A review of the performance indicators of night-time ventilation

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ABSTRACT

Night-time ventilation is a natural cooling technology, in which cold ambient air is used to cool indoor spaces. This literature review analyses how recent studies have defined the effectiveness or efficiency of night-time ventilation. Most studies used the similar indicators related to heat removal, energy saving, cooling demand reduction, and thermal comfort. However, there were significant differences between the definitions of performance of night-time ventilation, both in terms of criteria of judgement and methods of analysis. This review shows that the assessment of night-time ventilation effectiveness or efficiency should be determined according to the task of the ventilation system, such as removal of heat, provide better thermal comfort. The objective of this article is to review the scientific literature on night-time ventilation indicators to identify and categorize the most suitable indicators for performance assessment. The analysis results form a basic framework regarding the application and operation of night-time ventilation.

KEYWORDS

Night-time ventilation; Performance indicators; Review

1 INTRODUCTION

Overheating in buildings and need for cooling is emerging as a challenge both at the design stage and during operation in most buildings, which leads to high energy consumption in the building sector. Night-time ventilation – meant as combined effect of both natural or mechanical ventilation at night, and building thermal mass – can be seen as a promising passive cooling concept to reduce cooling loads (Ramponi, Angelotti, & Blocken, 2014). The basic concept of night ventilative means cooling the building structure during the night-time period and provide a heat sink for the following occupied time. The efficiency of night cooling depends on the thermal properties of buildings and on the local climate conditions, i.e. night-time wind speed and temperature swing of the ambient air (N. Artmann, Jensen, Manz, & Heiselberg, 2010).

According to the previous research, four methods can be utilized to assess the performance of night ventilation, which are field study, chamber study, simulation study, and development of mathematical models (A. Landsman, 2016). Liddament summarized the evaluation parameters for ventilation efficiency based on air change efficiency and contaminant removal effectiveness (Liddament, 1996). Cao reviewed the index of different ventilation performance and air distribution system (Cao et al., 2014). However, as the night-time ventilation mainly focuses on the cooling effect for the building sector, no framework for night ventilative cooling performance evaluation has been developed so far. This is a major barrier for the application and the further development of the technologies related to night-time ventilation. Therefore, this paper summarizes the most commonly used indicators for assessing night ventilation.

2 FEASIBILITY OF BOUNDARY CONDITION FOR NIGHT-TIME VENTILATION

Night ventilative cooling is dependent on the availability of suitable external conditions to provide cooling. It is also influenced by the building type and its thermal characteristics, which determine the cooling ability of night-time ventilation.

Initially, analyses of the heat storage efficiency and the cooling potential should be carried out in relation to the application prospect of the night-time ventilation. As climatic conditions, building with different levels of thermal mass, use patterns, internal load levels react differently to the external climate conditions, the climate analysis cannot abstract from building characteristics and use.

2.1 Heat storage efficiency

Because heat gains and night ventilation periods typically do not coincide in time, heat storage is essential for effective night cooling, and thus a sufficient amount of thermal mass is needed in the building. In order to satisfy the thermal comfort criteria, the building thermal capacity needs to be sufficient to accumulate the heat gains from daily solar radiation and the internal load from people and equipment within an acceptable temperature variation, which can provide enough heat sink for the night ventilative cooling (Nikolai Artmann, 2008). In the European Standard prEN 15251 (EN 15251, 2007), the temperature ranges for thermal comfort are given in three categories: A) 2 K, B) 3 K, and C) 5 K, while in the ASHRAE Standard 55 (ASHRAE, 2013) the acceptable temperature range for thermal comfort is from 5K (PPD: 10%) to 7K (PPD: 20%). Therefore, the heat storage efficiency η_h – defined as the ratio of the heat storage in building elements Q_{hs} and the daily heat gains Q_{hg} – can be calculated as:

$$\eta_h = \frac{Q_{hs}}{Q_{hg}} = \frac{c_{dyn} A(\overline{T}_{n,j} - \overline{T}_{n,k})}{Q_{hg}} \tag{1}$$

where $\overline{T}_{n,j}$ and $\overline{T}_{n,k}$ are the average building element temperature at daytime j and k respectively, A is the building elements area (m^2). The dynamic storage capacity of the building elements c_{dyn} (kJ/m^2K) can be calculated by European standard EN ISO 13786 (EN ISO 13786, 2007). The heat storage efficiency of building elements is an important precondition for the application of night cooling. However, the effectiveness of night-time ventilation also depends on other parameters such as climatic conditions (ambient temperature) and ventilation air change rate.

