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Impact of adaptive thermal comfort on climatic suitability of natural ventilation in office buildings

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ABSTRACT

In earlier work [1], NIST developed a climate suitability analysis method to evaluate the potential of a given location for direct ventilative cooling and nighttime ventilative cooling. The direct ventilative cooling may be provided by either a natural ventilation system or a fan-powered economizer system. The climate suitability analysis is based on a general single-zone thermal model of a building configured to make optimal use of direct and/or nighttime ventilative cooling. This paper describes a new tool implementing this climate suitability methodology and its capability to consider an adaptive thermal comfort option and presents results from its application to analyze a variety of U.S. climates. The adaptive thermal comfort option has the potential to substantially increase the effectiveness of natural ventilation cooling for many U.S. cities. However, this impact is very dependent on the acceptable humidity range. If a dewpoint limit is used, the increase is significant for a dry climate such as Phoenix but much smaller for humid climates such as Miami. While ASHRAE Standard 55 does not impose a limit on humidity when using the adaptive thermal comfort option, the necessity of limiting humidity for other reasons needs to be considered.

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1. Introduction

In earlier work [2], the National Institute of Standards and Technology (NIST) developed a climate suitability analysis method to evaluate the potential of a given location for direct ventilative cooling and complementary nighttime ventilative cooling. The direct ventilative cooling may be provided by either a natural ventilation system or a fan-powered economizer system. The nighttime ventilative cooling is intended to cool the building's thermal mass to help manage cooling loads during the following day. As such, this climate analysis is a useful analytical technique during the early stages of design when building and system configuration decisions are being made. It also establishes first order estimates of design ventilation rates needed for preliminary design calculations, based on knowledge of the likely internal heat gains in a building and local climatic conditions. Specifically, a designer may estimate the ventilation rate needed to offset internal gains when direct ventilation can be effective and the daytime internal gains that may be offset by nighttime ventilation when direct ventilation will not suffice. Since the technique requires no building-specific information other than estimated thermal loads, it may be applied to evaluate the potential impact of natural ventilation in a given climate for buildings over a range of thermal loads and thereby assist in fundamental decisions about how the building will be cooled and ventilated.

The climate suitability analysis technique is based on a general single-zone thermal model of a building (i.e., a whole building, a portion of the building, or a single space that are effectively isothermal) configured and operated to make optimal use of direct and/or nighttime ventilative cooling. With this model, an algorithm was defined to process hourly annual weather data, using established thermal comfort criteria. The details of this approach are presented in earlier reports [1–3]. In these earlier works, the climate suitability analysis calculations were performed in a spreadsheet via a template file created for that purpose. To provide users with easier access to the tool, the method has been implemented via a new, web-based program (available from http://www.bfrl.nist.gov/IAQanalysis/software/CSTprogram.htm).

The new tool also has additional capabilities compared to the original spreadsheet calculation including an option for an adaptive thermal comfort method which is an option in the American Society of Heating, Refrigeration, and Air-conditioning Engineers' (ASHRAE's) thermal comfort standard [4] for determining acceptable thermal conditions in naturally conditioned spaces. Under this option, the allowable internal temperature range of a building depends on the outdoor climate rather than being fixed. Surveys of comfort in naturally ventilated office buildings worldwide provide compelling evidence that occupants tolerate a larger range of temperatures than in air-conditioned buildings [6,11]. This is thought to

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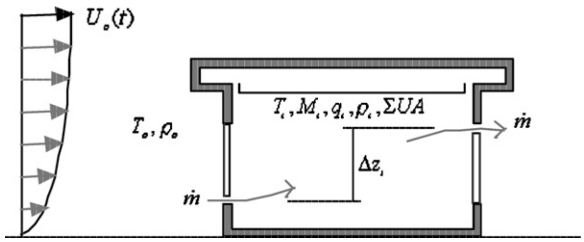

Fig. 1. Single-zone model of a building.

be due to occupant *adaptive* behavior that is fostered by naturally ventilated buildings [6,12]. Similar though not identical requirements are included for European buildings in Standard EN15251 [13].

This paper describes the climate suitability method and presents results from applying the method with an adaptive thermal comfort model to a variety of U.S. climates.

2. Theory

For climatic suitability analysis, a building may be idealized as a control volume with a uniform temperature distribution as illustrated in Fig. 1.

Applying conservation of thermal energy yields:

Dynamic model

$$KT_i + M\frac{dT_i}{dt} = E \quad (1)$$

with

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

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

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 is the indoor thermal mass, $\sum UA$ 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 $(\sum UA)T_i$ and a rate in $(\sum UA)T_o$. Thus, the net conductive heat transfer rate is the more familiar product of the envelope conductance and the outside-to-inside temperature difference $(\sum UA)(T_o - T_i)$. 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 Eq. (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 Eq. (3) to be the system excitation E.

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

$$\text{Steady state model} \quad KT_i = E \quad (4)$$

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 need to be maintained at the minimum level required for indoor 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:

$$\text{Heating balance point} \quad K(T_{i-hsp} - T_{o-hbp}) = q_i \quad (5)$$

Solving this equation for $T_{o\text{-}hbp}$ and expanding based on Eq. (2) we obtain:

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

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

2.1. 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 regions may be identified for summer and winter conditions. 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 (specified as a zone with clothing insulation of 1.0 clo in Standard 55) and summer (specified as a zone with clothing insulation of 0.5 clo in Standard 55) comfort zones [5], 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:

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

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

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

ASHRAE Standard 55 [4] now recognizes the phenomenon of adaptive thermal comfort by offering an optional path for determining acceptable thermal conditions in naturally conditioned spaces. The standard allows the adaptive method if the following conditions are met: