the building or if inside air is leaving through the façade openings to see whether the fans can overcome cross-ventilation within each floor, caused by wind effects.

4 Results and Discussion

Concordia University's EV Building provides a good example in the use of hybrid ventilation with and without fan assistance. On-site tests are performed and full-scale data are collected to evaluate the control of hybrid ventilation without compromising occupant comfort. A key component is to determine the lowest allowable outside air temperature for its admission into the building. To do so, measurements during and after employing hybrid ventilation were recorded at a corridor region with the motorized opening on the façade. In addition, thermal comfort in the atria when hybrid ventilation is not in operation was gauged with a quick test by measuring the air and floor surface temperature on different floors of each atrium. Moreover, after the variable speed fans were installed, a preliminary test was performed to observe the effects of increasing the fans' frequency. The results of these tests and their implications in terms of heat removal and thermal comfort to the occupants are discussed in this chapter.

4.1 Corridor measurements results

From the setup of the sensors for the measurements in the corridor, there are many intrusive thermocouples which are also visually displeasing to the occupants. To remedy the situation, as mentioned previously, a combined surface temperature is used in the thermal model to represent those of the walls and ceilings, such that it is equal to the sum of 2/3 of the acoustic tiles temperature and 1/3 of the walls temperature. These proportions are used since the air is expected to affect the ceiling due to buoyancy of air, whereas the predicted main airflow path will lead the bulk of air mostly towards only one of the wall. A linear regression was performed using the measured data to estimate this surface temperature based on its corridor section number, the floor surface temperature at the corridor section, and the inlet air temperature. These correlations can be applied when the relevant outdoor environmental conditions are similar to those on the night of the test; however, additional tests can be performed in order to ascertain the range of applicability for these correlations.

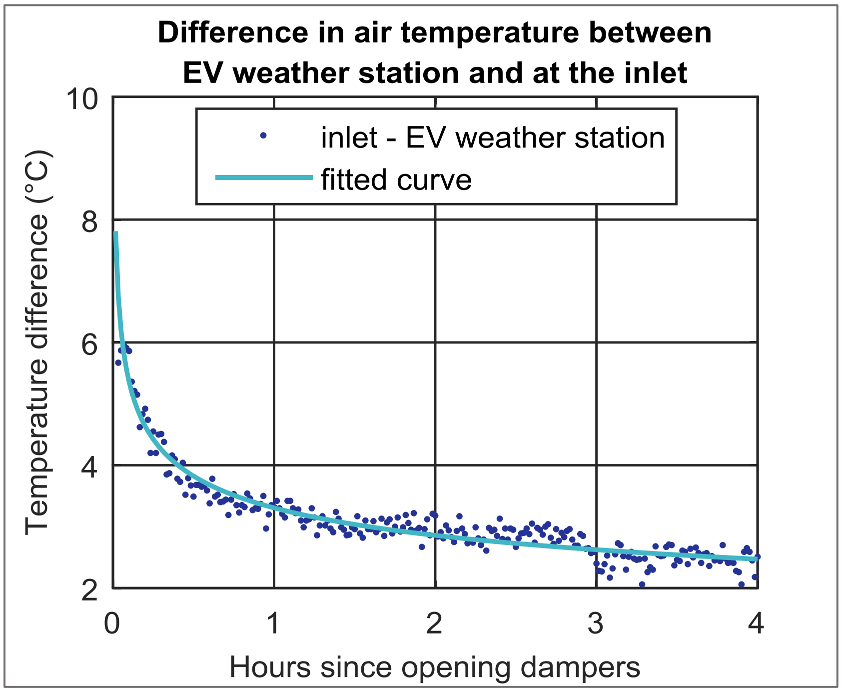

Figure 4-1: Correlating the measured air temperature at the rooftop weather station to the inlet at the corridor.

A second correlation, shown in Eq. 7 and depicted in Figure 4-1, is developed to link the local outdoor air temperature measured at the rooftop weather station, T_{EV}, to the inlet temperature, T_{inlet}, measured from the inside of the building, and requires the time elapsed in seconds, t, since the opening of the façade motorized dampers. Additional tests should be performed in order to verify the applicability of the correlation by repeating the measurements on a night with similar conditions. Other tests can be performed on slightly warmer conditions or even on similar air temperature conditions, but different wind conditions to investigate the applicability extent of the correlation with various outdoor conditions. Initially, the air temperature measured at the weather station is about 6 °C cooler than at the inlet near the motorized dampers. This difference can be explained by the air being warmed up by the heat released from the EV building façade and surrounding building, and potentially also from the street at low wind conditions. The opening of the façade dampers led to a quick drop within the first half hour in terms of the temperature difference between the two measured locations. Afterwards, this difference is only further reduced by 1 °C in the three following hours, and reaches an asymptotic value of 2.5 °C. The correlation has an R-squared of 0.91, which is very close to 1, indicating that it describes well the variability in the temperature differential. As such, it can be used when there are similar temperature differences between the indoor and exterior environment. For example, if the outdoor temperature when starting up hybrid ventilation is only 2 °C cooler than at the inlet, then this equation would no longer apply.

$$T_{inlet} = T_{EV} + 16 * t^{-0.2} \qquad \text{Eq. 7}$$

The measured floor surface temperature and calculated average air temperature from the thermocouples at three heights from the floor along the corridor are shown in Figure 4-2; there is a clear separation in terms of the measured temperatures at 3 m and 6 m. The corridor is then considered as having two regions: the primary region being the first half of the corridor near the inlets, and the secondary region being the second half of the corridor. The cooling effect is greater at the primary region, since bulk of the incoming air is expected to cross from the motorized inlets towards the wall on the other side, passing directly through both the thermocouples for air temperature and the floor where the infrared sensor is recording the surface temperature at 3 m from the façade. This results in the temperatures being cooler at 3 m than at 1 m from the façade during hybrid ventilation. On the other hand, in the secondary region, the air movement is predicted to be along the wall opposite from the inlet's side; however, the sensors are all located to measure the temperatures at the center of the corridor width, resulting in the possibility that the main cooling effect in the secondary region is not captured by this set-up. Hence, the sudden 2 °C jump to a higher temperature between these two regions can be explained by the mismatch between the airflow path in the secondary region and the location of the sensors. As well, as the outside air is being mixed with the inside air in the primary region, the air that moves into the secondary region is already warmed and reduces the temperature difference between the air and concrete surface, leading to a smaller potential for cooling when compared to the primary region. Nonetheless, the measurements still provide useful insight as to the general behaviour when hybrid ventilation is operated without fan-assistance. For instance, the concrete surface temperature experiences a decrease of 5 °C and 3.5 °C in the primary and secondary region respectively after 4 hours of hybrid ventilation – a significant amount for thermal mass cooling.

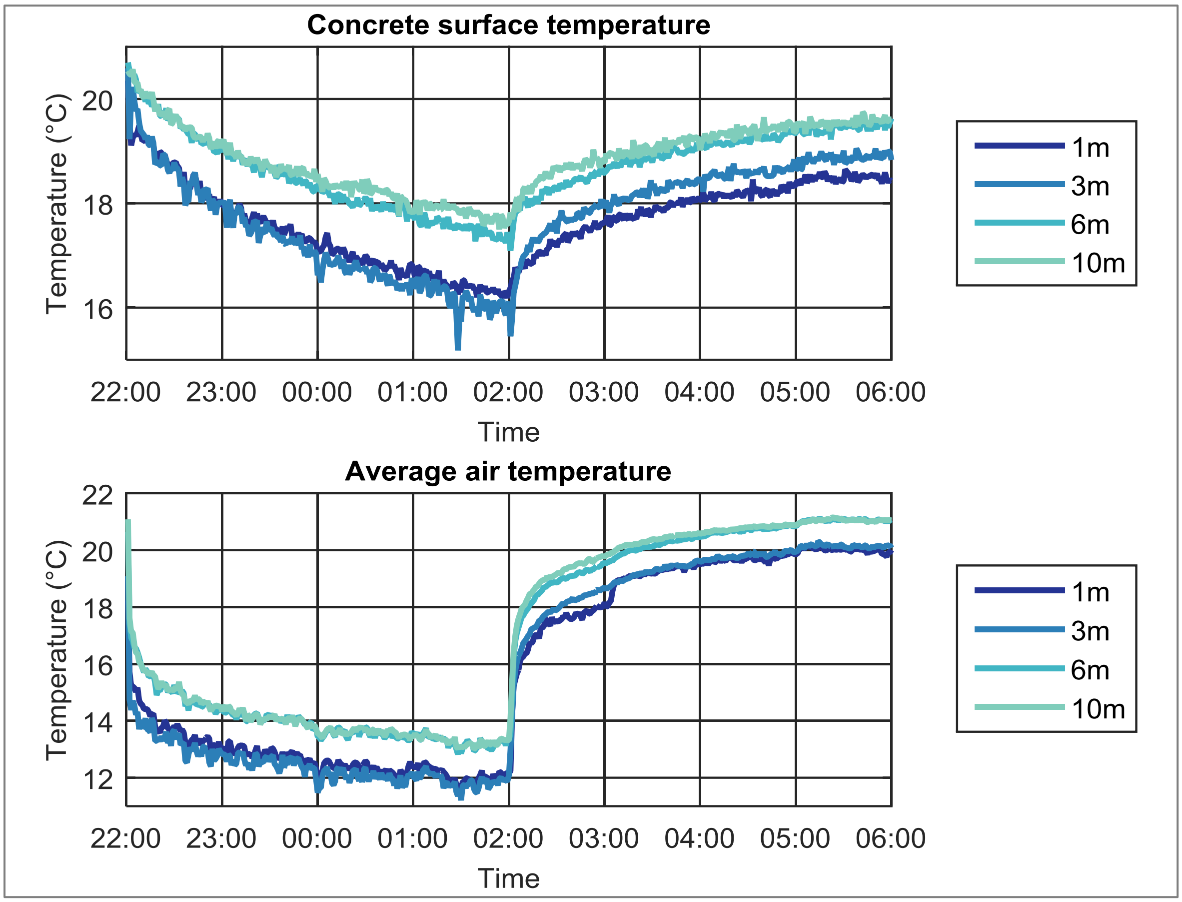

Figure 4-2: Measured floor surface temperature and average air temperature along the corridor.

