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Optimal design for a dual-airflow window for different climate regions in China

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Abstract

The dual-airflow window could be used to conserve energy and improve indoor air quality in buildings because it works like a heat exchanger and can introduce outdoor air into buildings. In order to optimize the window design, this investigation used the orthogonal method to evaluate the importance of these 13 design parameters of the dual airflow window in energy conservation: outdoor air supply rate, window cavity width, window width, window height, glazing thermal conductivity, glazing thickness, solar heat gain coefficient, glazing emissivity, thermal conductivity of window frame, window frame width, window orientation, shading coefficient, and window blinds position. The outdoor air supply rate, window height, solar heat gain coefficient, and window orientation were found to be the most important. The first four parameters were further studied by using the listing method to identify their optimal values for the window design. With the optimal design, the dual-airflow window could save 25% energy in a warm climate region such as Guangzhou and 34% in a cold climate region such as Harbin. The dual-airflow window is recommended for use in colder climate regions.

Keywords: window, energy performance, optimal design, orthogonal method, listing method

1 Introduction

In China, energy demand for buildings accounts for nearly 27.5% of the total primary energy used in the nation [1]. In general, the energy lost through windows accounts for 20-25% of the total energy demand for buildings. In energy-efficient buildings, the ratio could be as high as 40% [2], because it is difficult to reduce the amount of energy lost through windows. The issue of reducing the energy demand becomes more important in severely cold climates. Thus, super-insulated windows and construction materials are used in buildings to reduce energy lost across a building envelope [3]. In addition, air infiltration in buildings typically accounts for 1/3 of the total energy lost [1]. To reduce the infiltration by sealing the building envelope sacrifices indoor air quality. Poor indoor air quality can then lead to sick building syndrome [4]. Thus, adequate outdoor air supply is essential for diluting indoor contaminant concentration and maintaining acceptable indoor air quality.

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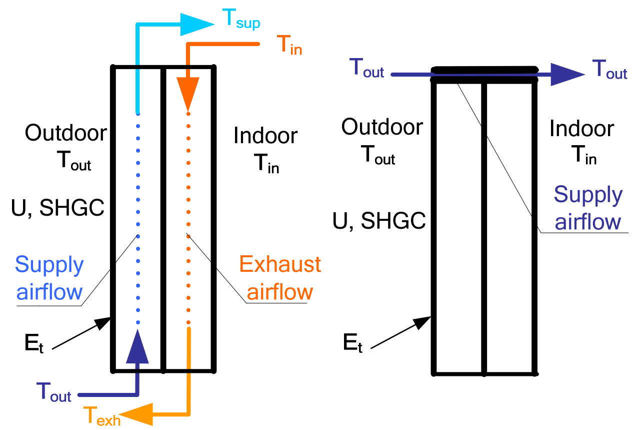
The design of sustainable buildings should consider building energy conservation and acceptable indoor air quality at the same time. The dual-airflow window as shown in Fig. 1(a) can help meet the needs. The dual-airflow window can supply fresh outdoor air to the indoors and can conserve energy by recovering energy from the exhaust flow to the supply airflow [5]. This has been demonstrated in our previous studies by comparing the dual-airflow window with a low-emissivity window and a blinds window under different climate zones in China [6, 7]. The studies found that this window can conserve energy, but its performance varies in different climates. The dual-airflow window used in our previous studies was not optimal in its design. Thus, its performance was not fully revealed.



(a) Dual-airflow window (b) Three-layer conventional window

***Fig.1** Schematic of heat balance on the windows*

In recent years, several studies on window design have demonstrated that optimal design of a window can greatly improve the window performance in energy demand. For example, Monhelnikova [8] added reflective coatings on window glass to reduce radiative heat loss since the thin coating has high transmittance for visible light waves and high reflectance in long-wave infrared waves. Since a window frame may represent up to 25% of a window area, some efforts were made into finding out how to decrease the heat transfer coefficient of a window frame. Scheuer et al. [9] used wood and vinyl-clad and aluminum-clad wood frames instead of aluminum frames to reduce energy loss by 17%. Kuhn [10, 11] used venetian blinds and other solar control systems to decrease window solar heat gain in summer time. Rubin and Lampert [12] found that multiple window glass-pane constructions were effective in reducing energy lost through windows.

The previous studies showed a strong correlation between energy lost through windows and window design. For the dual-airflow window shown in Fig. 1(a), the heat transfer process becomes very complicated because of the flow in the cavities. The wisdom applied in designing a conventional window may not be applicable to the dual-airflow window. How to optimize the design parameters for the dual airflow window is still an unsolved problem. Thus, this investigation has tried to do optimal design of the dual-airflow window, keeping energy conservation and acceptable indoor air quality in mind. The investigation was carried out for different climate zones in China in order to generalize the window applications.

