Experimental and Simulation Study to Improve Operation of a Hybrid Ventilation System in an Institutional Building

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Abstract

Buildings with high thermal mass can use hybrid ventilation to achieve free cooling and reduce energy consumption and peak cooling demand, while maintaining comfort. This paper considers a high rise institutional building and focuses on a typical corridor, where the fresh air enters the building through insulated motorized inlet dampers on two opposite façades and is exhausted through a façade atrium. A transient two-dimensional thermal network model was developed for the inlet corridor zone and calibrated with measured data from on-site monitoring. It estimates the air temperature, floor concrete surface temperature and heat removal. The model also estimates the discomfort of the occupants, based on the PPD index, and weighs it against the energy performance to decide whether the motorized inlet dampers should be open or closed. The simulation shows that for 12 days in May, at one of the 27 inlet regions, at least 1.022 kWh/m^2 of free cooling can be extracted just from the concrete floor, exceeding the discomfort limit 10.2% of the time.

Introduction

At night occupancy in commercial and institutional buildings is low and the temperature difference between interior and exterior air is significant during the cooling season. Hybrid ventilation in buildings that have high thermal mass can utilize free night cooling to reduce energy consumption. With effective control strategies, it can also reduce peak cooling demand by pre-cooling the mass, while maintaining thermal comfort.

Chenari et al. (2016) reviewed the literature in energy-efficient ventilation systems, energy consumption, the way occupants behave towards the ventilation and the relation between their productivity and health to hybrid ventilation. The study showed that ventilation is interrelated not only with indoor and outdoor conditions but also with many other parameters, such as building characteristics, application, occupants' behavior, etc. Menassa et al. (2013) studied different model-based hybrid ventilation strategies and their effects on energy efficiency and thermal comfort in a public occupied building. They focused on three performance criteria: energy savings, occupant comfort and indoor-air quality. Yang and Li (2015) developed and validated a dimensionless design approach for hybrid ventilation, introducing a route for understanding the principle of stack-based hybrid ventilation. They state that solar gains and their impact on temperature difference between stack air and indoor air is worthy of further investigation. Hu and Karava (2014) created model predictive control (MPC) strategies for the institutional building presented in this study. They developed a transient, multi-zone building energy prediction model and found that MPC can significantly reduce the cooling requirements, while heuristic control based on outdoor conditions increases the risk of over-cooling and lowering thermal comfort acceptability.

The subject of this paper is a corridor on the 5$^{\text{th}}$ floor of the EV building of Concordia University. It is a typical high-rise institutional building in Montreal, Canada. It was designed and constructed to take advantage of hybrid ventilation, which can also be fan-assisted, as seen in Figure 1. The building consists of five, interconnected, three-story high atria. Each floor has two motorized, insulated inlet dampers, on the southeast and northwest façade of the building. These dampers allow cool air to enter the building, pass through the grilles that connect the atria and exit from the roof exhaust. The atria function as a solar chimney, and when the stack effect is not strong enough, the pressure difference can be enhanced by variable speed fans, installed at the roof outlet in 2015. The concrete floor has a thickness of 40 cm. According to Yuan et al. (2016), this thermal mass can be used to store heat during the day and hybrid ventilation can be used to remove this heat while respecting occupancy comfort.

A weather station, installed on the roof of the building, measures air temperature and humidity, wind speed and direction, and solar radiation. The weather station instrumentation is connected to a BACnet controller. As it is common in institutional buildings, the building uses a Building Automation System (BAS) to store, read and distribute data of various sensors placed around the building. The weather data can be accessed by any other controller connected to

