Impact of passive measures on indoor thermal environment and energy consumption under various operating modes of HVAC equipment

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Abstract. Based on the characteristics of climatic conditions and intermittent energy use in the hot summer and cold winter regions, this paper takes a simplified residential building in Chongqing as an example, use DesignBuilder to simulate and explore the influence of passive methods on the indoor thermal environment and energy consumption of buildings. To make the cooling method used more in line with the actual situation of the residents, this research uses the passive cooling technology such as sunshades and ventilation, and combine them with the intermittent operated air conditioner to achieve a comfortable condition in the room. Under the thermal parameters of the building envelopes were set according to the current 65% energy-saving standards, the results show that the sunshade combined with the intermittent ventilation can extend the non-air-conditioning period of 2041 hours. The building energy consumption of the method combined intermittent air conditioner with sunshade and intermittent ventilation is 22.2 Kwh/m², which is 56.5% lower than the continuous air conditioner operation.

1. Introduction

Since the 18th National Congress of China, the growth rate of total building energy consumption has slowed down, and the average annual growth rate has dropped to 5%, which clearly shows that existing building energy-saving measures have an important potency. However, with the extensive application of equipment such as HVAC [1], the energy consumption of building air conditioning and ventilation systems still accounts for more than 85% of the total energy consumption of the building [2]. Therefore, the way to further tap the energy saving potential and reduce the energy consumption of building air conditioning and ventilation systems is essential to reduce building energy consumption.

According to the existing literature, the ventilation of windows can also achieve a more comfortable thermal environment of indoor in the hot summer and cold winter region, and the residents of southern China have always had the habit of window ventilation in summer [3-4]. In the actual operation of the buildings, the use of the air conditioning is always combined with natural ventilation, which is significantly different from the continuous operation of the air conditioning defined by the current standard for energy efficiency of buildings [5]. Moreover, the intermittent operation of the air conditioning also results in an unsteady-state of the indoor temperature, which is also different from the steady-state condition in which the standard is specified to be constant at 26 °C in summer. Natural ventilation, especially the night ventilation, is a typical passive measure which can effectively reduce indoor temperature and extend non-air conditioning time which can further reduce air conditioning...
energy consumption. This passive measure combined with intermittent air conditioning is also considered to be the core of the design of the climate-adapted energy-efficient buildings [6]. In most of the existing research, however, the passive measures are independent of intermittent air conditioning. The research on intermittent air conditioning is mostly based on the energy consumption systems of air conditioning. For example, the schedule of the operation, the operation temperature of air-conditioning [7-9]. And the study of passive measures always revolves around natural ventilation and external shading [9]. The real use of residents combined passive measures with air conditioning was ignored.

In order to quantitatively analyze the energy saving potential of passive measures combined with the intermittent air conditioning, in this paper, the numerical simulation method was used, and selected typical urban dwellings in the hot summer and cold winter regions to explore the appropriate schedule and the energy saving efficiency of this measure.

2. Methods and Materials

The typical residential building in Shapingba District in Chongqing was selected, and the software of DesignBuilder was used to establish a model that based on the actual building. The indoor thermal environment and energy consumption of building under different combinations were simulated and analyzed.

2.1. Building model

The simulated building is a steel reinforced concrete board building with a standard floor plan as shown in figure 1. The building is oriented from north to south with a total of 5 floors, each with a height of 3.0m and a total construction area of 2210.0m². The building envelope structure meets the current energy-saving standards for residential buildings in Chongqing [16], and the thermal parameters of envelope structures are shown in table 1.

![Figure 1. The standard floor plan of the selected building.](image)

Table 1. Comparison of heat transfer coefficient(K) of the simulated building and those in standard.

| Building envelope | Normative standard W/(㎡•K) | Research object W/(㎡•K) |
|-------------------|-----------------------------|--------------------------|
| Roof              | K ≤0.6                      | 0.6                      |
| External wall     | K ≤0.8                      | 0.8                      |
| Internal wall     | K ≤2.0                      | 2.4                      |

| Window to wall ratio(WR) | Normative standard W/(㎡•K) | Building orientation | WR of Research object | K W/(㎡•K) |
|--------------------------|-----------------------------|----------------------|-----------------------|-----------|
| External window          | WR≤0.20                     | K ≤3.4               | East/West             | 0.12      |
|                          | 0.20<WR≤0.30                | K ≤3.2               | North                 | 0.29      |
|                          | 0.40<WR≤0.45                | K ≤2.5               | South                 | 0.43      |