2 Method

2.1 A model for window performance evaluation

In order to optimize the window design for energy conservation and acceptable indoor air quality under different climate regions, an evaluation model is needed to assess the window performance. The main difference between the dual-airflow window and a conventional window as shown in Fig. 1(b) is that the former can bring fresh outdoor air into an indoor space and the supply air is also tempered by the exhaust air. Not only is the energy loss different, but so also is the cooling/heating load caused by the fresh outdoor air compared with the air from infiltration or mechanical ventilation. Thus, the calculation of the energy lost through the dual-airflow window should include the sensible and latent heat from the supply air, the heat transfer across the window due to the temperature difference between the indoor and outdoor spaces, and the solar heat gain. An energy balance equation for the dual-airflow window can be written as:

$$\begin{aligned} Q_{dual-airflow} &= Q_{ventilation} + Q_{window} \\ &= V_e \rho c_p \left(T_{in} - T_{\sup}\right) + V_e \rho \left(2501 + 1.85 \times \frac{T_{in} + T_{\sup}}{2}\right)\left(d_{in} - d_{out}\right), \\ &+ UA\left(T_{in} - T_{out}\right) + \left(SHGC\right) \times A \times E_t \end{aligned} \tag{1}$$

where $Q_{dual-airflow}$ is the total load transmitted through the dual-airflow window (W), $Q_{ventilation}$ is the load caused by ventilation (W), Q_{window} is the load caused by temperature differences between indoors and outdoors and solar radiation (W), V_e is the air supply rate (m^3/s), ρ is the air density (kg/m^3), C_p is the specific heat of the air (J/(kg·K)), T_{in} is the indoor air temperature (^oC), T_{sup} is the supply air temperature from the window (^oC), d_{in} is the indoor air humidity ratio (kg_v/kg), d_{out} is the outdoor air humidity ratio (kg_v/kg), U is the window heat transfer coefficient ($W/(m^2, K)$), SHGC is the solar heat gain coefficient (-), A is the window area (m^2), and E_t is the incident total irradiance, (W/m^2).

Similarly, the energy balance equation for a conventional window that supplies air into the indoor space by infiltration or mechanical ventilation through its window frame as shown in Fig. 1(b) is,

$$\begin{aligned} Q_{conventional} &= Q_{ventilation} + Q_{window} \\ &= V_e \rho c_p \left(T_{in} - T_{out}\right) + V_e \rho \left(2501 + 1.85 \times \frac{T_{in} + T_{out}}{2}\right)\left(d_{in} - d_{out}\right), \\ &+ UA\left(T_{in} - T_{out}\right) + \left(SHGC\right) \times A \times E_t \end{aligned} \tag{2}$$

The only differences between the two equations are the supply air temperature and the U value if the window size and materials are the same. The T_{sup} for the dual-airflow window is the tempered outdoor air temperature due to the heat exchange between the two cavities in the window. It is warmer than outdoor air in winter and cooler than outdoor air in summer. For the conventional window, outdoor air is assumed to be directly supplied to indoors through window cracks or a fan in the window frame. Apparently, the dual-airflow window is superior because the supply air is tempered. The difference in the U value is again caused by the two air streams in the cavity that make the air temperature in the glazing panes different in a conventional window.

This study used EnergyPlus [13] to calculate $Q_{dual-airflow}$ and $Q_{conventional}$. The energy balance equation for the dual-airflow window was implemented into EnergyPlus in our previous study [7]. For the conventional window, this investigation assumed it had a constant ventilation rate V_e. Then, the energy demand by the dual-airflow window can be compared with the energy demand by the conventional window via

$$ER = \frac{Q_{conventional} - Q_{dual-airflow}}{Q_{conventional}} 100\% \tag{3}$$

This investigation used the ER for window performance evaluation.

2.2 Identification of prominent window design parameters

With the energy balance equations built in EnergyPlus, it is possible to calculate the energy performance of the dual-airflow window under various window design parameters by using ER. Equation (1) shows that the parameters include ventilation rate, heat transfer through the window glass panes and frames, window size, solar radiation (window orientation), and solar shading device, etc. Table 1 gives a list of these parameters.

