E3S Web of Conferences **379**, 04003 (2023) https://doi.org/10.1051/e3sconf/202337904003
ICFEE 2023

Simulation of performance of five types of external windows: a case study in Chongqing, China

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Abstract. The efficiency of transparent envelopes must be improved in purpose of saving energy. The EnergyPlus software was used to examine the inside glass surface temperature and annual energy performance (AEP) of five different types of external windows, including built-in louvre ventilation windows (BLVW), built-in louvre hollow windows (BLHW), interior side louvre ventilation windows (ILVW), ventilation windows (VW), and regular hollow windows (HW), using office buildings in Chongqing as the target. The results demonstrate that the design of ventilation and louvres can reduce energy consumption of buildings, lower the room's radiant asymmetry, and raise occupant thermal comfort. During the cooling season, built-in louvre ventilation windows and hollow windows for rooms facing south are the best window operation options. During the heating season, ventilation windows are the best option. In four orientations of north, east, south, and west, respectively, the overall building energy efficiency rate of the optimal operation mode compared to typical hollow windows is 5.87%, 5.70%, 2.80%, and 5.74%. This will serve as a guide for the building design of energy-efficient windows and the mode of the windows' year-round functioning in Chongqing.

1 Introduction

Windows are a vital element in buildings that have significant effects on energy consumption as well as on occupants' thermal sensations. Windows account for 10% of the total building energy consumption [1]. Besides, direct exposure to transmitted solar irradiation frequently causes heat discomfort near windows.

Thermal conduction and solar radiation through the glass make up most of the heat that is sent into a space through transparent envelops [2]. In order to deal with these two heat

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transfer paths, many scholars have proposed a few solutions by ventilation trough the cavity of windows. Some researchers have used double glazing with moving air in recent years to meet the goal of thermal insulation [3]. According to Pei Gang et al. [4], installing ventilation windows in areas with subtropical climates can dramatically lower the amount of energy consumed for air conditioning. As shown by Khalvati F et al. [5], rooms with ventilation windows can reduce interior heat gain by 16.6% on average in Iran's hot season when compared to hollow windows. According to Carlos et al. [6], ventilation windows can efficiently warm indoor air in the winter. On the other hand, Huang Qiming et al. [7] and He Wei et al. [8] discovered that the ventilation window's low transmittance efficiently prevents interior heat gain in summer, but hinders winter solar heat gain. According to Wang Chunlei et al. [9], increasing the transmittance of photovoltaic windows increases solar heat gain and decrease power generation while improving indoor illumination and reducing lighting energy use.

Numerous studies have been done on the static performance of windows, but they failed to consider different working situations or flexible adjustment. Therefore, improving dynamic adjustability to windows and developing sensible operation control systems can help to further cut down on building energy use. Luo Dana et al. [10] investigated the effect of changing the angle of the built-in louver on the window's thermal performance. To reduce energy consumption, the shutters are set to 90 degrees during the summer and 0 degrees during the winter. By analyzing the energy consumption of three different ventilation modes—natural ventilation, hot pressure ventilation, and no ventilation—Zhao Chuan et al. [11] dynamically changed the angle of the solar louver and suggested the optimal monthly operation mode. A photovoltaic exterior window construction with reversible rotating ventilation was suggested by Etzion Y et al [3]. It is advised to switch to the internal circulation ventilation mode in the winter to lower heating demand and to the external circulation ventilation mode in the summer to reduce interior heat gain. Peng et al. [12] set switches to modify the working mode of the ventilation window. External circulation ventilation is used to reduce summertime heat gain in buildings. Closed ventilation is utilized in the winter to prevent heat loss from buildings.

Some study has been conducted on the dynamic performance of windows, but little is known about energy-efficient windows that combine louvers and ventilation in hot summer and cold winter zone of China. The following windows are combined with ventilation function or louvre shading: ventilation window, interior louvre ventilation window, built-in louvre ventilation window, built-in louvre hollow window. The structural design and annual operation mode of energy-saving windows suitable for Chongqing are suggested by contrasting the four types of windows mentioned above with regular hollow windows typically used in existing structures in Chongqing. The result and methodology from case study can be applied to other projects to improve energy efficiency in both existing and newly constructed building in the future.