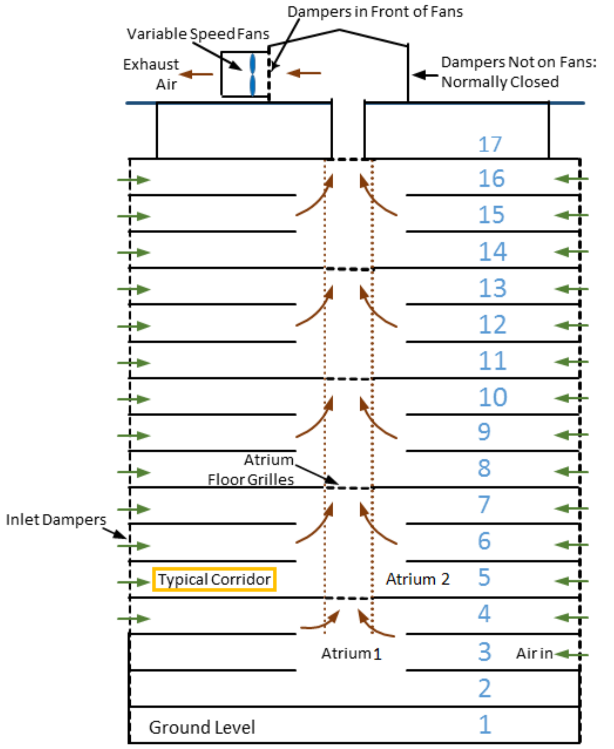

Figure 1: Schematic of the components of hybrid ventilation of Concordia EV building

the BAS and make decisions for the state or set-point of any other controller.

Experimental Set-up

To investigate the effect of ventilation on the building, an experiment was conducted at night, when the occupancy of the building is minimal, and the temperature difference between the interior and exterior air is high (having, as a result, stronger buoyancy forces). The experiment was conducted on the fifth floor, acquiring data for the first ten meters past the inlet dampers of the south-east corridor. Four infra-red sensors (±1 °C in the range of 0 to 70 °C), 25 thermocouples (accuracy of ±0.5 °C), and one one-directional anemometer (0.03 m/s or ±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).

Figure 2 shows the sensor locations. The corridor was divided into 4 sections, with thermocouples at 1.5 m, 3 m, 6 m, and 10 m from the inlet. At each position the temperature of the air is measured, at heights of 0.1 m, 1.1 m, and 1.7 m. The temperature of the suspended ceiling and of the right and left wall is measured with thermocouples. The temperature of the concrete floor was measured with infra-red sensors. Inside the building, just after the inlet dampers, the temperature of the inlet air is measured with a thermocouple and the velocity with the anemometer. The dampers were closed until 22:00, when the experiment started. They were kept open for four hours until 02:00. Then they were closed, but the data acquisition system was running for four hours, until 06:00. The exterior temperature, according to the weather station, fluctuated between 7.8 °C and 8.9 °C. The temperature of the interior air was kept at a constant set-point of 21 °C. The results for the air temperature and the concrete temperature can be seen in Figure 3.

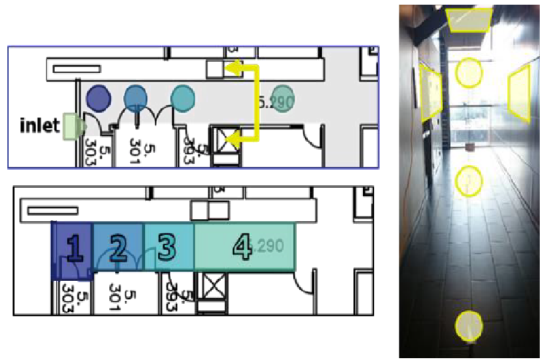

Figure 2: Measurement locations along the corridor (top and right) and separation of the corridor into 4 numbered sections (bottom)

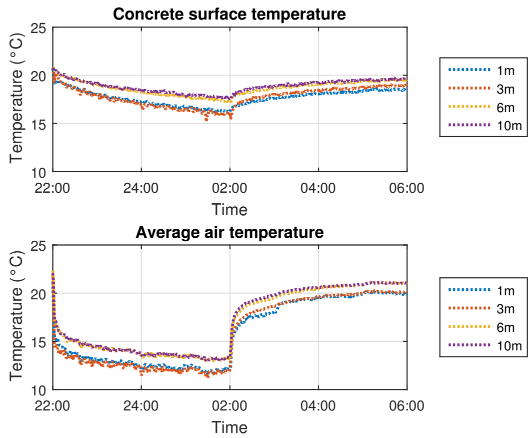

Figure 3: Concrete surface temperature (top) and average air temperature (bottom) as measured over the 8 hours of the experiment

Simulation Process

The purpose of the simulation is to determine whether the dampers should be open or closed depending on the occupancy comfort and free cooling availability. Right now, this is done in a reactive manner, meaning that the algorithm checks the conditions of the past minutes to make a decision. However, a predictive approach will be considered and implemented in the future, so that the algorithm predicts the conditions of the future and the response of the building and makes the decisions based on that. The end goal is to develop a control strategy to optimally control the hybrid ventilation system. The simulation will obtain data from the BAS as inputs. The result of the simulation will be used as set-point to automatically change the motorized dampers opening. This is done by changing the corresponding points in the BAS through BACnet and commanding the actuators on the dampers.