The mathematical model built in EnergyPlus depicted U value used in Eq. (1) in detail [7]. It was determined by the conductive heat transfer coefficient of window glass, airflow path convective heat transfer coefficient, indoor and outdoor convective heat transfer coefficient. The convective heat transfer coefficient along the airflow path depends on airflow velocity calculated by outdoor air supply rate, window cavity width and window width. Outdoor convective heat transfer coefficient is associated with wind velocity. Both conductive and convective heat transfer are related with indoor/outdoor air temperature difference. Radiative heat gain is related with solar radiation and solar heat gain coefficient, window blinds and window orientation. This means all the parameters listed in Table 1 can influence window heat transferred by temperature difference or solar heat gain. Thus, different outdoor weather condition will bring different window energy performance, so it is necessary to conduct dynamic simulation in different climate zones.

Table 1. *Influencing parameters and their values*

No.	Parameter	Level 1	Level 2	Remark
1	Outdoor air supply rate (m^3/h)	20	108	Air quality
2	Window cavity width (mm)	10	50	Window size
3	Window width (m)	2.4	0.6	
4	Window height (m)	0.6	2.4	
5	Glazing conductivity (W/(m, K))	0.6	1.1	Each window glass pane
6	Glazing thickness (mm)	3	20	
7	SHGC (solar heat gain coefficient) (-)	0.25	0.85	
8	Glazing emissivity	0.3	0.8	
9	Thermal conductivity of window frame (W/(m, K))	0.2	170	Window frame
10	The width of the window frame (cm)	4	10	
11	Window orientation (^{o})	180 (south)	0 (north)	
12	Shading coefficient	0	0.8	Window blinds
13	Window blinds position	Interior	Exterior	

Since there are so many parameters listed in Table 1, hundreds of simulations must be conducted on a combination of these parameters in order to identify their impact on the window performance. This approach may not be feasible. In fact, some of the parameters listed in Table 1 may not have a major impact on the thermal performance of the window. Therefore, it is important to identify only the most important parameters for doing an optimal design of the dual-airflow window.

To identify the prominent parameters, this investigation used the orthogonal method developed by Taguchi [14]. To limit simulation cases to a manageable number, this study varied each parameter at two levels of values. The values were almost the minimum and maximum that can be found in building design, as shown in Table 1. The orthogonal method also considers interactional parameters that may not be independent, such as window area depending on window height and width. This study had three interactional parameters. With a total of 16 independent and interactional parameters and each of them varied at two levels of values, the appropriate orthogonal array should be $L_{20}(2^{19})$ as shown in Table 2, according to the Taguchi method. The 19 in $L_{20}(2^{19})$ means that the array can be used for a maximum of 19 parameters. Since the window only had 16 parameters, columns 17, 18, and 19 in Table 2 (shaded one) was not used. The 20 in $L_{20}(2^{19})$ stands for the total cases of energy simulations performed in order to identify prominent parameters. Numbers 1 or 2 in Table 2 show the value of level 1 or level 2 for each parameter used in the case. For example, Case 1 uses only a level 1 value for all 16 parameters. The ER calculated by EnergyPlus for each case is placed in the last column.

Table 2. *Orthogonal array used in this study*

$L_{20}(2^{19})$																				
Case\ Column	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	**ER**
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
2	2	2	1	1	2	2	2	2	1	2	1	2	1	1	1	1	2	2	1	
3	2	1	1	2	2	2	2	1	2	1	2	1	1	1	1	2	2	1	2	
4	1	1	2	2	2	2	1	2	1	2	1	1	1	1	2	2	1	2	2	
5	1	2	2	2	2	1	2	1	2	1	1	1	1	2	2	1	2	2	1	
6	2	2	2	2	1	2	1	2	1	1	1	1	2	2	1	2	2	1	1	
7	2	2	2	1	2	1	2	1	1	1	1	2	2	1	2	2	1	1	2	
8	2	2	1	2	1	2	1	1	1	1	2	2	1	2	2	1	1	2	2	
9	2	1	2	1	2	1	1	1	1	2	2	1	2	2	1	1	2	2	2	
10	1	2	1	2	1	1	1	1	2	2	1	2	1	1	2	2	2	2	2	
11	2	1	2	1	1	1	1	2	2	1	2	2	1	1	2	2	2	2	1	
12	1	2	1	1	1	1	2	2	1	2	2	1	1	2	2	2	2	1	2	
13	2	1	1	1	1	2	2	1	2	2	1	1	2	2	2	2	1	2	1	
14	1	1	1	1	2	2	1	2	2	1	1	2	2	2	2	1	2	1	2	
15	1	1	1	2	2	1	2	2	1	1	2	2	2	2	1	2	1	2	1	
16	1	1	2	2	1	2	2	1	1	2	2	2	2	1	2	1	2	1	1	
17	1	2	2	1	2	2	1	1	2	2	2	2	1	2	1	2	1	1	1	
18	2	2	1	2	2	1	1	2	2	2	2	1	2	1	2	1	1	1	1	
19	2	1	2	2	1	1	2	2	2	2	1	2	1	2	1	1	1	1	2	
20	1	2	2	1	1	2	2	2	2	1	2	1	2	1	1	1	1	2	2	
I_j																				
II_j																				
I_j/K_j																				
II_j/K_j																				
D_j																				

