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A METHOD TO ASSESS THE SUITABILITY OF A CLIMATE FOR NATURAL VENTILATION OF COMMERCIAL BUILDINGS

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ABSTRACT

Increasingly, European building designers have used natural ventilation to control air quality and cool commercial buildings to conserve energy compared to mechanical cooling and fan operation. These advanced natural and hybrid ventilation systems may be adapted to the North American context, but work is needed including consideration of the broader diversity of climates. An approach to the analysis of climate suitability is presented and applied to a number of North American climates. The climate suitability method presented offers an approach to predesign analysis for ventilative cooling that is climate specific and accounts for the expected level of internal and solar gains for a building. The climate suitability analysis also yields estimates of ventilation rates that are likely to be needed to achieve either a direct ventilative or night cooling design strategy.

INDEX TERMS

Natural Ventilation, Hybrid Ventilation, Design Method, Climate Suitability

INTRODUCTION

Cooling residences by opening windows and doors during mild weather is a familiar strategy indigenous to practically all climates. In a few climates, indigenous residential cooling strategies also include pre-cooling building thermal mass by nighttime ventilation to mitigate anticipated uncomfortably warm conditions during the coming day. These ventilative cooling strategies are more useful in some climates than others. Unfortunately, lessons learned for residential ventilative cooling are not directly applicable to commercial buildings because they typically have larger internal heat gains and smaller ratios of envelope area to enclosed volumes compared to residences. Consequently, cooling tends to be required for larger portions of the year in commercial buildings.

This paper describes a method to evaluate climate suitability for ventilative cooling of commercial buildings. This method is applied to specific climatic data to characterize the statistical distribution of the natural direct ventilation rates needed to offset given internal heat gains rates and the potential internal heat gain that may be offset by night-time cooling for those days when direct ventilative cooling is insufficient.

THEORY

For climatic suitability analysis, a commercial building may be idealized as a control volume with a uniform temperature distribution. Applying conservation of thermal energy yields:

Dynamic Model
$$KT_i + M\frac{dT_i}{dt} = E \qquad (1)$$

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with:

$$K = \Sigma UA + \dot{m}c_P \quad (2)$$

$$E = KT_o + q_i \quad (3)$$

where T_o is the outdoor air temperature, T_i is the indoor air temperature, q_i is the indoor internal plus solar gains, M_i is the indoor thermal mass, ΣUA is the building envelope thermal conductance, and $\dot{m}$ is the mass flow rate of ventilation air.

In this formulation, conductive heat transfer is arbitrarily separated into a rate out equal to the product of the envelope conductance and the indoor air temperature $(\Sigma UA)T_i$ and a rate in $(\Sigma UA)T_o$. Thus, the net conductive heat transfer rate is the more familiar product of the envelope conductance and the outside-to-inside temperature difference $(\Sigma UA)(T_o\text{-}T_i)$. Similarly, the ventilative heat transfer rate is separated into a rate out and a rate in. Together, the combined conductive and ventilative heat transfer rate out of the control volume is, thus, KT_i where K is the combined conductive and ventilative transfer coefficient defined by Equation 2. This formulation stresses the fact that the response of the thermal system is excited by the sum of conductive, ventilative, and internal gains Kt_o+q_i that are defined by Equation 3 to be the system excitation E.

If either M_i is negligibly small or T_i is relatively constant, then the accumulation term of Equation 1 may become insignificantly small. Under these conditions, the thermal response of the building system will be governed by the steady-state limiting case:

$$\textit{Steady State Model} \qquad KT_i = E \quad (4)$$

This steady-state approximation is the essential basis of the heating and cooling degree day methods used for preliminary determination of annual heating or cooling energy needs and as metrics of a given climate's heating and cooling season. It will also provide an approximate means to characterize the ventilative cooling potential of a given climate.

The heating balance point temperature $T_{o\text{-}hbp}$ establishes the outdoor air temperature below which heating must be provided to maintain indoor air temperatures at a desired internal heating set point temperature $T_{i\text{-}hsp}$. Hence, when outdoor temperatures exceed $T_{o\text{-}hbp}$, direct ventilative cooling can usefully offset internal heat gains to maintain thermal comfort. At or below $T_{o\text{-}hbp}$, ventilative cooling is no longer useful although ventilation would still be maintained at the minimum level required for air quality control.