At first a simple preliminary transient computational fluid dynamics (CFD) simulation was developed, using ANSYS FLUENT. The large computational resources required by FLUENT, however, make the model unsuitable. For this reason, this model is used to better understand the general behaviour of the air flow when the inlet dampers are open.

A faster and simpler transient finite difference model is developed in MATLAB. Using the information obtained by the CFD simulation, the simpler model is adjusted to fit the data better. At first the model is calibrated with the experimental data, with different parameters for cooling (dampers open) and heating (dampers closed), and then it is run for a series of twelve days to estimate how much free cooling can be achieved without compromising occupancy comfort.

Preliminary Analysis

A 10 meters long and 3 meters high corridor was modelled. The measured data were used as boundary conditions for the problem and a k-ω scheme was used to simulate the air flow.

The results can be seen in Figure 4. The air flows close to the left wall, then, at approximately 3 m from the inlet, across the corridor to the right wall, and then hugs the right wall until the end of the corridor. There are two main regions of recirculation, a smaller one next to the inlet and a bigger one on the left side of the corridor. The velocity is small close to those recirculation regions (below 0.2 m/s) and higher (around 0.6 m/s) along the main airflow path.

The heat transfer effect is expected to be higher on the main airflow path, because of the greater velocity. The sensors placed at 3 m from the inlet are on the main airflow path, and this explains why in Figure 3 the temperature of both the air and the concrete is higher at 1 m than in 3 m.

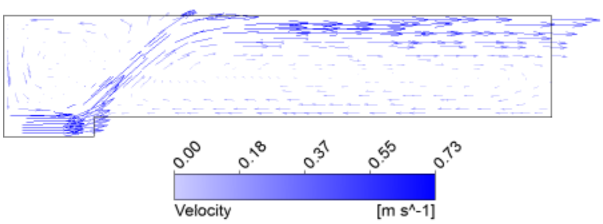

Figure 4: Airflow path, as a result of CFD simulation

Assumptions

In order to develop the finite difference model some assumptions were made:

- The geometry is simplified, assuming the corridor is a 1.8 m x 3 m x 10 m rectangular prism. That means that the bend near the inlet is not considered, and the suspended ceiling is considered the true ceiling.
- The corridor is divided into 4 control volumes, similar to the sections of the experiment. Each is represented by one node for the air, one for the surface of the concrete and one for the rest of the combined surfaces (ceiling and vertical walls).
- The temperatures of the vertical walls and the ceiling are grouped to an effective surface temperature T_{sfc}.
- The thermal capacitance of the air is taken into account.
- The concrete floor is discretized into 10 horizontal layers of 0.5 cm, 1.5 cm, 3 cm, 5 cm and 10 cm thickness symmetrically starting from exposed surfaces.
- The solar radiation through the window is not taken into account. It would affect significantly the first control volume during bright days.
- Radiation between the surfaces is not considered directly. The effective heat transfer coefficient takes into account not only the radiation, but also represents the effects of air infiltration and heat from luminaires. It is also adjusted to take into account the difference in heat transfer of the different sections found in the preliminary analysis. The values used can be seen in Table 1.

Table 1: Effective heat transfer coefficient connected to air (W/m^2K)

Control Volume	1	2	3	4
Between air and surfaces	4	4	3	2
Between air and concrete	9	12	9	8

- The properties of concrete and air used in this study are considered constant, to be consistent with those used in previous studies of EV building Karava et al. (2012). They are shown in Table 2.

Table 2: Properties of concrete and air

Properties	Concrete	Air
Density, ρ (kg/m^3)	1700	1.2
Specific heat capacity, C_p (J/kgK)	800	1005
Thermal conductivity, k (W/mK)	1.7	-

- To account for the recirculation of the air, correction factors are applied to reduce the velocity of the air, shown in Table 3. Inlet velocity is considered to be zero when the inlet dampers are closed.