This investigation used the extreme difference analysis method to determine the prominent parameters from the ER obtained for each case. Row I_j represents the sum of ER values corresponding to level 1 in column j and row II_j is the sum of ER values corresponding to level 2 in column j. For example, I_j for column 3 should be the sum of ER for all the red rows and II_j the sum of the green rows. K_j is the number of levels for each variable, which is 2 for column 3. D_j is the extreme difference in column j expressed as,

$$D_j = \max\left\{ I_j / K_j , II_j / K_j \right\} - \min\left\{ I_j / K_j , II_j / K_j \right\} \tag{4}$$

The larger the D_j for a parameter, the more important the parameter is.

2.3 Optimal design of prominent parameters

Once the prominent parameters are identified, the listing method can be used to further determine the optimal value for each parameter. The listing method calculates the effect of each parameter on energy performance by changing its value at multi-levels while it keeps the rest of the parameters unchanged at the most desirable value (or standard value). For example, if there were only 2 prominent parameters and each parameter was to be varied on four different levels, the total number of simulations should be 7, as shown in Table 3. The optimal value for a parameter is the one corresponding to the highest ER.

Table 3. *Example of the case design used in the listing method for two parameters varied at four levels*

Case No.	Parameter 1	Parameter 2
Reference case (Case 1)	Reference value (Level 1)	Reference value (Level 1)
Case 2	Level 2	Reference value
Case 3	Level 3	Reference value
Case 4	Level 4	Reference value
Case 5	Reference value	Level 2
Case 6	Reference value	Level 3
Case 7	Reference value	Level 4

With the Taguchi and listing methods, this following section reports the results on how optimal design of the dual-airflow window is achieved.

3 Results

3.1 Case design

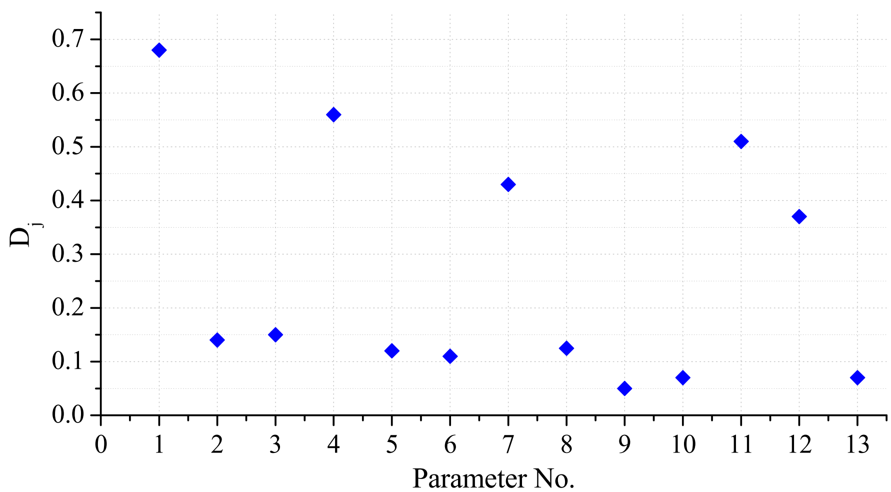
This study assumed that the dual-airflow windows were installed in an apartment with a floor area of 100 m^2 (10 m long, 10 m wide and 2.8 m high) in the middle of an apartment building. This study further assumed that the apartment had only one exterior wall with windows. The exterior walls were assumed to be of 240 mm thick reinforced concrete with 120 mm polystyrene insulation board. Table 4 shows the operating schedule of the apartment and its control in room air temperature.