2 Methodology

The research subject comprises five distinct types of office building outside windows. This work applies computer simulation to examine the interior glass surface temperature, heating/cooling energy consumption, AEP, and other indications of five distinct types of external windows. EnergyPlus, which was developed by the U.S. Department of Energy and Lawrence Berkeley National Lab, is used in this study to calculate the cooling and heating loads of buildings, as well as their annual dynamic energy consumption, and to output a variety of detailed data to meet the requirements of this study.

The basic window type comprises of ventilation windows and hollow windows to which blinds devices are added to make energy-efficient windows. Four vents are located at the top

 https://doi.org/10.1051/e3sconf/202337904003

and bottom of the room's interior and exterior sides, respectively, on the ventilation window. Depending on the weather and fresh air intake, the vents can be opened and closed manually or automatically. Depending on how the vent is opened, four types of ventilation can be created: exhaust, air supply, internal circulation, and outside circulation [13]. Under the current prevalent form of air conditioning system with fresh air system [4], the ventilation window typically employs the exhaust type with the highest energy-saving impact. When the air conditioner is activated, the internal air will be under positive pressure and will be forced out via the ventilation window's cavity. As a result, the ventilation windows on the paper are of the exhaust variety.

The building model is a residential and commercial office complex in Chongqing. The room has a floor height of 3 meters. Figure 1 depicts the building's floor plan. In this work, Room 1 serves as the experimental subject for examination. Its north-facing window is 1.2 meters by 1.5 meters and has a window wall ratio of 0.154.

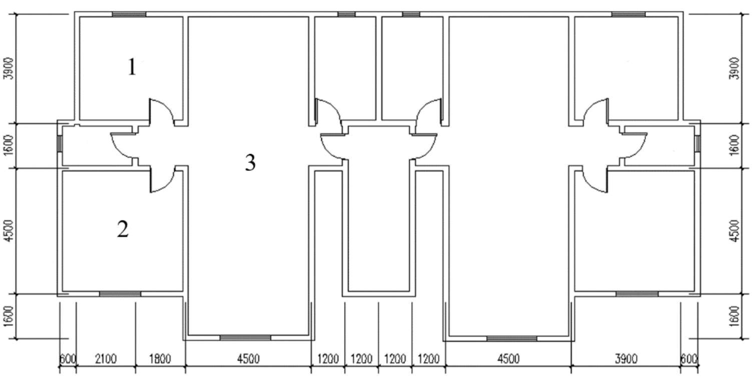


Fig. 1. Structure plan

Indoor air is intended to be 26 °C in the summer and 20 °C in the winter. 4 m^2/person is the population density, 8 W/m^2 is the lighting density, 15 W/m^2 is the equipment power density, and 30 m^3/ (h · person) is the fresh air volume. The ventilation window's vent opens at the same time as the fresh air system because it uses the exhaust air that is released to the outside when the fresh air system opens. On working days, the ventilation window is open from 8:00 to 18:00, while it is closed on rest days.

The external window frame is built of bridge cutoff aluminum alloy; the glass is made of regular white glass and uses the 6+40A+6 combination; the louver is the default louver from EP software. Table 1 and Table 2 present the structure and optical properties.

Table 1. Window glass optical characteristics.

Glass parameter	Value
Thermal conductivity (W/m · K)	0.9
Solar transmittance	0.775
Visible light transmittance	0.881
Visible light reflectance	0.08
Visible light absorption	0.039
Infrared emissivity	0.84

Table 2. Louver structure and optical characteristics.

Louver parameter	Value
Thickness (mm)	1
Width (mm)	25
Angle (°)	45
Thermal conductivity (W/m · K)	0.1
Solar reflectivity	0.7
Solar transmittance	0
Visible light reflectivity	0.5
Infrared emissivity	0.9

3 Results and discussion

Room 1 is the object in this section. The improvement of the energy-saving effect is demonstrated by comparing the inside glass surface temperature, the heating/cooling energy consumption, and AEP of five different types of windows from 8:00 to 18:00 on the design day in summer and winter (the "design day" in this article is different from the common air conditioning design day, which is the day when the maximum cold and heat loads occur during the simulation period, typically July 21 and January 21).

