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The alternate operation control strategy between natural ventilation and air-conditioning considering delay time

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Abstract

Most research in the field of indoor thermal environment control has been devoted to the search for an appropriate on/off temperature of air-conditioning while relatively ignoring the energy-saving effect of the transition period length after air-conditioning turned off. We proposed a control model for the alternate operation between natural ventilation and air-conditioning to measure the delay time of natural ventilation after air-conditioning turned off. We compared the energy consumption of two cooling modes (continuous cooling and alternative operation between natural ventilation and air-conditioning) in different thermal capacity buildings in China's hot summer and warm winter areas. Furthermore, we obtain the delay time of natural ventilation under different thermal capacity buildings. The results indicate that buildings with more thermal capacity have a greater delay time of natural ventilation. Alternative operation strategy can save at least 15% energy consumption compared with continuous air-conditioning cooling. The results are helpful to guide residents to adjust their use habits of air-conditioning according to the delay time of natural ventilation and to alleviate the pressure of air conditioning energy consumption in hot summer and warm winter areas in China.

Introduction

Air-conditioning systems are widely used in hot and humid areas. The high energy consumption of air-conditioning has brought pressure to local energy management and economic burden to users. From the perspective of air-conditioning system operation management, the alternative operation of natural ventilation and air-conditioning system according to the thermal adaptation characteristics of residents is one of the effective ways to solve the problem of high air-conditioning energy consumption in summer (Zhou et al. 2008; Kolokotroni et al. 2001; Ayata et al. 2007).

Many scholars have conducted extensive research on the switching operation control between air-conditioning and natural ventilation, especially on the control index. Homod et al. used Predicted Mean Vote (PMV) as an indicator for switching operation of natural ventilation and air-conditioning (Homod, Sahari, and Almurib 2014). The results show that the method can save 31% of the total energy consumption compared with the typical air conditioning system with a setpoint temperature of 26°C. The PMV model predicts human thermal comfort well in air-conditioned buildings, but is found to underestimate the upper thermal comfort limit of humans in mixed-mode buildings. The theory of human thermal adaptation takes into account the behavioural interaction between humans and the environment, has better interpretation and prediction capabilities for human thermal sensation in mixed-mode buildings, and may be more suitable as a criterion for switching control between air-conditioning and natural ventilation. Sorgato et al. designed an automatic ventilation system using the upper comfort temperature of the thermal adaptation criterion in ASHRAE 55 standard as an indicator for switching between natural ventilation and air-conditioning systems (Sorgato, Melo, and Lamberts 2016). The results show that residential buildings with automatic ventilation control technology had the most comfortable time and the least annual air-conditioning energy consumption compared with night ventilation and morning and evening ventilation systems. Zhang et al. developed a combined control system for windows, fans, and air-conditionings based on the thermal acceptable range of people under adaptive behaviours such as opening windows and adjusting fans (Zhang et al. 2017). The results show the incidence of sick building syndrome was reduced by 40% and the average daily energy consumption of indoor air-conditionings was reduced by more than 30% compared with typical air-conditioning control. In the above studies, the indoor and outdoor air temperatures in accordance with the thermal adaptation theory were chosen as the markers for turning on natural ventilation. However, the generation of adaptive behaviours is driven by indoor comfort and all thermal environmental factors that affect it. Therefore, the operation criteria for switching between air-conditioning and natural ventilation should choose the index that can reflect the thermal environment factors comprehensively, not only the air temperature. In addition, most researches in the field of indoor thermal environment control were devoted to finding the appropriate on/off temperature of air-conditionings, while relatively ignoring the energy-saving effect during the transition period between air-conditioning and natural ventilation.

Therefore, we proposed an alternative operation control of natural ventilation and air-conditioning system based on the indoor and outdoor wet-bulb globe temperature (WBGT) difference, and measured the delay time before switching natural ventilation after the air-conditioning was turned off in buildings with different thermal capacities. The results are expected to provide theoretical reference for indoor thermal environment control in hot and humid areas, and help guide residents to adjust their air-conditioning habits according to the delay time of natural ventilation, so as to alleviate the pressure of air-conditioning energy consumption in hot summer and warm winter areas in China.

