Ventilative cooling potential based on climatic condition and building thermal characteristics

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ABSTRACT

We introduce a new method for defining ventilative cooling potential (VCP) for office buildings that depends not only on the climatic conditions but also on building thermal characteristics. The energy savings from ventilative cooling differs from building to building; therefore, VCP should be able to represent the actual energy savings—though not perfectly—in order to guide optimization of ventilative cooling parameters during the initial design stage.

In this paper, we proposed the VCP with temperature shift index representing building thermal characteristics. The temperature shift is based on the adaptive thermal comfort region shifted in the psychrometric chart. The index of temperature shift can be determined by the balance temperature difference of the building, which is defined as the heat gain in the building divided by the thermal loss characteristics of the building envelope.

To validate the concept, we conducted simulations using a model office building in four representative cities during summer climates: tropical, dry–semi-arid, Mediterranean, and continental. Using energy analysis software, we calculated the amount of energy consumed in each case of ventilative cooling whenever possible compared to the energy consumed by solely mechanical cooling during summer. Comparisons were made on a weekly basis. Results demonstrate a strong correlation between energy savings and VCP in cases when a proper balance temperature difference was applied.

KEYWORDS

Building design, Ventilative cooling, Balance temperature difference, Cooling potential

1 INTRODUCTION

Ventilative cooling is an energy-efficient way of cooling a building using outdoor air through natural or mechanical ventilation (Kolokotroni and Heiselberg, 2015). It requires only fan power or minor power to control the system, which is usually much less than the power consumed by a mechanical cooling system's compressor. We cannot totally rely on ventilative cooling because of its dependence on climatic conditions but can take advantage of it as much as possible to reduce cooling energy consumption. It is necessary to quantify how much cooling energy can be saved using ventilative cooling.

In recent years, an index to quantify climatic potential has been introduced in several ways. Yao (2009) assesses an index of the natural ventilation cooling potential (NVCP) for an office building. The NVCP was described as the ratio of the number of hours within the comfort zone to the total occupied hours. Herein, building characteristics, ventilation type, and internal heat load should be defined in advance to match natural ventilation with the expected occupancy thermal comfort. Artmann (2007) introduced a concept to quantify the climatic cooling potential (CCP) for buildings due to night-time ventilation. The potential is defined as the sum of the product of the indoor–outdoor temperature difference and the time interval at night with acceptable outdoor conditions. Given that building temperature oscillates harmonically within the range of 24.5°C ± 2.5°C, the CCP does not consider any building-specific parameters. For night cooling purposes, the largest air temperature differences are the most valuable benefit that can be extracted from the climate. Meanwhile, for direct cooling during the day, limitations should be made on outdoor air supplies to prevent overcooling of the indoor space.

Ghiaus and Allard (2006) addressed energy-saving potential based on temperature difference and free running temperature, and they considered the probability distribution of outdoor temperature and the applied degree-hour bin method to estimate energy savings. Without including the building model, Causone (2016) proposed an index of the climatic potential for natural ventilation (CPNV). The index is based on the number of hours that natural ventilation agrees with temperature and humidity constraints. The acceptable supply air conditions should be within the lower and upper temperature limits of 10°C and 3.5°C higher than the adaptive thermal comfort, respectively, and the humidity ratio (W) uses a range within 30% RH and 70% RH. However, a wide acceptable temperature ranges in CPNV may create over capacity in the design of ventilation systems or cause occupant dissatisfaction.

This study introduces an index to evaluate ventilation cooling potential based on the shifted temperature from the adaptive thermal comfort zone. Lookup tables of VCPs at various temperature shifts are suggested to provide for various cities so that designers can look up corresponding building characteristics represented by the balance temperature difference. The VCP index introduced in this paper can be used to design ventilation systems in conjunction with thermal characteristics of a new building and to adjust ventilation system operation in an existing building to maximize energy savings by ventilative cooling during summer.