At $T_{o\text{-}hbp}$, the combined conductive and ventilative heat loss from the building just offsets internal gains or, using the steady state approximation:

$$\textit{Heating Balance Point} \qquad K\left(T_{i-hsp} - T_{o-hbp}\right) = q_i \quad (5)$$

Solving this equation for $T_{o\text{-}hbp}$ and expanding we obtain:

$$T_{o-hbp} = T_{i-hsp} - \frac{q_i}{\dot{m}_{\min} c_p + \Sigma UA} \quad (6)$$

where the ventilation flow rate has been set to the minimum required for air quality control.

Thermal Comfort and Humidity Control

The heating balance point temperature, based on a prescribed $T_{i\text{-}hsp}$ set equal to the lowest T_i that is acceptable for thermal comfort, establishes a lower bound of acceptable outdoor temperatures for ventilative cooling. The T_o equal to the highest acceptable temperature for thermal comfort establishes an upper bound above which ventilative cooling will not be useful. Here, this limiting temperature will be assumed to equal the indoor cooling set point temperature $T_{i\text{-}csp}$ above which mechanical cooling would normally be activated to maintain thermal comfort. In addition, indoor air humidity must be limited to achieve comfortable conditions and to avoid moisture-related problems.

Distinct thermal comfort zones may be identified for summer and winter conditions. However, due to internal gains, natural ventilation may be expected to be useful to limit overheating in commercial buildings during both summer and cooler periods of the year. Consequently, for ventilative cooling of commercial buildings, it is useful to use a comfort zone that covers all seasons of the year. A reasonable comfort zone for ventilative cooling, based on combining ASHRAE's winter and summer comfort zones [ASHRAE 1997b], would be delimited by lower and upper dry bulb temperatures of 20 °C and 26°C and a limiting dew point temperature of 17 °C. Thus, the *Direct Ventilative Cooling Criteria* may be defined as:

$$T_{o-hbp}(q_i, T_{i-hsp} = 20°\text{C}) \le T_o \le T_{i-csp} = 26°\text{C} \quad \text{and} \quad T_{o-dp} \le 17°\text{C} \qquad (7)$$

For night ventilative cooling, no lower limit need be placed on outdoor air temperatures but the humidity limit will be maintained to avoid moisture-related problems in building materials and furnishings. Thus, the *Night Ventilative Cooling Criteria* are:

$$T_o \le T_{i-csp} = 26°\text{C} \quad \text{and} \quad T_{o-dp} \le 17°\text{C} \qquad (8)$$

METHOD

With the theory and comfort criteria established above, a method to evaluate the suitability of a given climate for ventilative cooling may be formulated. This method includes both a direct ventilation procedure and a nighttime cooling procedure.

Direct Ventilation

Relative to enclosed volume, commercial buildings typically have small envelope surface areas yet require relatively large minimum ventilation rates for air quality control. Consequently, the conductive conductance of commercial buildings may be expected to be small relative to the minimum ventilative conductance:

$$\dot{m}_{\min} c_p > \Sigma UA \qquad (9)$$

Thus, the heating balance point temperature of commercial buildings may be roughly estimated by introducing the condition of Equation 9 into Equation 6 to obtain:

$$T_{o-hbp} = T_{i-hsp} - \frac{q_i}{\dot{m}_{\min} c_p + \Sigma UA} \approx T_{i-hsp} - \frac{q_i}{\dot{m}_{\min} c_p} \qquad (10)$$

ASHRAE Standard 62 [ASHRAE 1999] prescribes minimum ventilation rates for commercial buildings. For offices, due to relatively low occupancy levels (e.g., 7 person/100 m^2) and moderate rate requirements (i.e., 10 L/s-person), the specific ventilation rate required is 0.7 L/s-m^2. Thus, $T_{o\text{-}hbp}$ is 8 °C, -4 °C, -28 °C, and –75 °C for internal gains of 10 W/m^2, 20

W/m^2, 40 W/m^2, and 80 W/m^2 respectively. It is clearly evident that internal gains expected in commercial buildings can quite easily extend the ventilative cooling season well into winter months in North America.