3.1 Inner glass surface temperature

The inner glass of the double glass window has direct convection with the inside air during the process of heat transfer from the outer environment to the indoor environment. The surface temperature of the inner glass acts as the interior surface of the envelopes, affecting the human body's apparent temperature in addition to the indoor load. The performance of different windows can therefore be intuitively assessed by using the inner glass surface temperature as the assessment index. In Figure 2, it's shown that the process of the inner glass surface temperature change of various windows on the design day in summer is shown.

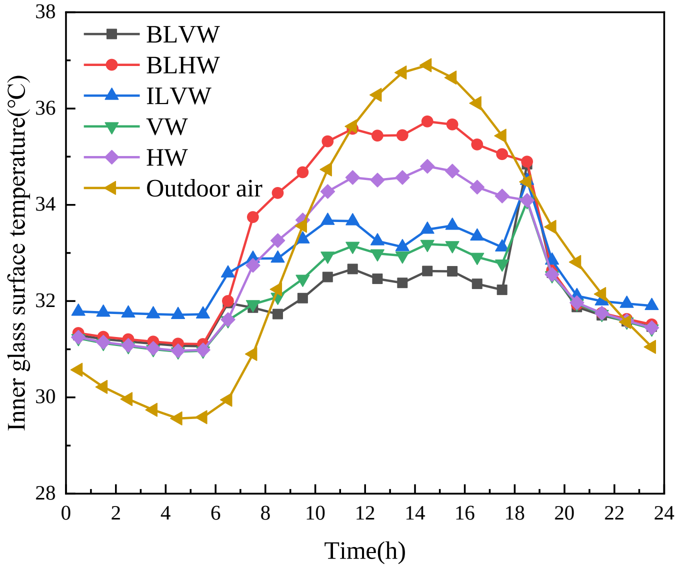


Fig. 2. Temperature change of inner glass surface on design day in summer

Taking the interior glass surface temperature on the design day in summer as the index, as shown in Figure 2, the average temperature of the interior glass surface with louver ventilation window is the lowest, 32.32 °C, while the average temperature of the interior glass surface with louver hollow window is the highest, 35.10 °C, and the maximum temperature difference of the interior glass surface is 2.78 °C during the service period of office buildings from 8:00 to 18:00. From high to low, the inside glass surface's average temperature is as follows: built-in louver hollow window>hollow window>indoor louver ventilation window>ventilation window>built-in louver ventilation window. The three windows with the lowest temperature have the function of ventilation, which indicates that the cavity ventilation between the double glazing has a significant cooling effect on the temperature of the inner glass surface. Second, the comparable temperatures for ventilation windows and hollow windows without louvers are 32.78 °C for the former and 34.15 °C for the latter, with a 1.47 °C difference between the two. The room's radiation asymmetry will be impacted by the temperature of the glass surface inside the window. The former can increase the thermal comfort of individuals working indoors in the summer because its surface temperature is lower.

The inner glass surface temperature of the built-in louver hollow window is higher than the inner glass surface temperature of the hollow window, apart from the three windows with ventilation function. This is because even if the louver prevents direct solar energy from entering the room, it nevertheless absorbs more solar radiation than the glass does. This means that with the addition of louver, the built-in louver hollow window's rate of solar radiation absorption rises above that of the hollow window. Due to a lack of ventilation, heat that has been absorbed from the sun builds up. As a result, the air inside the built-in louver's cavity is even hotter than the air inside the hollow window's cavity, causing the inner glass surface temperature of the former to be higher than that of the latter.

