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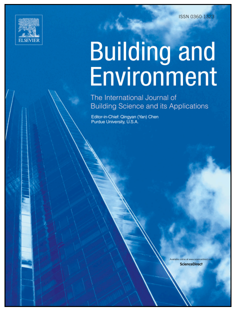

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A study of hybrid ventilation in an institutional building for predictive control

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Abstract

Hybrid ventilation can be employed to precool thermally massive buildings, reducing energy consumption for cooling the following day, particularly at night when the outdoor temperature is lower, and especially when its operation is done in a predictive manner by incorporating weather forecasts. An important requirement is defining the temperature low limit for admitting exterior cool air into a building through transition spaces, to ensure thermal comfort. This paper uses a case study of a 17-story high institutional building with a hybrid ventilation system. To develop a strategy for the admission of outside air into the building, this study focuses on the corridors as generic transition zones/buffer spaces with flexible thermal comfort limits and with the motorized façade openings to determine how the air temperature evolves with distance from the inlets. A developed thermal model, calibrated from a full-scale test, calculates the amount of heat removed from the 0.4 m thick concrete floor. Through 4 hours of night cooling with an average local exterior temperature of 8.3 °C, the air temperature rises to about 12 °C in the transition corridor region at a time when occupancy in that area is expected to be nearly zero. Taking into consideration the flexibility in thermal comfort in the corridor transition spaces, control strategies are developed, based on exterior temperature and humidity. Using humidity ratio instead of relative humidity as criterion for admitting outdoor air potentially results in the system being active for 49% - 180% more hours during the year.

Keywords

Hybrid ventilation; night cooling; thermal comfort; institutional building; experimental

Highlights

- A thermal model for a hybrid ventilated thermally massive building is developed.
- On-site data collected during and following hybrid ventilation is presented.
- Using humidity ratio as a criterion for hybrid ventilation is proposed.
- A lower limit for outdoor air during day and night hybrid ventilation is proposed.

1. Introduction

In Canada's commercial and institutional sector, from 1990 to 2010, the total energy use for space cooling increased by 84.2% [1]. In fact, the energy consumption for space cooling in these buildings is substantial, reaching about 50% of the energy use in Ontario's 2002 summer peak demand [2]. Buildings in temperate climates can take advantage of the high diurnal temperature difference to cool buildings via natural or hybrid ventilation [3]. Heat that is stored within the building thermal mass during the day is removed through night ventilation so that it can reduce the rise in indoor temperature and cooling load of the following day [4]. Incorporating natural or hybrid ventilation in highly glazed, thermally massive buildings with a core or side atrium that acts as a solar chimney can achieve energy savings by reducing both cooling demand and fan energy required for recirculating air within the building. In these types of commercial and institutional buildings, cooling loads are high, due to their high window to wall ratio, and the internal gains due to plug loads and occupants. As a result, cooling is often needed as early as April and until the end of October, and sometimes even during the first weeks of November. Natural ventilation can thus be used during shoulder and cooling seasons, when outdoor conditions are acceptable, and should be considered when renovating or designing new buildings.

There are many studies on ventilation thermal performance prediction. These can be divided into analytical models, empirical, small-scale experimental, full-scale experimental, multizone, zonal and CFD models [5]. Holford and Woods [6] used analytical models to study naturally ventilated, thermally massive buildings and concluded that lumped parameter models are more useful in the design process, than more detailed models. Bassiouny and Koura [7] investigated natural ventilation with a solar chimney and developed a simple relationship between solar intensity and room temperature. Mahdavi and Pröglhöf [8] studied the control of natural ventilation in buildings, using an empirical model calibrated with on-site data. Larsen and Heiselberg [9] conducted an experiment in a wind-tunnel experimental facility and developed a method to estimate the air-flow in single-sided natural ventilation. They reported uncertainties of 23%, which is an improvement compared to earlier expressions. Nishizawa et al. [10] used the same experimental facility to study cross ventilation in a simple space of 4 rooms and the impact of wind direction on the airflow.

Through the several standards and guidelines that exist for designing buildings [11, 12, 13], it is evident that occupant comfort, including thermal comfort, needs to be a priority. The ASHRAE Standard 55 and ISO 7730 both use predicted mean vote (PMV) as a means to gauge whether occupants would find the interior conditions acceptable [11, 12]. From the specified acceptable limits of PMV, the predicted percentage dissatisfied (PPD) can be calculated. A generally thermally acceptable environment in offices would have less than 10% PPD, corresponding to a PMV range between -0.5 to +0.5.

For naturally ventilated buildings, the ASHRAE Standard 55 [11] acknowledges adaptive thermal comfort, establishing acceptability ranges of indoor operative temperature based on the mean monthly outdoor temperature. This results in indoor temperatures that are closer to the outdoor environment, and should be seen in a positive light. In fact, Ning et al.'s study [14] on students' thermal comfort during shoulder seasons leading to the winter showed that they were adapting themselves to the gradually colder environment, and concluded that the students' neutral temperature is continually shifting towards the interior setpoint, which should be lowered since they would become acclimatized from the outdoor environment. They point out that having drastic temperature differences between the indoor and outdoor environment hinders the students' capability to acclimatize.

In buildings with hybrid ventilation systems transitions spaces such as corridors with motorized inlets have more flexible thermal comfort limits than office spaces and can thus be used to bring cooler outdoor air and thus increase cooling energy savings. In transition spaces, people are expected to be walking/passing by or lingering only for a short amount of time. Chun et al. [15]reviewed the different studies on thermal comfort in transition spaces. They concluded that the term "transition space" involves a range of spaces, such as balconies, atria, corridors, or even metro stations and shopping malls. They divided transition spaces into three categories and reported that in places where people enter and exit the building frequently, in terms of PMV, the space was predicted warm, because of the higher than usual metabolic rate.

Pitts [16] terms transition spaces as buffer spaces and physical links between the outdoor and indoor environment; including atria and corridors. Of the types of transition spaces, he offered a means of distinguishing between entrance, circulation, and long-term occupancy zone, based on the occupant's expected metabolic rate, clothing, and the duration of their stay in the zone. His study showed that the acceptable PMV range for indoor spaces and circulation zones can be extended by ±0.7 and ±1.5 respectively while still providing a comfortable environment. This is largely due to different expectations of the occupant relative to the type of space they are located in.

In commercial and institutional buildings, natural ventilation can be employed during both occupied and unoccupied hours. During the unoccupied hours, the thermal comfort criteria are less stringent, allowing for lower tempeartures. Blondeau et al. [17] concluded that for a cooling load of 20 W/m^2 the potential energy reduction of up to 25% is possible in France. The night ventilation was also found to succeed in decreasing the diurnal indoor air temperatures from 1.5 °C to 2 °C. Pfafferott et al. [18] monitored the operation of an office building in Germany for 2 years. The percentage of working hours with operative temperatures above than 25 °C is approximately 10%. They concluded that passive cooling by free night ventilation improves thermal comfort without increasing electricity demand. They warn that hybrid ventilation strategies are important to the operation, in order to avoid disturbance of natural ventilation by mechanically-induced airflows. They report that an adapted simulation model for advanced control strategies using weather forecasts can be implemented.

