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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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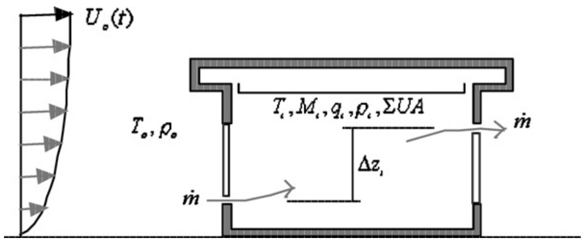

Fig. 1. Single-zone model of a building.

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

$$KT_i + M\frac{dT_i}{dt} = E \tag{1}$$

with

$$K = \sum UA + \dot{m}c_P \tag{2}$$

$$E = KT_o + q_i \tag{3}$$

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:

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

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:

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

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

$$T_{o-hbp} = T_{i-hsp} - \frac{q_i}{\dot{m}_{\min}c_P + \sum UA} \tag{6}$$

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:

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

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:

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

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:

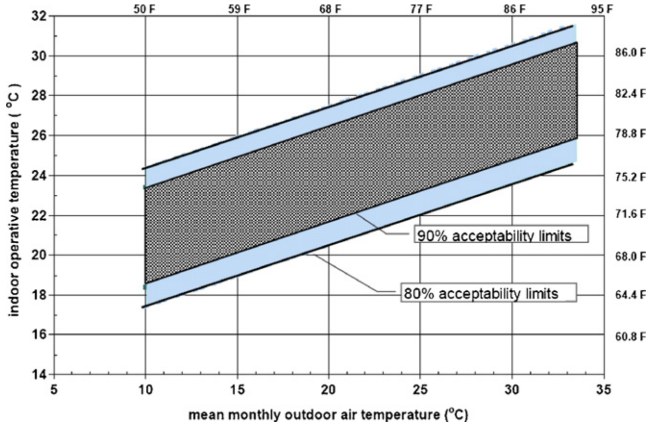

Fig. 2. Acceptable operative temperature ranges for naturally conditioned spaces (Copyright 2004 ASHRAE. Reprinted from ASHRAE Standard 55–2004 [4]).

1. The space has operable windows that open to the outdoors and that can be readily adjusted by the occupants.
2. There must be no mechanical cooling system for the space.
3. The space may have a heating system but the adaptive model does not apply when it is used.
4. The occupants in the space are engaged in near sedentary physical activities (1.0 met–1.3 met).
5. Occupants may freely adapt their clothing to the indoor thermal conditions.

If these conditions are met, allowable indoor operative temperatures for the space (and thus the limits for $T_{i\text{-}csp}$ and $T_{i\text{-}hsp}$ used in Eq. (7) above) depend on the outdoor climate, rather than being fixed, and may be determined from Fig. 2 below [4]. Standard 55 does not allow this option to be used when mean monthly outdoor temperatures are above 33.5 °C or below 10 °C and does not provide any specific guidance for those situations. As applied in the NIST Climate Suitability Tool, the adaptive thermal comfort limits at 10 °C and 33.5 °C in Fig. 2 are used for months with mean outdoor temperatures above and below those points. Per Standard 55, no humidity limit is imposed when using the limits of Fig. 2. However, it may still be desirable to limit the allowable humidity for reasons apart from occupant thermal comfort.

3. 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 (first described by Axley [2]) includes both a direct ventilation procedure and a nighttime cooling procedure.

3.1. Direct ventilation

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

$$\dot{m}_{\min} c_p > \sum UA \tag{9}$$

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

$$T_{o-hbp} = T_{i-hsp} - \frac{q_i}{\dot{m}_{\min} c_p + \sum UA} \approx T_{i-hsp} - \frac{q_i}{\dot{m}_{\min} c_p} \tag{10}$$

Table 1
Climate suitability statistics for fixed thermal comfort zone (results from NIST Climate Suitability Tool).