Table 3: Velocity factor to account for recirculation of the air in the corridor

Control Volume	1	2	3	4
Velocity factor	1	0.6	0.2	0.2

- The air inlet temperature is correlated to the temperature given by the weather station on the 17$^{\text{th}}$ floor. This way there is no need for thermocouples on the inlet dampers (see Section Estimation of Inlet Temperature).

- The same procedure was tested for the air inlet velocity, but on the 5$^{\text{th}}$ floor the fluctuations of velocity are stochastic and no correlation could be found. It was noted, however, that for wind speeds of 0.1-6 m/s, as measured by the weather station, the velocity on the 5$^{\text{th}}$ floor was between 0.2-0.5 m/s. For this reason, a random value in this range is used each moment as air inlet velocity.

- When the dampers are closed, the heating of the corridor is modelled as an air heater with a PI controller (see Section Closed Dampers).

- The first two sections of the corridor (up to 3 m) are not considered for the discomfort of the occupants. This part of the corridor leads to an emergency staircase and is expected to be unoccupied. On the other hand, the last two sections (6 m to 10 m) thermal comfort is important, because they include the door to a conference room. To estimate the occupancy comfort, Fanger's model was used. (see Section Estimation of Thermal Comfort).

Explicit Finite Difference Scheme

The thermal network that represents the problem, with the assumptions that were made, can be seen in Figure 5. Using the explicit finite difference scheme, the temperature of the air and concrete can be found, through Eq. (1) and Eq. (2) respectively.

$$\begin{aligned} T_{a_m}^{p+1} =& T_{a_m}^{p} + \frac{\Delta t}{C_{a_m}}\Big[U_{a-c_m}\left(T_{c_{n,m}}^{p} - T_{a_m}^{p}\right) \\ &+ U_{a-sfc_m}\left(T_{sfc_m}^{p} - T_{a_m}^{p}\right) \\ &+ \rho_a C_{p_a} v_a^p A_{cor}\left(T_{a_{m-1}}^{p} - T_{a_m}^{p}\right) \\ &+ \rho_a C_{p_a} v_a^p A_{cor}\left(T_{a_{m+1}}^{p} - T_{a_m}^{p}\right)\Big] \end{aligned} \tag{1}$$

$$\begin{aligned} T_{c_{n,m}}^{p+1} =& T_{c_{n,m}}^{p} + \frac{\Delta t}{C_{c_{n,m}}}\Big[U_{a-c_m}\left(T_{a_m}^{p} - T_{c_{n,m}}^{p}\right) \\ &+ U_{c_{n,m-1\to m}}\left(T_{c_{n,m-1}}^{p} - T_{c_{n,m}}^{p}\right) \\ &+ U_{c_{n,m\to m+1}}\left(T_{c_{n,m+1}}^{p} - T_{c_{n,m}}^{p}\right) \\ &+ U_{c_{n\to n+1,m}}\left(T_{c_{n+1,m}}^{p} - T_{c_{n,m}}^{p}\right)\Big] \end{aligned} \tag{2}$$

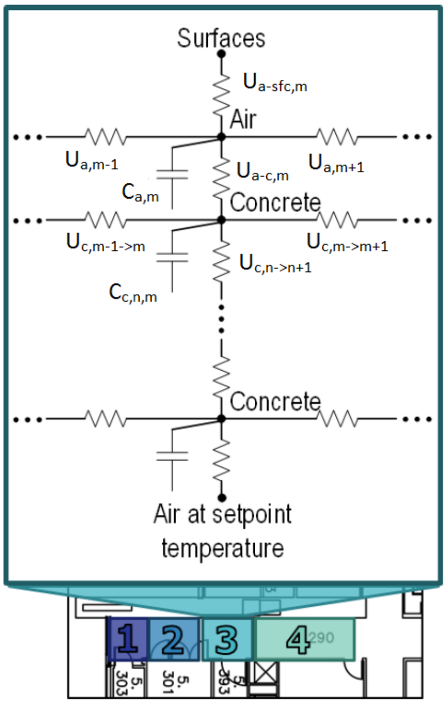

Figure 5: Thermal network representing the finite difference scheme used

Estimation of Inlet Temperature

For convenience and robustness, the air inlet temperature was correlated to the weather station temperature and the time elapsed after the dampers are open. The Curve Fitting Tool in Matlab was used to obtain a bisquare linear regression model for the air inlet temperature (Eq. (3)). Figure 6 shows the temperature profiles of the two different days, which were used to create the correlation, along with Eq. (3). The coefficient of determination (R^2) is 0.9975 and the root mean squared error (RMSE) is 0.26 °C, showing that Eq. (3) fits the data well.