In the majority of institutional and commercial buildings the building façade openings are controlled by the building automation system (BAS). A program within the BAS will determine whether the openings should be opened for natural ventilation based on specified criteria. These can be as simple as allowing natural ventilation when the outdoor temperature and relative humidity are within a certain range [19], or based on the air change per hour [20]. Schulze and Eicker [21], on the other hand, use not only the outdoor, indoor and operative indoor temperature as criteria, but also the concentration of carbon dioxide as a criterion to gauge air quality. As well, many studies use different criteria based on a specified schedule such as a day and night schedule [19, 20, 22, 23, 24, 16]. For example, extending the range of acceptable exterior temperature at night can add to the pre-cooling potential of the building. Each of these studies uses their own performance criteria to measure the effectiveness of natural ventilation. For instance, Artmann et al. [23] focus on thermal comfort by including calculations using a simulation software HELIOS for the operative temperature and overheating degree hours above 26 °C, whereas Prajongsan and Sharples [25] calculate the percentage of hours within comfortable operative temperature through simulations using both EnergyPlus and a CFD package in DesignBuilder. Moreover, the performance analysis can be also geared towards the amount of energy savings. A study by Hu and Karava [26] evaluates the performance based on simulated hourly mean energy consumption, peak demand, and operative temperature deviation, whereas Spindler and Norford [24] use linear models to calculate the indoor temperature range and aim to minimize the electric energy required to operate fans. Overall, regardless of the differing criteria used in the many studies, the occupants' thermal satisfaction within the building is prioritized before considering how to increase energy savings. Pitts and Saleh's study [27] on thermal comfort in transitional spaces showed that these spaces can allow a 2 °C decrease of the temperature setpoint compared to the main spaces during heating season. Given such spaces can take up a significant portion of the building, the heating energy requirements are directly affected. In fact, depending on the layout, lowering the temperature setpoint from 21 °C to 18 °C and 16 °C can yield up to 22% and 35% respectively in energy savings [27]. This brings the attention towards the lower limit of the acceptable air temperature range for natural ventilation in buildings.

In fact, the exterior weather conditions are crucial criteria for proper natural ventilation and night pre-cooling of the building. The lower temperature limit to allow air into the building is chosen by heuristics and experience in many of the aforementioned cases. Even though exposed thermal mass, usually in the form of concrete floors, is identified in both IEA-EBC Annex 35 HybVent [28] and IEA-EBC Annex 62 Ventilative Cooling [29] as an important factor for hybrid ventilation and especially night cooling, it is not widely used as a factor when deciding the lower temperature limit. The temperature of the air is kept relatively high to avoid overcooling, but without taking into account the energy that can be dissipated from the thermal mass, which will maximize the energy or peak power savings of the next day. This study calibrates a model with experimental data and then explores the different criteria for allowing cool air into the building. It considers the effect of thermal mass and evaluates the effect of temperature and humidity content of the inlet air on the thermal comfort and the energy savings potential.

The paper focuses on high-rise buildings that are thermally massive, can use fan-assisted hybrid ventilation, and have a solar chimney – typically a core or side atrium with an exhaust fan at the top. The key interest is to investigate the lower limit for the range of allowable outdoor air temperature and other criteria for operating in hybrid ventilation, which is essential for predictive control where typically one day weather forecast can be used to precool a building at night. A representative building is the Engineering, Computer Science, and Visual Arts Integrated Complex (EV building) located in Concordia University downtown campus in Montreal, Canada. During the building design phase, a study was performed to provide suggestions towards incorporating natural or hybrid ventilation, in addition to managing daylighting and solar heat gains comparing different options in terms of glazing, shading devices, and window-to-wall ratio [30]. This study was beneficial for ensuring that the building would be ready for incorporating different technologies as well as being able to control the components in the BAS. After its construction, the building was monitored in order to study thermal conditions in the atria as well as different cooling strategies for thermal mass [30]. The EV building is continuously being monitored and studied, in order to improve the controls for hybrid ventilation. The different studies on this building are steps towards creating simple models that would be sufficient to predict the comfort of the indoor environment as well as to predictably manage heat flows in the building thermal mass. These models can then be implemented into the BAS along with forecast weather data to perform model predictive control strategies (MPC) that optimize energy savings and operating costs while ensuring acceptable comfort conditions.

2. Description of the case study building hybrid ventilation system and general aspects

The Concordia EV building was chosen for this study because of its unique characteristics - a midrise modern office building with strong stack effect in a side atrium extending for 15 storeys high (5 3-storey high connected atria), motorized inlets on two sides controlled individually by floor and recently installed motorized variable speed exhaust fans at the top of the atrium. Our search of the literature did not reveal any other similar well documented modern building with a flexible hybrid ventilation system.

The construction of the 17-storey high institutional building ended in 2005. The EV building has an average 50% window-to-wall ratio to allow natural daylight and solar heat gains in winter. In addition, it has a high level of thermal mass mainly due to the 0.4 m thick exposed concrete floor, which reduces the indoor temperature fluctuations by retaining heat during the day when cooling loads are highest, and cooling down at night through natural ventilation when outdoor temperatures are at its lowest. The building was designed and constructed for the use of fan-assisted hybrid ventilation (Figure 1 shows a schematic of the different components of the design) although the rooftop atrium exhaust fans were only recently installed. Outdoor air enters the building through the South-East and North-West façades at the openings with motorized dampers which open only when hybrid ventilation is in use. At the middle of the South-West façade are 5 stacked atria, shown at the top right corner of Figure 1, that are connected through openings on the floor with motorized dampers, forming a solar chimney when hybrid ventilation is used. There are grilles at these floor openings so that occupants can stand directly on top of them if they wish. Each atrium is 3 floors high and was separated for smoke control purposes in the event of a fire. Due to buoyancy with or without fan-assistance, the hot air exits through the roof exhaust above the highest atrium and draws in air from the side openings on the façade. Installed at the end of 2015, the variable speed fan system at the roof exhaust has a maximum airflow of 40,000 L/s and is to be operated in a predictive manner to enhance the cooling of the building when needed by assisting the stack effect. In general, this building requires cooling from as early as mid-April until the end of October, and possibly even in the beginning of November due to factors such as high window to wall ratio (resulting in high solar heat gains), high occupancy rate and associated heat gains, and high plug loads.