In terms of air temperature measurements, there is a significant drop of 9 °C and 7 °C in the primary and secondary region within the first half hour of hybrid ventilation. As opposed to the concrete surface temperature which seems to be continuously decreasing with time linearly at a rate of 0.5-0.7 °C/hour after the initial drop of temperature in the first hour, the average air temperature steadily approaches a constant temperature of 12 °C and 13.5 °C in the primary and secondary regions respectively after the initial decrease. The reduction of temperature will be less significant if the outside air temperature is closer to the inside air temperature since there is less driving force to draw outside air into the building. Comparing the 8 °C average temperature at the rooftop weather station to the steady average air temperature of 13.5 °C at the end of the corridor, a temperature difference of roughly 5.5°C can be expected for similarly cool exterior conditions.

After the 4 hours of hybrid ventilation, a 4 hour period without it followed to determine how quickly the indoor environment changes back towards the setpoint. In terms of average air temperature, since mechanical cooling is functional and is actively restoring the air temperature to the setpoint of 21 °C. The whole 4 hours was required for the average air temperature at the end of the corridor to be restored to the setpoint temperature. It would be more effective to have the building passively warm up to 21 °C to reduce energy consumption.

4.1.1 Thermal comfort: indoor air temperature

A building that brings discomfort to its occupants is not conditioned properly, as its primary function is to provide a sheltered and comfortable environment. The measurements at the corridor where the motorized inlets are located were collected to have some insight on how the indoor environment evolves as cool outside air enters the building and mixes with the air inside the building. In other words, the mixed air is expected to be warm enough so as to not cause discomfort to occupants by the time it reaches the end of the 10 m corridor section. In fact, there are only an emergency escape staircase as well as an electrical room within the 10 m corridor length, and a room for meetings at roughly 12 m from the façade, where corridors intersect. As a result, occupants mostly do not enter the corridor, or are only passing by to access the staircases. To this effect, the thermal comfort aspects are only considered for the corridor section furthest away from the inlet, where the measurements are collected at 9.5 m from the façade. Furthermore, the corridor being considered a transition space, more specifically a circulation space, occupants are likely to be walking past and be at that space for less than 10 minutes. Their expectation of thermal comfort are less strict in transition spaces, and thus the range of acceptable predicted mean vote (PMV) can be increased from ±0.5 to ±1.5, translating to an increase in acceptable predicted percentage of dissatisfied (PPD) from 10% to 50% [47] as shown in Figure 4-3.

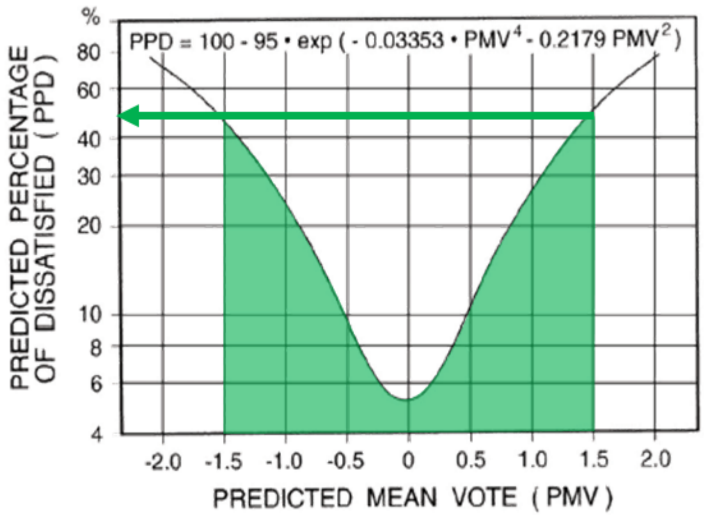

Figure 4-3: Acceptable PMV range in circulation spaces and its corresponding acceptable PPD (Adapted from ASHRAE 55).

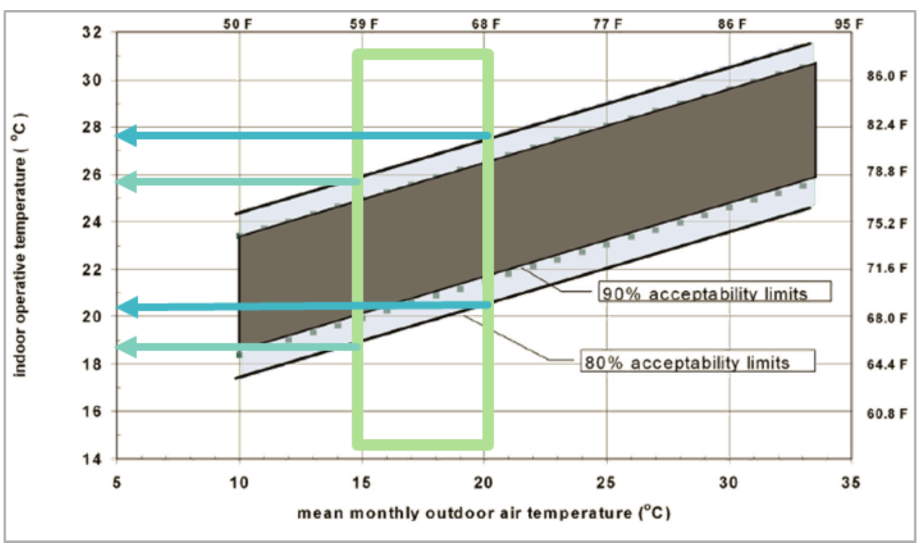

Figure 4-4: Acceptable operative temperature ranges for naturally conditioned spaces (Adapted from ASHRAE 55).

For the use of natural ventilation, the ASHRAE Standard 55 suggests that when the monthly average temperature is 15 °C and 20 °C, the range for 80% acceptability limits in indoor operative air temperature are 19.0-26.0 °C and 20.5-27.5 °C respectively, as shown in Figure 4-4 [15]. The indoor operative air temperature range can be further widened for the circulation spaces; however since the 50% acceptability limits for are not included in the standard, the exact values are unknown. The 1981-2010 Canadian Climate Normals station data for Montreal at Mirabel airport shows that the months of May to September have average temperatures within the 15-20 °C range [50], with a high diurnal temperature difference of around 12 °C allowing for effective night cooling after and before a hot day. Although the months of April and October are colder, since it is during the transition from winter to spring, there are still days at the end of and beginning of April and October respectively that can benefit from using hybrid ventilation. In fact, hybrid ventilation was in use until the first weeks of November due to the weather being warmer than the norm. For the EV building, there are no fixed date switch hybrid ventilation on or off, as it is the building manager allow or deny the use of hybrid ventilation when the daytime average temperature is consistently around 10 °C, which corresponds roughly to the heating or cooling balance point of the building, for a week.

During the test for night ventilation, the temperature difference between the air at the rooftop weather station and at the end of the corridor was found to be stabilizing around 5.5 °C after 4 hours of night ventilation. In that case, if the average air temperature measured at the building weather station was 8 °C, then a mixed average air temperature of 13.5 °C at the end of the corridor is expected. Similarly, if the outside air temperature of 12 °C, then the average air temperature at the end of the corridor should be at least 17.5 °C. For night ventilation, even though 13.5 °C is below 19.0 °C, the lower temperature is sought after in order to have a high temperature difference between the cool air and warm concrete floor to further precool the building. The cool air of 13.5 °C can be allowed since there are essentially no occupants during the hours of night ventilation, as it occurs at night after usual work hours. As such, the criteria for thermal comfort during that period of time can be extended in order to increase the potential free cooling as well as bring more fresh air into the building. As for during the day, the temperature at the end of the corridor is 17.5 °C, which is 1.5 °C lower than the 19.0 °C for 80% acceptability. In addition to this difference being possibly covered by the extension of the acceptability range to 50%, the air continues to be warmed as it gets deeper into the building and gets further mixed with the indoor environment. By the time it reaches the atrium, the air temperature would have risen high enough to satisfy the 19.0 °C criterion. In fact, a study on night ventilation by Blondeau et al. showed that even with an average outdoor temperature of about 8.4 °C, a decrease in 1.5-2 °C in the diurnal indoor air temperature was achieved, leading to an improvement in thermal comfort for occupants [51]. All in all, the outdoor conditions during the full-scale test is deemed acceptable as the lower limit for accepting air into the building for night ventilation, while the acceptable lower limit for daytime can be 12 °C. After stopping hybrid ventilation, the time required for the end of the corridor to reach the 80% acceptability limit of 19 °C is only 0.5 hour, whereas it requires 1.5 hours for the secondary zone to reach that temperature. This suggests that night ventilation can potentially be used up until half an hour before expected occupancy in the building, since mechanical ventilation is fully active post hybrid ventilation.