$$T_{inlet} = 0.8532 \cdot T_{ws} + 6.684 \cdot t^{-0.1024} \tag{3}$$

Estimation of Effective Temperature of Surfaces

The effective surface temperature consists of 2/3 of the ceiling temperature and 1/3 of the vertical walls,

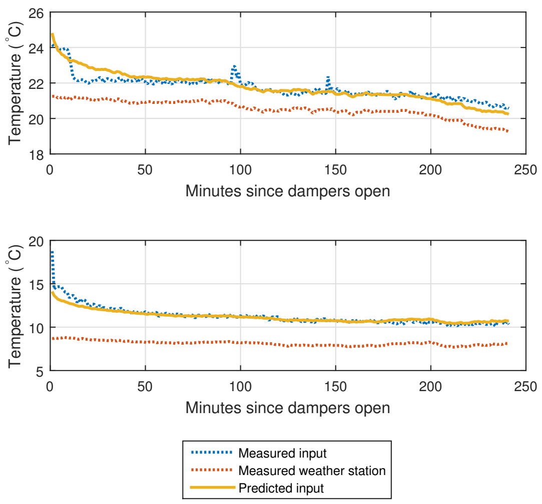

Figure 6: Estimated inlet air temperature on the 5th floor and measured temperature from the weather station on the roof for day 1 (top) and day 2 (bottom)

since the ceiling has a bigger effect on the heat transfer. It was correlated to the concrete temperature and the inlet temperature when the dampers are open (cooling mode) and to the concrete temperature when the dampers are closed (heating mode). Eq. (4) shows the general form of the correlation, with f, g and h changing for each section. When the dampers are closed h is 0. Table 4 shows the goodness of fit for each one.

$$T_{sfc} = f + g \cdot T_c + h \cdot T_{inlet} \tag{4}$$

Table 4: Goodness of fit for different sections

Section	R^2	RMSE (°C)
Open dampers		
1	0.9968	0.30
2	0.9983	0.17
3	0.9986	0.12
4	0.9969	0.13
Closed dampers		
1	0.9738	0.25
2	0.9715	0.23
3	0.9816	0.12
4	0.9500	0.16

Estimation of Thermal Comfort

Hybrid ventilation is mostly used at night, when the building is expected to be unoccupied, and therefore there is flexibility in thermal comfort. That way, the building can be pre-cooled for the next day. However, to use free cooling to its full potential, the dampers should open during the day as well, always having in mind the thermal comfort of the occupant.
A corridor like the one presented can be considered a transitional space, and, specifically, a circulation space. Occupants will pass to access the staircase and are expected to be at the place for less than 10 minutes. The thermal comfort restrictions are less strict in transitional spaces, and according to Pitts (2013) the acceptable predicted mean vote (PMV) can be increased from ±0.5 to ±1.5. This, according to ASHRAE (2004) can be translated to an increase in acceptable predicted percentage of dissatisfied (PPD) from 10% to 50%.
Discomfort was calculated according to ISO 7730:2005 (2005), based on Fanger model and PPD index, based on Carlucci et al. (2015). According to the standard, the PPD index is obtained for steady-state conditions. In order to use it in this model, an one-hour average was used, assuming that in every hour the conditions can be considered steady-state, having small fluctuations.

Inlet Dampers Control Strategy

To avoid any damage on the motors of the dampers and any noise discomfort, the dampers change position only once every fifteen minutes. In order for the model to decide if the dampers should be open or closed for the next fifteen minutes, Eq. (5) is used, taking into account the discomfort and the energy stored in concrete. The model is reactive, which means that, when a decision needs to be made, information from the past hour is used. The discomfort and energy storage are normalized using the maximum and minimum values, so that they can be used in one equation, despite having different units, according to Sakellariou (2011).
Parameter α in Eq. (5) defines how much free cooling is weighted against discomfort. The effect of this parameter on the hybrid ventilation control is studied. Discomfort is always weighted more than free cooling, because it is considered a more important objective. Thermal comfort highly affects the productivity and performance of the occupants, according to Kosonen and Tan (2004).

$$CF = \alpha Dis_{nor} + (1 - \alpha) En_{nor} \tag{5}$$

Results and Analysis

At first the model was verified on the experimental data, for open and closed dampers. Then it was run for twelve consecutive days to test different criteria for the control strategy.