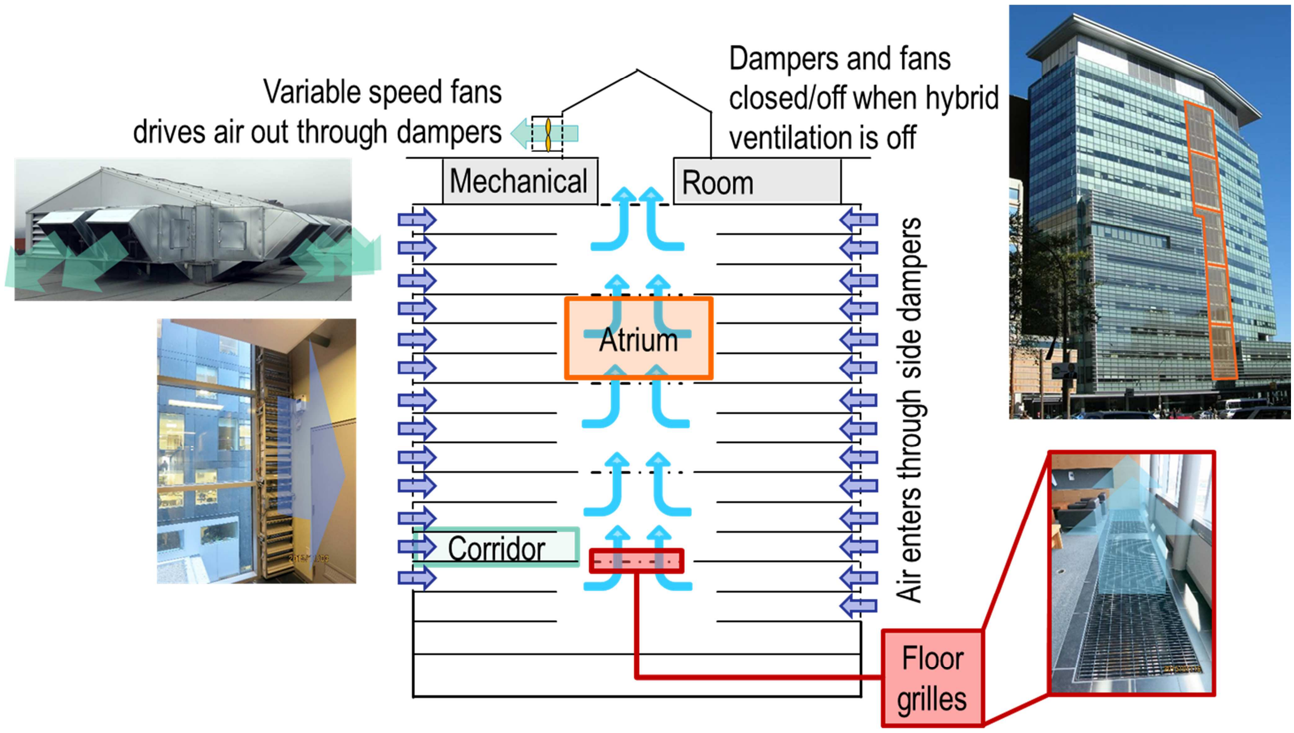

Figure 1: Components for fan-assisted hybrid ventilation in EV building.

The typical floor plan is shown in Figure 2 along with the expected airflow path, when hybrid ventilation is on, from the façade openings at the end of corridors to the atrium. It is expected that without fan-assistance, air movement is highly influenced by wind and results in cross-ventilation through the corridor from one opening to the other, with some portion heading towards the atrium. While hybrid ventilation is in operation, the mechanical system of the building continues to provide air as usual to the interior zones of the building, but the air supply rate at the corridors and the atria are lowered to a minimum. This approach will reduce the energy required for circulating air through the building, since fresh air is directly brought into the building via the façade openings and is moving naturally via wind and buoyancy forces, assisted by exhaust fans when needed.

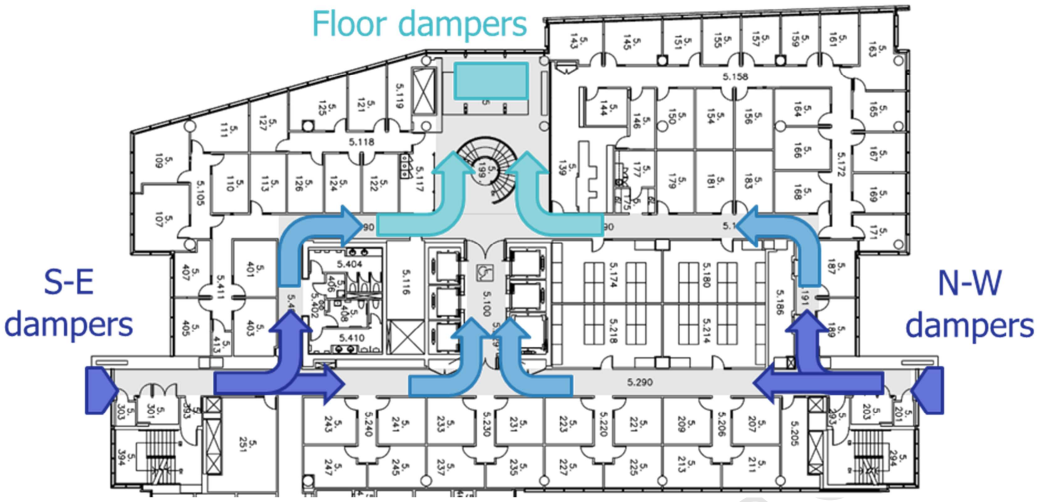

Figure 2: Typical floor plan of the EV building with the expected airflow path.

In this study, the attention is on the entrance region at the South-East façade opening: a 10 m corridor section. With hybrid ventilation, these openings act as inlets and outlets for the cool outdoor air and warm indoor air. Since the cool air would first interact with the building elements within the first few meters of the corridor region, it is the location where the cooling effects would be greatest. More importantly, in terms of occupant comfort, the goal of the study is to observe the evolution of air temperature along the corridor in order to determine a lower limit for the temperature range to use hybrid ventilation without causing discomfort to occupants.

As shown in Figure 3, the openings with motorized dampers are on one side of the façade and where the corridor width is extended by 0.35 m, so as not to be visually intrusive to occupants; however, the turn causes more resistance in the airflow. On-site data is collected to investigate the average air temperature along the corridor.

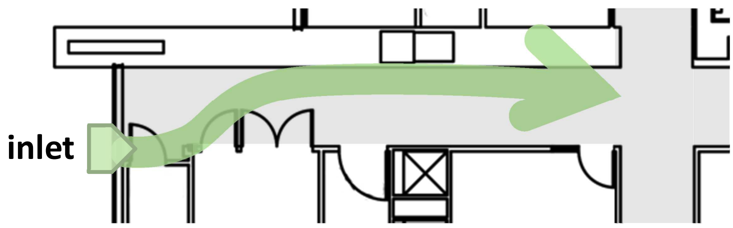

Figure 3: Schematic of South-East corridor region and expected flow path

3. Experimental Set-up

In this study, the interest is in maintaining thermal comfort in the high-rise building when hybrid ventilation is in operation and in estimating the heat removed from interior thermal mass. Since a higher temperature difference between the indoor and outdoor environment is beneficial to drive air movement through the building, a night with forecast air temperature between 8 and 9 °C, in contrast to the interior temperature setpoint of 21 °C, is deemed acceptable. This low temperature is also chosen in order to verify the thermal condition within the building and decide the suitability of setting 8 °C, measured from the local weather station, as the lower limit for allowing hybrid ventilation to be in operation. Since the variable speed fans were installed after this experiment, they could not have been used to promote airflow into the building. This study was used to show also the potential benefits of the fans since they would increase the airflow due to buoyancy and wind. As a result, the measurements are taken on the 5^{th} floor of the building, as it is at the bottom floor of an atrium and is far below the neutral plane in order to ensure airflow into the building.

The corridors are 1.8 m wide, and the floor consists of a 0.4 m thick concrete slab with thin tiles cover. The concrete is assumed to be light-weight with a density of 1,700 kg/m^3, specific heat capacity of 800 J/kg·K and thermal conductivity of 1.7 W/m·K. These values are consistent with the ones used in previous studies of Concordia EV building [19]. There is a suspended ceiling consisting of acoustic tiles and luminaires, at 3 m height.

On the inside of the building, at the dampers, 0.4 m above the floor, the inlet temperature is measured with thermocouples (accuracy: ± 0.5 °C), whereas the inlet velocity parallel to the ground is measured with a one-directional anemometer, (repeatability: 0.03 m/s ±1 % of readings in the range of 0.15 to 1.5 m/s). Along the corridor, thermocouples and infrared sensors are placed identically at 0.75 m, 3 m, 6 m, and 9.5 m from the façade. A thermocouple is placed on each of the vertical walls and at the bottom of the suspended acoustic tile for surface surrounding surface temperatures. Three thermocouples are suspended at 0.1 m, 1.1 m, and 1.7 m off the ground measuring the air temperature. A representation of the corridor with the locations of measurements points is shown in Figure 4. The floor surface temperature is measured using infrared sensors (accuracy: ±1% of reading or ±1°C, whichever is greater) suspended between the acoustic tiles. These measurements will be used to verify the developed thermal model for determining the temperatures of air and the concrete floor.

