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An Experimental and Simulation Study of Night Cooling in a Building with Hybrid Ventilation

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Abstract

The cooling energy demand in a building can be reduced through night ventilation coupled with interior thermal mass. A building in Concordia University's downtown campus in Montreal is used in this paper as a case study of a typical institutional mid to high-rise building designed with this technology in mind. Cool outdoor air is allowed into the building through inlets at opposite ends of a corridor, heads towards interconnected atria while extracting heat from a thermally massive concrete floor, and exits at the roof. By pre-cooling the building, the peak cooling load for the next day can be reduced. On site data was acquired and to verify the developed thermal model for a section of the building corridors near the inlets. A computational fluids dynamics model is created in FLUENT using measured data as boundary conditions. A two-dimensional transient finite difference thermal model of a portion of a typical corridor linked to an inlet is developed. This model predicts the air and floor surface temperature, so as to estimate the amount of heat that can be extracted from the concrete floor with free night cooling. Hybrid ventilation, not limited to night ventilation, must not compromise occupant comfort. Their dissatisfaction due to draft or cool air and floor is considered in this paper, with regards to the ASHRAE standard for thermal environmental comfort of occupants, along with its limitation in terms of defining acceptable thermal comfort in transitional zones of a building.

Keywords – hybrid ventilation; thermal model; occupant comfort; energy demand reduction

1. Introduction

During seasons when days are warm and nights are cool, commercial and institutional buildings can reduce their cooling energy consumption through natural ventilation, which takes advantage of natural physical processes, such

as wind and stack effect to remove heat [1, 2]. When used in conjunction with mechanical ventilation systems, it is termed hybrid ventilation, and both can be fan-assisted or not. Regardless of the means of ventilation, occupants must not feel uncomfortable in the indoor environment.

In Montreal, Canada, the outdoor air temperature is expected to show a diurnal temperature difference of at least 10 °C during the months of April to October [3]. These months include the shoulder seasons and summer season, and are when natural ventilation is used for free cooling. In fact, the amount of energy used for space cooling in commercial and institutional buildings in Canada has increased by 84% from 1990 to 2010 [4], and in Ontario, heating, ventilating and air-conditioning for these types of building took up to 50 % of total energy consumption in their 2003 summer peak profile [5].

The EV building of Concordia University, located in Montreal, Canada, is a typical institutional building designed and constructed for fan-assisted hybrid ventilation, and serves as a great example for future buildings' hybrid ventilation designs [6]. This building has motorized insulated inlet dampers, on opposing façades, that allow cool outdoor air directly into the corridors, which creates a driving force for hot air to rise through the solar chimney, created by a series of five stacked atria (each of them connecting three floors of the 17-storey high building), and then exit from the roof exhaust. The addition of variable speed fans at the top atrium outlet in 2015 became an invaluable asset in helping the airflow in the future when stack effect is not adequate. Fig. 1 shows a schematic of the whole building with the arrows indicating the expected airflow path, while Fig. 2 shows the airflow within a typical floor. The 0.4 m thick concrete floor makes the EV building thermally massive, which allows for heat storage during the day, while hybrid ventilation removes this heat during both occupied and unoccupied hours, with care to not cause thermal discomfort to occupants.

