Ventilated hollow core slab cooling load reduction under the operative temperature metric

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Abstract. This paper evaluates the cooling load reduction of a commercial office building through the use of a ventilated hollow core slab in Toronto Canada. Two scenarios were evaluated – SmartVent (SV) in which outdoor air is ventilated through concrete slab hollow cores when the outdoor air temperature is lower than that of the hollow core surface; and NoVent (NV), in which no ventilation takes place. A numerical model was created to simulate the heat transfer between the outdoor air stream and slab; and associated heat transfer between the slab and interior environment. The mean radiant temperature experienced by an occupant was then evaluated in both scenarios to determine the required ambient air temperature to achieve an operative temperature of 24.8°C. The cooling loads required to maintain this operative temperature setpoint were then determined for and compared.

1. Introduction
Passive design provides an opportunity to reduce the conditioning load of buildings through the use of solar energy, free cooling, and thermal mass; among others. These passive strategies can be coupled with active technology such as sensors and fans to fully exploit the potential of the passive system. In the case of cooling, heat from internal gains, solar radiation, and transmission though the building envelope must be met by the cooling system in order to achieve the desired interior air temperature. Conventionally, these heat sources are matched by the cooling system, however, it is possible to store a portion of this energy in the building mass during occupancy and purge it to the external environment at night when temperatures are comparatively cooler, reducing the amount of cooling required during the day and providing a free cooling source at night.

Several studies have evaluated the use of building thermal mass for peak cooling load shifting and reduction [1][2][3], finding that high thermal mass assemblies result in more stable interior environments compared to lightweight assemblies. Furthermore, assessment of thermal mass coupled with free cooling/nighttime ventilation [4][5][6] has been found to increase thermal mass activation, further reducing the cooling load. Past studies have effectively evaluated the cooling effect of cooled surfaces on interior air temperature, but there has been little work on evaluating dynamic interior air temperature setpoints based on the radiative heat transfer from interior surfaces in order to achieve a desired operative temperature. The goal of this research is to evaluate the radiative cooling effects of a ventilated hollow core slab on surrounding interior surfaces as well as to the occupants of a room in order determine the ambient air temperature setpoint and associated cooling load.

2. Scope
Ventilation of exterior air at night through the concrete slab hollow cores presents an opportunity to purge thermal energy from building thermal mass at in order to absorb excess heat during the day. In order to evaluate the energy savings potential of night ventilation through hollow core slabs, the heat transfer between the exterior air stream and concrete slab; and within the interior space of a sample
office building was simulated using a numerical model. The goal of the simulation was to determine the required interior air temperature and associated cooling load during the summer design week to maintain the operative temperature, and thus same level of occupant comfort, in two scenarios – (1) Smart Ventilation (SV) in which the slab hollow cores undergo ventilation via the use of fans when the exterior temperature is less than that of the hollow core surface temperature; and (2) No Ventilation (NV), in which no night ventilation/free cooling is employed.

3. Methodology
A custom simulation engine was created in MATLAB to effectively model the ventilated slab heat transfer and to evaluate the interaction between the ventilated hollow core slab and the interior environment. The simulation engine treated the sample office model as an array of thermal networks and evaluated the temperature evaluation of each node in the network at each time step based on the respective boundary conditions and power sources. Nodes we placed at the center of material thicknesses, therefore the thermal resistance between nodes were equal to half of the sum of the thermal resistance of the connected nodes. The model used a CN2014 design week weather data file for Pearson International Airport in Toronto, Canada. The file was created by Whitebox Technologies to reflect the most recent 2000-2014 climate data. The design week weather file was selected to consider the greatest outdoor air temperature and cooling load, allowing for a conservative predication of cooling energy savings and possibility of cooling system size reduction. The model considered the interaction between the slab and the exterior environment during ventilation, as well as the interaction between the slab and the interior air and among all interior surfaces.

The evaluated building is comprised of 5 stories, each 3m in height, with a footprint of 10m x 20m. The window to wall ratio is 40% with a continuous window strip around the perimeter of the building on each story placed at the top of the wall (1.2m in height placed from 1.8m to 3m.). The construction is typical of modern era commercial office buildings in North America. The building is oriented such that the main axis is in the north-south direction with no shading provisions. This orientation was chosen in order to consider the most extreme cooling condition associated with maximum solar gains. The wall assembly is comprised of 10cm brick, 8cm XPS, 10cm concrete block, and 1.3cm gypsum board; typical of the post-war construction common in Toronto. The glazing units are dual pane low-e coated 6mm plate glass with an argon filled air void achieving an effective U-value of 1.978 W/m2K. The floor finish is 2cm hardwood. The ceiling has no finish and is therefore represented by the hollow core slab. The slab is 0.27m in height with 0.135m radius hollow cores spaced at 0.23m on center, offset from the base and top of the slab by 0.045m. The ventilation velocity through the hollow core was set to 2 m/s. It is assumed that there is sufficient insulation between the floor finish and slab to allow for an adiabatic boundary at the top of the slab in order to facilitate maximum heat transfer from the bottom of the slab to the room.