Methods

Determination of control indicators

From July to August 2016, we conducted a thermal comfort survey of residents in a natural ventilation environment in Qionghai, China. Qionghai is located in China's hot summer and warm winter region, the annual average temperature of 23-26 ℃, annual average relative humidity of more than 80% (Yu et al. 2019). We obtained a total of 156 valid questionnaires. Males and females accounted for 56.4% and 43.6% of the total number of subjects, respectively. The air temperature, relative humidity, globe temperature, and air velocity around the subjects were measured during the survey. The measurement equipment and specifications are shown in Table 1.

During the survey, most of the subjects were performing light activities such as sitting and chatting, and the subjects' behavioural regulation was not restricted. The paper-based questionnaire was administered to residents on their thermal comfort status during the survey. The questionnaire contained the residents' health status, activity level, clothing, and thermal acceptability vote. The questionnaire used an intermittent scale for thermal acceptability assessment (Zhang and Zhao 2008; Gunnarsen and Fanger 1992), as shown in Figure 1.

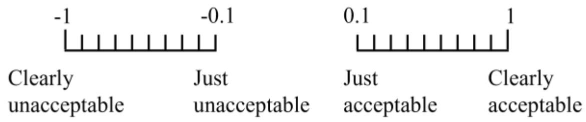

Figure 1: Thermal acceptability scale.

WBGT is a comprehensive evaluation index of thermal stress that covers thermal environment factors such as temperature, humidity, radiation, and wind speed (Institution 1982). Compared to the PMV index used as a control index, WBGT can overcome the limitation of considering the effect of outdoor solar radiation, therefore WBGT is recommended for indoor and outdoor comfort analysis (Mirzabeigi et al. 2021). In this investigation, we use WBGT to determine human thermal comfort conditions in a naturally ventilated environment. The calculation method is shown in Equations 1-4 (Lemke et al. 2012; Carter et al. 2020).

$$WBGT_{od} = 0.7T_{nwb} + 0.2T_g + 0.1T_a \quad (1)$$

$$WBGT_{id} = 0.67T_{pwb} + 0.33T_a \quad (2)$$

$$T_g - T_a < 4,\ T_{nwb} = T_a - C(T_a - T_{pwb}) \quad (3)$$

$$T_g - T_a \geq 4,\ T_{nwb} = T_{pwb} + 0.25(T_g - T_a) + e \quad (4)$$

Where,

$WBGT_{od}$ is WBGT in the outdoor environment, ℃;

$WBGT_{id}$ is WBGT in the indoor environment, ℃;

T_{pwb} is the wet bulb temperature, ℃;

T_g is the globe temperature, ℃;

T_a is the air temperature, ℃;

T_{nwb} is the natural wet bulb temperature, ℃, which can be calculated by T_{pwb}, T_g, and T_a, as shown in Equations 3-4.

Table 1: The measurement equipment and specifications.

Measurement-Parameter	Type	Images	Specification	Time-interval
Ambient temperature and relative humidity	Thermo Recorder TR-72wf		Accuracy: ±0.3 °C, 75% Resolution: 0.11 °C, ±5% Range:0–50 °C, 10–95%	1 min interval
Globe temperature	HWZY-1		Accuracy: ±0.3 °C Resolution: 0.1 °C Range: -50°C ~100 °C	1 min interval
Ambient air velocity	Testo 425		Accuracy: ± (0.03 m/s+5% rdg) Resolution: 0.01 m/s Range: 0~+20 m/s	1 min interval

C and *e* are constants related to the wind speed *V*, the selection methods are shown in Tables 2 and 3, respectively.

Table 2: The selection of coefficient C.

V(m/s)	<0.03m/s	0.03~3m/s	>3m/s
C	0.85	$0.96+0.069\log_{10}V$	1

Table 3: The selection of constant e.

V(m/s)	<0.1m/s	0.1~1m/s	>1m/s
e	1.1	$0.10/V^{1.1}-0.2$	-0.1

Thermal acceptability can show to some extent the satisfaction and tolerance of the population to the current thermal environment (Langevin, Wen, and Gurian 2013). A thermal acceptability of 80% of the population is recommended by ASHRAE 55 standard as the maximum acceptable limit for thermal environments, while a thermal acceptability of 90% of the population represents a more comfortable thermal environment at the present time (Standard 2017). Therefore, the regression relationship between thermal acceptability and WBGT can reflect the comprehensive evaluation of the population for the thermal environment and determine the comfort boundary of people for the thermal environment.