Table 4. Operation time and indoor air temperature control

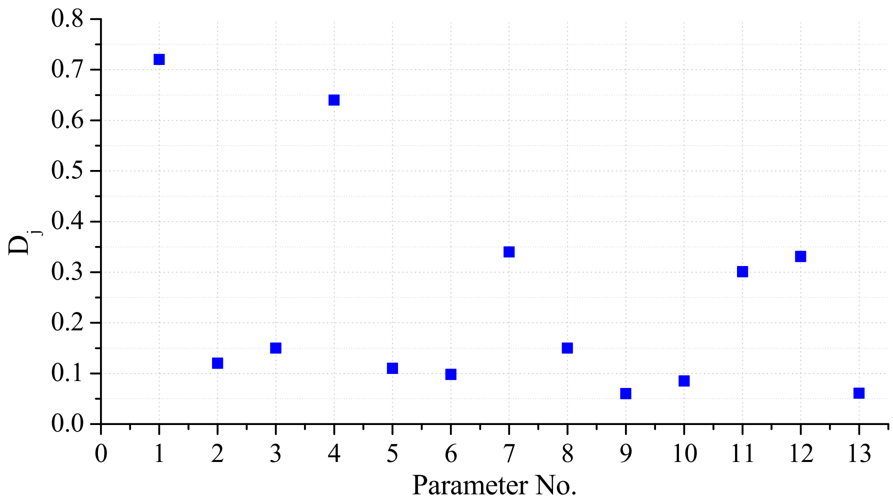
	Weekdays			Weekends
	00:00~9:00	9:00~17:00	17:00~24:00	00:00~24:00
Heating	18ºC	⩾10ºC	18ºC	18ºC
Cooling	26ºC	No control	26ºC	26ºC

3.2 Identification of prominent parameters

Since the Taguchi method cannot be used for dynamic simulation analysis, this study conducted energy performance simulations for Table 2 at two typical times, 00:00 and 12:00, in the winter and summer design days for a severely cold climate zone in China (Harbin). The D_j values for the window design day were similar to those for the summer design day. Figure 2 only shows the D_j for the winter design day. In fact, the D_j distribution for the two different times looks similar too.



a) 12:00 *in the summer design day*



b) 0:00 *in the winter design day*

Fig. 2 *The D_j for each parameter listed in Table 1*

Figure 2 shows that the following five parameters had a D_j greater than the others: outdoor air supply rate (1), window height (4), SHGC (7), window orientation (11), and window blind shading coefficient (12). These five parameters are prominent in the energy performance of the window. This investigation did not consider the dual-airflow window with venetian blinds. Thus, only four prominent parameters were considered.

3.2 Optimization of the prominent parameters

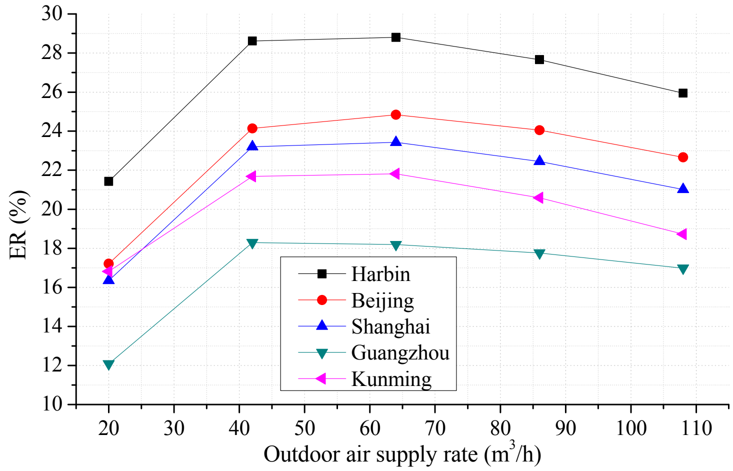
To optimize the four prominent parameters identified, they were varied on five levels as shown in Table 5. For outdoor air supply rate, the smallest value corresponded to the minimum fresh airflow rate for one person and the largest value to the desirable air rate for three persons in the apartment. The variation of the SHGC was considered by using different kinds of window glazing. The listing method led to 17 simulation cases in total (1 reference case + 4 parameters × 4 variations) in one climate zone. The simulations were performed for five climate regions in China: Harbin (severe cold), Beijing (cold), Shanghai (hot in summer and cold in winter), Guangzhou (hot in summer and mild in winter), and Kunming (mild). It should be noted that the heat transfer principle is the same for different climates, but the performance (heat exchange efficiency) of the window depends on climate conditions. Since China is a large country that covers a wide variation of climate conditions, the results obtained from this study can be extended to regions with similar climates studied here. The total number of cases simulated was 85.

Table 5. *Values studied for the four parameters*

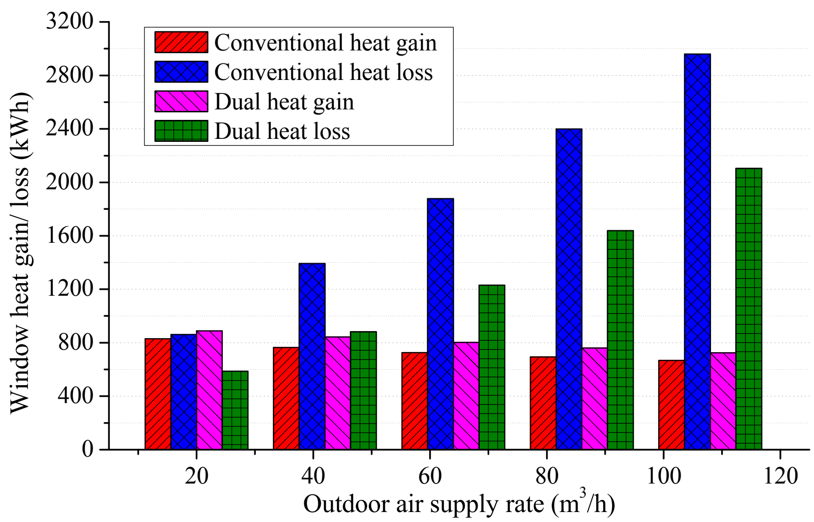
No.	1	2	3	4
Parameters	Outdoor air supply rate (m^3/h)	Window height (m)	Window orientation (^{o})	SHGC (Glass pane type)
Level 1	20	0.6	0 (North)	0.85 (Clear float glass)
Level 2	42	1.05	90 (East)	0.70 (Brown float glass)
Level 3 (reference)	**64**	**1.5**	**180 (South)**	**0.55 (heat-absorbing glass)**
Level 4	86	1.95	270 (West)	0.40 (heat-reflecting glass)
Level 5	108	2.4	360 (North)	0.25 (low-emissivity glass)

Figure 3(a) shows the ER variation with different air supply rates. The figure also shows that the ER changes with a similar trend in the five climate regions, but the energy saving is the largest in a cold climate (Harbin) and the smallest in a hot summer and a mild winter climate

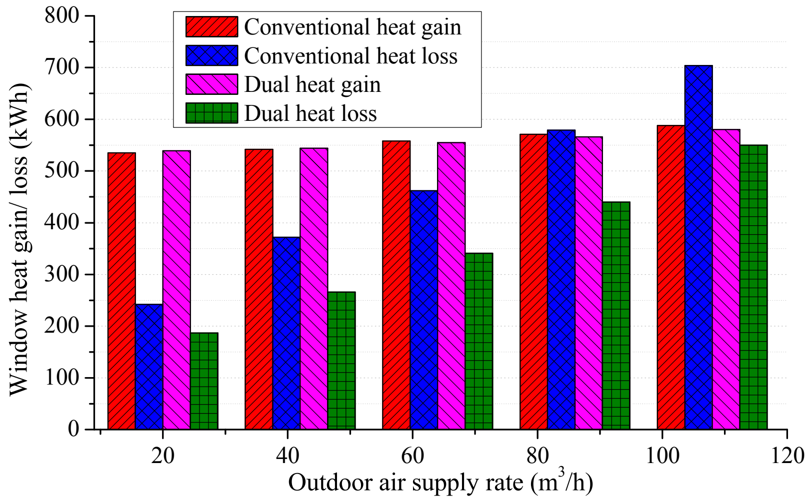
(Guangzhou). When the flow rate was between 42 and 64 m^3/h, the ER for the dual-airflow window was the highest. A larger air supply rate can lead to a higher air velocity in the cavity, which would increase convective heat transfer and heat exchange between the supply and exhaust flow. When the supply airflow rate was too large, the supply air could not be sufficiently tempered so the heat exchange efficiency decreased. The optimal air supply rate for one window is about 50m^3/h.



(a) ER in five climate zones



(b) Window heat gain/ loss in Harbin



(c) Window heat gain/ loss in Guangzhou

***Fig. 3** The energy performance of the dual-airflow window with different outdoor air supply rates*

Figures 3(b) and 3(c) show that the dual-airflow window can reduce window heat loss, but not window heat gain. In winter, the temperature difference between the indoor and outdoor air was much larger than in summer. Due to the heat exchange between the two cavities, the temperature difference between the inside and outside glass panes was reduced. Therefore, the heat loss in winter was reduced. The same principle is applicable to the summer. However, the supply air absorbed a lot of solar radiation in summer, which increased the supply air temperature and increased the heat gain. As a result, the overall heat gain in the summer by the dual-airflow window was higher than by the conventional window.