Open Dampers

Figures 7 and 8 show the measured and predicted temperatures of the air and concrete surface for the different sections, after the dampers are open. The maximum temperature differences between the measured and predicted temperatures were 1.14 °C for the air and 1.24 °C for the concrete. The normalized root mean squared error (NRMSE) is 8.3% for the air temperature of the first section and less than

4.5% for all the rest sections and for concrete surface temperature.
In the four hours since the dampers were open, a total of 0.1778 kWh/m^2 of heat was dissipated from the concrete floor. It should be noted that the air temperature in the end of the corridor can be low enough to allow further cooling of the thermal mass of the building, past the corridor of 10 m. In this paper, however, only the amount of heat extracted from the concrete floor of this section is studied. The section that gets cooled more is the second one, because this is where the main flow path of the air is. The first two sections, which are considered the primary zone, have 41% more energy extracted than the last two (secondary zone). As expected, the heat removal is stronger in the first hour and when the dampers are closed it is close to reaching an asymptotic value of 42.2 W/m^2.
Since the experiment was performed at night, the dampers were open without having any thermal comfort constraints. Should those apply, the dampers would not be open for the full 4 hours.

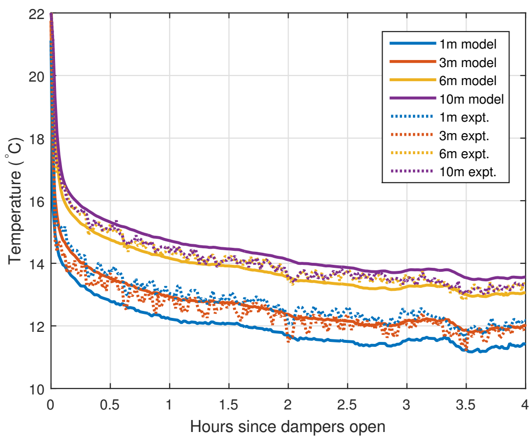

Figure 7: Experimental and predicted air temperatures for open dampers (day 2)

Closed Dampers

When the inlet dampers are shut, the HVAC system of the building starts normal operation to get the temperature back to the set-point. Part of the future work is implementing a time lag between closing the inlet dampers and starting the HVAC system heating. When the dampers close, the thermal mass will heat the air further. Throughout the time after the dampers close, but before the HVAC system starts, there would be no energy consumption required for heating, but the discomfort of the occupants would not be compromised. Currently, the HVAC control for the corridor after the dampers close was modeled as a PI controller, the properties of which were calibrated with the experimental data.
Figures 9 and 10 show the experimental and predicted temperature of the air and the concrete surface for the

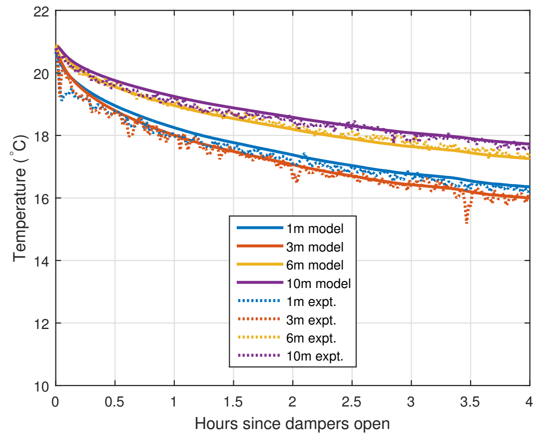

Figure 8: Experimental and predicted concrete surface temperatures for open dampers (day 2)

different sections, when the dampers are closed. The maximum temperature differences between the experimental and predicted temperatures were 0.93 °C for the air and 0.73 °C for the concrete. The NRMSE is less than 4.3% for the air temperature in all sections and less than 9.8% for the concrete surface temperature. The accuracy of the sensors used in the experiment was ±0.5 °C.