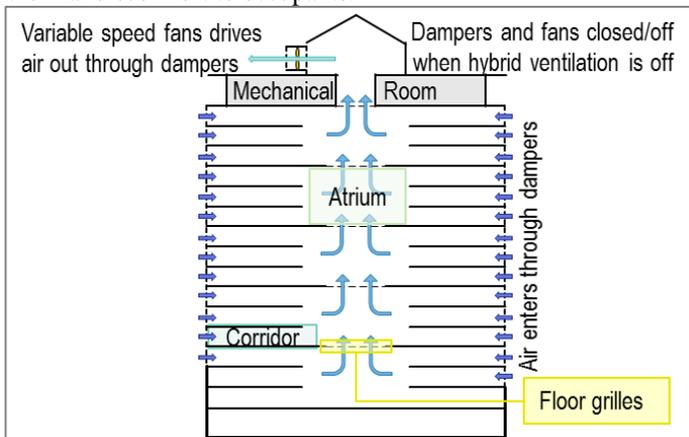


Fig. 1 Schematic of the EV building's fan-assisted hybrid ventilation process

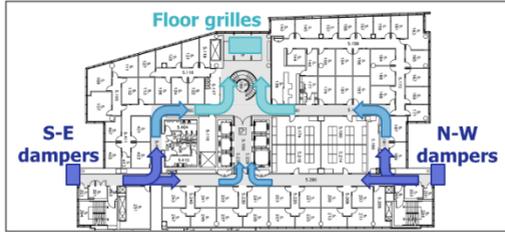


Fig. 2 Schematic of the expected airflow path through a typical floor

A thermal model was previously developed for the corridors and atria over 8 floors for a total of 864 m² [7]. The results from this model showed that allowing outdoor air from 9 to 15 °C, it would take about 6 hours to remove 25 kWh of heat. The focus of this paper, on the other hand, is on the corridor region close to the inlet, specifically on the 5th floor, and near the S-E dampers to examine how long the inlet temperature can be without adversely affecting comfort.

2. Data Acquisition

Night ventilation is most effective when there is a greater temperature difference between the indoor and outdoor air temperature, since it supports the airflow into the naturally ventilated building by buoyancy forces. Data was acquired for a typical corridor at EV building on a cool night, where the forecasted air temperature was between 8 and 9 °C, and the measured local air temperature at the building's own weather station at the roof was between 7.8 and 8.9 °C. The indoor temperature has a setpoint of 21 °C, resulting in roughly 13 °C temperature difference between the indoor and outdoor environment. The dampers were closed during the day until 22:00. Hybrid ventilation was in effect from then until 2:00, after which the dampers were closed again for at least 4 hours. A data acquisition system was set up to collect measurements during the 4 hours of hybrid ventilation and the 4 hours following its end.

A total of 4 infrared sensors ($\pm 1\%$ of reading or ± 1 °C in the range of 0 to 70 °C), 25 thermocouples (accuracy of ± 0.5 °C), and 1 one-directional anemometer (0.03 m/s $\pm 1\%$ of readings in the range of 0.15 to 1.5 m/s or $\pm 3\%$ of readings in the range of 1.5 to 10 m/s) was installed at the corridor on that night. The corridor was separated into 4 sections that are numbered as in Fig. 3, and will be used later in the analysis. The typical set-up at each section is at 1.5 m, 3 m, 6 m, and 10 m from the inlet and is shown in Fig. 3; 3 thermocouples are supported in the air at heights of 0.1 m, 1.1 m, and 1.7m; one thermocouple is on the underside of the suspended acoustic tile, and two thermocouples are placed on the left and right walls. As well, an infrared temperature sensor is suspended from the ceiling to measure the floor surface temperature. The anemometer is placed on the inside of the building along

with a thermocouple, in front of the dampers, to measure the inlet velocity parallel to the floor and the inlet air temperature.

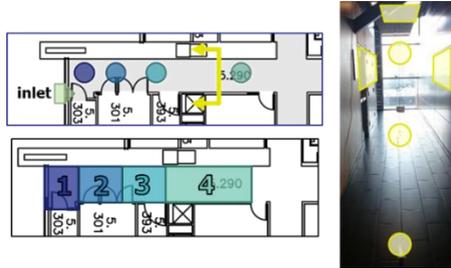


Fig. 3 Measurement locations along the corridor (top and right) and separation of the corridor into 4 numbered sections (bottom)

The measured temperatures for the floor surface and the average air are shown in Fig. 4, with the inlet dampers open from 22:00 to 2:00 and then closed until the end.

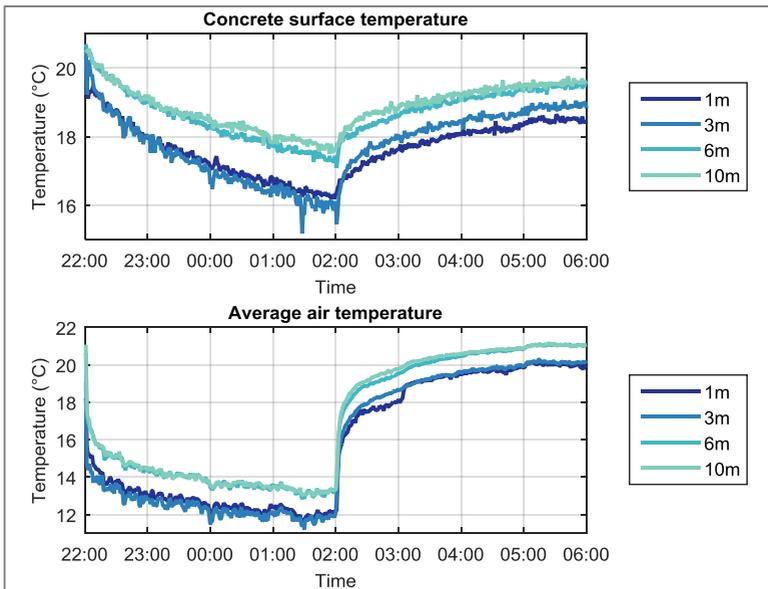


Fig. 4 Measured data, at differing distances from the inlet, of concrete surface (top) and average air (bottom) temperature