The difference between the indoor and outdoor air temperatures in cold Harbin was much higher than in warm Guangzhou in winter. The window heat loss showed a similar trend. On the other hand, the heat gain did not change much with the ventilation rate. In warm Guangzhou, the heat gain in summer is more important than the heat loss in winter. Therefore, the ER in warm Guangzhou was smaller than in cold Harbin. This implies that the window is more suitable in cold climate regions.

The ER was the highest when the window height was 1.5 m as shown in Fig. 4. With a notable temperature differential between the two cavities, the taller the window was, the higher the heat exchange efficiency. When the temperature differential became small, a further increase in window height would not lead to more heat exchange. Instead, the flow resistance would become very high. The results indicate that the optimal window height should be 1.5 m. The climate impact on window energy performance in this case was similar to that shown in Fig. 3.

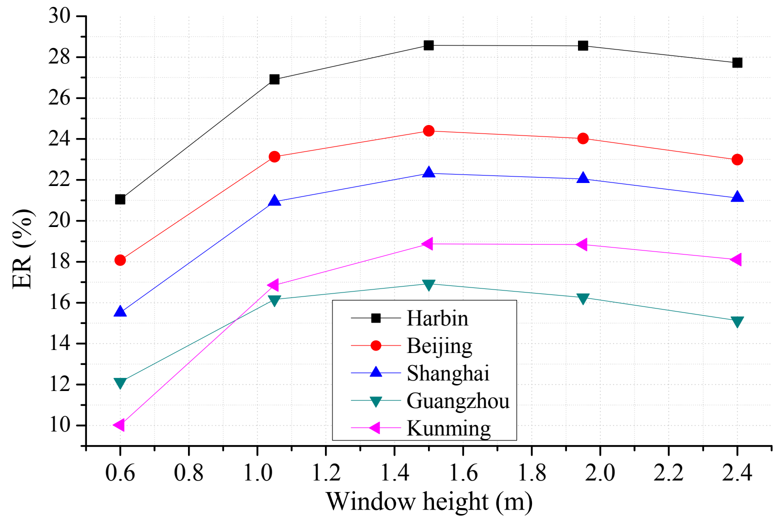


Fig. 4 *The energy performance of the dual-airflow window with different window heights*

A window can be installed in different orientations. Figure 5 shows that the ER was the highest when the dual-airflow window was installed in the north facing façade, and it was the lowest in the south. This is because the dual-airflow window performed better when the heat loss was the highest, which is typical in a north facing façade. In the south façade, the solar gain was the highest. Figures 3(b) and 3(c) show that the dual-airflow window would not save much energy if there were a significant heat gain from solar radiation compared with the conventional window.

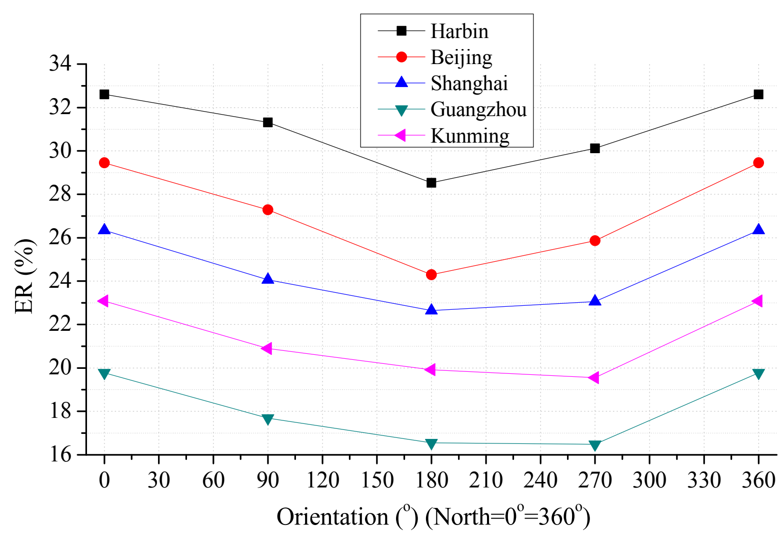


Fig. 5 *The energy performance of the dual-airflow window with different window orientations*

Figure 6 shows the window performance with different inner glass panes. The lower the SHGC was, the higher the ER was. When the SHGC was low, the window performance mainly depended on the air temperature difference. Similar to the discussion for Figs. 3(a) and 3(b), the dual-airflow window performed better with a large temperature differential in winter. The dual-airflow window performed optimally when SHGC approached zero, which is impossible. Thus, this study recommended the use of a high window shading coefficient for the dual-airflow window. From the material library, this study suggested the use of a low-emissivity glazing that corresponds to the lowest SHGC.