2.2 Cooling potential

Cooling potential for night-time ventilation is defined as the ability of the outdoor air flow by ventilation at night to reduce or remove the absorbed heat during daytime and/or the energy consumption by mechanical cooling in buildings, while maintaining a comfortable thermal environment. Artmann put forward a method to calculate the climatic cooling potential for night-time ventilation based on degree-hour approaches which rely on indoor and outdoor temperature gradients on an hourly basis (N. Artmann, Manz, & Heiselberg, 2007). The method assumes the thermal capacity of the building mass is sufficiently high, and therefore all the exceeding internal gains can be stored in the building mass. The International Energy Agency (IEA) Annex 62 project experts utilized Artmann's method in another form to calculate the cooling potential of ventilative cooling with regard to the building envelope thermal properties, occupancy patterns, internal gains, and ventilation needs (Belleri, Avantaggiato, Psomas, & Heiselberg, 2017). The cooling potential can be calculated as follows:

$$NCP = \frac{H \rho C_p (T_{i-\max} - T_o)}{3600} \tag{2}$$

$$T_{i-\max} = 0.33 \cdot T_{rm} + 18.8 + K \tag{3}$$

where NCP is the night-time cooling potential (W/m^2-h^{-1}), which means how much the internal gains (W/m^2) can be offset with the airflow of 1 h^{-1}. H is the floor height (m), ρ is the air density (kg/m^3), c_p is the specific heat of air. $T_{i\text{-}max}$, T_o and T_{rm} are the upper operative temperature limit of the comfort zone, outdoor dry bulb temperature, and outdoor running mean temperature respectively. K means the constant depending on required comfort category. For EN 15251, K=2 for comfort category I, K=3 for comfort category II, and K=4 for comfort category III.

In order to reinforce the night ventilative cooling potential, the night outdoor air temperature should be low. Generally, mechanically driven ventilation is used during occupancy hours and naturally driven ventilation is activated at night time to increase the cooling potential; however, it would increase the energy consumption for fan operation.

3 PERFORMANCE INDICATORS FOR NIGHT-TIME VENTILATION

When assessing the performance of night cooling, the first step is to determine under which conditions the strategy is to be analyzed. Once the conditions have been chosen for comparison, a suitable performance assessment method should be selected. As to the previous studies, the following conditions were usually compared: air conditioned vs. free-floating, fan-assisted ventilation vs. natural ventilation, only daytime ventilation vs. night-time ventilation, full day ventilation vs. nighttime ventilation, no ventilation vs. nighttime ventilation, and low thermal mass vs. high thermal mass.

The performance of night ventilation can be quantified by the thermodynamically cause (energy balance) and by its cooling effect (room temperature): this paper sorts the night ventilation performance: 1. Heat removal effectiveness, 2. Energy efficiency, 3. Reduction in cooling energy use, 4. Thermal comfort improvement. Heat removal efficiency quantifies the effectiveness with which internal heat is removed. Energy efficiency means how much cooling energy is provided. Reduction in cooling energy use represents the energy saving for the daytime mechanical cooling. Thermal comfort improvement means the reduction of uncomfortable thermal comfort during the occupied time.

3.1 Heat removal effectiveness

Heat removal effectiveness includes heat removal efficiency and temperature reduction efficiency, which both represent how much heat can be removed by night ventilation. For temperature reduction caused by night cooling, the most commonly used evaluation indicators include the reduction of the maximum indoor air/operative/surface temperature and the indoor average air/operative/surface temperature. Slightly more complex is the daily maximum damping, which is the difference between the peak indoor and outdoor daily air temperatures, and the daily indoor temperature, which represents the range of the difference between the indoor maximum and minimum air temperatures in a specific day, can be used for assessment.

3.1.1 Heat removal efficiency

The indicator of heat removal efficiency is the ratio of indoor heat removed by night air Q_n to the night cooling potential NCP (W/m^2-h^{-1}) multiple floor area S (m^2) and air change rate ACH (h^{-1}), which can be calculated as follows:

$$\eta_H = \frac{Q_n}{\int_{t_s}^{t_e} NCP \cdot S \cdot ACH} = \frac{\int_{t_s}^{t_e} \dot{m}_{air} c_p (T_i(t) - T_o(t)) dt}{\int_{t_s}^{t_e} NCP \cdot S \cdot ACH} \tag{4}$$

where $\dot{m}_{air}$, c_p are the airflow rate (kg/s) and specific heat capacity (kJ/kg.□) respectively. T_{in} and T_{out} are air temperatures at the inlet and outlet of the room, respectively. NCP is the night-time ventilation cooling potential (W/m^2-h^{-1}), S is the indoor room floor square (m^2), ACH is the air change rate (h^{-1}). t_i and t_f represent the start and end time of the night-time ventilation period (h). In order to reinforce the heat removal efficiency, it is important to position the air inlets in a cool environment (shaded side of the building). Furthermore, supplementary natural cooling solutions like ground cooling (earth to air heat exchange) or evaporative cooling to reduce the ambient air inlet temperature might be necessary. Besides, the building should be well-designed with well-balanced glass area in the facades, efficient solar shading, and exposed thermal mass to enhance the heat transfer between cool air with interior surface.

3.1.2 Ventilation effectiveness for heat removal

An indicator with regard to the temperature distribution within the building is defined as the ventilation effectiveness for heat removal ε_t (Awbi, 1993), which depends on air distribution method (mixing or displacement ventilation), difference between inlet and outlet air temperatures, airflow rate, and location of internal heat source. The ventilation effectiveness for heat removal can be calculated experimentally or numerically for each ventilation strategy, which is defined as follows:

$$\varepsilon_t = \frac{T_{out} - T_{in}}{T_m - T_{in}} \tag{5}$$

where T_{out} and T_{in} are the outlet and inlet air temperatures respectively, while T_m is the mean occupied zone temperature. In general, the ε_t is smaller than 100% for mixing night ventilation, while bigger than 100% for displacement night ventilation. Obviously the higher the value of the indicator, the more effective the removal of heat is.

3.1.3 Temperature efficiency

The temperature efficiency originated from the measurements mainly depends on the ventilation concepts and the airflow rate, which can be described as follows (N. Artmann et al., 2010):

$$\eta_T = \frac{T_{out} - T_{in}}{\overline{T}_{\mathrm{surface}} - T_{in}} \tag{6}$$

where T_{out} and T_{in} are the outlet and inlet air temperatures respectively, and $\overline{T}_{\mathrm{surface}}$ is the average building indoor surface temperature. Artmann found that the temperature efficiency indicator was almost constant during each experiment (excluding the first hour) and for various inlet air temperatures. The value of this indicator for mixing ventilation decreases slightly with the increasing airflow rate, while for the efficiency for displacement ventilation decreases obviously. Same as in 3.1 Heat removal effectiveness, η <1 for mixing ventilation whereas >1 for displacement ventilation.

3.1.4 Temperature difference ratio

The indicator of temperature difference ratio (TDR) was put forward by Givoni and verified by good results to judge the efficiency of different passive cooling systems that include the night-time ventilation (Givoni, 1992). TDR can be expressed as follows:

$$TDR = \frac{T_{o,\max} - T_{i,\max}}{T_{o,\max} - T_{o,\min}} \tag{7}$$

where $T_{o,\max}$ and $T_{o,\min}$ means maximum and minimum ambient temperatures respectively, and $T_{i,\max}$ represents the maximum building indoor temperature. The denominator is the ambient temperature swing whereas the numerator is the difference between the outdoor and indoor maximum temperature. For a building with natural night ventilative cooling, the TDR can be expressed as a percentage that is smaller than 1. The higher the value of TDR, the larger temperature difference between the outdoors and indoors, and more cooling, which means the better the cooling performance of the night-time ventilation.

3.1.5 Decrement factor and daily time lag

In order to characterize the thermal behavior of the building envelope with natural night ventilation, two dynamic factors – decrement factor (f) and time lag (φ) – originating from the heat wave propagating through the external wall in a whole day (24h) are put forward. The decrement factor is the ratio of temperature amplitude of the inner and outer surface, whereas the time lag is the time difference between the outer and inner surface maximum temperature (Gagliano, Patania, Nocera, & Signorello, 2014). The two indicators can be calculated as follows:

$$f = \frac{T_{si,\max} - T_{si,\min}}{T_{so,\max} - T_{so,\min}} \tag{8}$$

$$\varphi = \tau(T_{so,\max}) - \tau(T_{si,\max}) \tag{9}$$

where T_{si} and T_{so} are the inner surface and outer surface temperatures respectively, while $\tau(T_{so,max})$ and $\tau(T_{si,max})$ mean the time when the temperature of the outer and inner surface reach their maximum. The subscript *max* and *min* represents the maximum and minimum respectively. The lower the value of φ, the longer the time shift and more peak load shave by night ventilation. Moreover, the higher the value of f, the more cooling effect provided by night ventilative cooling.

Following Gagliano's principle, Landsman substituted the inner surface and outer surface of external wall temperature with the indoor air temperature and outdoor air temperature respectively to express the decrement factor and time lag for buildings caused by night cooling (J. Landsman, Brager, & Doctor-Pingel, 2018). The expression for new factors can be shown as follows:

$$f' = \frac{T_{i,\max} - T_{i,\min}}{T_{o,\max} - T_{o,\min}} \tag{10}$$

$$\varphi' = \tau(T_{o,\max}) - \tau(T_{i,\max}) \tag{11}$$

where T_i and T_o are the indoor and outdoor air temperature respectively. The tendency of f' and φ' are same with it of f and φ.

