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Energy performance of a dual airflow window under different climates

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Abstract

Ventilated windows have shown great potential in conserving energy in buildings and provide fresh air to improve indoor air quality. This paper reports our effort to use EnergyPlus to simulate the energy performance of a dual airflow window under different climate. Our investigation first developed a network model to account for the two-dimensional heat transfer in the window system and implemented it in EnergyPlus. The two-dimensional assumption and the modified EnergyPlus program were validated by the measured temperatures of the window and the energy demand of a test cell with the window under actual weather conditions. Then EnergyPlus was applied to analyze energy performance of a small apartment installed with the dual airflow windows in five different climate zones in China. The energy used by the apartment with blinds windows and low-e windows was also calculated for comparison. The dual airflow window can reduce heating energy of the apartment, especially in cold climate. The cooling energy reduction by the window was less important than that by shading solar radiation. The dual airflow window is recommended for colder climate. If improving air quality is a major consideration for a building, the window can be used in any climate.

Keywords: Dual airflow window; Energy demand; Indoor air quality; Different climates

1. Introduction

Energy demand by buildings in China accounts for nearly 30 % of the total primary energy and HVAC systems use 55 % of the energy for buildings [1]. In order to reduce energy demand by the HVAC systems, it is essential to reduce energy loss in winter and energy gain in summer through building envelopes, such as windows, walls, roofs, and floors, and through infiltration. The heat loss through windows and infiltration in residential buildings accounts for roughly 50% in Northern China. As a result, glazing has been increased from single to double, even triple layers. A parallel effort has been made to improve the frame and glazing properties. For example, it is becoming more and more common to use low emissivity (low-e) coatings to reduce radiation and to seal window leakage.

Nomenclature

C_p	specific heat capacity (J/(kg,K))
Q_{solar1}	solar heat gain rate (W)
Q_{cond}	condutive heat exchange rate (W)
Q_{conv}	convective heat exchange rate (W)
Q_r	radiative heat exchange rate between surfaces (W)
$Q_{sup,in}$	energy brought in by supply airflow (W)
$Q_{sup,out}$	energy carried away by supply airflow (W)
$Q_{exh,in}$	energy brought in by exhaust airflow (W)
$Q_{exh,out}$	energy carried away by exhaust airflow (W)
T	absolute temperature (K)
h	convective heat transfer coefficient ($W/(m^2,K)$)
ι	conductive heat transfer coefficient ($W/(m^2,K)$)
ε	infrared emissivity for each glass layer
ρ	air density (kg/m^3)

Subscripts

e	exhaust airflow
in	indoor space
j	layer j of the dual-airflow window
out	outdoor space
s	supply airflow
1	outer surface of outer glass pane
2	inner surface of outer glass pane
3	outer surface of middle glass pane
4	inner surface of middle glass pane
5	outer surface of inner glass pane
6	inner surface of inner glass pane

Better window and wall construction have made buildings increasingly tighter, which is good for energy conservation. However, the effort may be at the expense of adequate indoor air quality (IAQ) [2]. The Environmental Protection Agency in the United States (http://www.epa.gov/iaq/ia-intro.html) reported that, inadequate ventilation can increase indoor pollutant levels. Poor indoor air quality has been linked to respiratory illness, allergies, asthma, and sick building syndrome [3]. Therefore, how to conserve energy and to maintain acceptable indoor air quality has been challenging.

One way to improve indoor air quality is to supply fresh air through window frame. By supply directly very cold air in winter and very warm air in summer to a room through the window frame can waste a lot of energy and cause discomfort. Heat recovery ventilator or enthalpy recovery ventilator are popular used in commercial and industrial buildings. It can transfer heat between the exhaust air and the supply fresh air is thus used to conserve energy [4,5]. Such heat recovery system is often integrated with central air-conditioning systems [5], so it is not suitable for residential buildings with hydraulic heating systems and window/split air-conditioning units. Some buildings used double skin facade to trap solar energy and to supply fresh air into indoor space [6]. However, it is too expensive to be used in residential buildings [7].