When outdoor air temperatures exceed T_{o-hbp}, yet fall below T_{i-csp}, ventilation can directly offset internal gains. Recognizing conductive losses during warm periods are typically small relative to internal gains for commercial buildings (i.e., $(\Sigma UA)(T_o-T_i)<q_i$), the ventilation rate required to offset internal gains while maintaining indoor air temperatures within the comfort zone may be estimated using the steady state model, Equation 4 as:

$$\dot{m}_{cool} = \frac{q_i - \Sigma UA(T_i - T_0)}{c_p(T_i - T_o)} \approx \frac{q_i}{c_p(T_i - T_o)} \qquad (11)$$

If $T_o<T_{o-hbp}$, no ventilative cooling will be required. When outdoor air temperatures fall within an increment of $(T_{i-csp}-T_{i-hsp})$ above T_{o-hbp}, the minimum ventilation rate will suffice:

$$\dot{m}_{cool} = \dot{m}_{\min} \ \ when \ \ T_{o-hbp} \le T_o \le T_{o-hbp} + (T_{i-csp} - T_{i-hsp}) \qquad (12)$$

Above this range, the ventilation rate will have to increase as T_o increases:

$$\dot{m}_{cool} = \frac{q_i}{c_p(T_{i-csp} - T_o)} \ \ when \ \ T_{o-hbp} + (T_{i-csp} - T_{i-hsp}) < T_o \le T_{i-csp} \qquad (13)$$

Equations 11, 12, and 13 may be used to determine periods when direct ventilative cooling may be applied and to estimate the ventilation rates needed to maintain thermal comfort during these periods. If $T_o>T_{i-csp}$ or $T_o>17$ °C then ventilative cooling is not useful and evaluation of cooling using nighttime ventilation is pursued as below.

Nighttime Cooling

When daytime outdoor temperatures exceed T_{i-csp}, direct ventilation is no longer useful. Cooling the building's thermal mass with outdoor air during the previous night may be able to offset daytime internal gains, however, if the outdoor air temperature drops below T_{i-csp} during the night. When this is possible, the heat transfer rate at which energy may be removed from the buildings thermal mass q_{night} approaches, in the limit for a very massive building:

$$q_{night} \approx \dot{m}c_p\left(T_{i-csp} - T_o\right) \ \ when \ \ T_o < T_{i-csp} \qquad (14)$$

The total energy removed from the building's thermal mass during the evening may then be used to offset internal gains on the subsequent workday. The average internal gain that may be offset is equal to the integral of the night removal rate divided by the workday time period:

$$\bar{q}_{cool} = \int_{nighttime} q_{night} \Big/ \Delta t \qquad (15)$$

Equation 15 will be used to estimate the internal gain that may be offset for a nominal unit nighttime air change rate to maintain thermal comfort.

RESULTS

This method was applied to using WYEC2 hourly annual climatic data published by ASHRAE [ASHRAE 1997a]. The WYEC data sets were devised to be “typical year” data sets to evaluate typical year energy consumption. When evaluating the performance of a specific (proposed) natural ventilation system, it may be reasonable to consider extreme year rather than typical year conditions [Levermore and Wright 2000]. Calculations were made for specific internal gains from 10 W/m^2 to 80 W/m^2. The low end of this range corresponds to the combination of low-energy lighting systems with minimal plug-loads and relatively low occupant densities. The upper end corresponds to very intensive lighting, plug loads, and occupancy levels. A story height of 2.5 m is assumed for these calculations.

Table 1 presents the results for four U.S. locations (results for additional locations may be found in Axley 2001 and Emmerich, Dols and Axley 2001). The table contains a set of four columns that report the direct ventilative cooling results:

- the average air change rate required to effect direct ventilative cooling for each of four specific internal gain rates when direct cooling is effective,
- the standard deviation of these ventilation rates, and
- the fraction of the year direct cooling is effective for each case – i.e., the number of hours direct ventilation is effective out of the total number of hours in a year's record.

A final column reports the results for complimentary night cooling:

- the average specific internal gain that can be offset by a nominal unit air change rate of (previous) nighttime cooling for overheated days,
- the fraction of overheated days that might be cooled using nighttime ventilation, and
- the total number of days per year that nighttime cooling might be effective.