Because the top-west household is the worst thermal environment and the most energy-intensive room, we select this household for later analysis (drew by the dotted line in Figure 1). The household consists of three bedrooms, two living rooms and two bathrooms, with a building area of 120.0 m².
2.2. Other simulation parameters
The typical meteorological data of Chongqing was selected. The air-conditioning running time is from June 1st to September 30th when the indoor overheating, and the heating running time is from December 1st to February 28th when the indoor is too cold. The indoor design temperature of the air conditioning is 26 °C, and the design temperature of the heating room is 18 °C. The thermal parameters of the envelope structures were set according to the actual building, and the ground temperature was set to the soil temperature of 0.5 m depth. The other heat obtained in the room was set to 4w/m², and the mechanical ventilation was 1ac/h.

2.3. Passive measures
In addition to the thermal insulation performance of the building envelopes, the passive measures affecting the indoor thermal environment and energy consumption of the building usually include natural ventilation, shading, and heat storage, and so forth [17]. In the hot summer and cold winter region, especially, the application of shading and ventilation is more extensive [18][19]. Ventilation is mainly used in the summer. And in the hot weather in summer, the outdoor temperature is low but the indoor temperature is high in some time. At this time, the ventilation through the opened window can meet the cooling requirements in the rooms. However, shading has different needs in winter and summer, so the use of dynamic shading is more beneficial for energy saving and indoor thermal comfort. This paper focuses on the effects of natural ventilation and shading on the thermal environment and energy consumption of buildings. The effects of natural ventilation and shading are expressed by the opening area ratio of the window (OR) and the solar transmittance of the window (ST), respectively, which are 10%, 15%, 20%, 30%, 50%, and 0.2, 0.3, 0.4, 0.5, 0.6.

2.4. Operation schedule
The purpose of this paper is to analyze the difference in indoor comfort and energy consumption of the buildings between intermittent operation mode and the current continuous operation mode defined by standard, and to compare the impact of different modes on energy consumption after combining passive measures. Therefore, the simulation conditions are divided into three models: non-operating equipment (only ventilation, shading or combination of them), intermittent operation and continuous operation conditions.

Under the intermittent operating conditions of the equipment, the indoor thermal environment evaluation standard uses the operative temperature as a reference parameter, so whether the equipment is operated or not is determined by the operative temperature. In addition, whether the window opening or not is determined by the difference between the operative temperature and the outdoor air temperature during the non-operating and intermittent operating conditions of the equipment. The "Evaluation standard for indoor thermal environment of civil buildings" (GB/T 50185-2012) [15] divides the thermal environment into three levels, and the first level is the best. It requires the indoor operative temperature of between 18 and 28°C in non-manual cold and heat sources in hot summer and cold winter region. Therefore, the operative temperature of 28°C as the tolerable upper limit temperature to resident, equipment operation and window opening schedule are shown in Table 2.

Table 2. Air conditioning operation and window ventilation temperature setting in three modes

| Operation Condition | Non-operation | Intermittent operation | Continuous operation |
|---------------------|---------------|------------------------|---------------------|
| **Cooling Dates**   |               |                        |                     |
| 6.1-9.30            | Temperature/Open Air conditioner | - | 
|                     | Temperature/Open Windows | top≤28°C and ti>to | top≤28°C |
|                     |                         | | top>28°C |
| **Heating Dates**   |               |                        |                     |
| 12.1-2.28           | Temperature/Open Air conditioner | - | ttop<18°C |
|                     | Temperature/Open Windows | - | - |

Note: top- operative temperature; to- outdoor air temperature; ti- indoor air temperature.
It can be seen from the table that when the equipment is not used in the summer and the indoor operative temperature is less than 28°C but higher than the outdoor air temperature, the window is opened for natural ventilation. Otherwise, the window is closed and there is no ventilation. In the intermittent operation mode, natural ventilation is preferred, that is, when the operative temperature is less than 28°C but higher than the outdoor air temperature, the window is opened; when the cooling of natural ventilation cannot make the operative temperature below 28°C, the air conditioning is started to operate. Otherwise, turn off the air conditioning. In continuous operation mode, when the indoor operative temperature is higher than 28°C, turn on the air conditioning, otherwise turn off, but do not open the window at any time. During the heating day, both the intermittent operation mode and the continuous operation mode do not open windows. When the operative temperature is lower than 18°C, turn on the air conditioner.