3.2 Energy efficiency

3.2.1 Coefficient of performance

One of the most commonly used indicators of the energy efficiency of night ventilative cooling is the coefficient of performance (COP), which is the ratio of the cooling energy delivered into the building to the auxiliary electric consumption by mechanical machines during night period (Pfafferott, Herkel, & Jäschke, 2003). COP can be calculated as follows:

$$COP = \frac{\int_{t_s}^{t_e} \dot{m}_{air} c_p (T_i(t) - T_o(t)) dt}{\int_{t_s}^{t_e} P_e(t) dt} \tag{12}$$

where $\dot{m}_{air}$, c_p are the airflow rate (kg/s) and specific heat capacity (kJ/kg.□) respectively. $T_i(t)$ represents indoor air temperature, $T_o(t)$ means ambient temperature, and P_e is the electric power of fan, t_i and t_f represent the start and end time of night-time ventilation period (s). According to the expression, the higher the temperature difference between inside room and ambient at night due to the reduction of ambient temperature, the higher the COP for night-time ventilation performance. On primary energy demand level, the value of COP should be high enough to compete with mechanical cooling and other free-cooling technologies such as evaporative cooling. In addition to the careful planning process, advanced control algorithms are needed to ensure that the COP value remains as high as possible (Vidrih, Arkar, & Medved, 2016). However, the COP just provides a rough evaluation of thermal performance of night-time ventilation, the efficiency cannot be quantified.

3.2.2 Potential energy efficiency index

The potential energy efficiency (PEE) is the ratio of energy removal Q_n to the corresponding electric energy of the mechanical fan Q_f to better symbolize the energy removal efficiency by night-time ventilation as it is necessary to take the mechanical ventilation into consideration when high air change rate are provided (Blondeau & Spe, 1997). PEE can be calculated as follows:

$$PEE = \frac{Q_n}{Q_f} = \frac{\int_{t_s}^{t_e} \dot{m}_{air} c_p (T_o(t) - T_{out}(t)) dt}{\int_{t_s}^{t_e} P_e(t) dt} \tag{13}$$

In contrast to the COP, the energy removal provided by night ventilation was calculated by the difference between ambient air temperature T_o and exhaust air temperature T_{out}. Blondeau found that the value of PEE increases when the temperature difference between ambient air and indoor air increases, which can be considered as the driving potential of the energy removal. Even if the value of PEE could be very high (more than 3), attention should be paid in the comparison with other scenarios, because the high value of PEE could be obtained by a better tuning of the night ventilation system which may lack optimization for the fan and its regulation mode.

3.2.3 Daily average cooling efficiency

The daily average cooling efficiency (DACE) is the ratio of useful cooling to the energy consumed, originating from the method of the European Seasonal Energy Efficiency Ratio (Monodraught, 2012), which means the ratio of the effective cooling energy to the energy input to the cooling plant over a year. The DACE for night-time ventilation coupled with active thermal mass system: hollow core (shown in Figure 1)+PCM system (embedded in aluminum sheeting and honey comb) can be calculated as follows (Whiffen, Russell-Smith, & Riffat, 2016):

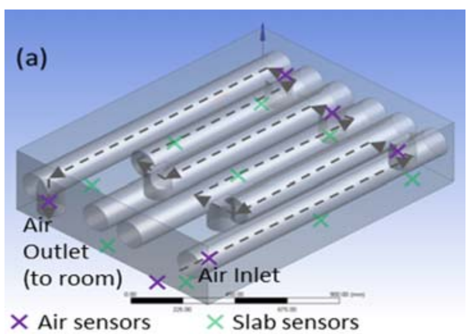

Figure 1: Pilot scale hollow core thermocouple and air network arrangements

$$DACE = \frac{Q_{useful,cooling}}{Q_{energy,consumed}} = \frac{\sum q_{slab} + \sum q_{PCM} + \sum q_{air} - \sum Q_{wall,transfer}}{\sum Q_{AC} + \sum Q_{fan}} \tag{14}$$

where $Q_{useful,cooling}$ is the useful cooling energy (kWh) provided by active thermal mass system, $Q_{energy,consumed}$ is the energy consumption (kWh) during occupied hours. q_{slab}, q_{PCM} and q_{air} are the useful cooling energy provided by slab, PCM, and night ventilation at time j respectively, while $Q_{wall,transfer}$ means the building heat loss through the wall, which can all be calculated by:

$$q_{n,j} = m_n c_{p,n} (\overline{T}_{n,j} - \overline{T}_{n,k}) \tag{15}$$

where m_n is the mass of corresponding material (kg), $c_{p,n}$ specific heat capacity of corresponding material (kJ/kgK), while $\overline{T}_{n,j}$ and $\overline{T}_{n,k}$ are the average material temperature at time j and k respectively. The average slab temperature was chosen to represent the temperature of slab approximately, while the temperature difference for air was between the average building indoor temperature at time j, and the inlet air temperature from slab at the previous time k. Because there are phase change processes for PCM, the specific heat capacity of PCM is not constant, which the effective heat capacity C_{eff} (J/kgK) was put forward to consider the identical properties for both liquid and solid phases (Darkwa & O'Callaghan, 2006). C_{eff} can be expressed by Gausian equation as follows:

$$c_{eff}(T_{PCM,i}) = c_s + ae^{-0.5(\frac{T_{PCM,i}-T_{melt}}{b})^2} \tag{16}$$

where $T_{PCM,i}$ is the PCM temperature (□), c_s is the heat capacity in solid state (kJ/kgK), a is the latent heat factor (kJ/kg), T_{melt} is the melt temperature (□), and b is the melting width factor (standard deviation, function of purity) (□).