4.1.2 Local thermal comfort

Other than feeling generally too cold or too hot, occupants can feel uncomfortable thermally in a smaller scale, such as feeling discomfort through radiant asymmetry by being in a warm room but close to cold windows. There is potential discomfort that passerby's can experience in the corridor due to incoming cool air through the motorized openings.

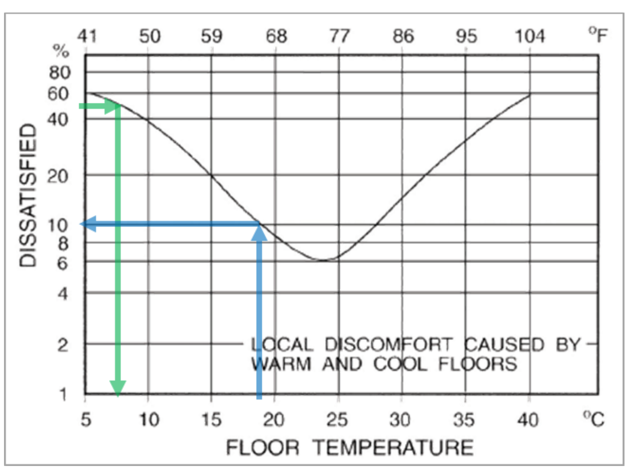

Figure 4-5: Local discomfort caused by warm and cool floors (Adapted from ASHRAE 55).

The floor temperature has to be in between 19 °C and 28 °C to be considered comfortable with a 10% PPD. Extending the acceptable limit to 50% since it is a circulation zone, the floor temperature can be as low as 7.5 °C, which is 1.1 °C less than the average exterior air temperature throughout the test. Thus, with 8 °C as the minimum exterior air temperature measured from the rooftop weather station for operating in night hybrid ventilation mode, the floor will at worst be close to 8 °C and remain above 7.5 °C. Moreover, the concrete floor being thermally massive, it will require more hours than the scheduled amount for night ventilation to even reach close to 8 °C. The measured floor surface temperature as a function of distance from the façade at different time since the start of hybrid ventilation mode is shown in Figure 4-6.

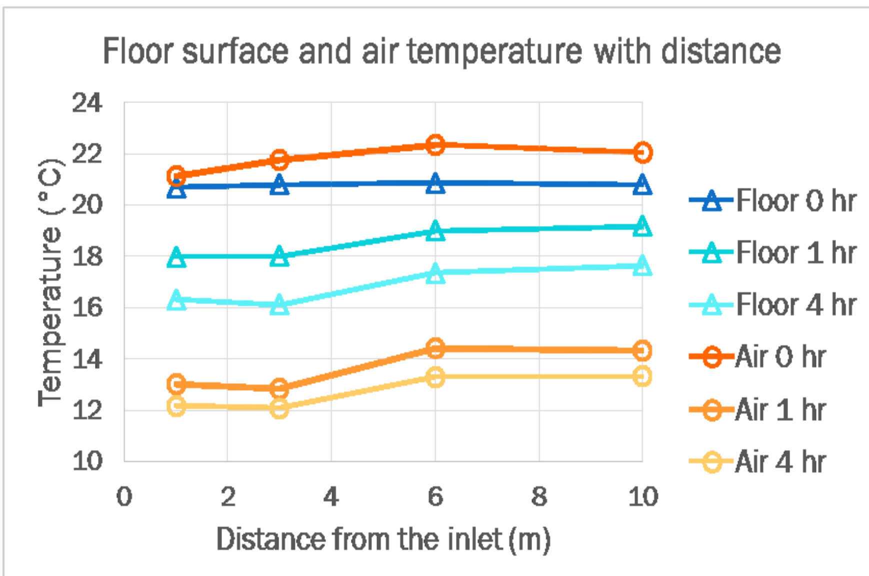

Figure 4-6: Measured floor surface and average air temperature along the corridor with time.

The temperature decrease at the surface in the first hour is approximately 3 °C in the primary region, and 2 °C in the secondary region. This is comparable to the 2 °C and 1.5 °C drop in the primary and secondary region respectively in the following 3 hours. The floor surface temperature drops to a low of 16 °C in the primary region, corresponding to 19% PPD, whereas in the secondary region, the surface temperature is 17.5 °C for roughly 12 % PPD. Overall, the difference in concrete surface temperature after the 4 hours of night ventilation decreased by 38%. Along the corridor, a 1.5 °C increase in floor surface temperature can be seen from the first corridor section to the last consistently as early as 1 hour of hybrid ventilation. Similarly, for the average air temperature, a 1.3 °C increase is shown from near the façade to the end of the corridor.

Due to the cool outdoor air mixing with the indoor environment, there is turbulence in the airflow which may cause a high temperature difference felt at the head and toe level. The ASHRAE-55 states that this difference should be less than 3 °C, which corresponds to 7% PPD, as shown in Figure 4-7. From the full-scale test at the corridor, this criteria is met without needing to extend the measured air temperature difference is less than 2.5 °C consistently throughout the 4 hours.

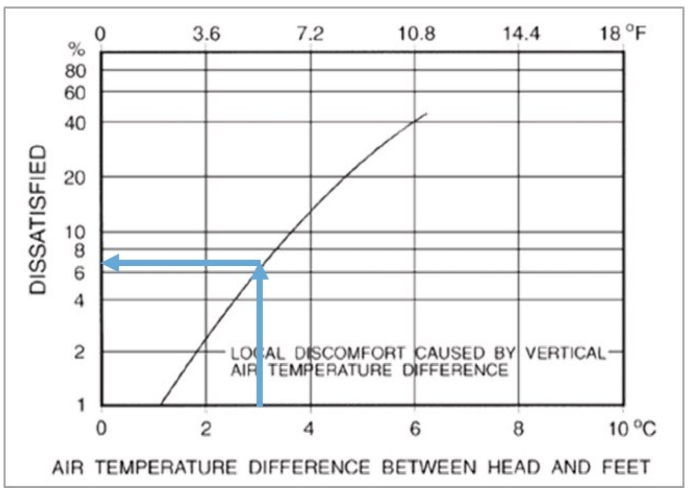

Figure 4-7: Local thermal discomfort caused by vertical temperature differences (Adapted from ASHRAE-55).

4.2 Thermal model simulations

The thermal model is developed with the purpose of simulating the average air temperature as well as the concrete temperature both at the surface and within the floor, in order to estimate the cooling of the concrete floor due to hybrid ventilation. First, the results from the calibrated thermal model is compared to the recorded data from the full-scale test with measurements at the corridor. After, using the simulation results, the temperature change of the concrete floor is used to determine the penetration depth after 4 hours and to calculate the amount of heat removed. Finally, a simulation using the forecasted air temperature is run to assess the model's prospect for predictive control.

4.2.1 Simulation using measured data

Using the developed calibrated thermal network model, the air and concrete temperatures are simulated for 4 hours. With the calibration of the velocity coefficients and the effective heat transfer coefficients, there is good agreement between the measured data and simulated temperatures. A visual comparison of these two sets of data for the temperatures of the floor surface and air temperatures along the corridor length is shown in Figure 4-8 and Figure 4-9 respectively.

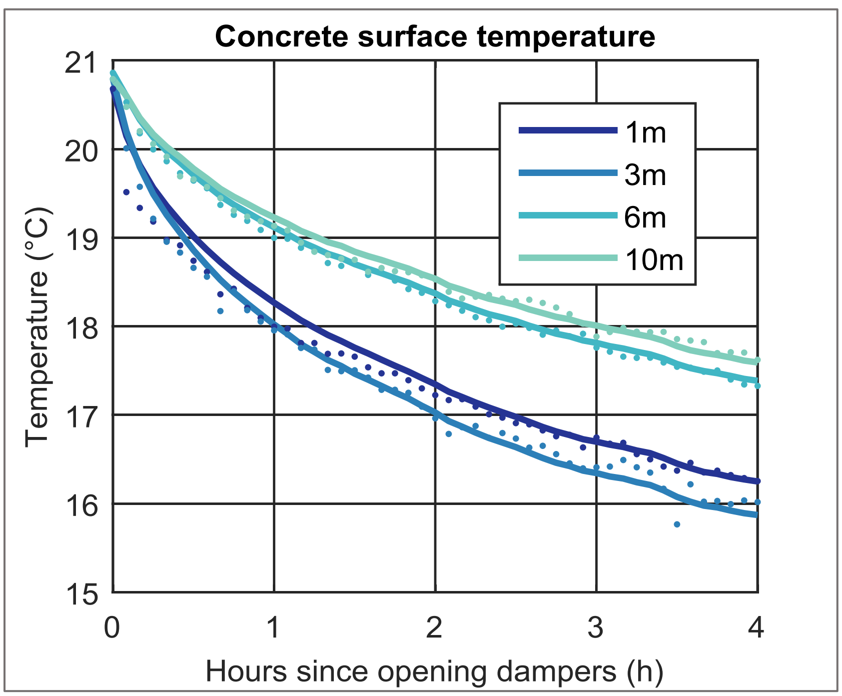

Figure 4-8: Simulated (solid) and measured (dotted) concrete surface temperature.