Table 1. Climate suitability statistics for four U.S. locations

	Direct Cooling				**Night Cooling**[1]
	10 W/m^2	20 W/m^2	40 W/m^2	80 W/m^2	
Miami, FL – FLMIAMIT.WY2 data {FLMIAMIT.WY2 data} Hot-Humid-Coastal					
Vent. Rate or Cooling Potential	3.1 ±2.6 ACH	6.0 ±5.3 ACH	11.9 ±10.6 ACH	23.9 ±21.2 ACH	2.9 ±1.9 W/m^2-ACH
% Effective[2]	26.5%	27.3%	27.3%	27.3%	26% (79 days)
Los Angeles, CA – CALOSANW.WY2 data Hot-Arid-Coastal					
Vent. Rate or Cooling Potential	1.5 ±1.0 ACH	3.0 ±2.1 ACH	5.9 ±4.2 ACH	11.8 ±8.4 ACH	5.9 ±2.3 W/m^2-ACH
% Effective[2]	94.9%	97.8%	97.8%	97.8%	93% (27 days)
Kansas City, MO – MOKANCTW.WY2 data Temperate-Continental					
Vent. Rate or Cooling Potential	1.9 ±1.8 ACH	2.6 ±3.1 ACH	4.8 ±6.1 ACH	9.7 ±12.1 ACH	4.5 ±3.2 W/m^2-ACH
% Effective[2]	37.8%	67.4%	73.9%	73.9%	57% (81 days)
Madison, WI – WIMADSNT.WY2 data Cold-Continental					
Vent. Rate or Cooling Potential	1.8 ±1.7 ACH	2.4 ±2.8 ACH	4.1 ±5.2 ACH	8.2 ±10.4 ACH	6.0 ±3.0 W/m^2-ACH
% Effective[2]	39.3%	72.4%	88.7%	88.7%	82% (68 days)

[1] Night cooling for subsequent days when direct cooling is not effective.

[2] For direct cooling % = hours effective ÷ 8760 hours; for night cooling % = days effective ÷ days needed.

These statistics have been devised to provide design guidance for preliminary considerations. The decision to employ ventilative cooling strategies depends in part on the ventilation rates that will be required to effect the cooling and in part on the relative effectiveness of the strategy. For example, the Miami, FL data shows that direct cooling will not only require relatively high ventilation rates but even then it will be useful for only a small fraction of the year. For this location, nighttime cooling also proves to be relatively marginal demanding relatively high nighttime ventilation rates to offset moderate specific internal gains and then only effective for 26% of the overheated days of the year. Examining these results reveals that direct ventilative cooling may be expected to be most feasible and effective in the cooler locations for moderate to high specific internal gains – a reasonable result that may at first seem unintuitive. Direct cooling will not be particularly feasible or effective in the hot-humid locations for moderate to high specific internal gains.

DISCUSSION

The proposed method has a rational physical basis and, therefore, should be considered relatively general. The first results of its application indicate that it is able to reveal significant differences between climates. Furthermore, the method has been devised to provide building designers with useful preliminary design guidance relating to the levels of ventilation required to implement the direct and nighttime cooling strategies. These observations suggest that the proposed method may prove to be a practical design tool. The method is not without its shortcomings, however. Estimates of the internal gains that may be offset by nighttime cooling are based on the assumption that the building has, essentially, infinite thermal mass thus these results may significantly overestimate the benefit of nighttime cooling. Also, the statistical representation of the required ventilation rate to offset a given specific internal gain may require reconsideration.

Bourgeois has published a similar method [Bourgeois et al. 2000] that doesn’t use the concept of the balance point temperature but limits direct ventilative cooling to outdoor air temperatures exceeding 12 °C (i.e., to avoid cold drafts). Consequently, Bourgeois’ method more narrowly limits the ventilative cooling season.

CONCLUSION

A method to evaluate the climate suitability of a given location for direct ventilative cooling and complimentary nighttime ventilative cooling of a building's thermal mass has been presented. Importantly, the method may be applied, in principle, to ventilative cooling achieved by natural, mechanical, or mechanically assisted natural means. This method allows the building designer to evaluate the feasibility and potential effectiveness of ventilative cooling strategies, given knowledge of the likely internal gains in the building, and make first estimates of the required ventilation rates.

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