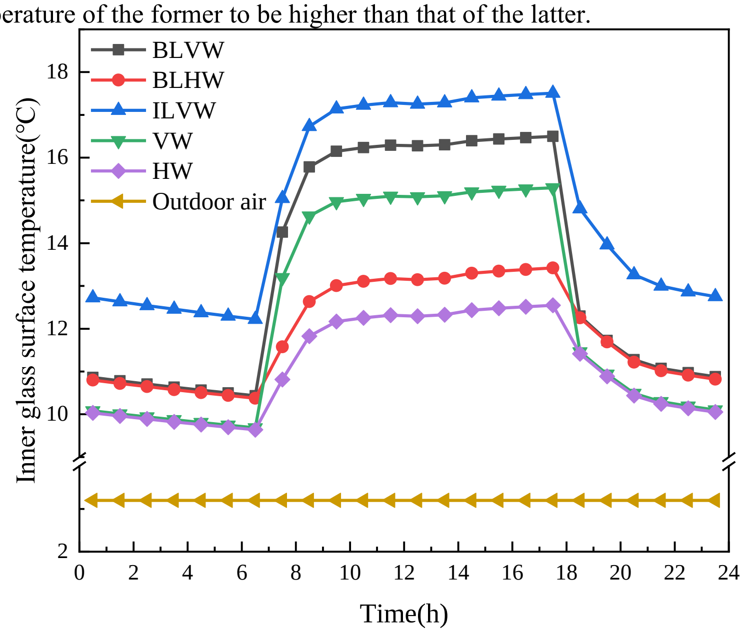


Fig. 3. Temperature change of inner glass surface on winter design day

Similarly, taking the temperature of the inner glass surface on the design day in winter as the index, as shown in Figure 3, the average temperature of the inner glass surface is sorted from high to low as follows: indoor louvered ventilation window>built-in louvered ventilation window>ventilation window>built-in louvered hollow window>hollow window. The three energy-saving windows with ventilation function still show good thermal insulation effect. The average temperature difference between the interior glass surface of the hollow window used in the existing building and the best performance energy-saving window is 4.89 °C, which will produce obvious radiation asymmetry on the room surface and have a negative impact on the thermal comfort of the room staff.

The louver with an integrated louver ventilation window, on the other hand, prevents heat transfer due to temperature differences by dividing the cavity, reducing convection, and increasing thermal resistance. Figure 4 illustrates the temperature changes of the inner and outer glass surfaces of the two windows. On the winter design day, the built-in louver ventilation window's outer glass surface is an average of 7.68 °C, its inner glass surface is an average of 16.10 °C, and the temperature difference is an 8.42 °C; the ventilation window's outer glass surface is an average of 8.12 °C, its inner glass surface is an average of 14.92 °C, and the temperature difference is 6.80 °C. As can be observed, the temperature difference of former is clearly bigger than the latter. This demonstrates that the louver plays a role in separating the ventilation cavity, decreasing the mutual disturbance of air in the cavities on both sides near the indoor side and outside of the room, weakening the process of outdoor cooling transfer to the indoor, and improving the thermal insulation performance of the built-in louver ventilation window.