Airflow windows work like a double skin facade, which can be used in residential buildings [8] and some of them can work like a heat exchanger [9]. The past studies show that the airflow windows have very promising performance on energy conservation and indoor air quality improvement. Our effort is to study one of the best airflow windows by analyzing its energy performance under different climates, by comparing with the energy performance of other popular windows. This study may provide guide under which climate such an airflow window should be used.

2. Principle of airflow windows

The main difference between an airflow window and a conventional window is the existence of free or forced flow convection in the cavity between two layers of glass. Depending on the airflow pattern and window structure, Fig. 1 shows five modes of operation for airflow windows [9]: supply, exhaust, indoor air curtain, outdoor air curtain, and dual airflow window. Note that the outside is on the left side of each window and the inside on the right side.

The supply mode (Fig. 1(a)) draws fresh outside air through the cavity into building. The air is heated in the cavity by solar radiation so the mode is for winter heating. The exhaust air mode (Fig. 1(b)) extracts inside air through cavity to the outside space. The window uses cool indoor air and buoyancy force from the solar radiation to cool the window panels and to remove heat accumulated in the cavity. The exhaust mode is for summer passive cooling. The indoor air curtain window (Fig. 1(c)) uses solar radiation to heat indoor air in winter. The outdoor air curtain window (Fig. 1(d)) circulates the outdoor air by solar radiation to cool the window panels in summer. There is no air exchange between indoor and outdoor through the air curtain windows. Venetian blinds are often added into the cavity to enhance the flow because solar radiation can be easily trapped by the blinds. The dual airflow window (Fig. 1(e)) has two airflow paths in which the outer airflow path supplies fresh outdoor air to the inside space and the inner airflow path extracts indoor air to the outside space. The mid-glazing works like a heat exchanger. The first four modes can be operated by buoyancy force from solar radiation or mechanical force by a fan. The dual airflow window must operate with two fans.

Compared to a conventional window, all the airflow windows can capture solar heat trapped in the cavity and directed it indoors or outdoors depending on the operating mode. This reclaimed solar energy is used as passive heating in winter or passive cooling in summer. The dual airflow window is better than the supply and exhaust mode windows because the former has a higher efficiency due to the heat exchanger function. The window is also better than the outside and inside curtain ones because it can bring in fresh air to inside [10].

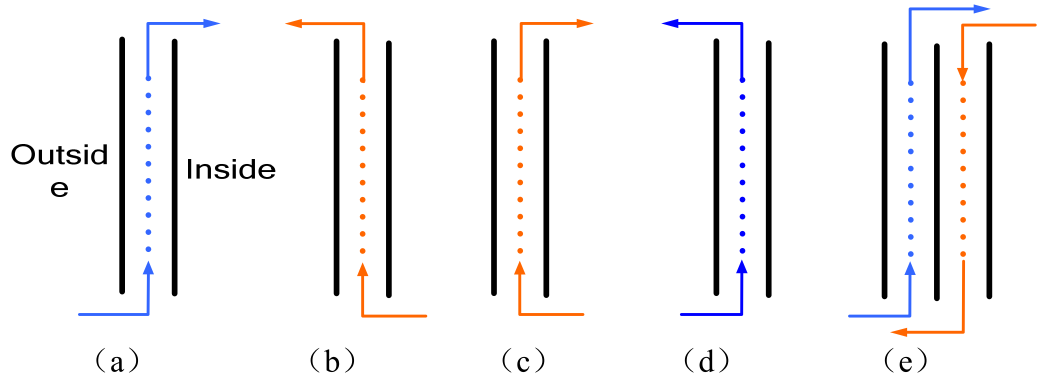


Fig.1. Operating modes of airflow windows: (a) supply mode, (b) exhaust mode, (c) indoor air curtain mode, (d) outdoor air curtain mode, and (e) dual airflow mode

The dual airflow window can conserve energy and can improve indoor air quality by supplying fresh outdoor air to indoor spaces. Gosselin and Chen [10] demonstrated in laboratory environment that the dual airflow window can conserve energy. However, their study was with steady-state heat transfer and did not compare with the performance of other windows. This investigation is to further evaluate the energy performance of the dual-air window for different climate in China and to compare the performance with that of other conventional windows.