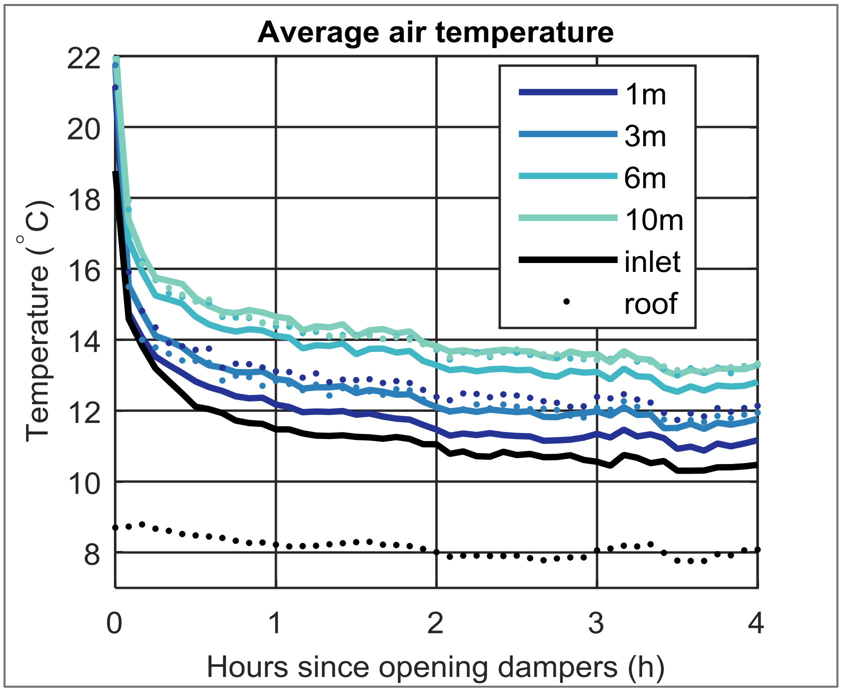

Figure 4-9: Simulated (solid) and measured (dotted) air temperature.

The separation of the corridor into a primary and secondary region is depicted clearly with the 1.5 °C jump in floor surface temperature going from 3 m to 6 m from the façade. For both concrete surface and air temperatures at each corridor section, the root mean squared error (RMSE), coefficient of variation of the root mean square error (CV-RMSE), mean bias error (MBE), and the standard deviation of the error between measured and simulated values are listed in Table 4-1 for each corridor section. A greater agreement is found between measured and simulated concrete surface temperature than those for average air temperature. The MBE shows that the simulated concrete has a positive bias, meaning the predicted values will tend to be greater than the measured ones, whereas simulated air temperature has a negative bias. The error for concrete surface temperature resulting from the simulation is expected to be within 0.3 °C, since the standard deviation of the error is 0.15 °C, the RMSE is less than that value, and the CV-RMSE is around 1%. This difference is acceptable for the model, since it lies within the range of error of the infrared sensors. There is also no significant increase in the expected error for simulated temperatures in the primary zone against the secondary zone.

Table 4-1: RMSE and standard deviation of the error for simulated temperatures.

Concrete surface				
Corridor section	1	2	3	4
RMSE (°C)	0.20	0.14	0.18	0.11
CV-RMSE (%)	1.1	0.8	1.0	0.6
MBE (%)	0.8	0.1	-0.8	0.1
Standard deviation (°C)	0.15	0.14	0.10	0.10
Air				
Corridor section	1	2	3	4
RMSE (°C)	0.98	0.22	0.46	0.14
CV-RMSE (%)	7.5	1.7	3.2	1.0
MBE (%)	-7.6	-0.1	-3.2	-0.2
Standard deviation (°C)	0.19	0.22	0.14	0.14

The simulated temperatures for air has a negative bias. With a relative error of 7.5%, the simulated temperatures in the first corridor section can be expected for have a 1 °C error, which is understandable as it is closest to the façade and is at the location of the recirculation zone. As for the rest of the corridor, the simulated air temperature should be within 0.5 °C of the actual average air temperature, which corresponds to the error range of the thermocouples. One of the goal for simulating the average air temperature is to verify whether the air at the end of the corridor is warm enough to not inconvenience any occupants, since that's where occupants would be likely to pass by if at all. Since the thermal model simulates the average air temperature most accurately at the end of the corridor, the model can be used at the start of hybrid ventilation to estimate how long hybrid ventilation can be run before the indoor air drops below a threshold value.

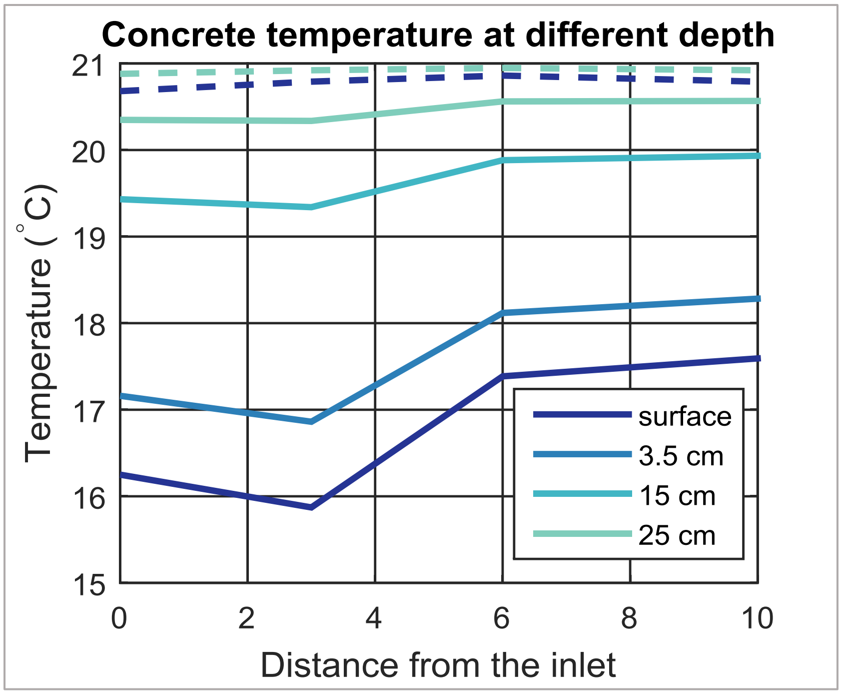

Figure 4-10: Simulated concrete temperature at different depths, at the start (dashed) and after 4 hours of hybrid ventilation (solid).

The main use of night ventilation is to precool the building thermal mass, consisting primarily of the exposed concrete floor. Using the developed model, the temperatures of the concrete at different depth levels can be simulated with time. At the start of the test with night ventilation, the temperature of the concrete slab at the surface are the measured values of around 20.5 °C. These are then linearly interpolated within the floor thickness to the assumed bottom surface temperature of 21 °C. After 4 hours, with an average outdoor air temperature of 8 °C, the concrete floor in the corridor is cooled down to the temperatures depicted in Figure 4-10. It can be seen that near the surface, the concrete is cooled the most in the primary zone; however, with only 4 hours of precooling, the cooling effect doesn't reach all the way through the floor thickness. The effective thermal mass for the duration of this test is around 25 cm, which is the depth at which there is less than 1 °C change in temperature. In other words, the cooling effect has reached just above half of the floor thickness. As a result, there is potential for achieving more cooling by lowering the minimum air temperature for allowing outside air into the building, or by significantly extending the time frame when night ventilation is applied, since the rate of heat removal decreases with time as the temperature gradient between the concrete surface and air is less pronounced.

Through night ventilation, the thermal mass is precooled in anticipation to the cooling loads of the following day. The rate at which heat is removed from the concrete floor is thus essential in order to determine the number of hours of night ventilation required to match the load. During the months of April and October, when it is still rather cool outdoor, but the building requires cooling nonetheless, night ventilation should not be used excessively to avoid overcooling the building and causing discomfort. From the results of the thermal model, the rate of heat removal from the floor per control volume is calculated using Eq. 8, where q is energy (W) and ΔT is the difference in temperature of the concrete between timesteps.

$$q = \rho * c_p * vol * \frac{\Delta T}{\Delta t} \quad \text{Eq. 8}$$

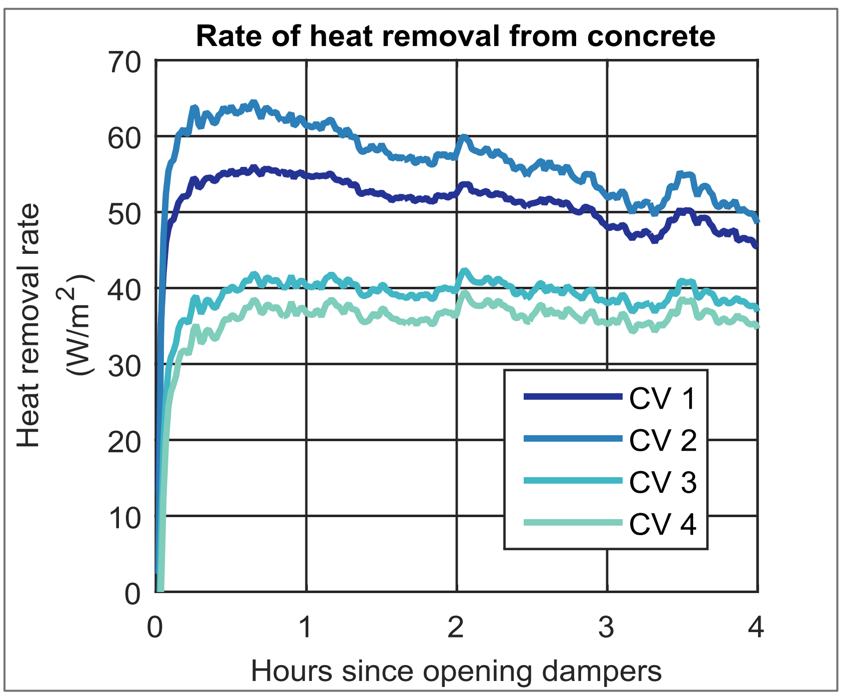

Figure 4-11: Rate of heat removal from concrete at each control volume (CV) along the corridor.