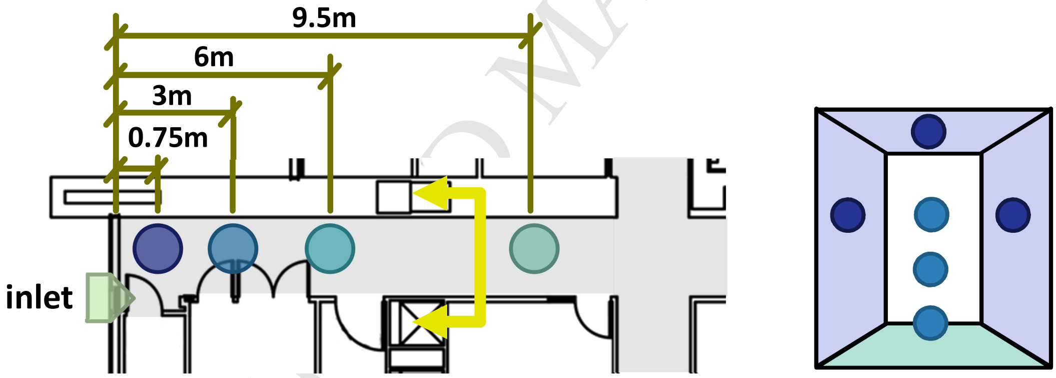

Figure 4: Measurement locations along the corridor (left) and each point's setup in a cross-sectional view of the corridor (right).

From the building automation system, data from the newly installed weather station on the roof of the EV building can be accessed. This rooftop weather station was set up in 2015 and includes sensors to measure air temperature and relative humidity to compare to the temperature measured at the inlet damper and within the corridor.

In terms of thermal comfort, for night cooling, a cooler environment is allowed, since the building is essentially unoccupied overnight. Also, even during the day, occupants do not linger in the corridor region since it does not lead to office spaces, and would only use it to access the emergency staircase located at roughly 6 m from the façade . Moreover, as the cool air moves towards the atria, it is warmed up by the building and gradually becomes closer to the interior temperature setpoint. As such, the thermal conditions at the end of the corridor are investigated in terms of average air temperature and thermal stratification.

4. Development of the numerical model

An explicit transient finite difference model was developed using the on-site data for calibration. The model uses the outdoor air temperature, measured at the rooftop weather station, and the time elapsed since opening the dampers to simulate the average indoor air temperature and the temperature of the concrete floor both at the surface and at specified depths. These results are used to calculate the amount of heat removed from the thermal mass in a region near the façade opening acting as an inlet for cool outdoor air via hybrid ventilation.

The geometry of the corridor is simplified as a rectangular prism of dimensions 1.8 m x 3 m x 10 m. The effect of the slightly wider portion of the corridor at the inlet will be taken into account during calibration. In addition, the space above the suspended ceiling is disregarded since incoming outdoor air being cool, descends towards the floor and does not influence significantly the air in that space. The corridor zone is discretized along its length, as shown in Figure 5. Starting from the inlet, there are four numbered sections of 1.5 m, 3 m, 3 m, and 2.5 m length, such that each point of measurement corresponds to a section. The concrete floor is also segmented as such along the length, and is also discretized along its depth into 10 control volumes. From the exposed surfaces to the center, the layers are 0.5 cm, 1.5 cm, 3 cm, 5 cm, and 10 cm thick. The exposed layers can be approximated as a lumped solid, since their

Biot number [31] is less than or equal to 0.1. This dimensionless number compares the resistive forces of convection at the solid surface to the ones of conduction within the solid and is calculated with 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). The discretization of the concrete slab can be seen in more detail in Figure 5.

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

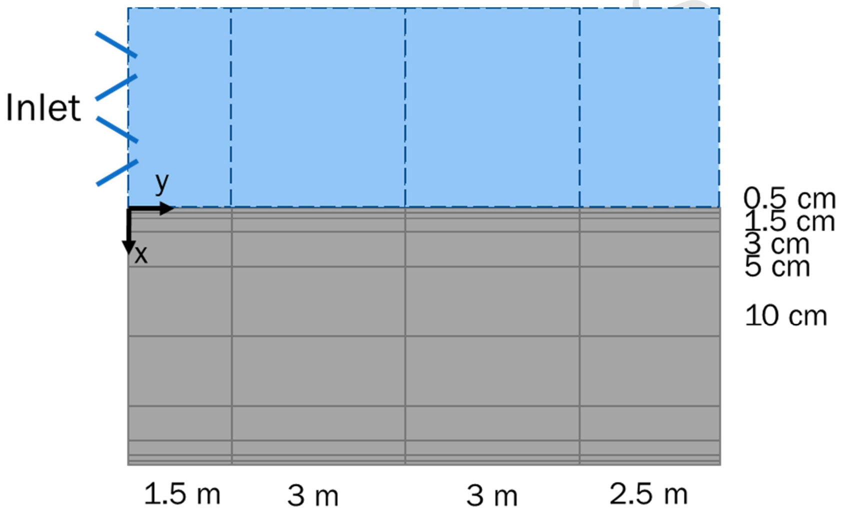

Figure 5: Discretization of concrete into 10 layers (10 control volumes in each section).

A second simplification to the thermal model is to assume the inlet covers the entire façade region, instead of a slim vertical strip on the side; however, due to the expected general air flow path shown previously in Figure 3, the air velocity will have coefficients as multipliers to calibrate the model. In actuality, the airflow is expected to be turbulent, with local recirculation areas horizontally between the corridor segment and vertically within each segment. These factors can be interpreted as the resulting airflow from one corridor segment to another given that backflow is highly probable. Table 1 shows the values of these calibration factors used in the thermal model.

Table 1: Coefficients to calibrate the velocity in the thermal model.

Velocity of air between locations	inlet →1	1→2	2→3	3→4
Velocity calibration factors	1	0.6	0.2	0.2

Next, in anticipation to future practical monitoring, having visible sensors is unwanted, meaning that the thermocouples that were placed on the walls and ceiling are to be removed. To that effect, a linear relationship was created for each corridor segment between a combined surfaces temperature, defined as $T_{sfc}=2/3*T_{ceiling}+1/3*T_{wall}$, the air temperature at the inlet, the corridor segment of these surfaces, and the time elapsed since opening the dampers. Since the air flowing into the corridor is likely to exchange heat with the wall farther from the inlet, as well as the ceiling due to buoyancy, these surfaces are combined to simplify the model. These relationships would be applicable for similar cool nights.

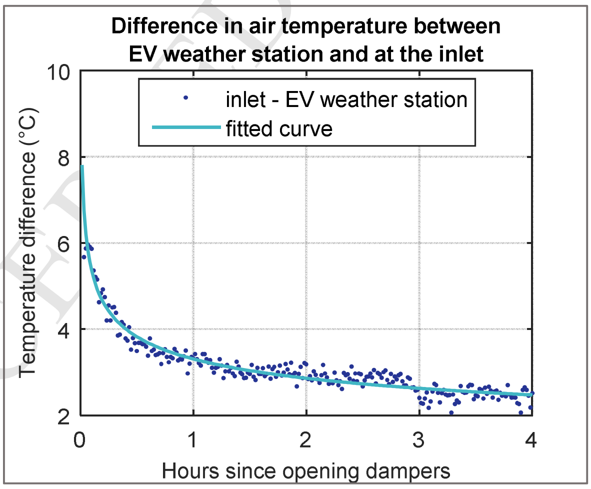

Figure 6: Difference in air temperature between EV rooftop weather station and at the inlet.