$Q_{wall,transfer}$, based on the wall properties and the difference between average building indoor air temperature and ambient temperature, can be calculated as follows:

$$Q_{wall,transfer,i} = U_{wall}A_{wall}(T_{o,k} - \overline{T}_{room,k}) \tag{17}$$

where U_{wall} means the heat transfer coefficient (W/m^{2}K), A_{wall} means the wall area (m^2), while the $T_{o,k}$ and $\overline{T}_{room,k}$ mean the ambient and building indoor air temperature respectively.

The denominator air conditioning consumption Q_{AC} and fan consumption Q_{fan} for DACE can be monitored by electric meters during the operation period. Because each cooling energy component was concluded during the occupied period, the DACE only represents the occupied efficiency. Different with 3.2.1 COP, this indicator not only accounts for the direct cooling effect of night ventilation but also takes the cooling effect of PCM and slab provided by night ventilative cooling and heat loss through wall into consideration.

3.2.4 Ventilative cooling seasonal energy efficiency ratio and Ventilative cooling advantage

Both the seasonal energy efficiency ratio (SEER$_{VC}$) and the ventilative cooling advantage (ADV$_{VC}$) refer to the performance of a particular part of the ventilative cooling system (Heiselberg, 2018). SEER$_{VC}$ evaluates the energy efficiency of whole ventilative cooling system by the ratio of the cooling demand reduction and the mechanical ventilative cooling system electrical energy consumption, which can be calculated as follows:

$$SEER_{VC} = \frac{Q_{t,c}^{ref} - Q_{t,c}^{scen}}{Q_{el,v}} \tag{18}$$

$$Q_{el,v} = P \times n \times H \tag{19}$$

where $Q_{t,c}^{ref}$ and $Q_{t,c}^{scen}$ are the cooling demands of the scenario without and with ventilative cooling (kWh/m^2) respectively, and $Q_{el,v}$ is ventilation system electrical energy consumption. For mechanical ventilation system, P is the insert power (W/(m^3/h)), n is the ventilation rate (m^3/h), and H is the operation time cooling (h). The higher the value of SEER$_{VC}$, the more benefit the ventilative cooling provides. However, when the value of SEER$_{VC}$ is negative, it means that ventilative cooling has an adverse effect on the overall cooling demand. When the value of SEER$_{VC}$ is positive but lower than 1, it means that the cooling demand reduction is lower than the electric energy consumption by ventilation system, while when the value of that is higher than 1, the situation is on the contrary.

The ventilative cooling advantage (ADV$_{VC}$) was defined by the ratio of difference cooling energy use and energy consumption for ventilation, which can be expressed as follows:

$$ADV_{VC} = \frac{Q_{el,c}^{ref} - Q_{el,c}^{scen}}{Q_{el,v}} \tag{20}$$

where $Q_{el,c}^{ref}$ and $Q_{el,c}^{scen}$ are the cooling system electrical energy consumption of the scenario without and with ventilative cooling (kWh/m^2) respectively, and $Q_{el,v}$ is ventilation system electrical energy consumption. The meaning value of ADV$_{VC}$ is similar with that of SEER$_{VC}$.

3.2.5 Cooling effectiveness factor

The indicator of cooling effectiveness factor, defined as the ratio of cooling energy provided by the night ventilation with solar chimney (SC) to the total solar radiation incident on the glazed surfaces of the SC (Koronaki, 2013). CEF can be calculated as follows:

$$CEF = \frac{\sum_{j=1}^{m}(\dot{m}_{air,j}C_p(T_{i,j} - T_{o,j})}{A\sum_{k=1}^{n}(I_k)} \tag{21}$$

where m and n are the duration of night ventilative cooling hours and the daytime hours with solar irradiance (h). $\dot{m}_{air,j}$ means the hourly average air mass flow rate at night (kg/s), C_p represents the mean specific heat of air at constant pressure (J/kgK). ($T_{i,j}$–$T_{o,j}$) means hourly air temperature difference between indoor and ambient during j-hour of the night (□), A is the SC glazed surface area (m^2), and I_j means solar irradiance incident upon a glazed surface (W/m^2), during k-hour of the day. The higher the CEF, the better the cooling effect of night ventilation.