The sum for each corridor section as a function of time is presented in Figure 4-11 and the total amount of heat extracted from the concrete floor after 4 hours of night ventilation and with a mean outdoor temperature of 8 °C is tabulated in Table 4-2. As the motorized dampers on the façade open, cool outdoor air enters the building corridor causing the initial peak in the rate of heat removal. The distinction between the primary and secondary zone is highlighted by a difference of at least 10 W/m^2. In the primary zone, the concrete around 3 m from the façade has a higher heat removal rate than closer to the inlet, which can be explained by the expected flow path of the air traversing right through that section from one wall of the corridor to opposing one. In fact, the primary zone has 38% more heat extracted than the secondary zone. Assuming a coefficient of performance (COP) of 3, the amount of cooling energy that was saved is 1,112 MWh. This excludes the amount of energy that would have been spent to use fans to circulate fresh air throughout the building.

Table 4-2: Heat removed from the concrete floor after 4 hours of night ventilation.

Heat extracted from the concrete floor				
Corridor section	1	2	3	4
After 4 hours (kJ/m^2)	738	818	605	519
Total (MWh)	3,337			

Located in that corridor section, an electrical room exists and heated air exits from under the door and around its frame. This heat then mixes with the incoming cool outdoor air and contributes to warming it up before it reaches the end of the corridor. After the first hour, the rate of heat removed from the floor in the secondary zone seems to stabilize at a constant value of roughly 35-38 W/m^2, whereas it is decreasing by about 5 Wm^2 in the primary zone. Given enough time, this rate in the primary zone would slowly turn into a plateau like in the secondary zone. As the concrete floor is cooled, its surface temperature is decreases, making it closer to the temperature of air which it is exchanging heat with. With the slimming of the temperature gradient, and the slow transfer of warmth from the inside of the floor towards the surface, there is less and less heat transferred from the concrete surface to the air.

4.2.2 Simulation using forecasted data

The development of thermal models that can produce reliable predictions is an important step towards better predictive controls within the building. For instance, having an accurate model that can calculate the average air temperature at a specific location can be used to assess whether the occupant will be thermally comfortable before initiating the control action of opening the inlet grilles. Ultimately, the program that controls when to open the motorized dampers on the façades would be automated based on predictions made by a model using forecast weather data, especially for the use of night ventilation.

It was previously shown that the calibrated thermal network model showed good agreement between the measured and simulated average air and floor surface temperature. The next point to consider is if the results of the simulation would be equally as good when replacing the measured air temperature from the rooftop weather station to Dorval airport's forecasted weather data, provided by Environment Canada. Ideally, the inlet velocity that was measured by an anemometer would be also replaced by a localizing the air direction and speed from the weather station; however, deriving the equation for its localization is a research topic on its own beyond building engineering. As a result, the simulation is carried through by switching only the exterior air temperature from measured data to what was forecast for the duration of the test. In addition, since forecast data are in an hourly format, it is assumed to be constant throughout the hour.

The measured air temperature at the rooftop weather station has a range from 7.7 °C to 8.85 °C, where the temperature gradually decreases with sudden increases lasting about half an hour. On the other hand, the forecast temperature predicted that the air temperature would be 9 °C at the start of the test and gradually get colder to 8 °C during the fourth hour. It had an average of 8.5 °C, which is only 0.1 °C less than the measured average air temperature at the EV building rooftop weather station. Since the forecast and actual local air temperature is very similar, the results are likely to be comparable.

Substituting the local measured data with the forecast from a nearby airport, the simulation is run and Table 4-3 lists the RMSE, CV-RMSE, MBE, and standard deviation of the error for the concrete surface and average air temperature. The bias directions remain the same and the overall relative error for concrete is similar, with a 0.6% increase for the first corridor section. The relative error for simulated air temperature, on the other hand, is doubled in the second and fourth corridor sections and lessened in the first and third corridor sections. In general, the expected error when using forecast data is similar to when using the measured data. An expected error of 0.3 °C and 0.7 °C can be expected for the concrete surface and average air temperature respectively, which in turn are within the infrared sensor and thermocouples' error range respectively. Next, Table 4-4 presents the calculated amount of heat extracted from the concrete floor, and shows a 3.5% decrease in the total amount of heat removed, which can be considered insignificant. Ultimately, the actual results may depend on how accurate is the forecast weather data compared to the actual measured data when the time arrives, but with forecast temperature updated every 6 hours, they are expected to be reliable, especially for air temperature.

Table 4-3: RMSE and standard deviation of the error for simulated temperatures using forecasted air temperature.

Concrete surface				
Corridor section	1	2	3	4
RMSE (°C)	0.30	0.20	0.09	0.14
CV-RMSE (%)	1.7	1.2	0.5	0.8
MBE (%)	1.5	0.9	-0.2	0.6
Standard deviation (°C)	0.14	0.14	0.08	0.10
Air				
Corridor section	1	2	3	4
RMSE (°C)	0.68	0.44	0.28	0.32
CV-RMSE (%)	5.3	3.5	1.9	2.2
MBE (%)	-4.9	2.4	-1.2	1.7
Standard deviation (°C)	0.28	0.34	0.22	0.22

Table 4-4: Heat removed from the concrete floor after 4 hours of night ventilation using forecasted air temperature.

Heat extracted from the concrete floor				
Corridor section	1	2	3	4
After 4 hours (kJ/m^2)	713	790	584	501
Total (MWh)	3,221			

Overall, the BAS should have a program that determines whether to use hybrid ventilation or not, by using MPC with forecast data, in order to predict the conditions within the building and ensure that they remain at a comfortable level for occupants. Without fan-assistance, the inflow of cool outdoor air is due to buoyancy and wind effects, making it essentially unpredictable, since there is no accessible means of localizing the forecasted wind direction and speed from an airport nearby to the opening at a specific façade of the EV building. The newly installed fans at the top of the atrium, which can be controlled based on a target exhaust flow, can lead to a more constant incoming airflow at the façade openings if the fans can overcome the wind forces driving air in and out of the building via cross-ventilation.

4.3 Addition of variable speed fans

When the building is operating in hybrid ventilation, outside air is allowed to freely enter and leave through the motorized inlet on two façades. The incoming air mixes with the indoor air and is gradually warmed up, and is exhausted from the solar chimney due to buoyancy. This creates a natural pressure gradient within a building with openings, such that there is a main neutral pressure level (NPL). Above the NPL, the pressure compared to the exterior is positive, whereas it is negative below the NPL. In other words, air will enter from openings at heights below the NPL, and exit from openings above the NPL. It can also enter and exit from the same opening if the height of the NPL lies within the opening's height. As such, the mixed air can also exit through the motorized openings, due to being above the NPL. In addition, outdoor air can be driven into and out of the building due to wind forces. By installing the variable speed fans at the top of the atrium, the goal is to be able to control how much air is entering the building and to bring in outside air at the top floors of the building which are above the NPL.

In buildings having openings on opposing façades, such as in EV building, airflow is promoted from one opening towards the other when there is wind, especially if it is in the direction connecting the two openings. The results from the preliminary tests performed after the variable speed fans installation shows that without fan-assistance, there is cross-ventilation in all floors from the south-eastern openings towards the north-western openings. The subsequent tests involve flow and temperature measurements at the openings and atrium floor grilles when operating in fan-assisted hybrid ventilation mode at 25%, 40%, 60% and 80% of the maximum frequency of the variable frequency drives (VFD).

The direction of airflow into and out of the building façade motorized openings are highly wind-driven from the south-eastern to north-western openings, even at the lowest frequency setting for the variable speed fans. At that setting and without fan-assistance, there are two incidents out of all the openings where the air would at times be entering and at exiting other times from a specific façade opening. At 40% of the maximum frequency and higher, outside air begins to enter from the north-western openings at the top atrium. Since it is the atrium closets to the fans, there is more force to assist the air into the building. At 60% maximum frequency and above, there is also inflow from the north-western opening on the 11th floor, which can be a combination of the fans pulling in air and the fact that there are surrounding buildings that are around the same height as the opening, which can cause a recirculation area above and/or behind these buildings close to the EV building. Overall, since the fans' contribution towards overcoming wind forces to draw air into the building was only effective for the top atrium, the cooling on all floors below the 14th floor is highly dependent on wind forces, an uncontrollable environmental factor.

The airflow out of the building through the solar chimney is expected to be brought higher as the fans operate at a higher frequency. It is worth noting that the flow out of the top atrium at the lowest fan frequency produced a smaller volumetric flow than without fan-assistance. In this case, using the fans not only decrease the effectiveness of hybrid ventilation, but the energy consumed towards its use could have been avoided. Increasing the VFD from 0% to 60% and 80% maximum frequency caused a 53% and 97% increase in the measured volumetric airflow during the preliminary test. With the use of the fans above 80% maximum frequency, even though there can be more cooling achieved, the noise from the fans begin to be noticeable in the atrium, causing acoustic discomfort to occupants, which is particularly important during daytime.

Using the measured airflow at the façade openings when hybrid ventilation was operated without fan-assistance and with the VFD at 80%, the portion of cooling due to cross-ventilation and due to hot air being drawn out of the building are estimated. Assuming that the interior and exterior conditions are the same during the two tests, the flow rate at the openings and the roof exhaust are compared and the result attribute around 40% of cooling to cross-ventilation and 60% to the chimney effect for the particular case study. More research and measurements are required to develop general conclusions.