Direct cooling					Night cooling	
Combined internal gain	10 W/m^2	20 W/m^2	40 W/m^2	80 W/m^2		
Los Angeles						
Ventilation rate	1.48 ach ± 0.774	2.96 ach ± 1.55	5.92 ach ± 3.1	11.8 ach ± 6.19	Cooling potential	5.66 ± 2.63 W/m^2 h^{-1}
% Effective	93.4	93.4	93.4	93.4	Days needed	66
% Too cold	0	0	0	0	% Effective	95.5
% Too hot	0.457	0.457	0.457	0.457		
% Too humid	5.67	5.67	5.67	5.67		
Phoenix						
Ventilation rate	1.82 ach ± 1.58	3.64 ach ± 3.17	7.29 ach ± 6.33	14.6 ach ± 12.7	Cooling potential	2.79 ± 2.78 W/m^2 h^{-1}
% Effective	52	52	52	52	Days needed	244
% Too cold	0	0	0	0	% Effective	97.5
% Too hot	44	44	44	44		
% Too humid	5.16	5.16	5.16	5.16		
Miami						
Ventilation rate	2.27 ach ± 1.64	4.53 ach ± 3.28	9.06 ach ± 6.55	18.1 ach ± 13.1	Cooling potential	2.96 ± 2.64 W/m^2 h^{-1}
% Effective	21.1	21.1	21.1	21.1	Days needed	323
% Too cold	0	0	0	0	% Effective	23.5
% Too hot	42.5	42.5	42.5	42.5		
% Too humid	76	76	76	76		
Kansas City						
Ventilation rate	1.26 ach ± 1.1	2.05 ach ± 2.06	4.09 ach ± 4.13	8.19 ach ± 8.26	Cooling potential	5.11 ± 3.35 W/m^2 h^{-1}
% Effective	56.4	56.4	56.4	56.4	Days needed	136
% Too cold	19.2	19.2	19.2	19.2	% Effective	60.3
% Too hot	12.9	12.9	12.9	12.9		
% Too humid	21.6	21.6	21.6	21.6		

Note: Night cooling for subsequent days when direct cooling is not effective.
For direct cooling % = hours effective/8760 h; for night cooling % = days effective/days needed.
white = 0–5 ACH.
light gray = 5–10 ACH.
medium gray = 10–15 ACH.
dark gray > 15 ACH.

Table 2
Climate suitability statistics for adaptive thermal comfort cases (80% acceptability with 17 °C dewpoint limit).

Direct cooling					Night cooling	
Combined internal gain	10 W/m²	20 W/m²	40 W/m²	80 W/m²		
Los Angeles						
Ventilation rate	1.36 ach ± 0.662	2.71 ach ± 1.32	5.42 ach ± 2.65	10.8 ach ± 5.3	Cooling potential	$3.77 \pm 1.55\ \mathrm{W/m^2\,h^{-1}}$
% Effective	93.8	93.8	93.8	93.8	Days needed	62
% Too cold	0	0	0	0	% Effective	95.2
% Too hot	0.331	0.331	0.331	0.331		
% Too humid	5.67	5.67	5.67	5.67		
Phoenix						
Ventilation rate	1.99 ach ± 1.81	3.97 ach ± 3.63	7.95 ach ± 7.26	15.9 ach ± 14.5	Cooling potential	$1.87 \pm 1.49\ \mathrm{W/m^2\,h^{-1}}$
% Effective	63.1	63.1	63.1	63.1	Days needed	226
% Too cold	0	0	0	0	% Effective	83.6
% Too hot	30.5	30.5	30.5	30.5		
% Too humid	5.16	5.16	5.16	5.16		
Miami						
Ventilation rate	1.95 ach ± 1.55	3.89 ach ± 3.11	7.79 ach ± 6.21	15.6 ach ± 12.4	Cooling potential	$1.94 \pm 1.77\ \mathrm{W/m^2\,h^{-1}}$
% Effective	23.6	23.6	23.6	23.6	Days needed	305
% Too cold	0	0	0	0	% Effective	19
% Too hot	10.9	10.9	10.9	10.9		
% Too humid	76	76	76	76		
Kansas City						
Ventilation rate	1.2 ach ± 1.1	2.06 ach ± 2.1	4.12 ach ± 4.21	8.25 ach ± 8.42	Cooling potential	$3.59 \pm 2.06\ \mathrm{W/m^2\,h^{-1}}$
% Effective	63.2	63.2	63.2	63.2	Days needed	124
% Too cold	13.9	13.9	13.9	13.9	% Effective	56.5
% Too hot	6.86	6.86	6.86	6.86		
% Too humid	21.6	21.6	21.6	21.6		