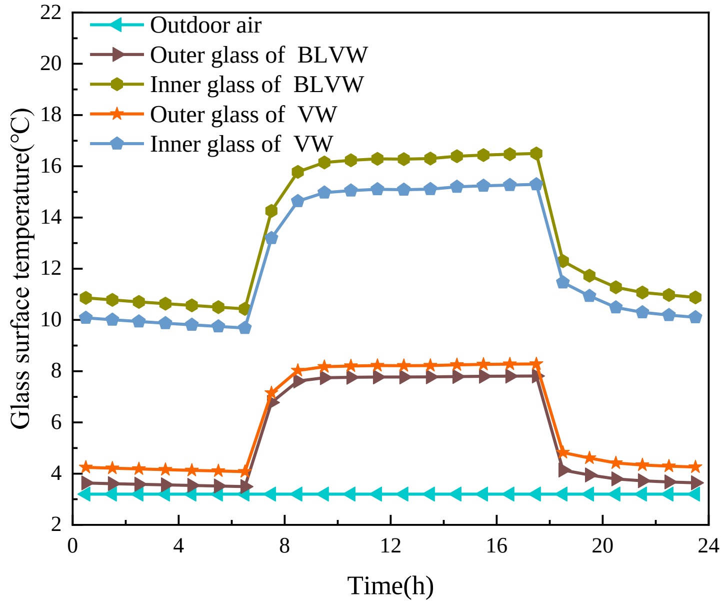


Fig. 4. Surface temperature change of inner and outer glass

3.2 Annual energy performance

The built-in louver ventilation window offers the greatest potential for energy savings on both summer and winter design days, according to the data presented above. However, as was already indicated, winter design days frequently have low outdoor temperatures and weak solar radiation, which obscures the disadvantage of louvers that block winter solar radiation. The above working conditions are relatively rare. The operation mode combination for the entire year's air conditioning season is determined in this part by comparing the heating and cooling energy consumption of room 1 with five windows. The annual energy efficiency index AEP is presented as a dimensionless parameter to analyze the effect of energy-saving windows on building air conditioning energy consumption and evaluate the energy efficiency of various energy-saving windows [14].

https://doi.org/10.1051/e3sconf/202337904003

$$AEP=\frac{E_{B-S}}{E_{B-A}} \quad (1)$$

$$E_{B-S}=E_B\text{-}E_S \quad (2)$$

$$E_{B-A}=E_B\text{-}E_A \quad (3)$$

Where: E_B is the annual air conditioning energy consumption when the benchmark window is arranged, kW·h; E_S is the annual energy consumption of air conditioning with energy-saving windows, kW·h; E_A is the annual air conditioning energy consumption when "thermal insulation" windows are arranged, kW·h; E_{B-S} is the reduced building energy consumption after the arrangement of energy-saving windows, kW·h; E_{B-A} refers to the increased building energy consumption due to windows, kW·h.

The benchmark window used in this example is a hollow window that is frequently found in existing buildings. The "thermal insulation" window is made of glass that performs exceptionally well in terms of thermal insulation, and its solar heat gain coefficient and transmission coefficient are both set to zero. With and without "thermal insulation" windows, a building's air conditioning uses roughly the same amount of energy.