Similarly, in order to reduce the number of sensors required in the building, an equation is developed to correlate the air temperature at the EV rooftop weather station and at the inlet with time as shown in

Figure 6Figure 6. The measured local air temperature at the building's own weather station at the roof was between 7.8 and 8.9 °C, with relative humidity between 54-63%; however, the air temperature at the inlet on the inside of the building was between 10.1-14.4 °C. This difference can be explained by the air being heated by the EV building façade as well as the heat released from the streets and surrounding buildings, as the measurements were done on the 5th floor. As expected, the temperature at the inlet quickly drops to around that of the outdoors, and a difference of at least 2 °C persists even after 4 hours of night ventilation under such cold conditions. As this fitted curve equation is only valid for similar nights, different relationships need to be created for warmer outdoor conditions. Similarly, new equations would be required for different inlets, as the intensity of the driving forces for cool air into the building varies.

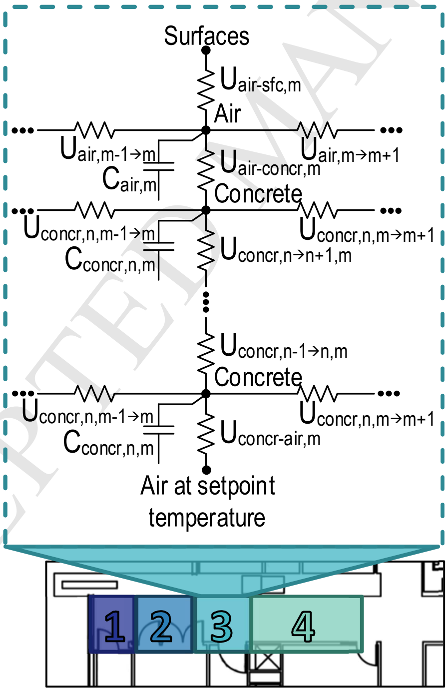

Figure 7: Separating the corridor into 4 segments (and associated control volumes). Typical thermal network representation of the 3rd corridor segment.

The explicit finite difference model schematic representation and the interaction between the different nodes for air, concrete, and the combined surfaces are shown in Figure 7. The corresponding typical heat balance equations are shown as Eq. 2 and Eq. 3 for the average air temperature node and concrete surface node respectively, where T, U, A, C, ρ, Cp, v, and Δt represent temperature (°C), thermal conductance (W/K), cross-sectional area (m^2), thermal capacity (J/K), density (kg/m^3), specific heat capacity (J/kg·K),velocity (m/s), and timestep (s) respectively. Subscripts are first to indicate whether the node pertains to air, combined surfaces (sfc), concrete (concr), the whole corridor, or an element between their segments. Then, subscripts m and n indicate the corridor segment number, and the concrete layer numbered from the top to bottom, respectively. The superscripts p and p+1 indicate the present and next timestep number respectively.

$$T_{air}{}_{m}^{p+1} = T_{air}{}_{m}^{i} + \frac{\Delta t}{C_{air_1}}\Big[\rho_{air} c_{p_{air}} v_{air_m}{}^{p} A_{corridor}\left(T_{m-1}^{p} - T_{air}{}_{m}^{p}\right) + UA_{air-sfc_m}\left(T_{sfc}{}_{m}^{p} - T_{air}{}_{m}^{p}\right) + UA_{air-concr_m}\left(T_{concr}{}_{n,m}^{p} - T_{air}{}_{m}^{p}\right) + \rho_{air} c_{p_{air}} v_{air_m}{}^{p} A_{corridor}\left(T_{air}{}_{m+1}^{p} - T_{air}{}_{m}^{p}\right)\Big] \quad \text{Eq. 2}$$

$$T_{concr}{}_{n,m}^{p+1} = T_{concr}{}_{n,m}^{p} + \frac{\Delta t}{C_{concr_{n,m}}}\Big[UA_{concr_{n,m-1\to m}}\left(T_{concr}{}_{n,m-1}^{p} - T_{concr}{}_{n,m}^{p}\right) + UA_{concr_{n,m\to m+1}}\left(Tc_{n,m+1}^{p} - Tc_{n,m}^{p}\right) + UA_{concr_{n\to n+1,m}}\left(T_{concr}{}_{n+1,m}^{p} - T_{concr}{}_{n,m}^{p}\right) + UA_{air-concr_2}\left(T_{air}{}_{m}^{p} - T_{concr}{}_{n,m}^{p}\right)\Big] \quad \text{Eq. 3}$$

The calibrated thermal model uses effective heat transfer coefficients, which encompass the effects from convective and radiative heat transfer, and heat from the luminaires and air infiltration to adjacent spaces. The used effective (calibrated) heat transfer coefficients used are listed in Table 2. They were chosen to enable good agreement between simulations and measured data. Values for the first two corridor segments are higher, as it is the portion where the air is expected to be along the main path and have a recirculation area due to the flow across from the inlet towards the wall as shown in Figure 3. Furthermore, as the air temperature is an average instead of the actual air temperature near the floor, which is expected to be lower, the coefficients between air and concrete floor is high in order to compensate for the smaller temperature difference that the model predicts.

Table 2: Effective (calibrated) heat transfer coefficient used in the calibrated thermal model.

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

Since the explicit scheme is used for this finite difference model, the time step used in the simulation must be small enough to ensure stability. The chosen timestep must be lesser than the smallest timestep determined from $\Delta t_{crit} \leq C_i / \sum_j (U_{ij})$, where Δt_{crit} 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.

The thermal model is used to simulate the temperatures of air and concrete both at the surface and within the floor. As the initial conditions, the air, surrounding surface, and concrete surface temperatures are assumed to be those measured, whereas for the interior nodes of the concrete floor, a linear interpolation was done between the surface and setpoint temperature for the floor below. From 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 using the equation $Q=\rho * Cp * vol * \Delta T / \Delta t$, where Q is heat (W) and ΔT is the difference in temperature.