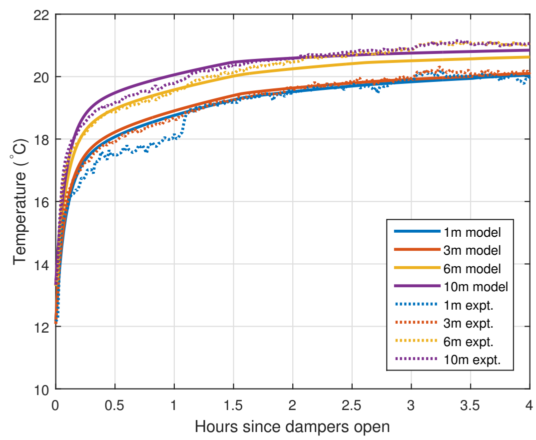

Figure 9: Experimental and predicted air temperatures for closed dampers (day 2)

Performance of Control Strategy

Using data from the weather station, the model was tested. It was run for twelve days, from May 14th 2016 to May 25th 2016. The specific days provide a wide range of temperatures, the minimum being 1.5 °C and the maximum 29.3 °C, according to the weather station. The outcome depends on the value of variable α, that is how much discomfort is weighted against energy storage.
Figure 11 shows the air temperature and Figure 12 the concrete temperature for the twelve days, if $\alpha = 1$ (if discomfort is the only criterion to open or close

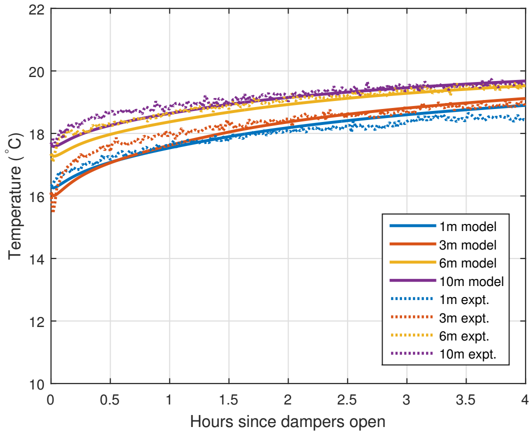

Figure 10: Experimental and predicted concrete surface temperatures for closed dampers (day 2)

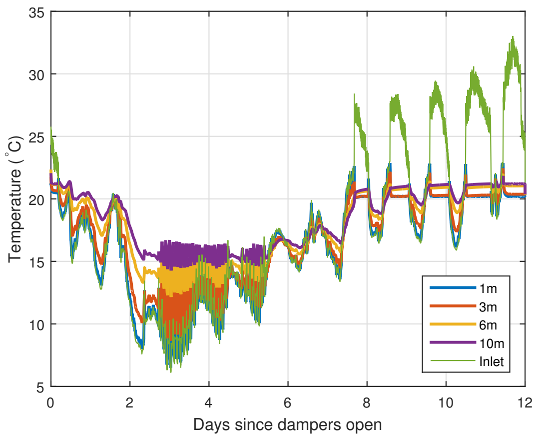

Figure 11: Predicted air temperature if the criterion for opening the dampers is taking into account discomfort only

the dampers).

The fluctuations of the temperature, when the inlet temperature is low, happen because the model does not predict the future, but only takes into account the past. As soon as the discomfort criterion gets below the limit, the dampers open for fifteen minutes, making the air temperature too cold, and forcing the dampers to close in the next fifteen minutes. Even when this happens, the temperature of the third and fourth sections never falls below 13 °C. When the inlet temperature is too high, the dampers do not open and the temperature is relatively constant around 21 °C.

The effect of pre-cooling is stronger in the primary region, where the concrete surface temperature reaches 12 °C, than in the secondary region, where it reaches 15 °C. The total free cooling that can be achieved from the concrete floor is 1.022 kWh/m^2. For this amount of free cooling, there are approximately 29.3 hours (10.2%), during which the discomfort is higher than the limit.

Table 5 shows the effect of parameter α on the open-

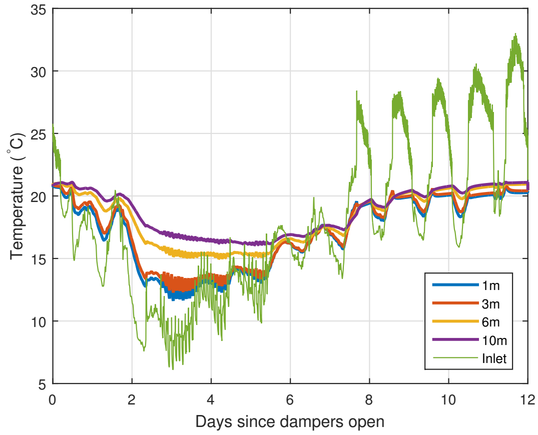

Figure 12: Predicted concrete surface temperature if the criterion for opening the dampers is taking into account discomfort only

ing and closing of the dampers. Having a smaller α value forces the discomfort to play a less significant role in the control criterion. The dampers open or stay open for lower temperatures, even if occupant discomfort is higher. Therefore, the amount of hours that discomfort is above the limit and the free cooling are expected to be higher.