3. Computational Fluid Dynamics Model

A transient computational fluids dynamics model of the corridor was developed using the $k-\omega$ scheme to simulate the air flow. The model considers

a 10 m long corridor including the placement of the dampers and the bend near the inlet, the height is assumed to be 3 m, and does not consider a suspended ceiling.

The measured data is used as boundary conditions and results in an airflow path visualization, shown in Fig. 5. It can be seen that the air from the inlet flows close to the left wall, then across the corridor's width at around 3 m from the façade, which is where the second set of sensors is located. The air then hugs the right wall until the end of the corridor. The air velocity is mostly below 0.2 m/s in the recirculation area, and is around 0.6 m/s along the main airflow path, but decreases towards the end of the corridor.

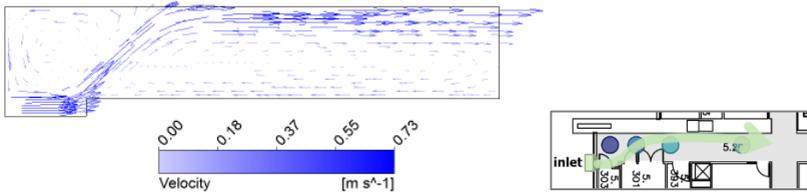


Fig. 5 Expected airflow path at mid-height from CFD simulation (left) and with positions of measurement points (right)

There are two regions of recirculation in the corridor. The first and smaller one is close to the inlet, in the right corner, and the second and bigger one exists throughout the corridor on the left side, next to the main air flow. The heat transfer in these regions is less because of the recirculation, and the resulting lower velocity.

4. Transient Finite Difference Model

The finite difference method replaces differentials in heat transfer equations by differences [8]. The corridor is modeled using a transient 2-dimensional finite difference model. Its geometry is simplified by assuming it is a 1.8 x 3 x 10 m rectangular prism, separated into 4 control volumes. This removes the bend near the inlet, and considers the suspended ceiling as the true ceiling. The properties of concrete and air is listed in Table 1 are consistent with those used in previous studies on the EV building.

Table 1. Properties of concrete and air [7]

Properties	Concrete	Air
Density, ρ (kg/m ³)	1700	1.2
Specific heat capacity, c_p (J/kg·K)	800	1005
Thermal conductivity, k (W/m·K)	1.7	-

The finite difference method is easily represented by a thermal network; the one for the corridor is shown in Fig. 6. The surfaces' node is a combined temperature of the walls and ceiling, and its value was correlated linearly with

the inlet temperature, and the floor temperature. 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 the exposed surfaces. To account for the actual geometrical shape, calibration factors are added to the air velocities.

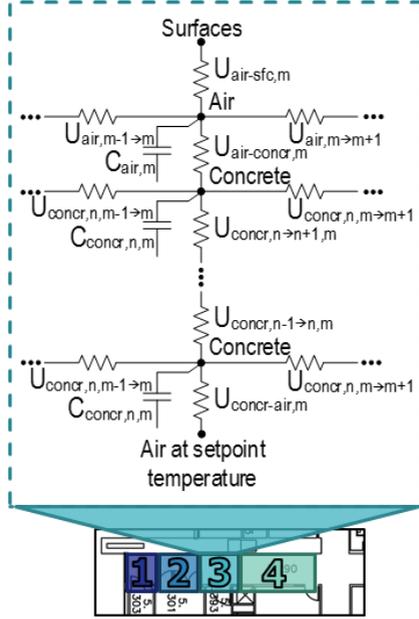


Fig. 6 Typical thermal network representation of a control volume

Equation (1) and Equation (2) are the typical heat balance equation [8] for the air and concrete surface node respectively:

$$T_{air_m}^{p+1} = T_{air_m}^p + \frac{\Delta t}{C_{air_m}} \left[\rho_{air} c_{p_{air}} v_{air}^p A_{corridor} (T_{m-1}^p - T_{air_m}^p) + U_{air-sfc_m} (T_{sfc_m}^p - T_{air_m}^p) + U_{air-concr_m} (T_{concr_{n,m}}^p - T_{air_m}^p) + \rho_{air} c_{p_{air}} v_{air}^p A_{corridor} (T_{air_{m+1}}^p - T_{air_m}^p) \right], \quad (1)$$