3. Methods

In order to evaluate the energy performance, this investigation compared the dual airflow window with a double-pane, low-e window and a double-pane, blinds window, as shown in Fig. 2. The low-e and blinds windows were selected because they were probably the best windows currently used in Chinese residential buildings.

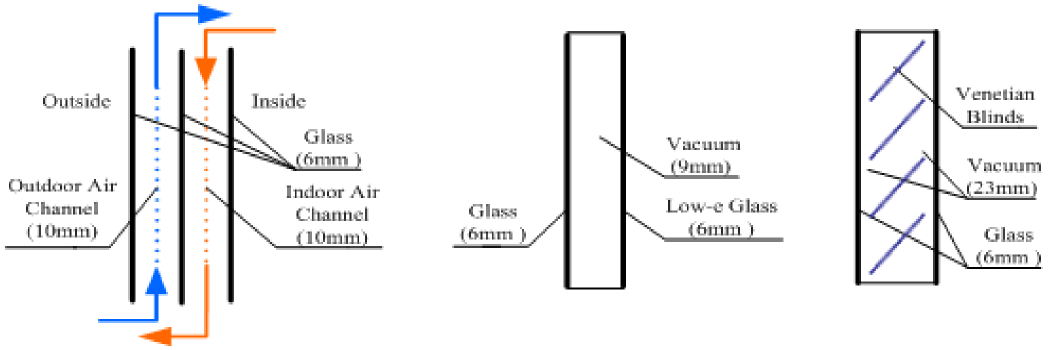


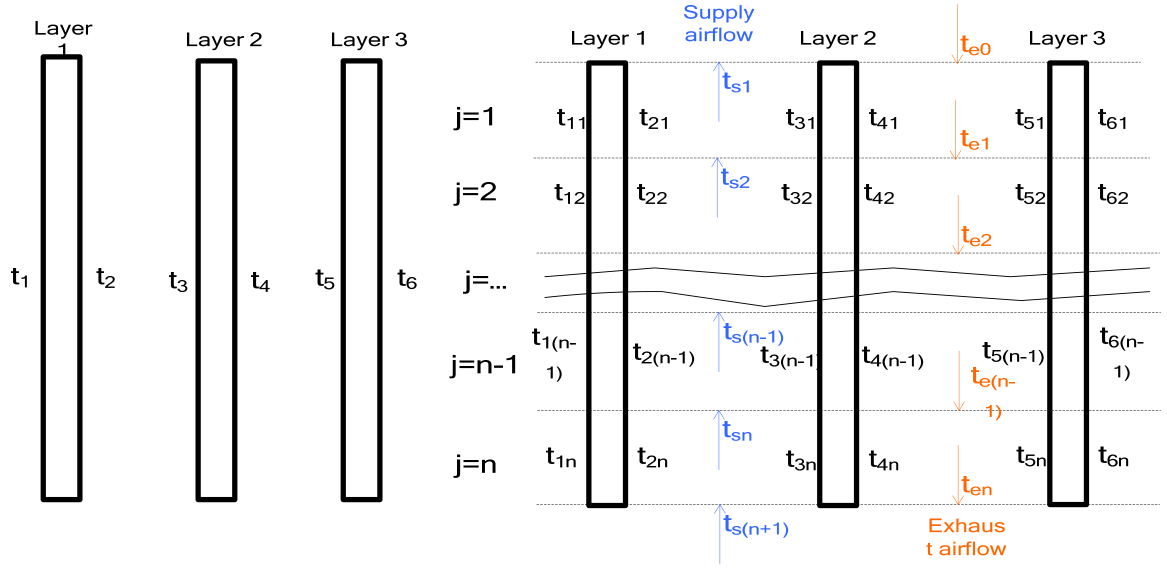
Fig. 2. Three different windows used in this study (a) dual airflow window, (b) low-e window, and (c) blinds window