4.4 Criteria for operating hybrid ventilation

The EV building uses a setpoint for interior air temperature of 24 °C in the summer and 21 °C in the winter. Due to its function as an institutional building having an expected occupancy of 4000-5000 people and high levels of plug loads and solar heat gain from the glass façade, cooling is often required even in spring and fall. Hybrid ventilation was incorporated into the design in order to reduce energy consumption for cooling and to provide fresh air into the building as well as to reduce the energy required for fans to recirculate air within the building. The original criteria to control hybrid ventilation is based on the temperature and relative humidity of the exterior air, measured from the rooftop weather station at EV building itself. The suggested changes to the controls are proposed in order to increase energy savings without causing discomfort to the occupants, and involve increasing the range for acceptable outdoor air temperature as well as substituting the relative humidity criterion with humidity ratio.

Currently, regardless of the time of day, the outside air must be between 15-22 °C and below 70% relative humidity for air to be admitted into the building through hybrid ventilation. In addition, the building manager is in charge of enabling the use of hybrid ventilation as the season changes from winter to spring. Usually this shift occurs near the end of April, whereas the change to disable its use as the season changes from fall to winter occurs around October and sometimes not even until November. As a result, hybrid ventilation is considered to be in use as early as April until the end of October in the calculations below. Using the original criteria, the month of April will have 44 hours of hybrid ventilation, most of which is during the day. Despite having an average air temperature of 6.5 °C, the temperature can rise up to approximately 20 °C near the end of the month. Even though for a portion of the month, the exterior environment may still be considered chilly as occupants are adapting to the change in season, the use of hybrid ventilation can still serve to provide fresh air into the building and remove heat from plug loads and the occupants themselves. The same can be observed about the month of October, when the transition from fall to winter is more perceived; however, hybrid ventilation can be used even until mid-November, as was the case in 2015. This section will focus on the reduction of cooling energy consumption using different criteria for employing hybrid ventilation over the 7 months from April to October.

The hourly weather data considered is a synthetic one year period designed for energy calculations provided by the Canadian Weather for Energy Calculations using data recorded from 1953-1995 for the location of Dorval airport in Montreal. An estimation of the amount mechanical cooling energy reduction through hybrid ventilation with and without fan-assistance is calculated by considering the change in air temperature from the motorized inlets to the exhaust at the top of the solar chimney, shown in Eq. 9.

$$Q = \sum \left[\frac{V * \rho * c_p * (T_{exhaust} - T_{inlet}) * 1hr}{COP} \right] \quad \text{Eq. 9}$$

Since there is an expected difference of 2.5 °C in air temperature from the rooftop weather station to the inlet, this difference needs to be added to the air temperature from the weather data to form the inlet temperature, T_{inlet}, when performing calculations. The exhaust temperature, $T_{exhaust}$, is assumed to be 24 °C, the setpoint temperature for indoor air during the cooling season. The mass flow rate at the exhaust is calculated as the product of the volumetric flow rate at the exhaust, V, air density, and specific heat capacity. The whole is divided by a system coefficient of performance (COP) of 3 which is representative of the amount of energy consumption for cooling the building. Using the aforementioned criteria for hybrid ventilation with no fans and assuming a volumetric flow of 17 m^3/s results in a total of 896 hours over 124 days and 18.9 kWh of cooling energy reduction. Using the same criteria, any increase in volumetric flow rate due to the newly installed fans will lead to an increase in cooling energy saving by a ratio of the new volumetric flow rate over the assumed value without the fans.

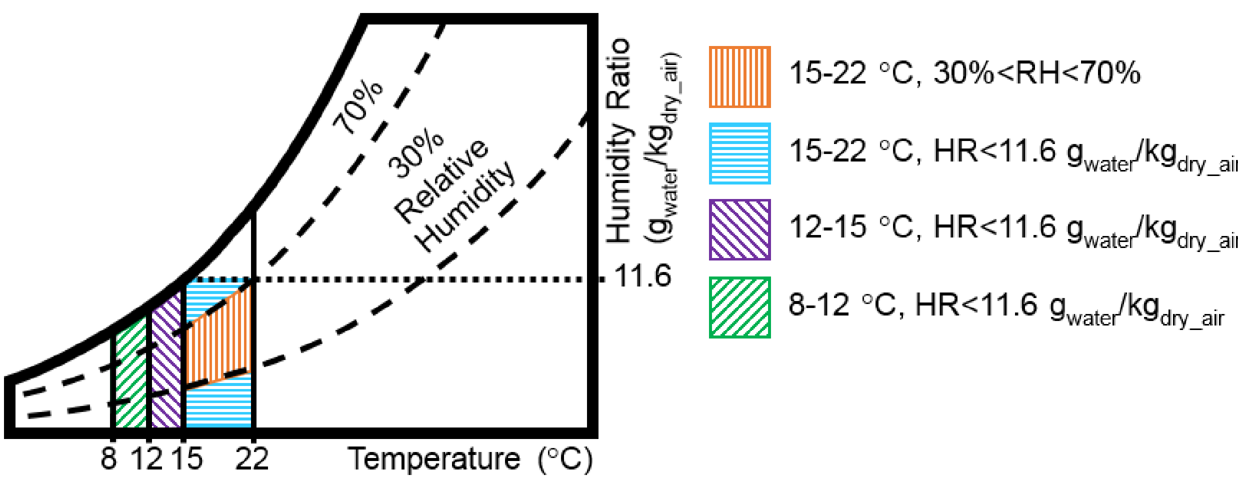

Figure 4-12: Regions of air condition satisfying the different criteria for employing hybrid ventilation.

The following subsections consider altering the criteria in order to increase the amount of free cooling available while still maintaining adequate occupant thermal comfort. A criterion limiting the humidity ratio of outside air to be less than a specified value is proposed to replace the current criterion of requiring outside air to be less than or equal to 70% relative humidity. In addition it is suggested to widen the range of allowable outside air temperature and also to implement a day-night schedule that varies the lower limit of said temperature range with time, without causing significant discomfort to the occupants. Finally, with a day-night schedule, the possible contribution of increasing the range of hours for night ventilation for precooling of the building at night is examined. The schematic of a psychrometric chart is shown in Figure 4-12 with the representative criterion variables, and regions for both the original and alternative criteria for operating in hybrid ventilation mode. The default zone is indicated in orange with vertical stripes and represents the original criterion with an additional lower limit for relative humidity. In order to increase the potential for free cooling, the acceptable outdoor air conditions needs to be increased. The other regions highlighted in Figure 4-12 represent the expansion of acceptable outdoor air conditions as the criteria for operating in hybrid ventilation mode is changed to those proposed in the upcoming subsections.

4.4.1 Humidity Ratio as a criterion

The main concern with changing the criteria for operating in hybrid ventilation mode is whether it will cause discomfort to the occupants. The first proposed change is to set a maximum value for the outdoor air humidity ratio instead of its relative humidity. In this case, allowing air with relative humidity greater than 70% may be too humid for the occupants. The outside air enters through openings on two façades when hybrid ventilation occurs, and travels through 3 m wide corridors to the atrium where it exhausts from the stacked atria. The incoming air is transported for a long distance, while being mixed with the interior environment, resulting in warmer and less humid air once it reaches the core of the building where occupants are present, meaning that they should not be any more uncomfortable than they would be under the initial criteria. Essentially, the return air for the HVAC system would be of the already warmed and less humid outdoor air mixture, which would be within the acceptable range of temperature and relative humidity for return air.

While the criterion doesn't include a lower limit for humidity ratio, the value for the maximum allowable humidity ratio of the outside air is determined by calculating the value corresponding to the outside air condition with the upper limits for both air temperature and relative humidity. For example, using the criteria from the base case, the upper limit for the admission of outdoor air temperature and relative humidity are 22 °C and 70% respectively. The corresponding humidity ratio is roughly 11.6 g_{water}/kg_{dry_air}. In Figure 4-12, introducing the humidity ratio criterion adds the blue regions with horizontal stripes immediately above and below the default region.

Using the new criteria yields 1334 hours of hybrid ventilation spread over 136 days and building cooling energy reduction of 33.3 kWh. While this 49% increase in the number of hours of free cooling appears impressive, the cooling energy savings increase is even greater at 76% relative to the original criteria. These calculations are made using the same inlet temperature and exhaust temperature for both cases.

4.4.2 Increasing temperature range

Changing the outside air temperature range criteria to adopt a day-night schedule can produce significant additional free cooling when compared to the original criteria. As mentioned in section 4.1.1, allowing hybrid ventilation to be used when the outside air temperature is between 12-22 °C during the day and 8-22 °C at night should not cause discomfort to the building occupants. From Figure 4-12, the purple and green regions with the diagonal stripes represent the extension of the acceptable outside air conditions down to 12 °C and 8 °C respectively for night ventilation.

The EV building being an institutional building, the occupancy levels are expected to be close to nil late at night until a few hours before working hours. As such, the schedule for lowering the minimum temperature for outside air from the daytime setting of 12 °C to night setting of 8 °C is considered to be from 21:00 to 6:00. Keeping the relative humidity criterion, hybrid ventilation can be operated for a total of 1305 hours, which is a 46% increase. Of the 147 days with adequate outside conditions, night ventilation can be operated for 99 nights, taking up 32% of the hours of hybrid ventilation. Using the day-night schedule also results in 43.7 kWh of savings in energy consumption, which is represents a 131% increase. More than doubling the free cooling, accepting cooler air into the building allows for a higher temperature differential, which means a higher driving force for heat transfer between the cool air and the warmer air and exposed building materials and furnishings. Furthermore, with the goal of precooling the building at night, the lower limit of outside air temperature was nearly cut in half as it dropped from the original 15 °C to 8 °C and is a major contributor to the extra potential savings in cooling energy for the building.