The operative temperature (weighted average of ambient air temperature and mean radiant temperature) was chosen as the metric of occupant comfort in order to consider the effects of both convective and radiative heat transfer to the occupant. The mean radiant temperature was evaluated in the center of the floor plan at a height of 0.6m using the method developed in [7] based on the original works of [8]. The operative temperature was set to 24.8°C and the required ambient air temperature was solved for at each time step based on the mean radiant temperature at the evaluated time step. The operative temperature considered convective and radiative heat transfer coefficients of 2.25 and 5.75 W/m2K respectively. The simulation engine determined the cooling power required to meet the desired ambient air temperature at each time step, ultimately leading to the cooling load reduction associated with night ventilation through the slab hollow cores.

4. Results and Discussion
4.1: Interior Conditions
The night cooling of the slab resulted in consistently cooler interior surface temperatures in the SV scenario than the NV scenario, reinforcing the idea that precoothing building thermal mass can reduce the cooling load required by the space. In addition to the ability of the cooled surfaces to reduce
positive/increase negative heat flux to the interior air, the cooled surfaces also have the ability to reduce heat transfer to/increase heat transfer from the occupant via radiation. As discussed in section 3, the operative temperature metric was used to evaluate the convective and radiative effects of reduced interior temperatures. Given that the interior surface temperatures are lower in the SV scenario than in the NV, the SV scenario can afford a higher interior ambient air temperature, not only decreasing the cooling load imposed by convective heat transfer from interior surfaces, but also reducing the cooling load of the system due to the increased setpoint temperature.

In the NV scenario visualized in Figure 4.1, the operative temperature increases above the setpoint temperature in the evening during unoccupied periods when the building conditioning system is off and solar gains are present. The operative temperature reaches a local maximum then decreases once net power to the interior is negative due to the absence of solar gains and comparatively cooler exterior air. When the exterior air temperature increases and solar gains are imposed on the space in the early morning (positive net power to the space), the operative temperature increases. Upon occupancy, the conditioning system cools the interior air to the temperature required to achieve the setpoint operative temperature based on the mean radiant temperature. When the building is unoccupied, the conditioning system shuts off and the operative temperature is allowed to evolve naturally.

![Figure 4.1 – Interior Temperatures; Summer Design Week (NV)](image)

Unlike the NV scenario, the operative temperature in the SV scenario decreases below the setpoint operative temperature during the night due to the radiative cooling effects of the ventilated slab. This precooling effect is observed in the first night where the mean radiant temperature drops below the interior air temperatures, as is also observed to a greater extent during the second, third, and fourth nights. The mean radiant temperature (and associated operative temperature) then increases at a lower rate than in the NV scenario due to the precooled building thermal mass’s ability to absorb interior gains. As in the NV scenario, the operative temperature is allowed to naturally evolve until cooling is required, after which the conditioning system cools the air to the required temperature. As can be observed in Figures 4.1 and 4.2, the duration of maximum operative temperature is much greater in the NV scenario than in the SV scenario due to the “overcooking” of the building thermal mass, resulting in a lower operative temperature than the setpoint operative temperature upon occupancy in the SV scenario. Given that the setpoint operative temperature is the temperature that should achieve the greatest level of occupant comfort, any temperature below the setpoint could result in reduced occupant comfort.
4.2 Cooling Load