Note: Night cooling for subsequent days when direct cooling is not effective.
For direct cooling % = hours effective/8760 h; for night cooling % = days effective/days needed.
white = 0–5 ACH.
light gray = 5–10 ACH.
medium gray = 10–15 ACH.
dark gray > 15 ACH.

When outdoor air temperatures exceed $T_{o\text{-}hbp}$, yet fall below $T_{i\text{-}csp}$, ventilation can directly offset internal gains. Recognizing conductive losses during warm periods are typically small relative to internal gains for commercial buildings (i.e. $(\sum UA)(T_o - T_i) < q_i$), 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, Eq. (4) as:

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

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

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

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

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

Eqs. (11)–(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 $T_o > T_{i\text{-}csp}$ or $T_{o\text{-}dp} > 17\,^\circ\mathrm{C}$ then ventilative cooling is not useful and evaluation of cooling using nighttime ventilation is pursued as below.

3.2. Nighttime cooling

When daytime outdoor temperatures exceed $T_{i\text{-}csp}$, 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 $T_{i\text{-}csp}$ during the night. When this is possible, the maximum 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:

$$q_{\rm night} \approx \dot{m}c_p(T_{i-csp} - T_o) \quad \text{when} \quad T_o < T_{i-csp} \tag{14}$$

The total energy removed from the building's thermal mass during the evening may then be used to offset internal gains on the subsequent day. The average internal gain that may be offset is equal to the integral of the night removal rate (i.e., the cooling potential stored in the building mass during the night) divided by the next day time period (Δt):

$$\bar{q}_{\rm cool} = \frac{\int_{\rm nighttime} q_{\rm night}}{\Delta t} \tag{15}$$

Eq. (15) will be used to estimate the internal gain that may be offset for a nominal unit nighttime air change rate (i.e., $1\ \mathrm{h}^{-1}$) to maintain thermal comfort.

4. Results

This method was applied to four U.S. cities with a range of climates, i.e., Los Angeles, Phoenix, Miami, and Kansas City. Climate suitability was evaluated for each city using three options:

1. Fixed heating and cooling setpoints with a 17 °C dewpoint limit.
2. Adaptive thermal comfort with 80% acceptability and a 17 °C dewpoint limit.
3. Adaptive thermal comfort with 80% acceptability and no dewpoint limit.

Calculations used TMY3 hourly annual climatic data published by the National Renewable Energy Laboratory

Table 3
Climate suitability statistics for adaptive thermal comfort cases (80% acceptability with no dewpoint limit).

Direct cooling					Night cooling	
Combined internal gain	10 W/m^2	20 W/m^2	40 W/m^2	80 W/m^2		
Los Angeles						
Ventilation rate	1.39 ach ± 0.698	2.79 ach ± 1.4	5.58 ach ± 2.79	11.2 ach ± 5.58	Cooling potential	5.11 ± 0.814 W/m^2 h^{-1}
% Effective	99.4	99.4	99.4	99.4	Days needed	18
% Too cold	0	0	0	0	% Effective	100
% Too hot	0.331	0.331	0.331	0.331		
% Too humid	0	0	0	0		
Phoenix						
Ventilation rate	2.04 ach ± 1.84	4.08 ach ± 3.69	8.16 ach ± 7.38	16.3 ach ± 14.8	Cooling potential	1.81 ± 1.51 W/m^2 h^{-1}
% Effective	65.2	65.2	65.2	65.2	Days needed	224
% Too cold	0	0	0	0	% Effective	91.5
% Too hot	30.5	30.5	30.5	30.5		
% Too humid	0	0	0	0		
Miami						
Ventilation rate	3.27 ach ± 2.21	6.53 ach ± 4.43	13.1 ach ± 8.85	26.1 ach ± 17.7	Cooling potential	1.95 ± 0.853 W/m^2 h^{-1}
% Effective	81.6	81.6	81.6	81.6	Days needed	225
% Too cold	0	0	0	0	% Effective	99.6
% Too hot	10.9	10.9	10.9	10.9		
% Too humid	0	0	0	0		
Kansas City						
Ventilation rate	1.59 ach ± 1.6	2.77 ach ± 3.1	5.55 ach ± 6.19	11.1 ach ± 12.4	Cooling potential	3.0 ± 1.84 W/m^2 h^{-1}
% Effective	77	90.9	90.9	90.9	Days needed	97
% Too cold	13.9	0	0	0	% Effective	100
% Too hot	6.86	6.86	6.86	6.86		
% Too humid	0	0	0	0		