By using the proposed maximum humidity ratio criterion in addition to the day-night pattern for the lower limit of allowable outside air temperature further increases the number of hours with hybrid ventilation, and cooling energy savings. The change in criteria to gauge humidity yields an extra 20 days of hybrid ventilation usage, translating to an addition of 1132 hours. This also indicates an extra increase of 136% in terms of cooling energy, amounting to a total of 103 kWh, of which 24.8 kWh is attributed to adding a day-night schedule and 59.6 kWh is associated with change from relative humidity to humidity ratio criteria. Using these combined criteria, the amount of hours dedicated to night ventilation takes up 45% of the total hours as opposed to the 33% that was before lowering the minimum outdoor air temperature at night than during the day.

4.4.3 Extending night ventilation hours

An alternative change in criteria is to increase the number of hours using the day-night schedule. From the calculated estimates, extending the hours of night ventilation by 3 hours, expanding the range from 21:00-6:00 to 20:00-8:00 is surprisingly insignificant in terms of increasing the amount of hours of hybrid ventilation and potential for free cooling. There is only approximately 6% and 8% increase of free cooling when extending the night ventilation hours while considering the relative humidity and humidity ratio criteria respectively. It can be concluded that the change in criteria that would yield the most additional cooling is to accept outside air at a lower temperature than originally planned.

4.4.4 Conclusion

Depending on the use of the building, different requirements for the indoor environment may be specified and care should be taken to satisfy them if they are not flexible. For example, if a building has rooms which must be constantly maintained below a certain temperature, then care must be taken so that operating in natural ventilation mode will not affect those rooms. However, for most commercial and institutional buildings, the air in indoor environments is only required to be near a certain setpoint temperature and to be within a certain range of relative humidity.

The potential for free cooling and its resulting reduction in energy consumption for cooling was discussed and is summarized in Table 4-5. With the base case being that outdoor air must be within 15-22 °C and less than 70% relative humidity, the extra number of nights or hours of hybrid ventilation available as the criteria for operating in hybrid ventilation mode changes are indicated along with the resulting additional free cooling. It was found that lowering the minimum exterior air temperature at which air would be admitted into the building has the greatest effect, especially when it is further lowered during practically unoccupied hours late in the evening until early morning before work hours. Increasing the time span for night ventilation did not significantly increase the hours when it can be operated and thus only reduces cooling energy requirements by 6-8%. Finally, changing the criterion from setting a maximum relative humidity value to having a maximum humidity ratio also produces more opportunity for free cooling and reduction in energy consumption for cooling.

Table 4-5: Effect of changing criteria to operate in hybrid ventilation mode on free cooling potential and cooling energy consumption reductions compared to the base case.

Criteria for operating in hybrid ventilation mode			
Temperature range (°C)	Night ventilation schedule	Relative humidity <70%	Humidity ratio <11.0 g_{water}/kg_{dry_air}
15-22	-	**Base case (current criteria)**	+ 10% nights + 49% hours + 76% free cooling
12-22 (day) 8-22 (night)	21:00-6:00	+ 19% nights + 46% hours + 131% free cooling	+ 35% nights + 172% hours + 447% free cooling
	20:00-8:00	+ 19% nights + 49% hours + 145% free cooling	+ 35% nights + 184% hours + 492% free cooling

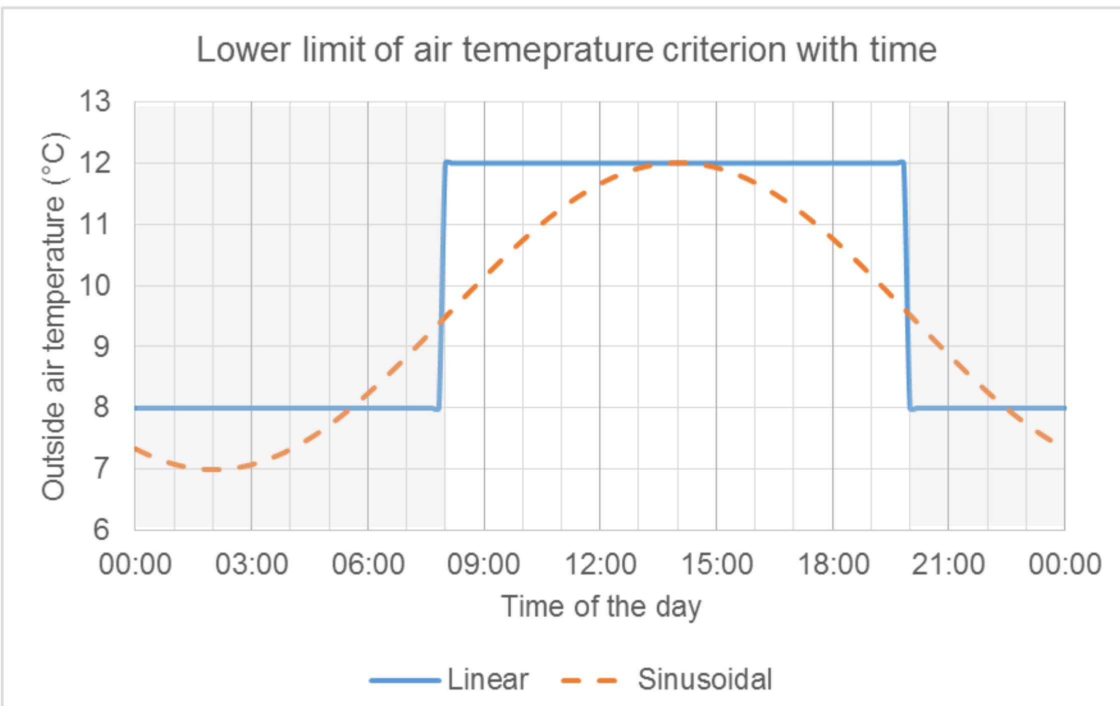

Figure 4-13: Different lower limit for outside air temperature criterion with time.

The suggestion of varying the lower limit of exterior air temperature with a day-night schedule involves a sudden jump in the criteria; however, this can also achieved in a sinusoidal manner so that there is a smooth transition with time, as shown in Figure 4-13, where the shaded regions indicate the hours of night ventilation. Using a sinusoidal wave, this minimum temperature value can be even further lowered between approximately 22:30 to 5:50, when access to the building is restricted to faculty members and students with permission. Furthermore, during the day, cooler air would be admitted into the building in the morning and evening periods when occupants are mostly entering and leaving the building. By doing so, the occupants can get a more gradual change in environment upon entering the building, allowing them to have time to adapt to the inside setting.

4.5 Atria air temperature stratification

Without operating in hybrid ventilation mode, the atria no longer form a solar chimney since they are separated, which leads to different temperature gradient within in each atrium. Through a test on a sunny day, the air temperature and floor surface temperature at the staircase in each atrium was recorded. Since there is a considerable distance from the highly glazed façade to the staircase, there is little direct solar radiation onto its concrete steps in comparison to the solar radiation received by the furniture and floor in the middle of the atrium. These measurements, presented in Figure 4-14, can only serve as a general idea, due to many uncontrollable factors, such as variable incoming solar radiation, floor-specific plug loads, unpredictable occupancy at the atria, and occupant controlled blinds setting. Establishing an optimized sinusoidal profile will be a subject of future research.

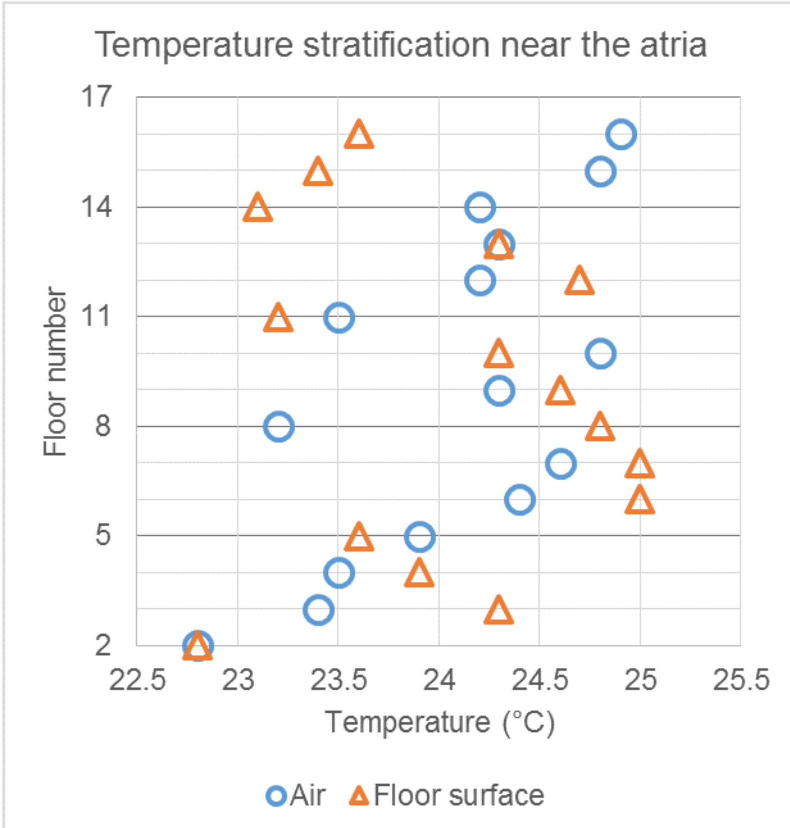

Figure 4-14: Air and floor surface temperature near the atria.