5. Results and discussion

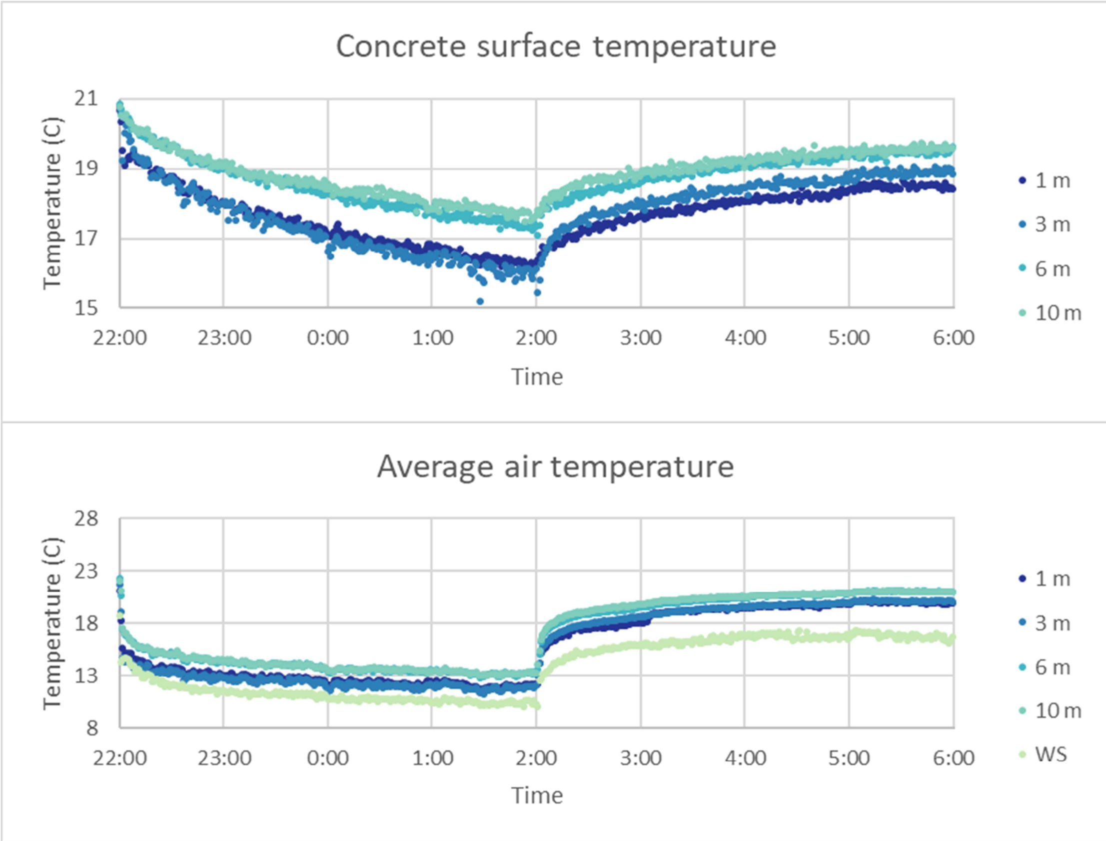

Figure 8: Measured floor surface temperature and average air temperature along the corridor (WS is the roof weather station temperature).

The on-site measurements, shown in Figure 8, were acquired throughout 4 hours from 22:00 to 2:00 and 4 hours from 2:00 to 6:00 for night hybrid ventilation. From these data, general expectations can be established for hybrid ventilation in terms of thermal comfort. Since the mechanical system supplying air to the corridor and atria resumes bringing the air temperature back to 21 °C and reaches this target within 2 hours, whereas only half an hour is necessary to raise the average air temperature at the end of the corridor to 19 °C, the setpoint during winter. Given this situation, halting hybrid ventilation system half an hour before the required time can be sufficient to minimize any thermal discomfort. However, it could be more efficient to let the building passively warm up to the setpoint temperature. This would increase the time needed for the temperature to reach an acceptable value for thermal comfort, but depending on the outdoor conditions it may be more advantageous than letting the mechanical system work to heat the air. The time that the hybrid ventilation system is not working is time that thermal energy is not being extracted from the thermal mass of the building. There are times that the thermal energy that would be extracted in this time is more than the energy used by the mechanical system to supply warm air to the building, in order to achieve the setpoint. Then it is advantageous to let the hybrid ventilation system cool the building as much as possible and use the mechanical system to heat the air. Otherwise, it is more advantageous to shut down the hybrid ventilation system earlier and let the building warm up on its own.

The specific local thermal comfort aspects that were considered are the vertical air temperature difference and floor surface temperature. The former has an acceptable limit 3 °C from the ASHRAE Standard 55. During the whole 4 hours of night ventilation, even with the outdoor conditions averaging 8.2 °C, the maximum temperature difference from the feet and head height is 1.9 °C at its highest, which lies within the acceptable limit. On the other hand, the lower limit for the acceptable floor surface temperature set by ASHRAE Standard 55 is 19 °C for 10% PPD; however, recalling the more flexible criteria of ±1.5 PMV for transition spaces, corresponding to 50% PPD, the acceptable floor temperature would then be 7.5 °C, which is less than the minimum exterior air temperature recorded during night ventilation. In other words, for a corridor region, the floor surface temperature will not lead to any significant discomfort, despite the incoming cool outdoor air.

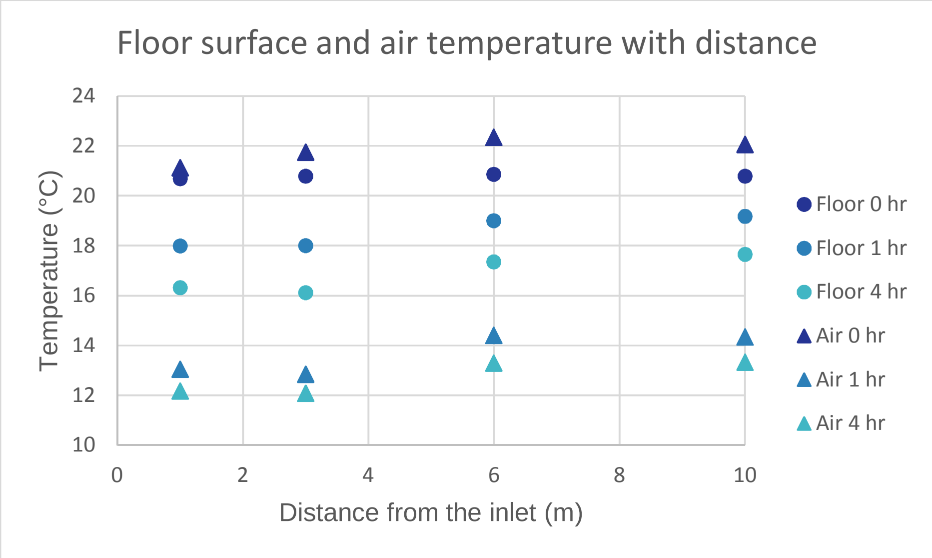

Figure 9: Floor surface and air temperatures along the corridor with time during night ventilation.

The measured change in floor surface temperature along the corridor with time, shown in Figure 9, depicts a significant decrease in the first half of the corridor close to the inlet, in comparison to the further half which seems to decrease uniformly in temperature along the corridor length. The air temperature decreases in time in a similar manner. It increases greatly between the two measurement points of 3 m and 6 m. This is explained by the predicted airflow path with the bulk of the incoming air passing through the second point of measurement at 3 m from the façade, and the expected recirculation area at the façade due to it. As a result, the corridor is separated into two regions: the primary region being the first half of the corridor, where most of the heat exchange occurs, and the secondary region being the latter half of the corridor, where the effects of hybrid ventilation are more uniform. With a temperature difference of 12.8 °C from the interior and exterior air temperature, a drop of 3 °C for the floor surface temperature of the primary region is seen within the first hour of night ventilation, and 4 °C within 2 hours. Afterwards, the decrease is slowed down to 0.2 °C per hour. In the secondary region, a 2 °C decrease is seen in the first hour, and another 1 °C by the 4-hour mark. Overall, the effect of night hybrid ventilation is greatest within the first two hours, after which it is slowed considerably since the interior and exterior environment is progressively more similar, and concrete being a thermally massive component, a long time is needed to keep extracting heat.

The measured and simulated concrete surface and average air temperature during the 4 hours of night ventilation, shown in Figure 10, are in good agreement. Their root mean square error and standard deviation of the error are listed in Table 3. Overall, the model underestimates the average air temperature in the primary region, but still remains within 1 °C of the measured data. In the secondary region, the expected error is expected to be within 0.5 °C. On the other hand, for concrete surface temperature, the error can be expected to be within 0.3 °C. Using the model, the amount of heat removed for a 10-m long corridor over 4 hours of night ventilation is 11.7 MJ. Moreover, it was found that the primary region has 30% more heat removed than the secondary region, highlighting that the first few meters of the corridor is enough to warm the air so that there is less temperature difference between the air and floor surface in the further portion of the corridor.