2 THEORY

2.1 Thermal comfort model

There are various thermal comfort models in the literature. In this study, we used the adaptive thermal comfort model of ASHRAE standard 55 (ASHRAE, 2004) for a naturally ventilated building, which was originally proposed by de Dear and Brager (2002). This is an optimum comfort temperature in a naturally conditioned space as a function of outdoor temperature as shown in Eq. (1). The criteria are differentiated into 80% and 90% occupant acceptability of ±3.5°C and ±2.5°C bands, respectively. This model assumes that occupants adapt their clothing to thermal conditions and are sedentary, with 1.0 to 1.3 met.

$$T_{comf} = 0.31T_{a,out} + 17.8 \quad . (1)$$

2.2 Balance temperature difference

When the total heat gain of an indoor space equals the heat losses through the building envelope, the indoor temperature is in equilibrium with outdoor temperature. The temperature difference can be defined as the balance temperature difference. The heat losses are composed of heat transmission through walls and heat infiltration by ventilation air exchange.

$$\widehat{UA}_{bldg}\Delta T_{bal} + \rho C_p Q \Delta T_{bal} = W_{IHG} \quad , (2)$$

$$\Delta T_{bal} = \frac{W_{IHG}}{\widehat{UA}_{bldg} + \rho C_p Q} = \frac{W_{IHG}}{\widehat{UA}_{bldg}(1+\alpha)} \quad , (3)$$

where α is defined as $\frac{\rho C_p Q}{\widehat{UA}_{bldg}}$, which means the ratio of infiltration loss to transmission loss. Building thermal characteristics include the UA value of the building walls and the air exchange rate, Q, by either mechanical ventilation or natural ventilation through cracks and openings in the envelope. The balance temperature difference expresses the overall thermal characteristics of a building with a single parameter. ΔT_{bal} is large for well-insulated and air-tight buildings with large internal heat gains, whereas it is small for poorly insulated and leaky buildings with small internal gains. Modern buildings tend to move toward large balance temperature differences as they increase insulation thickness to achieve zero-energy buildings and use high-energy-density electronic equipment.

2.3 Ventilative cooling potential with temperature shift

VCP is defined as the number of satisfied hours for ventilative cooling over total hours as described in Eq. (2). The satisfied hours may differ from one author to another depending on applications, but they are chosen here as the daytime hours when outdoor conditions are within the shifted zone. As seen in Fig. 1, the lower limit of the comfort zone (T_{cl}) is shifted by the balance temperature difference, and the upper limit (T_{cu}) is shifted by half of the balance temperature difference. When outdoor temperature is in region B (enclosed by a dotted line), outdoor air can be fully used for ventilative cooling. In region C (enclosed by a solid gray line) outdoor air can be partially used for ventilative cooling, as the temperature difference is not large enough to completely cover the cooling load. Assuming that the outdoor temperature is equally distributed in the region statistically, half of the region C is added to the shifted zone for VCP calculation.

$$VCP = \frac{1}{H}\sum_{d=d_i}^{d_f}\sum_{h=h_i}^{h_f} h_{vc} \quad , (4)$$

where H is the total number of hours considered, h_{vc} is the number of hours in the shifted comfort zone when ventilative cooling is possible, d and h are the standard time day and hour, and the subscripts i and f denote the initial and final time day and hour.

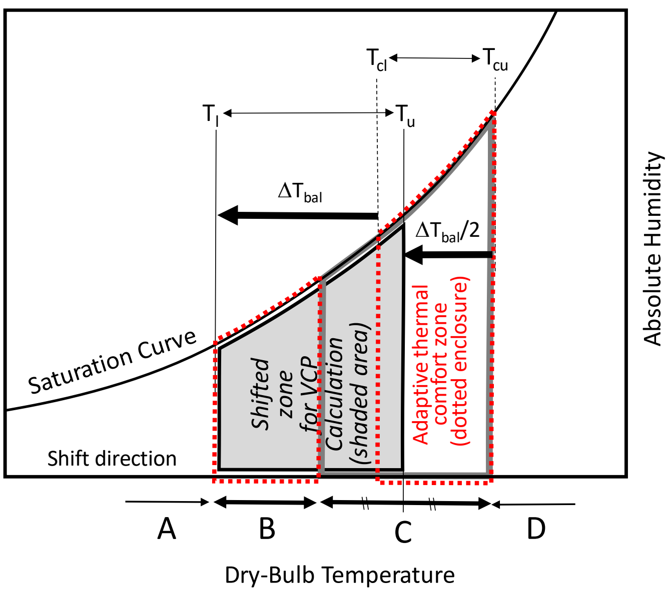

Figure 1:Thermal comfort zone shifted on psychrometric chart

3 METHOD

3.1 Climatic data

We investigated four representative cities in our analysis. Those cities belong to one of the following four main groups: megathermal, dry, mesothermal, and microthermal zones. These groups are from the five main groups according to the Köppen climate classification (Peel, 2007). The fifth group, polar, is not considered here because ventilative cooling is not quite necessary therein. The cities and their climate summaries are shown in Table 1, which shows average summer time outdoor temperature and average wind speed.