Within each atrium, the vertical air temperature difference from the bottom to the top floor ranges from 0.7-2 °C. The temperature gradient within each floor would thus also be expected to be less than 3 °C, the criterion for thermal comfort based on vertical air temperature difference. In general, the air temperature from the bottom floor to the top floor appears to follow a concave upward curve, where the difference between the first two floors are larger than between the second and third floor. These differences are roughly 0.6 °C and 0.1 °C respectively in the 1st, 2nd, 4th, and 5th atrium, counting from the bottom upwards. It is possible that the blinds were partially or fully closed on those atria, whereas they were open on the 3rd atrium, leading to a higher temperature difference. This is further supported by the high floor surface temperature in that atrium, likely caused by solar radiation.

Since the measurements were taken in November, the interior setpoint has changed to 21 °C, the setting for heating season. Overall, the measured air temperature all exceeded this setpoint, likely to be mainly due to high solar gains through the day. In fact, on the 16^{th} floor, the air temperature is almost 4 °C higher than the setpoint temperature. As a result, it could be advantageous to use the return air temperature from these atria as a means of determining whether hybrid ventilation should be used for a short period of time to exhaust the warm air out of the building. For example, even when the outdoor temperature is too cold to operate in hybrid ventilation mode, it could be temporarily used to flush out the air at the atrium that is mostly warmed up by solar radiation.

5 Conclusion

This thesis presents research to enhance the effectiveness of hybrid ventilation in Concordia University's EV building (and similar buildings), a representative high rise building with motorized dampers at openings on opposing façades, and a virtual solar exhaust chimney consisting of stacked atria. The objective is to increase the time period of use of the hybrid ventilation by relaxing and expanding the criteria of the initial base case which is conservative. To do this, the critical inlet corridor region is considered so as to decide when to admit outside air (lowest temperature) in order to increase cooling potential through primarily night cooling. The rules and new criteria generated will be used in predictive control of the system based on weather forecasts. A typical floor layout with common corridors connecting the façade openings to an atrium allows incoming outside air to navigate towards the solar chimney and be exhausted at the roof with or without fan-assistance. Since inflow of outside air is promoted, there are reductions in energy consumption that would have been used to operate fans within the building mechanical system to provide fresh air and recirculate air throughout the building. Depending on the criteria for operating in hybrid ventilation mode, air at temperatures lower than the indoor air temperature setpoint can enter the building through the façade openings and cool down the building thermal mass in anticipation of heat gains through the day. As such, aspects of occupant thermal comfort are taken into consideration and the reductions in cooling energy consumption by varying the criteria for outdoor air condition is examined.

A full scale on-site test was performed with the building using night hybrid ventilation to gather information on the response from the thermally massive 0.4 m thick concrete floor as well as the change in average air temperature along the length of a corridor located at the south-eastern façade opening of the EV building. For this experiment, the focus is on a 10 m length portion of a corridor acting as the entrance region for outdoor air as it is expected to be the region with the highest heat removal from the concrete floor. The recorded data show that a temperature difference of approximately 5.5 °C can be expected between the air temperature measured at the rooftop weather station and at the end of the corridor, where a meeting room is located. The corridor is found to exhibit different behaviour at the first half of the corridor closer to the inlet and the second half, named primary and secondary zone respectively. A calibrated thermal network model is developed to simulate both the average air temperature, and concrete temperature at the surface and its core. The model was calibrated such that the error in the simulation results compared to those measured are within or slightly above the error range of the instruments used in the test. Calculated from the simulated temperatures of concrete with time, the total cooling energy consumption reduction when a COP of 3 is assumed amounts to 1,112 MWh after 4 hours of night ventilation with an average exterior air temperature of 8 °C. In addition, the primary zone has 38% more heat extracted than the secondary zone.

The thermal model was run using hourly forecast air temperature as input instead of the measured values and the results are comparable, with expected error within the instruments' error range and only a 3.35% decrease in total amount of heat removed. In general, the forecasted air temperature is close to the measured air temperature at a given time, which indicates that it is reliable for the use in predictive controls. On the other hand, the input of air velocity at the inlet is difficult to be substituted by forecast data, since there is currently no general correlation to localize the forecasted wind direction and speed from the closest weather station providing forecast data to the velocity of air entering the building on a specific façade and specific heights of the building.

The criteria used for the employment of hybrid ventilation affects the free cooling potential and reduction of cooling energy consumption. The current criteria requires outside air measured at the rooftop weather station to be between 15-22 °C with relative humidity less than 70%. First, the incorporation of a time of day dependent schedule is proposed to admit air in the range of 12-22 °C and 8-22 °C during the day and night schedule respectively. Assuming that hybrid ventilation can be used from April to the end of October, free cooling potential is increased by 131%. Lowering the minimum air temperature for its admission into the building comes with risk of occupant discomfort;

however, since the corridor is a circulation area, occupants are more flexible with their expectations for thermal comfort. A study on transition spaces showed that the range of PMV can be increased such that the acceptable PPD is increased to 50%. With the advancement of research in that field, the thermal comfort within the corridor region of the EV building can be revisited if ever a revision of the ASHRAE 55 distinguishes circulation spaces from occupied spaces in terms of thermal comfort criteria. Next, replacing the relative humidity criterion with a maximum value for humidity ratio is proposed based on the fact that mixing cooler and more humid air with the air on the inside of the building will result in a mixed condition where the outside air is warmed up and is less humid. By doing so increases the free cooling potential by 76% compared to the original criteria; however, including the day-night schedule, the free cooling potential increase to 447% of the base case.

With the installation of six variable speed fans at the top of the highest atrium, more air can be drawn into the building to further cooling energy consumption savings as well as energy used for circulating air through the duct system. It was found through a preliminary test that operating the variable frequency drives at 40% of the maximum frequency, the fans would overcome wind forces at the top atrium (floors 14-16), allowing outside air to enter the building through openings on both façades. All floors below it are greatly affected by wind forces and generally has air coming in from the south-eastern openings and partly exiting through the north-western openings. From the measurements done without fan assistance and at 80% maximum frequency, the estimated amount of cooling due to cross-ventilation is about 40% whereas the cooling from air being exhausted from the solar chimney represents about 60%.

Continuous research on the EV building is being performed and generalized, especially since the fans are finally installed at the top of the highest atrium in 2016, years after the building's construction. The different ways of controlling these fans without inconveniencing occupants will be studied and using different time dependent criteria for allowing outside air into the building. Next step is implementation of heuristic predictive control (rules of thumb based on the results of this thesis) and eventually model predictive controls.

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Appendices

A. Controls for the fans at the top of the atrium

The initial design of the EV building included fans that would draw air at 30,000 L/s and expected about 4000-5000 occupants [18]. While the building is built ready to include these fans, they were only installed in September 2015. As shown in Figure A- 1, 6 installed fans are located at the exhaust hut on the roof, above the stacked atria. There are and 3 variable frequency drives (VFD), each controlling 2 fans. The 3 VFD together at 100% produces a frequency of 180 Hz. Combined, the 6 fans' total maximum flow is 40,000 L/s, which is greater than the initial designed flow.

Figure A- 1: Fans installed at the roof exhaust hut above the stacked atria.

The VFD operation must first be enabled through a physical switch; however, even with this switch turned on, the VFD can only operate when the dampers in front of the fans are open. These dampers are either fully open or closed, whereas the dampers that are at the façade openings can be modulated. It should be noted that the controls for the VFD and the dampers at the fans are with

Regulvar, whereas the dampers on the building façades and at the floor between atria are with Siemens.

In order to control the fans, a signal from Siemens regarding the states of the façade and floor dampers must be used as an input in the Regulvar control algorithm. If these dampers are open, then the dampers in front of the fans will open. The state of the physical switch for the VFD is checked followed by the modulation of the fans if the switch is turned on. Since each fan is a motor, they must operate at a frequency of at least 15 Hz.

Ebtron thermal dispersion airflow meters (model: Ebtron GTM116-P) are installed to monitor the temperature and flow at the 2 ducts at the top of the building. These are effective for low air velocities with an accuracy of ±2%. The measured data is recorded and stored on CopperCube, after which it can then be used for the VFD control strategies. It is possible to have different controls for day and night fan-assisted hybrid ventilation. At the moment, night ventilation occurs from 0:00 to 7:00.

Currently, there are two control strategies available. First is output control, which is when a specific percentage of the system is desired. For example, an input of 50% will have the VFD at 50% of its maximum frequency. Second is flow control, where a target volumetric flow is used as an input. The VFD will then operate at a calculated frequency and be adjusted based on the feedback from the measured flow at the exhaust. In any case, if the resulting output is between 30-45 Hz, then the load will be shared between 2 VFD. On the other hand, when the output is above 45 Hz, then it will be shared between the 3 VFD.

B. Error analysis on the thermal model results

The statistical measures used in analyzing the calibrated thermal model and its equations are shown below:

1) Root mean squared error (RMSE)

$$RMSE = \sqrt{\frac{\sum(M-P)^2}{n-1}}$$

where

P: predicted value

M: measured value

n: number of values

2) Coefficient of variation of the root mean squared error (CV-RMSE)

$$CV-RMSE = \frac{RMSE}{\mu} * 100\%$$

where

μ: mean measured value

3) Mean bias error (MBE)

$$NMBE = \frac{\sum(M-P)}{(n-1) * \mu} * 100\%$$

4) Standard deviation, σ

$$\sigma = \sqrt{\frac{1}{n}\sum\left((P-M)-(P-M)_{average}\right)^2}$$