Subjects' acceptability in natural ventilation environment was regressed with WBGT at 1°C intervals (de Dear et al. 1994), as shown in Equation 5 and Figure 2. The coefficient of determination of the regression was 0.94. The acceptable WBGT range for 90% of the residents was 20.9-26.2 °C. The acceptable WBGT range for 80% of the residents was 19.9-27.3 °C.

$$TA=-733+70.7WBGT_{id}-1.5WBGT_{id}^{2} \quad (5)$$

Where,

TA is the percentage of population acceptable to current WBGT of indoor thermal environment, %.

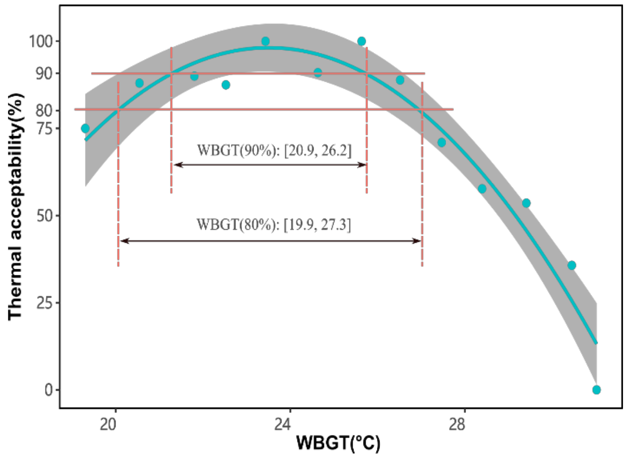

Figure 2: The acceptable WBGT range.

Alternate operation control logic of natural ventilation and air conditioning system

Figure 3 shows the control logic for switching between natural ventilation and air-conditioning. The control of air-conditioning and natural ventilation is determined by the resident's acceptable WBGT conditions. The outdoor temperature changes periodically, and there are rising and falling stages within a day. When the outdoor WBGT is higher than the indoor WBGT and the indoor temperature is higher than 80% of the upper thermal acceptable WBGT limit (27.3 °C), the air-conditioning is turned on. When the outdoor WBGT begins to decrease, considering that people's comfort zone will become narrower in an air-conditioned environment for a long time, we set the condition of turning off the air-conditioning as that the outdoor WBGT is lower than 90% of the upper thermal acceptable WBGT limit (26.2 °C). Natural ventilation will be turned on until the outdoor WBGT is lower than the indoor WBGT and not lower than 90% of the lower limit of thermal acceptable WBGT (20.9 °C). We defined the transition period between switching off the air-conditioning and turning on the natural ventilation as the delay time.

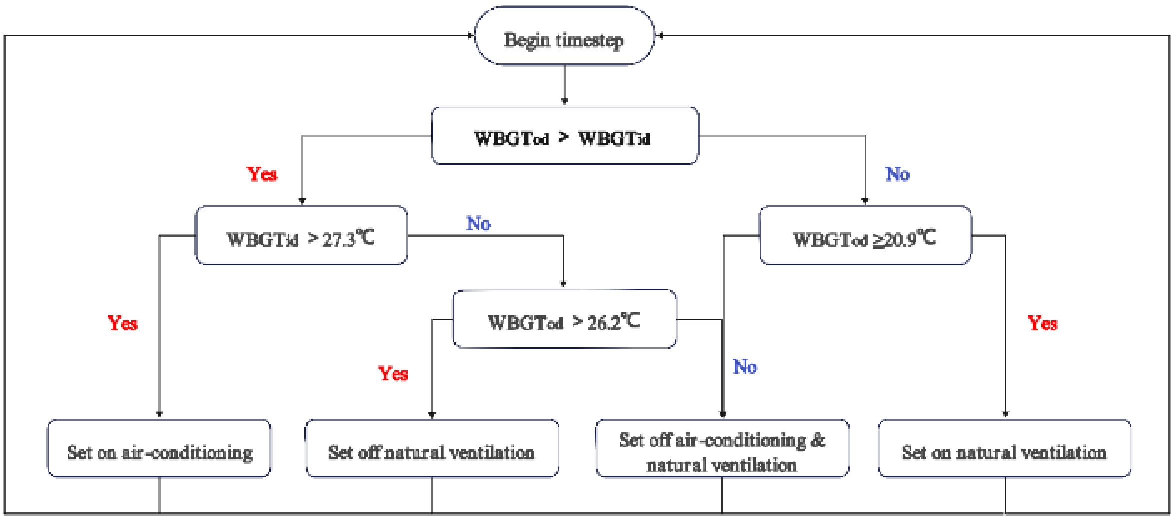

Figure 3: Alternate operation control logic of natural ventilation and air-conditioning system.