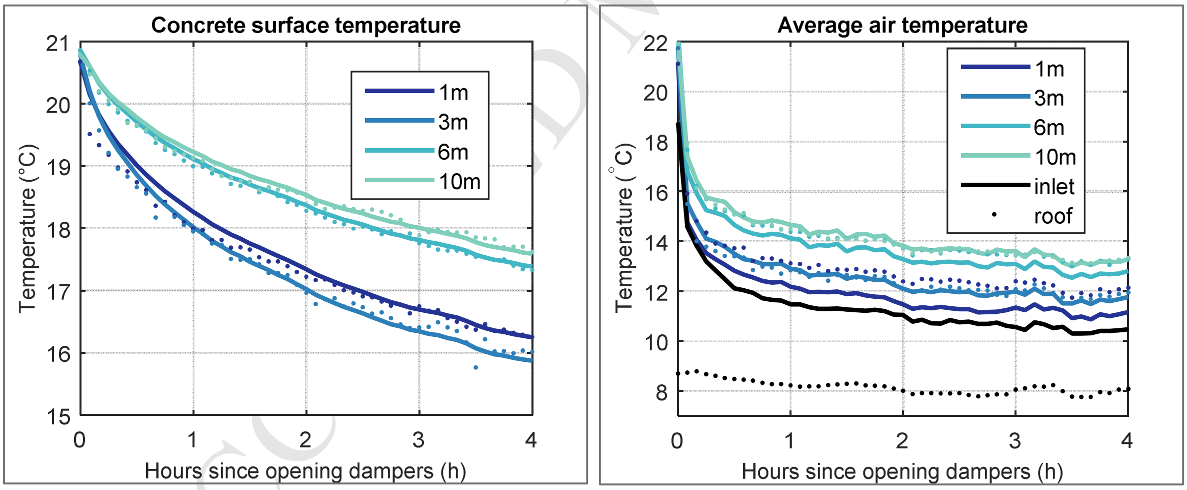

Figure 10: Measured and simulated concrete surface and average air temperature.

Concrete				
Corridor section	1	2	3	4
RMSE (°C)	0.20	0.14	0.07	0.10
Standard Deviation (°C)	0.15	0.14	0.05	0.09
Air				
Corridor section	1	2	3	4
RMSE (°C)	0.96	0.21	0.43	0.16
Standard Deviation (°C)	0.19	0.21	0.14	0.15

Table 3: RMSE and Standard Deviation for concrete and air

Through the developed thermal model, it is possible to predict the behaviour of the thermal mass in the building. In fact, using the hourly forecasted air temperature at the Dorval airport, between 8-9 °C, instead of the measured data at the rooftop resulted in similar simulated results, with less than 5% difference in the amount of heat removed. This highlights the possibility of using MPC to adjust the night ventilation plans in anticipation to an upcoming series of hot days or a sudden colder day. Ideally, the forecasted temperature at the airport will be localized for the EV building in order to produce better results, especially during extreme conditions, such as thunderstorms or extreme wind.

The amount of mechanical cooling energy saved by the hybrid ventilation system with and without fan-assistance can be estimated by calculating the change in air temperature from the motorized inlets to the exhaust at the top of the solar chimney, and it is shown in Eq. 4.

$$Q = \sum \left[\frac{V * \rho * c_p * (T_{exhaust} - T_{inlet}) * 1hr}{COP} \right] \quad \text{Eq. 4}$$

The expected difference of 2.5 °C in air temperature from the rooftop weather station to the inlet needs to be added to the air temperature from the weather data to form the inlet temperature T_{inlet}. 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 (m^3/s), air density ρ (kg/m^3), and specific heat capacity C_p (J/kg·K). The result is divided by a system coefficient of performance (COP) of 3 which is representative of the building HVAC system.

Originally, the initial criteria for operating hybrid ventilation required exterior air relative humidity to be between 30-70% and temperature between 15-22 °C; however, due to the incoming air being mixed with the interior air as it makes its way towards the exhaust, a new criterion is proposed to replace the constraint of relative humidity. The outdoor air, as it is being mixed with the indoor air, results in warmer and less humid air by the time it reaches the core of the building and the occupants. The maximum value of the humidity ratio of the air allowed into the space 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, for outdoor air temperature of 22 °C and relative humidity of 70%, the humidity ratio is roughly 11.6 g_{water}/kg_{dry_air}. In Figure 11, the outline of the psychrometric chart is shown along with two areas in orange and blue. The former represents the region for acceptable air condition based on the initial criteria, while the blue area represents the additional air condition that is deemed adequate during hybrid ventilation when the criterion is changed to having a humidity ratio less than around 11.6 g_{water}/kg_{dry_air}. The more humid air would mix with the dryer air within the building such that it would overall be unnoticeable. Assuming that night ventilation is allowed to operate with the original criteria, between 21:00 to 06:00 from April to October, for a typical year in Montreal, Canada, night ventilation will be in use for 55 nights for an average of 3.2 hours per night. Adapting the new criterion would result in 41% more nights, and an average of 5.1 hours per night. Additionally, changing the allowable range of air temperature to between 8-22 °C results in 149 nights oh hybrid ventilation, with an average of 7.4 hours per night.

For night ventilation, the lower limit for the acceptable air temperature can be lowered arguably down to 8 °C, as it does not produce discomfort for a transitional space. Furthermore, during the hours of night ventilation, the building is expected to be nearly unoccupied, making thermal comfort less of a concern. Now, increasing the time range for night ventilation increases the cooling potential, as it would allow more time to remove heat from the thermal mass of the building. If the criterion for operation is relative humidity, but with extending the air temperature to between 8-22 °C, and also increasing the operating hours from 21:00 to 06:00 to 20:00 to 08:00 doubles the amount of nights available (from the base case), for an average of 4.8 hours per night. If the humidity ratio criterion is also applied the system will be working for a total of 156 nights and an average of 9.4 hours per night. This means that it will be on for 57% of the time within the possible operating hours, and on average for at least twice as long as the time of the data collection, which was 4 hours. Due to the high amount of thermal mass of the corridor, the 4 hours of the experiment showed that there is still lots of potential for heat extraction from the concrete. Also, the longer operation will allow the cool air to reach further towards the core of the building. Since the ultimate purpose is pre-cooling the building during the unoccupied hours, to save energy and lower peak power demand during the occupied ones, it is effective to lower the criteria for outdoor air temperature and try to maximize the time the system is operating.

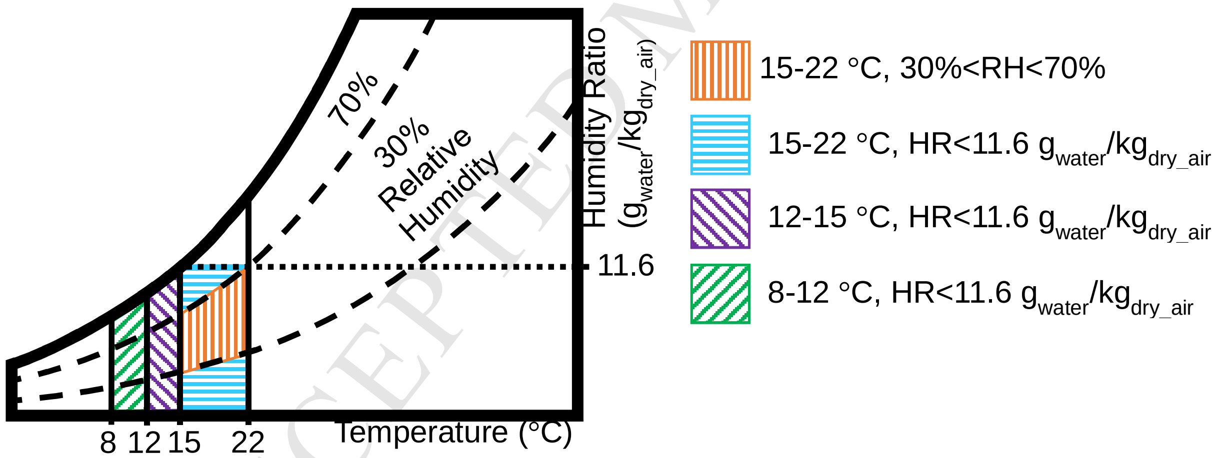

Figure 11: Comparison of acceptable air condition regions for different criteria.