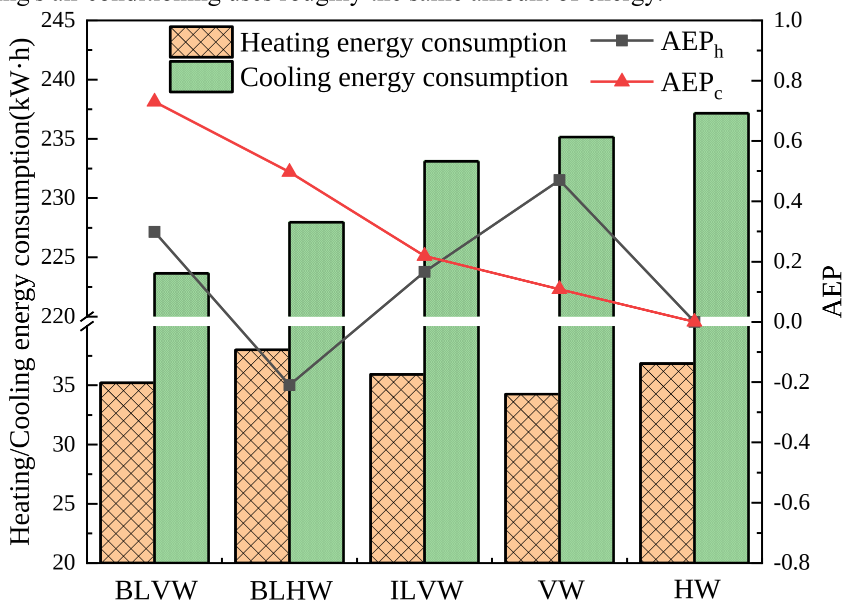


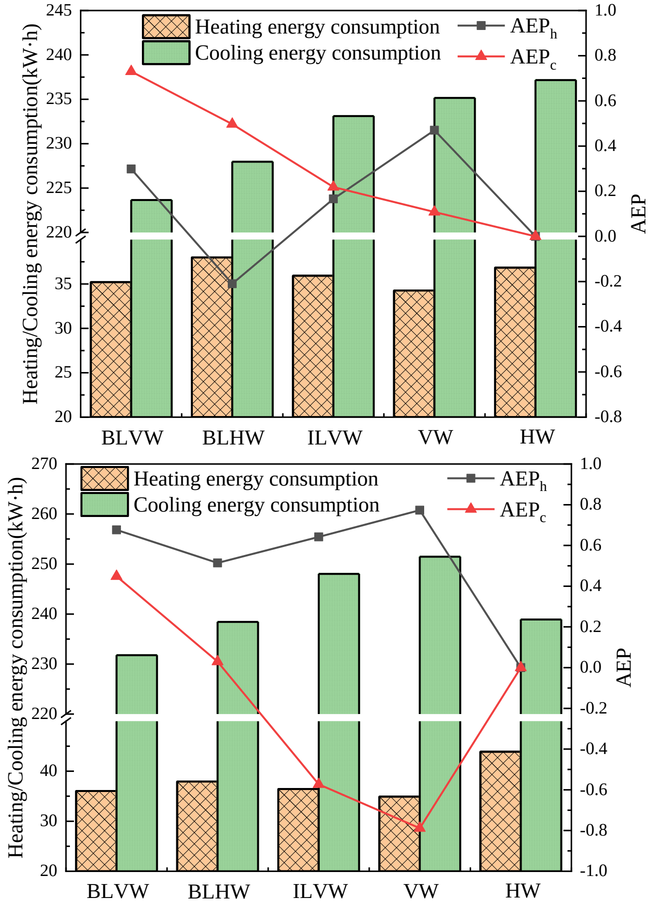
Fig. 5. Air conditioning energy consumption and AEP of rooms with five windows

The ventilation window has the best heating effect in winter, as can be seen in Figure 5. This is because the ventilation window does not use a shutter that can block solar radiation, allowing the maximum amount of solar energy to enter the room. Additionally, the indoor exhaust air passes through the double-layer glass cavity to create a thermal insulation air curtain, preventing the entry of outdoor cooling, resulting in an AEP_h value as high as 0.47. With a maximum AEP_c value of 0.73, built-in louver ventilation windows perform best in the summer; hollow windows without ventilation and windows with a louver design have the lowest AEP_c values. Use ventilation windows during the heating season and built-in louver ventilation windows during the cold season for the optimal window operation. This offers further recommendations and direction for the design of windows, such as making the louver retractable or changeable in angle to be in an open position.

3.3 Effect of orientation on operation mode

The analysis of room 1 with different windows and the AEP for air conditioning is shown above, but only if the orientation is north. The four orientations of north, east, south, and west are chosen in order to investigate whether orientation influences window operating mode. Room 1 with different windows has its air conditioning energy consumption and AEP assessed, and the best operation mode is suggested.

Figure 6 shows the air conditioning energy consumption and AEP of room 1 facing north, east, south, and west. From this figure, the optimal operation mode of windows in winter and summer in Chongqing can be summarized, as shown in Table 3.