3. Results
After the building model was established, the outdoor climatic conditions of the building model were selected from the typical meteorological data of Chongqing, and the simulation was performed using DesignBuilder software. Then analyze the energy consumption and indoor thermal environment in the three modes.

3.1. Non-operating equipment
Figure 2 and Figure 3 show the operative temperature of each room in the household under the condition that the equipment is not in operation. It can be seen from figure 2 that during the heating calculation period in winter, the operative temperature is lower than 18°C. So, in order to make the indoor comfort, the heating equipment needs to be continuously operated. Figure 3 shows the operative temperature in the summer without air conditioning (window transmittance is 0.2, and window area ratio is 50%). It can be seen that the indoor operative temperature is higher than 28°C in only some periods when using shading and natural ventilation, and the hours below 28°C is about 73% of the total hours. Therefore, in the summer of Chongqing, the mode of intermittent operation of the air conditioning combined with passive measures is more adaptable to the local climate.

The relationship between the thermal environment in the master bedroom and ST and OR is shown in Figure 4. In the model of non-operating equipment, the cumulative hours of operative temperature above 28°C are positively correlated with ST, and inversely related to OR. When OR is less than 30%, the effect of ST(shading) is more significant. When the window opening area exceeds 30%, however, the cumulative uncomfortable hours does not change substantially when the transmittance is changed, which is stable at 800h-1000h; when ST is 0.4, the uncomfortable hours is reduced by about half as the OR increases from 10% to 30%. Obviously, increasing the opening area ratio of the windows is the most effective passive measure to improve the indoor thermal environment, and only when OR exceeds 37%, it is possible to achieve the best indoor environment (the uncomfortable hours <900h).
3.2. Intermittent operation conditions

From the previous analysis, it is necessary to use continuous heating to make the interior comfortable in winter, while in summer, no more than 27% of the time needs to be improved by air conditioning. According to the air conditioning operation schedule (Table 2), when the OR is 50%, the relationship between the different ST and the energy consumption of the rooms is shown in figure 5. It can be seen that the cooling energy consumption per unit area of the four rooms is positively correlated with ST, but different rooms are affected by the ST. The largest energy consumption is the west-facing bedroom, which is also more affected by ST than other rooms. It is obvious that the shading of the west-facing windows has a greater impact on the building energy consumption.

In the intermittent operation mode, ventilation is often used to reduce the indoor air temperature. When the ST is 0.2, the relationship between the OR and the energy consumption is shown in Figure 6. It can be seen from the energy consumption of the living room that, the draught is formed because the living room runs through the north and south, and the use of natural ventilation greatly reduces the frequency of use of the air conditioning, thereby reducing the cooling energy consumption. This shows that natural ventilation has a great impact on the cooling energy consumption of the rooms, and reasonable window opening can greatly reduce the building energy consumption.
3.3. Continuous operation conditions

In this mode, the windows are closed, and then the whole household is simulated for the whole year, and the relationship between ST and energy consumption is shown in Figure 8. The cooling energy consumption is positively correlated with ST, while the heating energy consumption is negatively correlated with ST. But ST has a more significant impact on cooling energy consumption. Therefore, the better the shading, the less the cooling energy consumption, yet the heating energy consumption is slightly increased.

![Figure 8. Energy consumption of buildings in different solar transmission ratios with continuous operation](image)

4. Conclusions

The use of reasonable passive cooling of buildings can greatly reduce the operation time of air conditioning and further reduce the energy consumption of the buildings. In addition, under the condition that the indoor thermal environment is always in the level I comfort zone, this paper simulates and compares the indoor cooling energy consumption of the heating and cooling equipment during continuous operation and intermittent operation. The effects of these two passive measures on building energy consumption are analyzed when the building is shaded and ventilated. The results show that the combination of shading and intermittent ventilation in summer can reduce the running time of air conditioners by 2041h, and when combined with these two passive technologies, the energy consumption per unit area of buildings can be reduced to 22.2Kwh/m².

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