Note: Night cooling for subsequent days when direct cooling is not effective.
For direct cooling % = hours effective/8760 h; for night cooling % = days effective/days needed.
white = 0–5 ACH.
light gray = 5–10 ACH.
medium gray = 10–15 ACH.
dark gray > 15 ACH.

(http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/). The TMY3 data sets were devised to be "typical year" data sets. When evaluating the performance of a specific (proposed) natural ventilation system design, it may be necessary to also consider extreme year conditions as well [7]. Calculations were made for specific combined internal and solar gains, q_i, 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, relatively low occupant densities, and low solar gains. The upper end corresponds to very intensive lighting, plug loads, solar gains, and occupancy levels. A floor to ceiling height of 2.5 m is assumed for these calculations. Note that no additional knowledge of geometry is required for this simplified method and thus is not presented for these test cases. This enables use of this method to analyze the possible reliance on natural ventilative cooling at a very early stage of building design. More detailed methods could then be applied by a designer as the building design is further defined.

ASHRAE Standard 62.1 [8] prescribes minimum ventilation rates for commercial buildings. For offices, at a default occupancy level of 5 person/100 m^2, the specific minimum ventilation rate required is 0.425 L/s m^2, and this value was used as an input to the calculations.

The primary results are presented in Tables 1–3 in the form output by the new Climate Suitability Tool. Each table contains a set of four columns that report the direct ventilative cooling results:

- the average air change rate required to provide direct ventilative cooling for each of four specific internal gain rates, but including only those hours when direct cooling is effective (i.e., as defined by the outdoor temperature limits described in Eq. (7)),
- the standard deviation of these ventilation rates,
- the percentage 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 the weather file,
- the percentage of hours for which the ambient conditions were too cold, too hot, or too humid for natural ventilative cooling.

The tables also include a final column that reports the results for night cooling:

- the average specific internal gain that can be offset by an air change rate of 1 h^{-1} of (previous) nighttime cooling for overheated days (i.e., those days when direct ventilative cooling is not effective for all hours from 6 a.m. to 6 p.m.),
- the total number of days during the year that nighttime cooling is needed,
- the percentage of those days for which it may, potentially, be effective.

As expected, direct cooling with natural ventilation has the potential to be very effective in Los Angeles (over 90% for all cases). Applying the adaptive thermal comfort condition could increase the effectiveness to nearly 100% if no dewpoint limit is used as seen in Table 3.

In contrast, direct natural ventilation cooling is effective for around 50% of hours in Phoenix with a fixed thermal comfort model because 44% of the hours are too hot. The effectiveness increases to at least 60% if the adaptive thermal comfort condition is used with only a small further increase in effectiveness when the dewpoint limit is eliminated. The results also indicate that night cooling may be effective for many of the days on which direct cooling is ineffective.

For Miami, natural ventilation cooling is effective for around 20% of hours in the baseline case, which only increases by a few percent when applying the adaptive thermal comfort condition with a dewpoint limit because Miami has even more hours which are too humid (76%) rather than too hot (44%). If the dewpoint limit is eliminated, the effectiveness increases dramatically to over 80%. It is important to note that, for both Miami and Phoenix, achieving this high effectiveness for spaces with high heat gain rates requires very high average air change rates (up to 15 h^{-1} for Phoenix and 26 h^{-1} for Miami) which may be difficult to achieve. Additionally, supplemental night cooling is only an effective strategy in Miami if no dewpoint limit is used, which may not be a desirable approach.