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Numerical simulation

The numerical simulation process is established by the EnergyPlus program (V9.0.1). A single house with an area of 130m^2 in the Qionghai, China was simulated. The house has two bedrooms, a living room, a kitchen, and a bathroom. The house plan is shown in Figure 4.

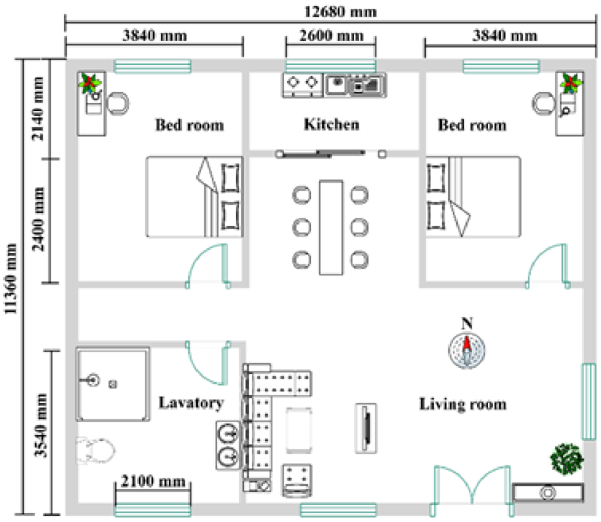

Figure 4: Floor plan.

The thermal performance of building envelope components was selected according to the typical building components of residential buildings in Qionghai (Development 2012). We simulated two building envelope combinations with the same thermal transmittance and different thermal capacities, as shown in Table 4.

The human heat dissipation capacity was 80 W/ person; the lighting power of each room was 5 W/m^2; the equipment loads of the kitchen and living room was considered as 200 W respectively.

Considering that the split type air-conditioning is more common in single houses, the air conditioning system was modelled as a Packaged Terminal Heat Pump (PTHP) system. The cooling coefficient of performance (COP) was set as 3.4 W/W.

This study focuses on the energy efficiency of alternate operation control logic of natural ventilation and air-conditioning system in buildings with different thermal capacities and compares it with the energy consumption of typical air-conditioning behaviours of residents in hot summer and warm winter regions of China. According to the field study, considering the continuous presence of people in the building, the typical air-conditioning operation mode was set to keep the air- conditioning on from 10 a.m. to 5 a.m. the next day. The alternate operation control logic of natural ventilation and air-conditioning system was coded and executed by the Energy Management System (EMS) module in Energy plus according to Figure 3. The cooling setpoint temperature for both scenarios were set as 26°C.

Results and discussion

The simulation of indoor and outdoor WBGT under different operation modes was carried out on a typical meteorological day, July 18th. Figure 5 shows the simulation results of indoor WBGT of the east bed room under typical air conditioning operation when the building envelope is type 1. In the typical air-conditioning operation mode, the indoor WBGT was in the acceptable range of 80% for people. The outdoor WBGT was within 90% of the acceptable range between 0 a.m.-8 a.m. and 8 p.m.-12 p.m., which indicates that people have the opportunity to obtain comfort through natural ventilation. The typical air-conditioning operation mode provided "excessive" comfort for a long period, depriving people of the opportunity to actively adapt to the thermal environment and expand their comfort zones and causing unnecessary energy waste.

Table 4: Thermal parameters of building envelope.