During daytime hybrid ventilation, the proposed criterion of having a maximum humidity ratio would still apply, however the lower limit of the acceptable outdoor temperature range can be lowered to 12 °C. Through the on-site measurements, even with an average exterior air temperature at the roof of 8.1 °C, there was at least a 5 °C difference between the rooftop weather station and the end of the corridor. Since there is no occupied space along the corridor until 11 m from the façade, and the thermal comfort criteria should be more flexible for transitional spaces, the interior air temperature would be expected to be at least 17 °C given a lower air temperature limit of 12 °C measured from the rooftop weather station. Additionally, the air is expected to be even warmer as it reaches the atrium, where occupants may stay during the day; thus, even though the air is cool at the corridor, it is expected to be even warmer as it reaches the atrium. On sunny days, the solar radiation from the highly-glazed façade provides additional heat to the atrium air and occupants.

The potential for free cooling and its resulting reduction in energy consumption for cooling is summarized in Table 4. The minimum outdoor air temperature allowed into the building has a great effect, especially when it is further lowered during the practically unoccupied hours late in the evening until early morning, before the work hours start. Increasing the time of the night pre-cooling did not affect the free cooling potential significantly. Changing the criterion from relative humidity to a maximum humidity ratio provides more operation opportunities and reduces remarkably the cooling energy consumption of the building.

Table 4: Effect of different criteria for hybrid ventilation operation on free cooling potential and cooling energy consumption reduction.

Criteria for operating in hybrid ventilation mode			
Temperature range (°C)	Night ventilation schedule	Relative humidity <70%	Humidity ratio <11.6 $g_{water}/kg_{dry\ air}$
15-22	-	**<u>Base case (current criteria)</u>**	+ 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	+ 35% nights + 184% hours

		+ 145% free cooling	+ 492% free cooling

The previous study by Karava et al. [19] on the building showed that for 3 months during the cooling season, the total cooling load for the atria and corridors is estimated to be 20,500 kWh, where 30% of it can be fulfilled through hybrid ventilation. Considering the 11.7 MJ free cooling calculated from the on-site measurements using the developed thermal model to be similar on each end of each floor and from the second to the tenth floor (due to the neutral plane being on the fourth atrium), the total cooling from the corridor sections in the whole building can be roughly estimated. The warmed air above the neutral plane would be naturally exiting from the roof exhaust and the façade openings, which produces less cooling than in the corridor sections below the neutral plane. Assuming night ventilation occurs 50% of the nights in 3 months, the total amount of heat removed would be 2691 kWh, representing 13% of the estimated cooling load from the previous study; however, the cooling effects from the thermal model is only for the corridor and does not consider the cooling that can be obtained at the atrium, in the connecting corridor sections, and above the neutral plane in this mode.

With the variable speed fans installed at the roof exhaust of the EV building, the potential airflow into the building is amplified, which will result in more heat removal from the building thermal mass. Studies are underway to observe the airflow patterns with fan-assisted hybrid ventilation. For example, through an initial examination by varying the fan speed, it appears that wind effects are significant as there is still cross-flow up to the 14th floor, except for the 11th floor at high fan speed. The wind predominantly flows in from the South-Eastern façade openings and its pattern around the building can be causing suction at the openings on the North-Western façade; however, the fans are able to overcome this and create inflow at the North-Western façade openings on top three floors since they are closest to the fans. Further investigation will be done with this building to draw out general conclusions on the behaviour of thermally massive high rise institutional or commercial buildings with fan-assisted hybrid ventilation through openings on opposing façades connected to a solar chimney.

Adjusting the present thermal model to consider the use of the fans on the roof can greatly assist in the development of a predictive control algorithm. The model will simulate the thermal response of the system according to the outdoor temperature, humidity and wind. Using forecast data, the model will predict the discomfort caused by the opening of the dampers, and decide whether the dampers should be open and the percentage of the opening. This decision will automatically control the hybrid ventilation system and the dampers, through the building automation system. Furthermore, the algorithm can be calibrated to weigh the discomfort of the occupants against the energy performance, and take different decisions depending on the building being occupied or not. Although the occupancy affects the allowable discomfort levels in the corridors, the fact that they are transition spaces provides a lot of flexibility for thermal comfort criteria, and as a result on energy efficiency. The people who would still be in the building after the official working hours will only be few and would be working in the offices or the labs. The amount of time that they would spend on the corridors will be minimal. For this reason, a simple assumption for the occupancy based on the time of the day and the day of the week would be sufficient for the control of the hybrid ventilation system.

6. Conclusions

This paper focused on hybrid night ventilation in a thermally massive institutional building with automatically controlled motorized openings on opposing façades and a side atrium with top exhaust in order to provide insight on the general behaviour of this archetype type of building when operating in night hybrid ventilation mode and to develop operating guidelines. On-site measurements at the EV building of Concordia University in Montreal, Canada were acquired for a corridor zone at the façade opening acting as an inlet for cool outdoor air for a period of 4 hours with hybrid ventilation at night followed by 4 hours without hybrid ventilation. This study showed the benefits of adding fan assist at the top of the atrium by considering a floor below the neutral plane with inflow trough the motorized inlets. As a result of the study, variable speed fans were added at the top of the atrium as was originally the intention of the building designers [30].

A study of thermal comfort for this corridor as a transitional space demonstrated that the mixed air conditions from the warm indoor and cool outdoor air should not cause excessive discomfort to the occupants that would happen to pass by overnight. Furthermore, it contributes to setting guidelines on how low the outdoor air temperature can be for opening the inlet motorized dampers in the corridor during the day and night. In locations with similar summer conditions as Montreal, 8 °C and 12 °C are proposed for night and day lower limits for outdoor air temperature respectively. Instead of using the relative humidity of outdoor air as a criterion, the use of the humidity ratio corresponding to the upper limit for temperature and relative humidity is suggested.

An explicit finite difference thermal network model was developed to study this corridor transition zone with special attention to both the average air and concrete temperature distribution along the corridor to predict the night cooling potential in such a zone. Night hybrid ventilation during the cooling season is estimated to be at least 13% of the total cooling load for corridors and atrium during the summer. The model provides input to a predictive control scheme under development for operating the hybrid ventilation system and its two key components: the motorized inlet grilles and the recently installed rooftop variable speed fans.

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8. Nomenclature

Latin letters

A	area, m^2
Bi	Biot number, dimensionless
C	thermal capacity, J/K
COP	coefficient of performance, dimensionless
Cp	specific heat capacity, J/kg·K
HR	humidity ratio, g_{water}/kg_{dry_air}
L	length, m
Q	heat, W
RH	relative humidity, percentage
T	temperature, °C
U	thermal conductance, W/K
V	volumetric flow rate, m^3/s
h	convective heat transfer coefficient, $W/m^2 \cdot K$
k	thermal conductivity, W/m·K
v	velocity, m/s

Greek letters

ρ	density, kg/m^3
Δt	timestep, s

subscripts

air	air node
air-concr	air to concrete
air-sfc	air to surfaces
c	characteristic
ceiling	ceiling
concr	concrete
crit	critical
i	node number
j	node next to node i
m	corridor segment number
n	concrete layer numbered from top to bottom
p	present timestep
sfc	combined surfaces
wall	wall

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