$$T_{concr_{n,m}}^{p+1} = T_{concr_{n,m}}^p + \frac{\Delta t}{C_{concr_{n,m}}} \left[U_{concr_{n,m-1 to m}} (T_{concr_{n,m-1}}^p - T_{concr_{n,m}}^p) + U_{concr_{n,m to m+1}} (T_{concr_{n,m+1}}^p - T_{concr_{n,m}}^p) + U_{concr_{n to n+1,m}} (T_{concr_{n+1,m}}^p - T_{concr_{n,m}}^p) + U_{air-concr_2} (T_{air_m}^p - T_{concr_{n,m}}^p) \right], \quad (2)$$

where T , U , A , C , ρ , c_p , v , and Δt represent temperature ($^{\circ}\text{C}$), thermal conductance (W/K), cross-sectional area (m^2), thermal capacity (J/K), density (kg/m^3), specific heat capacity ($\text{J/kg}\cdot\text{K}$), velocity (m/s), and timestep (s) respectively. Subscripts are first to indicate whether the node pertains to air, surfaces (sfc), concrete (concr), corridor, or an element between these. Then, subscripts m and n indicate the control volume 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.

The model, given initial temperatures, can march forward in time to calculate future temperatures. The effective heat transfer coefficient between the air and both surfaces and concrete floor surface encompasses the effects of radiation, air infiltration, and heat from luminaires. The values used for the model is listed in Table 2 and verified by the data collected.

Table 2. Effective heat transfer coefficient connected to air ($\text{W/m}^2\cdot\text{K}$)

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

The simulated values compared to the measured data is shown in Fig. 7, where a clear separation of the corridor into two zones, in terms of cooling of the concrete is seen: a primary zone near the inlet including where the airflow passes through the corridor's width, and a secondary zone, comprising mostly of the recirculation area. The model is more accurate in terms of concrete temperature than air, with their expected error to be within $0.5\text{ }^{\circ}\text{C}$ for both the floor and average air temperature.

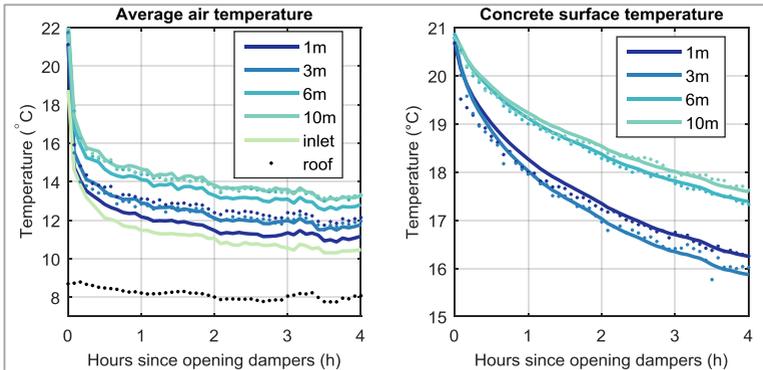


Fig. 7 Simulated (solid) and experimental (dotted) temperatures of air (left) and concrete (right)

Using the explicit finite difference model, the temperature of air and concrete is calculated with time. The rate of heat extraction is calculated by comparing the concrete floor's temperature with time, using the following equation [8]

$$Q = \rho * c_p * vol * \Delta T / \Delta t , \quad (3)$$

where Q is the heat energy (W), vol is the volume of the material (m^3), and ΔT is the difference in temperature with time ($^{\circ}C$). The result for the 4 hours of night cooling is a total of 11.7 MJ or 651 kJ/m^2 removed from the concrete floor, and the rate of heat removal is shown in Fig. 8. For the whole 10 m slab, a maximum rate of heat removal of 876 W or 49 W/m^2 is reached shortly after half an hour of hybrid ventilation. By the end of the 4 hours, this rate is close to reaching an asymptotic value of 740 W or 41 W/m^2 . As expected, the control volume with the most heat removed is the second one, where the main airflow is.