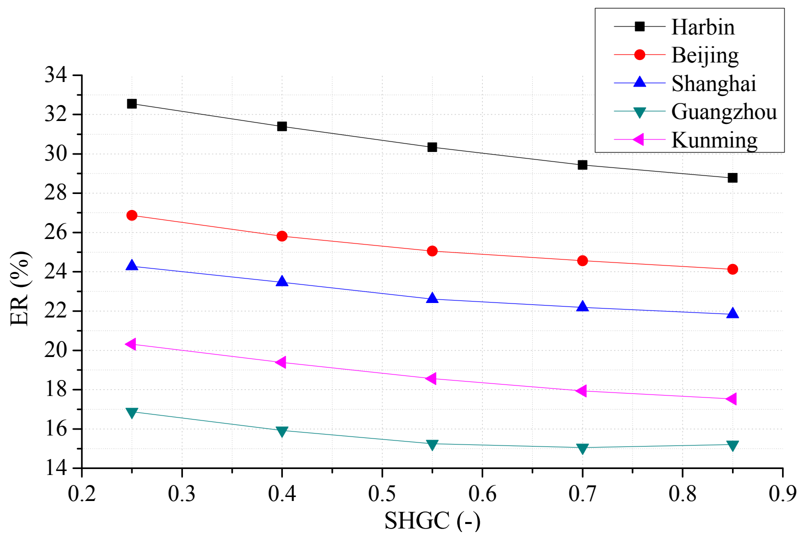


Fig. 6 *The energy performance of the dual-airflow window with different inner glass panes*

The above analysis led to the optimal design of the prominent parameters as summarized in Table 7.

Table 7. *Optimal design parameters for the dual-airflow window*

No.	1	2	3	4
Parameters	Outdoor air supply rate (m^3/h)	Window height (m)	Window orientation (^{o})	SHGC (Glass pane type)
Optimal value	50	1.5	0^o (north)	0.25 (low-emissivity glass)

With the optimal design parameters, the energy saving by the dual airflow window is shown in Fig. 7, compared with that of a conventional window in the same conditions. The energy saving was the highest (34%) for cold climate (Harbin) and the lowest (25%) for warm climate (Guangzhou).

It should also be noted that this study compared only the dual-airflow window with a two-layer conventional window. The glazing layer was not further studied since it may cause confusion by comparing window performance with different glazing layers. It can be a subject for further study.

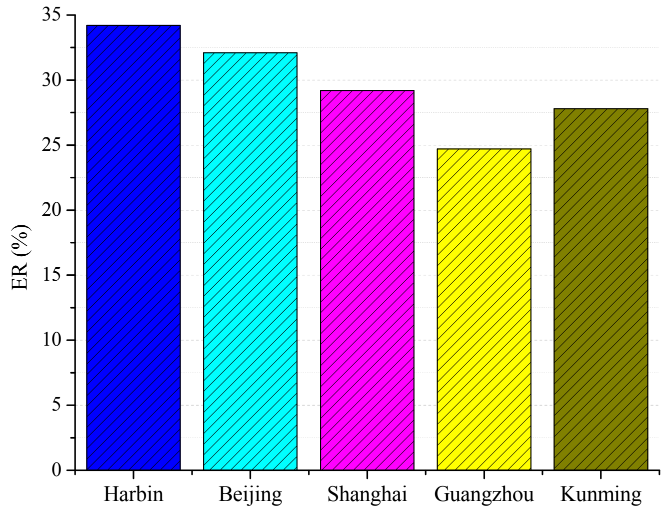


Fig. 7 *Energy saving with the dual airflow window compared with a conventional window under the optimal design parameters for different climate regions in China*

5 Conclusions

This investigation used ER and compared the energy saving of the dual airflow window with that of a conventional window for evaluating the energy performance of the dual-airflow window. The ER was used as a criterion for identifying the optimal design parameters of the dual-airflow window under different climate regions in China. This study yielded the following conclusions:

By using the orthogonal method, this investigation examined 13 design parameters and found the outdoor air supply rate, window height, window orientation, solar heat gain coefficient of window glass pane, and window blinds position to be prominent for the energy performance of the dual-airflow window.

This investigation further used the listing method to study in detail how outdoor air supply rate, window height, window orientation, and solar heat gain coefficient of window glass pane could influence the energy performance of the dual-airflow window in five typical climate zones in China. By varying each of these parameters at five different values, this study identified their optimal values.

With the optimal parameters, this investigation found that the dual-airflow window can save 25% energy in warm climate regions such as Guangzhou and 34% in cold climate regions such as Harbin. Thus, the dual-airflow window has greater energy saving potential in colder climate regions.

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