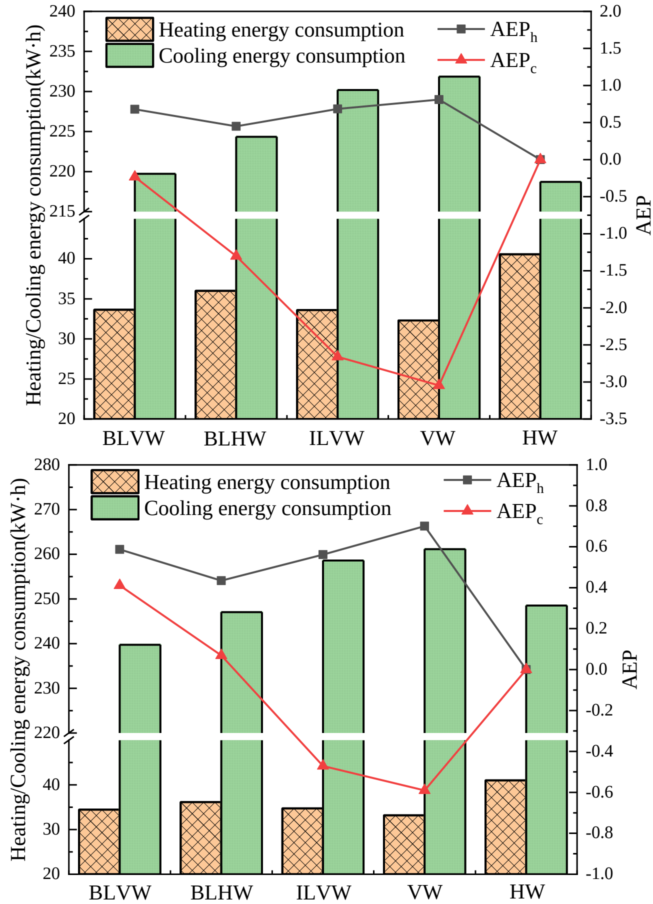


Fig. 6. Air conditioning energy consumption and AEP of rooms with five windows in each direction

Table 3. Optimal Operation Mode.

Direction	Summer	Winter
North	built-in louver ventilation window	ventilation window
East	built-in louver ventilation window	ventilation window
South	built-in louver ventilation window/hollow window	ventilation window
West	built-in louver ventilation window	ventilation window

It can be seen from Table 3 that the best window operation mode in summer is built-in louver ventilation window, and the room facing south can use hollow window, the difference between the two is very small; In winter, the best window operation mode is ventilation window. This shows that the operation mode of windows with different orientations is basically the same in the air conditioning season, and orientation is not the influencing factor of window operation mode. Figure 7 compares the energy consumption of air conditioning in the optimal operation mode with the conventional operation mode. The overall energy saving rate of buildings with the optimal operation mode in the north, east, south, and west directions is 5.87%, 5.70%, 2.80%, and 5.74%, respectively, compared to the conventional operation mode with hollow windows.

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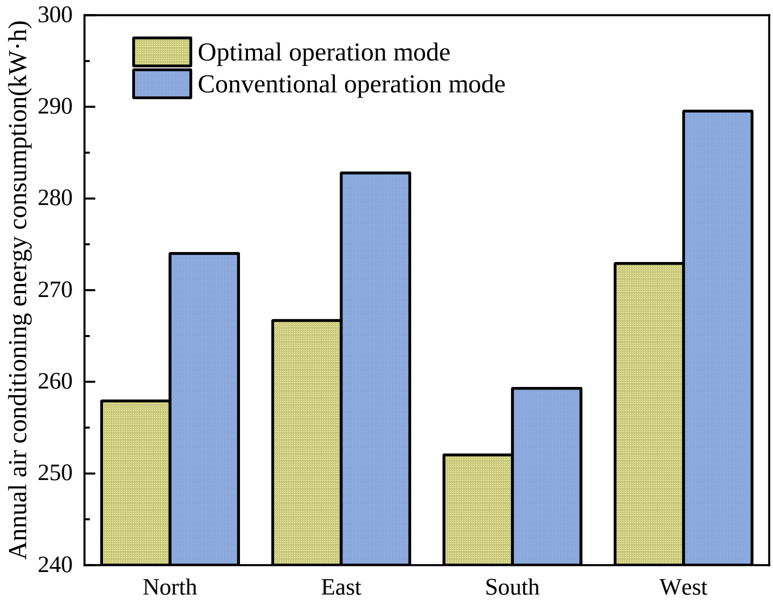

Fig. 7. Comparison of annual air conditioning energy consumption between optimal operation mode and conventional operation mode in each direction

If the energy-saving potential of a single window is taken into consideration, the indication of annual cumulative unhelpful heat flow may be used to illustrate the energy-saving potential of windows. This indication is utilized for analysis because, in Chongqing, most heat flow occurs through windows, entering from the outside in the summer and exiting from the inside in the winter. The two heat fluxes are going in different directions, and both are adverse to the regulation of the indoor environment, which will eventually lead to an increase in energy consumption. Therefore, it is called " unhelpful heat flow". When calculating the energy saving rate of windows through this indicator, the annual cumulative unhelpful heat flow of hollow windows commonly used in existing buildings is taken as the calculation basis. It is specified that the heat flow enters the room from the outside through the window in the positive direction, and its expression is as follows:

$$Q_N = Q_S - Q_W \tag{4}$$

Where: Q_N is the annual cumulative useless heat flow, kW·h; Q_S is the accumulated heat flow through the window in summer, kW·h; Q_W is the accumulated heat flow through the window in winter, kW·h.