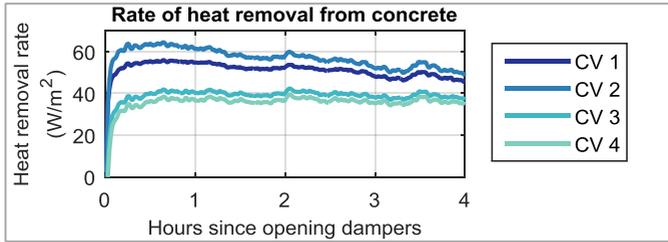


Fig. 8 Rate of heat removal at different control volumes (CV)

5. Discussion

For night ventilation, the building is expected to be almost unoccupied so there is flexibility in thermal comfort; however, hybrid ventilation can be used during the day as well, thus the importance of occupant comfort. The focus is on discomfort due to draft, and the lower limit of air temperature, as this paper pertains to cool nights with outdoor temperatures around $8^{\circ}C$.

Allowing cool air into the building presents a risk of dissatisfied occupants from being exposed to a draft. The predicted percentage of people dissatisfied due to draft (DR) is a function of local air temperature, local mean air speed, and local turbulence intensity, and its value should not be more than 20 % [9]. Using the maximum allowed air speed of 0.15 m/s for operative temperature below $22.5^{\circ}C$ [9], 11 % turbulence intensity from the inlet measurement point, and air temperature of $11^{\circ}C$, the DR is calculated to be just over the limit at 20.7 %. In the future, when the variable speed fans are used to assist airflow into the building, the air speed can be increased during non-occupied hours, and controlled to be within 0.15 m/s during the day. On the other hand, corridors can be considered as transitional or circulation zone, despite its study-specific definitions due to the absence of a formal occupancy definition [10, 11, 12]. Thus, its occupant comfort criterion should be less stringent and allow a higher maximum air speed for these types of regions.

In terms of air temperature for thermal comfort, a study shows that the acceptable predicted mean vote (PMV), which is a predicted mean value of

votes from a large group of people on a thermal sensation scale from -3 to +3 [9], can be increased from ± 0.5 to ± 0.7 for indoor spaces, corresponding to a predicted percentage of dissatisfied people (PPD) of less than 15 %, and ± 1.5 for circulation zones, where PPD no longer applies [10]. Furthermore, another study showed that there is a greater acceptance of coolness during shoulder seasons than during heating season [13], which further encourages accepting cool air into the building during those times. In the measured data, shown in Fig. 4, after closing the dampers, the air temperature at the end of the corridor quickly rose from around 13 to 19 °C within half an hour, whereas the concrete surface reaches 19 °C, the minimum value for acceptable floor surface temperature [9], within an hour. Even with the cool outdoor conditions, the dampers would only need to be closed an hour before occupied hours to avoid thermal discomfort in occupants, given current standards.

A simple thermal model is useful for model predictive control (MPC), by predicting how much heat can be removed at night. For this, it is essential to be able to localize forecast data, which can then be input into the model. The simulation result will indicate how much heat can be removed, and how long the dampers can be and need to be open without over-cooling so as to not impede on thermal comfort during occupied hours.

According to past weather data of Montreal between April and October, if hybrid ventilation is employed between 21:00 and 6:00, when outdoor temperature is between 12 and 22 °C and relative humidity is below 70 %, there are 75 nights where hybrid ventilation can be in operation for a total of 295 hours. Increasing the range of acceptable temperature to between 8 and 22 °C yields 94 nights where hybrid ventilation can be used for a total of 389 hours, and an average of 4.1 hours per night. It is clear that broadening the acceptable temperature range to accept colder air into the naturally ventilated building is advantageous for heat removal. The lower bound setting depends on the temperature at the inlet and at the end of the corridor, since that's where the closest room is located. The collected data shows that the average air temperature at the end of the corridor reaches an asymptotic value of 13 °C and is consistently 3.5 °C higher than at the inlet, which indicates that despite the outdoor conditions being around 8 °C, the air reaching working spaces has a significantly higher temperature even on a cool night. Warmer nights would have less temperature difference, causing less concern both in terms of air temperature and draft, as there would be less driving force for air movement throughout the building without any fan assistance.

6. Conclusion

This paper present an experimental and numerical study of night cooling as part of a hybrid ventilation system in a 17-storey high university building. A CFD model was used to study the airflow in a typical corridor zone near the motorized inlet grilles using measured data as boundary conditions.

An explicit finite difference thermal network model was used to study the same zone in the corridor with special attention to predicting the night cooling possible and also the temperature distribution in the corridor after allowing cool night outdoor air. This study will allow us to develop guidelines on how low the outdoor temperature can be for opening the inlet motorized dampers in the corridors as a function of time. This will provide essential input to a predictive control scheme under development for optimally operating the hybrid ventilation system and its two key components: the motorized inlet grilles and the recently installed rooftop variable speed fans.

Acknowledgment

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