3.2.6 Life cycle efficiency ratio

A new indicator based on the effects of the whole life cycle named life cycle efficiency ratio (LCER) has been addressed to evaluate the environmental benefit of ventilative cooling with different thermal inertia system. LCER both takes the embodied impacts and operational impacts which are usually accumulated to assess the life cycle impact of a building (Brambilla, Bonvin, Flourentzou, & Jusselme, 2018). This indicator originated from $SEER_{VC}$ methodology, which compares the operational savings of a scenario analyzed with the referenced ones and weights the difference of embodied impact of the two scenarios. LCER can be calculated as follows:

$$LCER = \frac{OI_{ref} - OI}{EI - EI_{ref}} \tag{22}$$

where OI and EI are the operational impacts and embodied impacts of the scenario analyzed respectively. The subscript ref represents the reference scenario. LCER can be assessed by three parts: cumulative energy demand (CED) (MJ-eq), non-renewable cumulative energy demand (CED_{nr}) (MJ-eq), and global warming potential (GWP) ($kgCO_2$-eq). The corresponding energy indicators can come from the process-based *LCI* database such as KBOB database, and the emissions can be calculated based on the impact assessment method described in IPCC 2007 (IPCC, 2007). According to the expression of LCER, the higher the value, the greater the life cycle benefits. When the value of LCER is lower than 1, it means that the benefits from the scenario analyzed are smaller than the reference one, while when the value of LCER is negative, meaning that the operational savings are smaller than the embodied impacts.

3.3 Reduction in cooling energy use

3.3.1 Cooling requirements reduction

The indicator of cooling requirements reduction (CRR) means the ratio of cooling demand reduction of a scenario with night-time ventilation and the cooling demand of the reference scenario without night-time ventilation, which can calculate cooling effectiveness of any mechanical or natural night ventilative cooling scenario, can be calculated as follows:

$$CRR = \frac{Q_{t,c}^{ref} - Q_{t,c}^{scen}}{Q_{t,c}^{ref}} \tag{23}$$

where $Q_{t,c}^{ref}$ and $Q_{t,c}^{scen}$ mean the cooling demand of the reference scenario and the analyzed scenario with ventilation respectively. It can be easily calculated by results from building energy simulation, experiments, and empirical formulas for a reference scenario such as a mechanically cooled building and an analyzed scenario such as a building with mechanical cooling at daytime and natural ventilation at night.

The value of CRR can range between a negative value and +1. If the value of CRR is negative or 0, it means that the night ventilative cooling system does not reduce the cooling requirements, while if the value is positive or 1, which means that the ventilative system reduces the cooling requirements or even eliminate the cooling requirements for the scenario with night cooling.

3.3.2 Cooling load reduction efficiency

A method based on the principle of "Balance Point Temperature" was put forward to calculate the energy contribution of night-time ventilation to the cooling load of a building and was verified by data from an extended and detailed simulation with TRNSYS software (Asimakopoulos, 1996). This method makes it possible to calculate both the energy required to cool a building to acceptable comfort conditions with night-time ventilation and to calculate the energy contribution of a building with night-time ventilation in comparison with a conventional air conditioned building. The energy reduction due to the night ventilation Q_{NV} can be written as follows:

$$Q_{NV} = \frac{mc\,\text{NDD}}{\text{DAY}} \tag{24}$$

where

$$\text{NDD}=\sum (T_{ngh} - T_0) S_j \quad \begin{cases} S_j = 1 \text{ if } T_0 < T_{ngh} \\ S_j = 0 \text{ if } T_0 \geqslant T_{ngh} \end{cases} \tag{25}$$

m represents the average night ventilation rate at night, c means the air specific heat, NDD is the abbreviation of night degree days and DAY is the daytime period in hours. T_{ngh} is the average indoor temperature of the building without night-time ventilation. The equation for T_{ngh} originated from the energy balance of the indoor air at night can be written as follows:

$$T_{ngh} = \frac{h_{in} A T_k + m_a c T_{on}}{h_{in} A + m_a c} \tag{26}$$

where

$$T_k = f_1 (T_i + T_{on}) \tag{27}$$

h_{in} is the internal heat transfer coefficients, A is the total internal surface of the building, m_a is the night inflation flow rate of the building without night-time ventilation. T_k is the function of the indoor temperature T_i and the average night-time ambient temperature T_{on}. At last, f_1 is a coefficient for the average temperature of the thermal mass, which was set as 0.5. The total energy losses due to the night ventilation Q_{NVL} can be written as:

$$Q_{NVL} = 3600 mc\text{NDD} \tag{28}$$

There are two checks for the Q_{NVL}, one is the comparison between Q_{NVL} and the maximum possible stored energy MCMAX which is defined as:

$$\text{MCMAX} = \sum (M_i C_i)(T_{ngh} - T_{on}) > 0 \tag{29}$$

If the MCMAX < Q_{NVL}, then the cooling degree hours (CDD) should be adjusted appropriately by f_2 (suggested 0.8) which is a coefficient for the heat transfer efficiency between the wall and the indoor air, and the degree to the night-time ventilation coupled with thermal mass. The NDD should be calculated as follows:

$$\text{NDD} = \frac{f_2\ \text{MCMAX}}{Q_{NVL}} \tag{30}$$

The second check is the comparison between Q_{NVL} and the cooling load of the building without night-time ventilation Q_{cm}, defined as:

$$Q_{cm} = 3600\ k\ \text{CDD}(T_b) \tag{31}$$

where

$$T_b = T_i - \frac{Q_s + Q_{in}}{k} \tag{32}$$

CDD(T_b) are the cooling degree hours on the hourly value of the balance temperature T_b for a day or a month respectively. Q_s means the critical part of solar "gains" absorbed by the building through transparent and opaque elements (W) and Q_{in} means the critical percentage of the internal gains (W). If the $Q_{cm} < Q_{NVL}$, then:

$$\text{NDD} = \frac{f_3\ Q_{cm}}{Q_{NVL}} \tag{33}$$

where f_3 is a coefficient calculated by the occupancy pattern, and the thermal mass of the building, expressing the cool energy stored in the building for the occupied period on the following day. For heavyweight buildings, f_3 can vary between 0.8 and 1 as a function of the occupancy pattern and for buildings occupied at least 10 hours per day (Baker, 1987).

Then the daily or monthly cooling load of the building with night-time ventilation Q_{cnv} can be calculated by:

$$Q_{cnv} = 3600\ k\ CDD(T_{bvn}) \tag{34}$$

where

$$T_{bvn} = T_i - \frac{Q_s + Q_{in} - Q_{NV}}{k} \tag{35}$$

$$\text{CDD}(T_{bvn}) = \sum (T_0 - T_{bvn}) S_j \quad \begin{cases} S_j = 1\ if \quad T_0 > T_{bvn} \\ S_j = 0\ if \quad T_0 \leqslant T_{bvn} \end{cases} \tag{36}$$

T_{bvn} and CDD(T_{bvn}) are the balance temperature and daily or monthly modified cooling degree hours for buildings with night-time ventilation respectively. According to the above building cooling load reduction contributed by night-time ventilation, the cooling load reduction efficiency f can be calculated as:

$$f = \frac{(Q_{cm} - Q_{cnv})}{Q_{cm}} \tag{37}$$

3.4 Thermal comfort improvement in daytime

3.4.1 Percentage outside the range

A straightforward and simple indicator named percentage outside the range (POR) was first put forward by ISO 7730 (ISO, 2005), which accumulated the percentage of occupied hours when the simulated or actual thermal comfort parameters (e.g. *PMV*, operative temperature T_{op}, dry resultant temperature T_{res}) exceeded the specified comfort range in corresponding standards (Carlucci & Pagliano, 2012).

$$POR = \frac{\sum_{t=1}^{Oh} (wf_i \cdot h_i)}{\sum_{t=1}^{Oh} h_i} \tag{38}$$

where wf_i is a weighting factor depending on the comfort range, h_i represents the occupied hours. POR can not only be applicable to Fanger or adaptive comfortable models, but also to CIBSE overheating criteria (G. J. CIBSE, 2002)(G. A. CIBSE, 2006). If the PMV, operative temperature T_{op} or dry resultant temperature T_{res} exceeds the corresponding comfort range, the wf_i would be 1, or the wf_i would be 0.

3.4.2 Degree-hours criterion

A simple way of overheating degree hours above 26□ (ODH 26) during the occupied period are often utilized to evaluate the thermal comfort of night-time ventilation (N. Artmann, Manz, & Heiselberg, 2008). A maximum 10% of working hours with an indoor operative temperature over 26□ is acceptable with respect to the German standard DIN 4108 (DIN V 4108-6, 2003).

Different with the POR, the degree-hours criterion (DhC) can be calculated by the time when the actual operative temperature surpasses the specified range during the occupied hours multiplied with a weighing factor.

$$DhC = \sum_{i=1}^{Oh} (wf_i \cdot h_i) \tag{39}$$

where weighting factor wf_i is a function of how many degrees the range has been exceeded and can be calculated by the difference between actual or calculated operative temperature T_{op} and the lower or upper limit $T_{op,limit}$ of a specified comfort range. If the comfort range is expressed in terms of PMV, the comfort operative temperature range has to be translated by making assumptions on clothing, metabolic activity, air velocity, relative humidity, etc.

3.4.3 Long-term percentage of dissatisfied

In case of compliance demonstration, a concise indicator is recommended to summarize the building performance in terms of thermal comfort. Previous studies identified the long-term percentage of dissatisfied (*LPD*) index as the optimal index to evaluate comfort conditions (Carlucci & Pagliano, 2013).

$$LPD(LD) = \frac{\sum_{t=1}^{T}\sum_{z=1}^{Z}\left(p_{z,t} \cdot LD_{z,t} \cdot h_t\right)}{\sum_{t=1}^{T}\sum_{z=1}^{Z}\left(p_{z,t} \cdot h_t\right)} \tag{40}$$

where t and T are the counter for time step and last progressive time step of the calculation period respectively, while z and Z are the counter and total number of zones respectively. $p_{z,t}$ is the zone occupation rate at a certain time step, $LD_{z,t}$ is the likelihood of dissatisfied inside a certain zone at a certain time step, and h_t is the duration of a calculation time step.