Table 5: Effect of parameter a

α	Concrete Free Cooling (kWh/m^2)	Discomfort above limit (hr)	Discomfort above limit (%)
1	1.022	29.3	10.2
0.9	1.034	37.7	13.1
0.8	1.054	54.8	19.0
0.7	1.068	67.6	23.5
0.6	1.091	76.0	26.4
0.5	1.107	93.1	32.3

As α decreases, free cooling increases from 1.022 kWh/m^2 to 1.107 kWh/m^2, but the amount of time that occupant discomfort is predicted to be above the limit increases significantly from 10.2% of the twelve days to almost one third (32.3%).

Discussion and Future Work

Utilizing a hybrid ventilation system in an institutional building is a challenge, because the high amount of occupants and their different schedules affect the important factor of thermal comfort to the control of the system. The discomfort will be higher close to the inlet of the fresh air to the building, since the thermal effects are stronger there.

Using Table 5 different control strategies for different situations can be applied. Parameter α can be higher during the day, prioritizing thermal comfort, and lower during the night, prioritizing energy removal, since the building is relatively unoccupied.

The same principle can be applied on weekends and holidays.

To improve the use of hybrid ventilation, the relative humidity of the inlet air should also be considered before opening the dampers. Relative humidity does not only introduce occupant discomfort, but also affects the energy load of the building, increasing significantly the latent load. Another consideration should be the quality of air, since the building is located in downtown and the exhaust of the cars on the nearby roads can affect it significantly.

To have a smoother performance of the system, the control strategy will be changed from reactive to predictive. The model will then enable a model predictive control (MPC) of the hybrid ventilation, predicting how much heat can be removed and deciding whether the dampers should be open or not in the next control horizon. That way the fluctuations of the temperature when the inlet temperature is low will be avoided.

Furthermore, the motors controlling the dampers allow their partial opening. This means, that having this model with a predictive control strategy, the cost function (Eq. (5)) can be minimized over a control horizon, giving as an input to the BAS the percentage that the dampers should open.

Another important factor that can be implemented in the model is the use of the fans on the 17^{th} floor. These fans can help enhance free cooling and precooling of the building through hybrid ventilation. The draft that can be created needs to be taken into account in the control strategy, in order to avoid any potential occupant discomfort.

Conclusion

This paper presented an experimental and numerical study of cooling, utilizing a hybrid ventilation system in a 17-story high building. It considered a corridor on the 5^{th} floor with inlet motorized dampers. An experiment was conducted and the data were used as boundary conditions to a preliminary CFD study, which helped to better understand the problem. An explicit finite difference thermal network model was used to predict the air and concrete temperature, based on the exterior temperature and air velocity. A reactive control strategy was studied to decide when the inlet dampers should be open or closed. Different thermal comfort and energy saving criteria were evaluated. This study will help us develop a predictive control strategy for the opening of the motorized dampers and incorporate it in the BAS. This will help to optimize the operation of the hybrid ventilation system.

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Nomenclature

A	area of contact or cross-sectional area, m^2
C	thermal capacity, J/K
CF	cost function
Cp	specific heat capacity, J/kgK
Dis	discomfort
En	energy
T	temperature, °C
U	thermal conductance, W/m^2K
f,g,h	parameters used in Eq. (4)
k	thermal conductivity, W/mK
t	time since dampers opened, min
v	velocity, m/s

Greek letters

α	parameter used in Eq. (5)
ρ	density, kg/m^3
Δt	timestep of simulation, s

Subscripts

a	air
a-c	air to concrete
a-sfc	air to surfaces
c	concrete
cor	corridor
inlet	damper inlet
m	control volume number
n	concrete layer number
nor	normalized
sfc	combined surfaces
ws	weather station

Superscripts

p	timestep number

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