Table 1:Representative cities of four main groups of Köppen climate (data source taken from Energyplus, 2007)

Climate zone	City	Location	Average outdoor temperature (°C)				Average wind speed (m/s)			
			Jun	Jul	Aug	Sep	Jun	Jul	Aug	Sep
Megathermal-tropical monsoon	Jakarta, Indonesia	6.13S, 106.75E	29.0	29.0	29.4	29.6	4.51	4.76	5.11	4.89
Dry semi-arid	Madrid, Spain	40.45N, 3.55W	23.2	27.0	20.6	25.5	2.73	3.26	3.61	3.46
Mesothermal-mediterranean	Los Angles, USA	33.93N, 118,4W	24.7	20.1	21.9	21.6	4.54	5.00	5.10	4.49
Microthermal-hot summer continental	Seoul, Korea	37.57N, 126.97E	23.2	26.2	27.0	22.3	2.46	2.60	2.25	2.17

3.2 Building and ventilation model

To verify our results, we performed an energy simulation for a sample building. The building is a medium sized office building (Deru, 2011) with 4,982 m^2 of total area. There are three stories and a 5-m central atrium lengthwise in between the building floors with a floor-to-ceiling height of 3 m as shown in Fig. 2. A simple input parameter of total heat gain density produced by occupants, lights, and equipment is given as 31.24 W/m^2 with the schedule of loads lasting from 8 a.m. to 8 p.m. (12 hours). There are 33% and 11% of glazing and opening areas, respectively, over wall ratio per floor area. The building terrain is located in a rural area with low buildings and faces 90° to the north.

The three ventilation schemes used for cooling the space inside the building are shown in Table 2. In the air conditioner (AC)-only scheme, the cooling system is handled by the AC only. The Fan-AC assist scheme uses fans as a main cooling device to replace indoor air with cool outdoor air and the air conditioner as a backup device in case ventilative cooling is not possible. In the natural ventilation-air conditioner (NV-AC) assist scheme, natural driving forces are used to entrain cool outdoor air when it is available. The AC is always on during the occupied hours when the indoor temperature above T_{cu}. The coefficient of performance of the AC is 3.0, and mechanical fans are on at a constant flow rate of 14 m^3/s when the internal temperature is between 22°C and T_{cu}. The ACs and windows are independently controlled in each zone. Night ventilation based on thermal mass is not considered and is assumed to not affect cooling potential during the day. Energy consumption and indoor conditions are calculated using Coolvent software (Maria-Alexandra, 2008) from June till September on an hourly basis. The energy savings from utilizing a mechanical fan or natural ventilation are obtained based on the energy consumption by the reference case of the AC-only scheme.

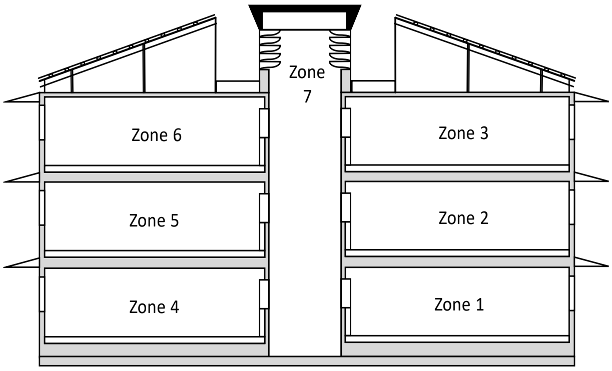

Figure 2:Building model for validation

Table 2:Air conditioner, fan, and window operations

Operation	Cooling scheme		
	Scheme 1 (AC-only)	**Scheme 2 (Fan-AC assist)**	**Scheme 3 (NV-AC assist)**
Air conditioner	On $T_{in} > T_{cu}$	On $T_{in} > T_{cu}$	On $T_{in} > T_{cu}$
Natural ventilation	No	No	Window opening
Mechanical fan	No	Fan operation	No

According to the given building model, the balance temperature difference, ΔT_{bal}, is obtained manually by considering the energy balance between internal heat gain and building heat transfer. The UA value of the building is estimated to be 3600 W/K, and the internal heat generation is 16,800 W/K; solar radiation is not included in the calculation. The balance temperature difference is calculated to be approximately 7°C for this building.