Although the baseline effectiveness for Kansas City is much higher than Miami (as high as 75%), the increase possible with the adaptive thermal comfort condition was similarly dependent on whether the dewpoint limit was used. Without a dewpoint limit, the effectiveness reaches 90%. Again, as for Miami, night cooling is only partially effective unless the dewpoint limit is removed.

5. Discussion

The proposed method for evaluating climate suitability for natural ventilation has a rational physical basis and, therefore, should be considered relatively general. Its application indicates that it is able to reveal significant differences between climates and between fixed versus adaptive thermal comfort goals. 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. The ASHRAE Indoor Air Quality Guide [9] discusses the importance of heating, ventilating and air-conditioning (HVAC) system selection early in the design process under Strategy 1.3 – Select HVAC Systems to Improve IAQ and Reduce the Energy Impacts of Ventilation. The information provided by this tool can support the building design team's decision making when considering a natural ventilation option for the HVAC system.

The ASHRAE Indoor Air Quality Guide [9] also discusses the importance of controlling indoor humidity for occupant health and comfort and because high humidity can cause condensation, leading to potential material degradation and biological contamination such as mold and because high humidity supports dust mite populations, which contribute to allergies and notes that HVAC designers often choose indoor conditions of 50% RH to 60% RH and that Standard 62.1 requires a limit of 65% RH for systems that dehumidify. However, no specific guidance is provided for natural ventilation systems. If higher moisture levels are allowed, materials should be selected to be moisture tolerant.

This climate suitability method has a few noteworthy limitations. The statistics have been devised to provide design guidance for preliminary consideration only. However, 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. Also, the analysis method is based on a simplified thermal model that does not rely on detailed knowledge of building geometry, internal loads, etc. This limitation yields an approximate result that may be expected to be most accurate at high ventilation rates and thus for those very climatic conditions that can best benefit from natural or hybrid ventilation. But the method may be applied early in a building's design at a time when inclusion of natural ventilative cooling may be decided. As more detailed design information becomes available, a more complete analysis method can be applied. 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 will overestimate the benefit of nighttime cooling and, as with the direct cooling analysis, a more detailed analysis method should be applied when the building and system design details are determined. It should also be emphasized again that q_i is the sum of internal and solar gains, not internal gains alone. Consequently, control of solar gains will always lead to greater direct ventilative and night cooling benefits. Other considerations such as humidity control for reasons other than thermal comfort require careful consideration and analysis.

Another critical aspect of the local climate when considering natural ventilation is outdoor air quality. Future versions of the Climate Suitability Tool may include the capability to access and analyze data on outdoor air quality for the building location. Such information is available through the U.S. Environmental Protection Agency from http://www.epa.gov/air/data/index.html. This data may be used to indicate time periods (days or even entire seasons) for which outdoor air quality is not acceptable without treatment (i.e., filtration of particles or air cleaning of ozone) and thus ventilative cooling would be considered ineffective for those time periods unless some provision is made for air cleaning.

6. Conclusion

This paper describes a new tool implementing a climate suitability analysis methodology for evaluating the possibility of ventilative cooling and its capability to consider an adaptive thermal comfort option. The climate suitability analysis technique uses a simplified method which requires minimal input making it appropriate for an early "predesign" stage during which the possibility of applying natural ventilation for a building space may be considered by architects based on the general design requirements and design conditions [10]. If the analysis indicates that natural ventilation is a reasonable option and as the system design is further developed, other methods would be applied such as the loop equation method for sizing system components and coupled multizone thermal-airflow analysis for evaluating system performance [10].

The adaptive thermal comfort option available in ASHRAE Standard 55 [4] has the potential to substantially increase the effectiveness of natural ventilation cooling for many U.S. cities. However, this impact is very dependent on whether a limit is included for the outdoor humidity. If a dew point limit is used, the potential increase in the effectiveness of direct ventilative cooling is significant for a dry climate such as Phoenix but much smaller for more humid climates such as Kansas City and 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 carefully considered.

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