Exterior wall	**Thermal transmittance U (W/(m^2·K))**	**Thermal capacity Kappa (kJ/m^2·K)**	Roof	**Thermal transmittance U (W/(m^2·K))**	**Thermal capacity Kappa (kJ/m^2·K)**
Type 1: gypsum + insulation+concrete+cement mortar	2.19	13	Materials: plaster+reinforced concrete+lightweight aggregate concrete+extruded polystyrene board+fine aggregate concrete+cement mortar	0.5	170
Type 2: clay wall + air cavity +cement mortar	2.19	155			

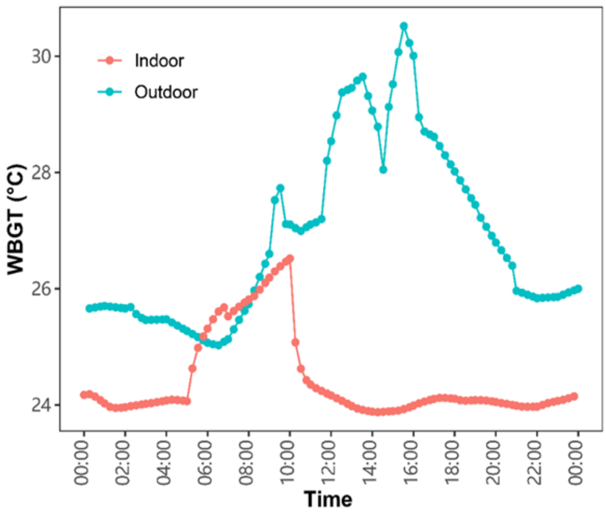

Figure 5: The indoor WBGT under typical air-conditioning operation. Outdoor conditions are also presented.

Figures 6 and 7 show the simulation results of indoor WBGT of the east bed room under alternate operation of natural ventilation and air-conditioning for building type 1 and type 2, respectively.

The indoor WBGT was always within 90% of people's thermal acceptable range from 0 a.m. to 8 a.m. when the natural ventilation was maintained in the room. The air-conditioning cooling under the low thermal capacity building lasted for 7 hours starting from about 2 p.m. In contrast, the air-conditioning cooling in the high thermal capacity building started almost one hour earlier.

After the air conditioner was turned off, the cooling stored in the envelope was gradually dissipated into the indoor environment. When the outdoor WBGT was higher than the indoor WBGT, indoor heat began to accumulate and the indoor WBGT gradually increases because the heat transferred from the outdoors to the indoors was greater than the cooling released from the envelope.

The outdoor temperature continued to drop over time until the difference between indoor and outdoor WBGT was zero, and natural ventilation was carried out. The delay time was 60 minutes for the low thermal capacity building, while it was 96 minutes for the high thermal capacity building. It is because the high thermal capacity buildings exhibit a stronger heat and cooling storage capacity compared to the low thermal capacity buildings. In addition, the delay in natural ventilation effectively extended the time for the bedroom to meet 90% of the thermal acceptability, and also avoided thermal discomfort such as thermal shock caused by opening windows immediately after cooling.

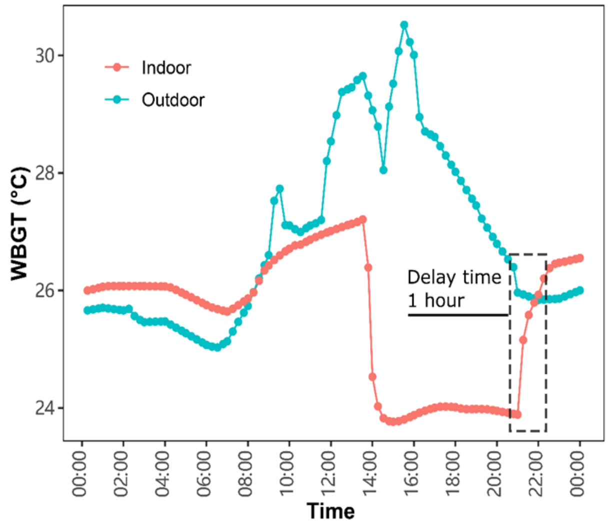

Figure 6: Indoor WBGT under alternate operation of natural ventilation and air-conditioning for building type 1 (low thermal capacity). Outdoor conditions are also presented.