4 RESULTS AND DISCUSSION

4.1 VCP with an index of temperature shift

Table 3 shows the VCPs obtained for four cities according to temperature shifts of 1°C–9°C for each summer month. It also gives the overall VCPs for the entire summer depending on the temperature shifts. The temperature shift for a given VCP can be selected by a designer to account for the balance temperature difference representing the thermal characteristics of the building.

For a tropical climate, such as that in Jakarta, where it is relatively hot and humid throughout the year, the VCP is as large as approximately 50%–60% for buildings with a zero-balance temperature difference, i.e., completely open space. However, VCP sharply decreases as the temperature shift increases. This means that it is very difficult to implement ventilative cooling for buildings with balance temperature differences greater than 4°C–5°C.

Madrid, which has a semi-arid climate, has a maximum VCP at temperature shifts between 3°C and 5°C from June till September. VCPs remain relatively large for a wide range of temperature shifts, which means most buildings with a wide range of thermal characteristics can benefit more or less from ventilative cooling. Los Angeles is typically not too hot during the day and cool at night during the summer season. This condition creates an excellent strategy for ventilative cooling during the day as well as at night. The peaks of VCP are between 4°C and 5°C, and the potential remains high until a temperature shift of around 9°C.

During the hot summer period in Seoul, VCP decreases almost linearly as the temperature shift increases. It would be beneficial for buildings to have a large balance temperature difference in terms of cooling energy savings. However, it is important to maintain building insulation above a certain level to account for cold winters. To take advantage of ventilative cooling, building designers would need to be able to adjust ventilation systems instead of building envelope specifications.

Based on the balance temperature difference of the present building (7°C), the acceptable VCP from June to September for four representative locations is illustrated in Fig. 3. Empty circles in the figures show selected hourly outdoor temperatures when the buildings were occupied. From the figure, it can be seen that Jakarta only have a few potentials to use outdoor air for cooling the indoor space. Meanwhile, Los Angeles can take advantage of outdoor cooling, especially in early summer. Madrid and Seoul are similar, having fairly good cooling potential in June and September but less in July and August.

Table 3:Ventilative cooling potential of four representative cities during June to September

Cities	**Month**	**Adaptive thermal comfort**	**Ventilative cooling potential (%) with temperature shift**								
			1 ºC	**2 ºC**	**3 ºC**	**4 ºC**	**5 ºC**	**6 ºC**	**7 ºC**	**8 ºC**	**9 ºC**
Jakarta	Jun	60.6	50.8	39.2	31.9	25.6	19.4	13.1	10.3	8.1	5.3
	Jul	58.3	49.5	40.3	32.5	27.4	21.8	16.9	10.8	7.8	5.6
	Aug	50.0	42.2	33.1	25.8	19.9	15.3	11.8	9.4	7.0	4.0
	Sep	51.4	40.0	33.3	26.1	21.4	16.9	11.9	8.3	5.8	4.4
	Ave	55.1	45.6	36.5	29.1	23.6	18.4	13.4	9.7	7.2	4.8
Madrid	Jun	42.5	46.1	46.9	52.8	50.8	52.2	49.4	49.7	49.7	48.9
	Jul	36.0	35.8	38.7	39.5	40.9	36.6	36.0	33.1	33.3	28.5
	Aug	32.8	36.0	35.8	37.6	37.1	37.1	34.7	33.6	33.6	32.8
	Sep	46.7	52.5	59.2	59.2	59.7	61.9	60.8	60.8	58.1	56.4
	Ave	39.5	42.6	45.1	47.3	47.1	47.0	45.2	44.3	43.7	41.6
Los Angeles	Jun	41.4	61.4	78.9	85.0	95.3	97.8	95.0	93.6	91.9	91.9
	Jul	65.6	75.3	89.5	96.5	97.0	95.4	95.4	89.8	86.0	80.6
	Aug	76.1	82.8	90.1	93.3	93.5	94.1	91.1	85.5	74.5	67.7
	Sep	57.8	67.5	80.3	89.4	90.6	88.1	88.1	85.8	81.9	77.5
	Ave	60.2	71.7	84.7	91.1	94.1	93.8	92.4	88.7	83.6	79.5
Seoul	Jun	63.9	70.3	73.9	75.8	73.3	70.3	67.2	60.6	55.0	51.9
	Jul	74.7	76.6	69.1	62.6	58.1	50.8	44.4	38.7	34.7	29.6
	Aug	69.1	65.9	59.7	55.6	49.5	43.3	36.6	29.3	23.9	20.4
	Sep	60.8	65.8	70.3	71.4	71.4	69.3	68.3	64.7	61.9	57.5
	Ave	67.1	69.6	68.2	66.4	63.1	58.4	54.1	48.3	43.9	39.9