The Likelihood of dissatisfied (*LD*) means the severity of the deviations from a theoretical thermal comfort objective, given certain outdoor and indoor conditions at specified time and space location. According to different reference comfort model, the *LD* can be calculated as follows:

$$LD_{Adaptive}^{EN} = \frac{e^{0.4734 \cdot \Delta T_{op} - 2.607}}{1 + e^{0.4734 \cdot \Delta T_{op} - 2.607}} \tag{41}$$

$$LD_{Adaptive}^{ASHRAE} = ALD = \frac{e^{0.008 \cdot \Delta T_{op}^2 + 0.406 \cdot \Delta T_{op} - 3.050}}{1 + e^{0.008 \cdot \Delta T_{op}^2 + 0.406 \cdot \Delta T_{op} - 3.050}} \tag{42}$$

$$LD_{Fanger} = PPD = 100 - 95^{-0.03353 PMV^4 - 0.2179 PMV^2} \tag{43}$$

where ΔT is the absolute temperature difference between the indoor operative temperature and the optimal comfort temperature calculated accordingly to the European or ASHRAE adaptive model. In addition to the use of Fanger analytical model, the *LD* is equal to *PPD*.

3.4.4 Discomfort over-temperature time percentage and weighted discomfort temperature index

In order to evaluate the thermal performance of night-time ventilation in maintain acceptable temperature level inside the building, two discomfort indexes of discomfort over-temperature time percentage (DTP) and weighted discomfort temperature index (DI) are defined (Corgnati & Kindinis, 2007). The DTP index is percentage of discomfort time where the indoor temperature higher than the comfort temperature upper limit that is fixed at 28 □ during the occupancy period, while the DI index is the discomfort weighted on the distance of calculated operative temperature from the acceptable temperature interval, can be defined as follows:

$$\mathrm{DI}=\sum w_i(T_i - T_{comf,\sup}) \tag{44}$$

$$w_i=(T_i - T_{comf,\sup}) \tag{45}$$

$$\mathrm{DI}=\sum (T_i - T_{comf,\sup})^2 \tag{46}$$

where w_i is the weight factor, T_i is the indoor air temperature, and $T_{comf,sup}$ means the upper comfort temperature limit. The two indicators integrated with the indoor air temperature profiles and the frequency distributions are appropriate tool to evaluate the performance of night-time ventilation.

4 DISCUSSIONS

Table 1 shows a graphical summary of the applicable conditions of the aforementioned indicators. Some indicators are more suitable for the simulation analysis, because they can be easily calculated by post processing outcomes of building energy simulation runs of a reference scenario (e.g. mechanically cooled building) and a ventilative cooling scenario (e.g. natural night cooling and daytime mechanical cooling). Therefore, it is particularly suitable to compare different design scenarios and drive design decisions. Whereas, other indicators are more suitable for the experiment analysis, since some data is easier to obtain in the field studies. In addition to experiment studies, thermal comfort improvement indicators are much more prevalent than energy efficiency indicators, probably because the indoor condition data is easier to obtain than energy data which is a challenge to be directly measured (A. Landsman, 2016). The rest of the indicators are both applicable in field and simulation studies, which are widely used in the assessment of night ventilative cooling.

Table 1: Summary of applicable conditions for each indicator

Family of indices	Indicator name	Simulation	Experiment
Heat removal effectiveness	Heat removal efficiency	√	
	Ventilation effectiveness for heat removal	√	
	Temperature efficiency		√
	Temperature difference ratio	√	√
	Decrement factor and daily time lag	√	√
Energy efficiency	Coefficient of performance	√	
	Potential energy efficiency index	√	
	Daily average cooling efficiency	√	
	Ventilative cooling seasonal energy efficiency ratio	√	
	Ventilative cooling advantage	√	
	Cooling effectiveness factor		√
	Life cycle efficiency ratio	√	
Reduction in cooling energy use	Cooling requirements reduction	√	
	Cooling load reduction efficiency	√	
Thermal comfort improvement in daytime	Percentage outside the range	√	√
	Degree-hours criterion	√	√
	Long-term percentage of dissatisfied	√	√
	Discomfort over-temperature time percentage and weighted discomfort temperature index	√	√

5 CONCLUSIONS

A set of performance indicators for night ventilative cooling is summarized to see the different definitions of effectiveness or efficiency of night-time ventilation and their influence on operation and performance. The heat storage efficiency of thermal mass and climatic cooling potential determines the ability of night cooling ability to a great extent. The performance indicators of night ventilation can be sorted into four categories: heat removal efficiency, energy efficiency, reduction in cooling energy use, and thermal comfort improvement. According to the application conditions of the night ventilation systems, appropriate performance indicators should be chosen in order to evaluate design goals and to provide means for the measurement or simulation of the progress of the design towards those goals. It should be noted that the performance of night ventilation could not be represented well by a single indicator, because it needs a combination of different types of indicators.

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