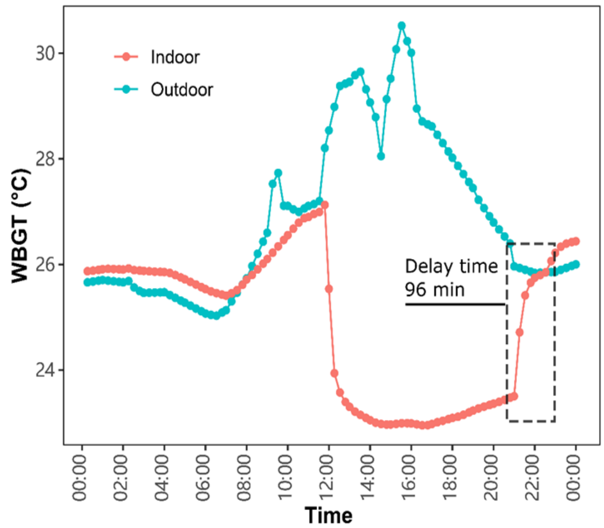

Figure 7: Indoor WBGT under alternate operation of natural ventilation and air-conditioning for building type 2 (high thermal capacity). Outdoor conditions are also presented.

Figure 8 shows the average daily air-conditioning cooling consumption per unit area. Compared to the use of typical air-conditioning behaviours, the energy savings in buildings with high thermal capacity applying the alternate operation control logic of natural ventilation and air-conditioning system are higher than those of buildings with low thermal capacity. The air-conditioning energy consumption of the new mode in the high and low thermal capacity buildings was reduced by 22% and 15%, respectively. It shows that alternate operation control logic of natural ventilation and air-conditioning system helps to relieve the pressure of air-conditioning energy consumption in hot summer and warm winter areas of China, as a preferred alternative to typical air-conditioning behaviour.

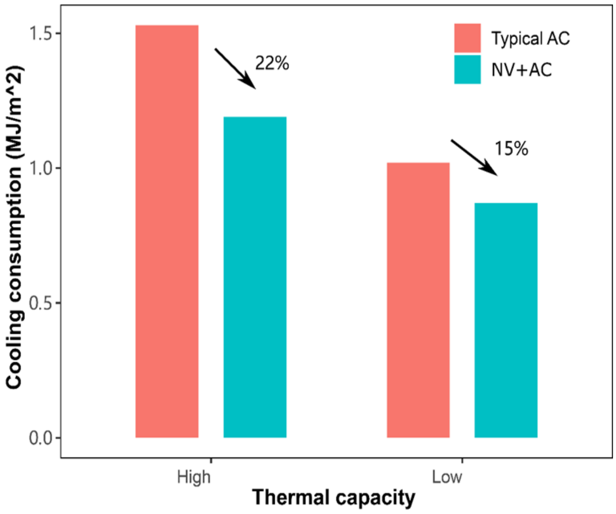

Figure 8: The average daily air-conditioning cooling consumption per unit area.

In summary, the recommendation for air-conditioning behaviour for high transmittance building users is to turn on the air-conditioning between 12a.m.-2p.m. and turn it off between 9 p.m. -10 p.m., then keep the windows closed for 1-1.5 hours to ensure thermal comfort and save energy. The current control logic is based on the continuous occupancy of the building by people. In the future, the influence of people's behaviour can be added to the control logic to provide more accurate air-conditioning behaviour recommendations.

In addition, we found that although high thermal capacity buildings have an advantage in delay time, the higher heat storage capacity led to earlier air-conditioning turn-on compared to low thermal capacity buildings and increased air-conditioning energy consumption.

Further exploration is still needed for the energy saving effect of alternating natural ventilation and air-conditioning operation logic in buildings with different thermal characteristics.

Conclusion

In this paper, we proposed an alternate operation control of natural ventilation and air-conditioning system using the difference between indoor and outdoor wet-bulb globe temperature (WBGT) as an indicator, and estimated the air-conditioning energy consumption and natural ventilation delay time of buildings with different thermal capacities under the new operation strategy. The conclusions are as follows:

(1) The switching operation logic of natural ventilation and air-conditioning was determined by the 80% and 90% thermal acceptable WBGT, which is consistent with the human thermal adaptation and takes into account the impact of an integrated thermal environment.

(2) Alternate operation of natural ventilation and air-conditioning can save at least 15% of cooling consumption compared to typical air-conditioning operation. The delay time after air-conditioning shutdown until natural ventilation starts were 60 minutes for the low thermal capacity building and 96 minutes for the high thermal capacity building.

(3) The recommendation for air-conditioning behaviour for high transmittance building users in hot and humid areas is to turn on the air-conditioning between 12a.m.-2p.m. and turn it off between 9 p.m. -10p.m., then keep the windows closed for 1-1.5 hours to ensure thermal comfort and save energy.

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