4.2 Energy saving and correlation with VCP

Figure 4 shows the reduction of building energy consumption from using the Fan-AC assist and NV-AC assist schemes. The percentage of energy savings is calculated based on the ratio of energy consumption by Fan-AC assist or NV-AC assist schemes over the AC-only scheme. In other words, the energy savings represent how many hours outside air can replace AC operation hours. The monthly profiles of energy savings between the two distinguished schemes are typically similar. The NV-AC assist scheme has a greater effect on average energy savings than the Fan-AC assist scheme in Jakarta and LA because it has a higher wind speed that contributes to increase ventilation rate.

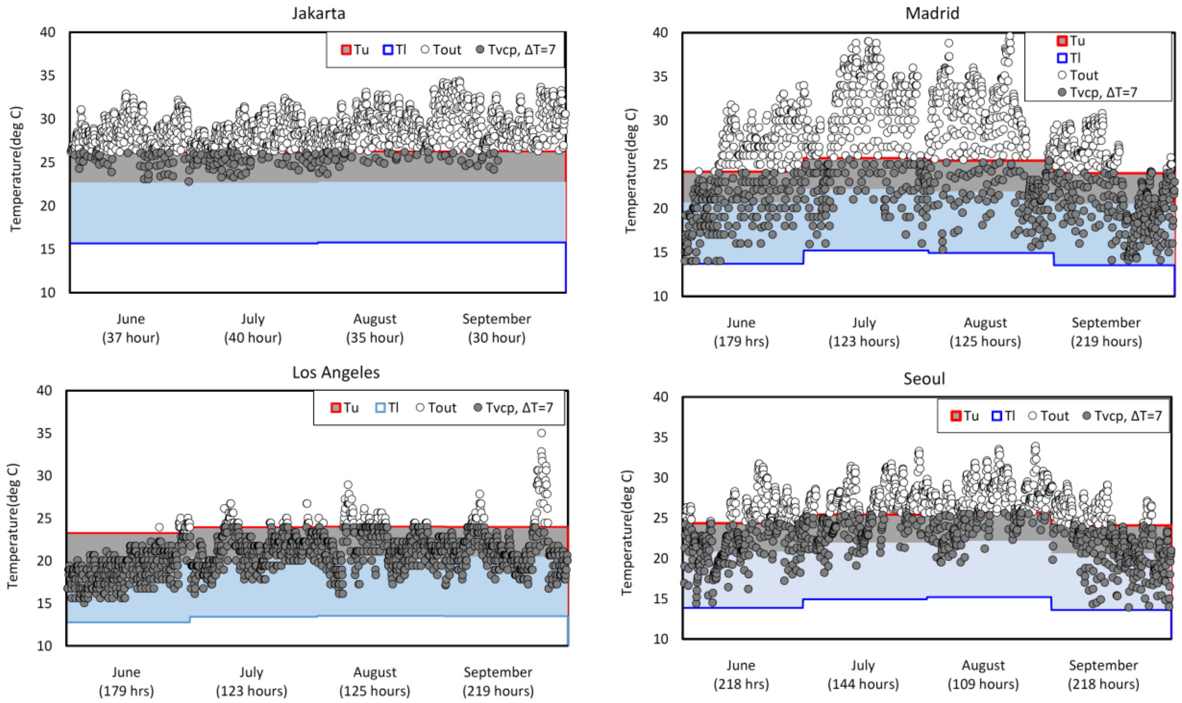

Figure 3:Selected VCP hours using 7°C temperature shift

The VCP discussed earlier should be able to represent the real energy savings even though they do not perfectly match. Figure 5 shows the correlations between calculated energy savings and the VCP obtained at a temperature shift of 7°C for the Fan-AC assist scheme and NV-AC scheme. The figure represents four cities from June till September on weekly basis. According to the given building model, energy savings strongly correlate with the VCP. That means the VCP can represent the energy savings estimation fairly well. The correlation between VCP and energy savings using the NV-AC scheme is found also to be strong but slightly weaker than using Fan-AC assist scheme because there are too many uncertainties involved in estimating energy consumption using climate data.