The cooling load was defined as the sum of internal gains, heat flux from interior surfaces, and energy required to meet the required air temperature at the end of the time step to achieve the desired operative temperature. Due to the cooled interior surfaces in the SV scenario, a greater interior air setpoint was allowed due to the comparatively lower mean radiant temperature. This resulted in a reduced load associated with achieving the temperature differential of the time step, as well as a reduced heat flux to the interior air from surrounding surfaces. The cooling load profiles of the SV and NV scenarios are visualized in Figure 4.3. In addition to reduced flux and required air temperature change, the radiant temperature is consistently lower in the SV scenario than the NV scenario, allowing the building thermal mass to act as a heat sink for internal gains for a greater period of time and to a greater extent. This is clearly illustrated through the difference in start time and amplitude of the cooling load profiles.
The NV scenario experiences a spike in the cooling load in the early morning at the onset of occupancy due to the need for the system to reduce the interior air temperature to the required temperature. The cooling load then reduces as the system must only match the gains to the zone as well as the load required to achieve the temperature drop of the time step. The cooling load experiences a local minimum after the initial cooling due to the need for the system to overcome the radiative warming caused by the interior surfaces. Once the interior air cools the interior surfaces, cooling load increases proportionally to the net power delivered to the space and the required air temperature change. Upon completion of occupancy, the cooling system is shut off and the air as well as assembly node temperatures are allowed to evolve naturally.

In comparison to the NV scenario, the cooling load profile in the SV scenario exhibits a significantly different trend. Unlike in the NV scenario, the SV scenario does not experience the initial spike in cooling load as the space does not experience an operative temperature greater than the setpoint temperature. Therefore, the cooling system must only match the load imposed on the system to maintain the desired operative setpoint temperature, rather than having to first achieve the setpoint temperature then maintain it as in the NV scenario. Given that the interior surfaces were cooled at night, the SV scenario doesn’t experience the local minimum in cooling load as the NV scenario. In the SV scenario, as the building thermal mass warms due to internal gains, the cooling load increases, but at a much lower rate than in the NV scenario. This is due to the greater weighting of the radiative heat transfer coefficient in the operative temperature definition, resulting in an even greater allowable air temperature than if the convective and radiative heat transfer were equally weighted. As the interior temperatures warm and the mean radiant temperature increases, the required air temperature decreases in proportion to the difference in mean radiant temperature and the ratio of radiative to convective heat transfer. That is to say, during periods of radiative cooling, as the mean radiant temperature increases, the required air temperature decreases at a lower rate. Similarly, during periods of radiative heating, the required air temperature decreases at an increased rate, evidenced by the greater negative slope of the cooling load at the end of day in the SV simulation compared to the NV. The cooling load of the SV scenario increases at a steady rate throughout the day as the building thermal mass warms. The cooling load then reaches a peak value at the end of the day just prior to occupancy reduction, after which the cooling load is reduced for the same reasons as in the NV scenario, and conditioning is terminated once occupancy is concluded. There are two significant phenomena occurring in the comparison of the SV and NV scenarios – the reduction in peak cooling load as well as the shift in start time of the cooling system. The cooling load system start-up is delayed by 2-4 hours and the peak load is reduced by about one third to one quarter in the third, fourth, and fifth days of the SV scenario.

From these trends in the cooling load profiles, it can be deduced that the overcooling of the interior thermal mass has the ability to allow for the thermal mass to act as a heatsink for the duration of occupancy. In order to achieve this, the thermal mass must be precooled to such a temperature that the building thermal mass is acting as a heat sink for the majority, if not for all, of the next day.

4.3: Cooling Load Reduction

The SV scenario exhibits a reduced cooling load in terms of both magnitude and duration, significantly reducing energy consumption compared to the SV scenario. The initial node temperatures were set to equal in both scenarios to allow for a fair comparison, resulting in low cooling load reduction in the first two days due to the need for the system to precool the building thermal mass. Still, the cooling load at the beginning of the first day is substantially lower in the SV scenario than in the NV. The cooling load of the second day is also substantially reduced, shifting the start-up time of the conditioning system forward in time and reducing the peak load experienced by the system. After the cool second night, the third day experiences a dramatic reduction in peak and total cooling load. This reduction is carried over to the fourth day due to the substantial charging of the thermal mass and the cool night temperature’s ability to maintain the degree of charging. From figure 7.5, it can be seen that the SV scenario results in about 35% energy savings during the 1-week simulated period.
5. Conclusion

In the case of a ventilated hollow core slab, night ventilation resulted in substantial activation of the thermal mass during the charging period. The charging of the slab mass resulted in the charging of surrounding masses due to the convective and radiative coupling with the interior air and surrounding surfaces. This effectively reduced the mean radiant temperature experienced by an occupant seated in the center of the space, allowing for an increased interior ambient air temperature in order to achieve the same operative temperature as in a situation with a greater mean radiant temperature. Based on the operative temperature metric, night ventilation through the hollow core slab was able to reduce the total energy consumption of the system, while also achieving a narrower operating window for the conditioning system and reduced cooling load for the duration of the cooling period.

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