Figure 8 displays the total heat flow in both the optimal and normal operating modes. Compared with the conventional operation mode, the energy saving rate of single window under the optimal operation mode in the north, east, south, and west directions is 94.45%, 88.96%, 117.79% and 88.38% respectively.

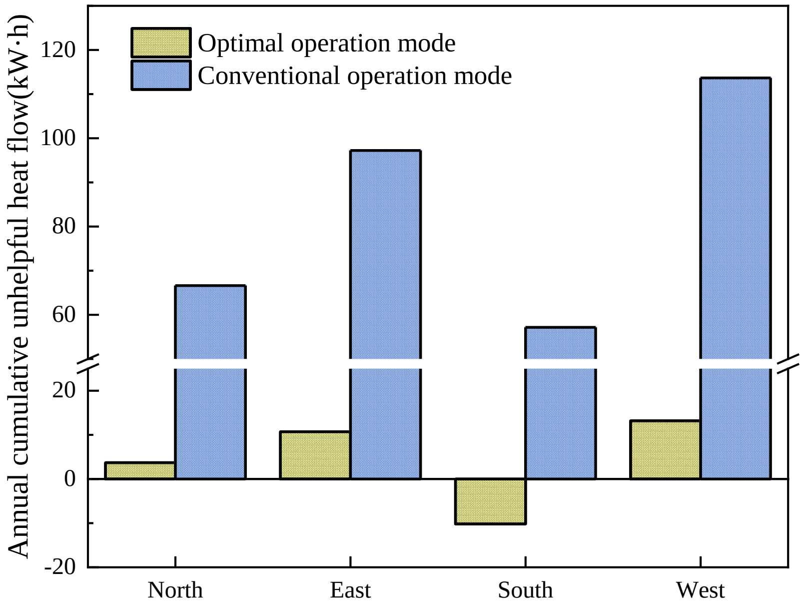

Fig. 8. Comparison of annual cumulative unhelpful heat flow between optimal operation mode and conventional operation mode in each direction

In general, the built-in louver ventilation window is the most suited external window type for office buildings in Chongqing, both in terms of the overall energy saving rate of buildings and the energy saving rate of individual windows. This is because cooling consumes most of the energy used for air conditioning in office buildings in Chongqing, where summer temperatures are high and sun radiation is intense. They prevent the two ways that heat can enter a room through temperature difference heat transfer and solar radiation heat transfer to cause cooling load. The functions of louver shading, ventilation and heat insulation have been targeted to solve these two problems. For other cities in the hot summer and cold winter climate zone to design the exterior window structure and set the operating mode, this has a certain reference relevance.

4 Conclusions

This study compared five different types of external windows of buildings by using EnergyPlus, and suggested energy-saving window design and operation mode choices relevant to directions to lower energy consumption and enhance thermal comfort of buildings in Chongqing. The results were of instructive for other cities in the hot summer and cold winter zone of China. The main conclusions are as fallowed:

Ventilation and louver design influence the inner glass surface temperature significantly. Energy-saving windows with ventilation function or louver designs have an average inner glass surface temperature that is 2.78 °C lower in the summer and 4.89 °C higher in the winter in comparison to hollow windows, and lessen the radiation asymmetry and enhance the thermal comfort of room.

Window operation mode is unaffected by orientation. During the air-conditioning season, windows operate essentially in the same way in all directions. The built-in louver ventilation window is the best window operation mode in the summer, and the hollow window can be also used in south-facing rooms, there is little gap between them in the south direction. Ventilation window is the best window operation mode in the winter.

The best operation mode for the entire year is the built-in louver ventilation window in the summer and ventilation window in the winter. The overall energy saving rates of the building are 5.87%, 5.70%, 2.80% and 5.74% in the north, east, south, and west directions, respectively, and the energy saving rates of single windows are 94.45%, 88.96%, 117.79% and 88.38%, respectively, compared to the conventional operation mode with hollow windows.

This work was supported by the China National Key R&D Program “Solutions to heating and cooling of buildings in the Yangtze River region” (No.2016YFC0700303).

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