The temperature shift at 7°C is not shown as the highest among VCPs at different temperature shifts, but it means that VCP with an appropriate temperature shift taking building thermal characteristics into account correlates well with the actual energy savings by adapting ventilative cooling.

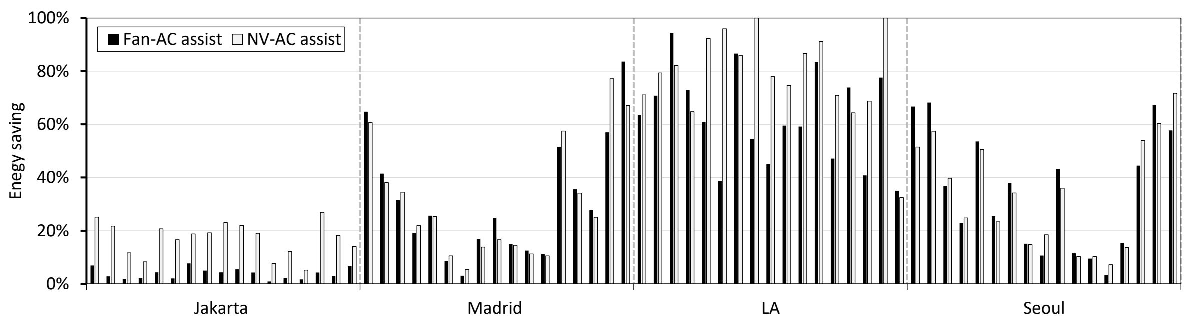

Figure 4:Energy savings by Fan-AC assist and NV-AC assist scheme

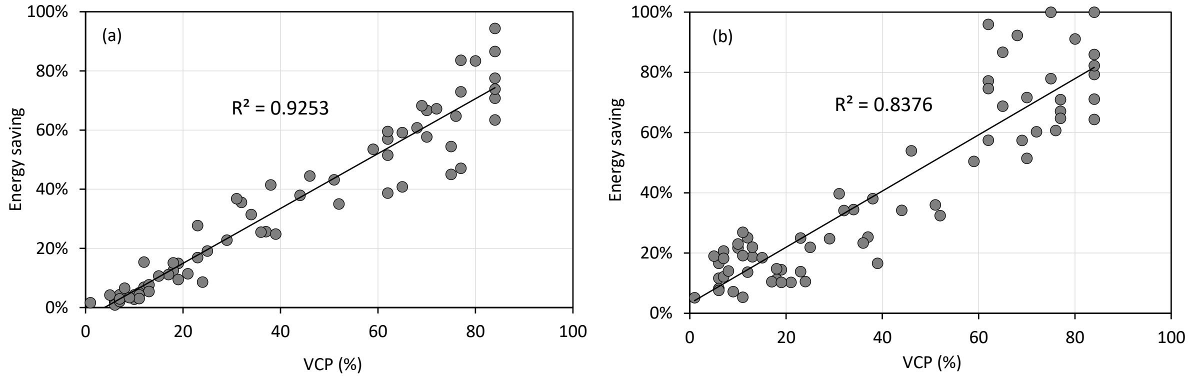

Figure 5:Correlation between weekly energy savings and VCP at 7°C during June to September in four representative cites (a) Fan-AC assist scheme (b) NV-AC assist scheme

5 CONCLUSIONS

The VCP with an index of temperature shift is introduced to account for building thermal characteristics for given climatic conditions. The temperature shift can be determined by a single parameter, balance temperature difference between indoors and outdoors. The following conclusions can be drawn:

1. The VCP distribution with respect to temperature shift shows different patterns depending on climatic zone. A tropical climate requires small temperature shifts for the maximum use of ventilative cooling. A similar conclusion can be made regarding a continental climate, but annual energy use should be addressed. Ventilative cooling is best applicable to a dry semi-arid climate where daily temperature fluctuations are large.

2. The VCP with temperature shift based on the balance temperature difference (lower limit by ΔT_{bal}, upper limit by $\Delta T_{bal}/2$) results in a good correlation with the actual energy savings of the building calculated on a weekly basis. We considered a simplified method to take into account the complicated probability distribution of outdoor temperature.

3. A lookup table can be provided for designers to easily estimate possible energy savings by adapting ventilative cooling in the initial design stage. The table shown in this paper can be modified further by optimizing the parameters appropriate for various applications.

Further research will be needed to investigate the effects of solar radiation, probability distribution of outdoor temperature, methods for estimating ventilation rate, applicability of the thermal comfort zone, and other factors.

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