The dual airflow window was constructed with three clear glasses with no coating. The thickness of airflow channel between two glasses was 10 mm as suggested by Gosselin and Chen [9]. The thickness of the glasses was 6 mm that provides sufficient strength. The same was used for the other two windows. Both the low-e and blinds windows were double-pane since they are traditional type in China and they can satisfy the insulation requirements by the Chinese national standards. The low-e window was with a low emissivity coating on interior surface of the inner glass. The coating can reduce the long-wave radiation loss to the outside space [11]. The cavity between the two glazing layers was 9 mm. The blinds window had venetian blinds in the cavity between the two glass panes that can mainly absorb solar radiation in winter and reflect a major part of solar radiation back to the outside in summer. In the winter night, the blinds work as an insulation layer that can reduce heat loss to the outside space [12]. The cavity thickness was 23 mm that permitted the movement of the 20 mm width of blinds in between. This study assumed the blinds were closed in summer daytime and in winter nighttime.

With the three types of windows, one may use different methods to analyze their energy performance, such as the bin-methods, experimental measurements, Computational Fluid Dynamics (CFD), and energy analysis programs. The bin-methods are too simple for the comparison of the energy performance of these windows since they do not consider solar radiation and approximate the energy demand as a linear function of outdoor air temperature. Thus, the methods are not suitable for our investigation, although they are simple and straightforward. The approach of experimental measurements is most reliable and realistic. However, the approach is very expensive and time consuming. It would be unrealistic to use the approach for studying energy demand in different climate regions for a period of one year. The CFD method can give accurate and informative results by solving highly reliable Navier-Stokes equations. Unfortunately, the method would demand a large computer for the simulation of energy demand for one year under various weather conditions. The approach by using energy analysis programs such as EnergyPlus [13] and ESP-r [14] simulates energy performance by solving one-dimensional energy equation [15]. It is very fast for calculating energy demand over a long period of time. Therefore, the approach was used for the present investigation. Since EnergyPlus was validated by many researchers and its source code was relatively simple to modify, it was used in this study.

EnergyPlus calculates heat and mass transfer through building enclosure, such as windows, walls, roofs, etc. The program solves different layers of a window as different nodes. It also assumes the temperature along the entire window height to be uniform as shown in the three-pane window in Fig. 3(a). The three-pane window has six nodes and six temperatures.

Due to the flow through the two cavities in the dual airflow window, the temperature of a glass pane in the vertical direction cannot be uniform. The air temperatures in the cavities also change along the height. Therefore, this study cannot use directly EnergyPlus without modifications for the vertical change of temperature. The modifications were to divide the window into n equal sections along the height as shown in Fig. 3(b).

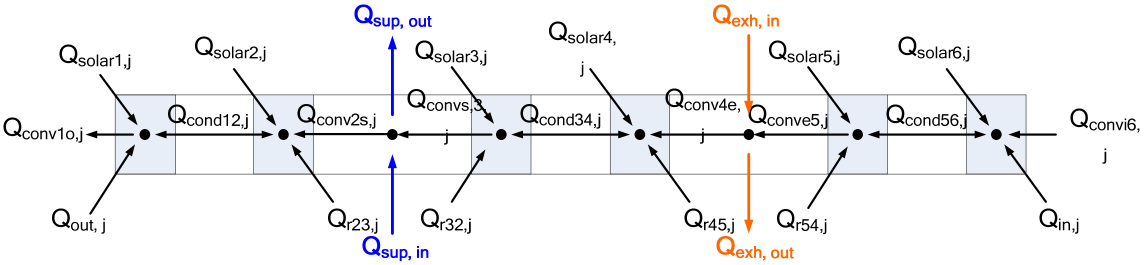


(a) A conventional three-pane window (b) A dual airflow window

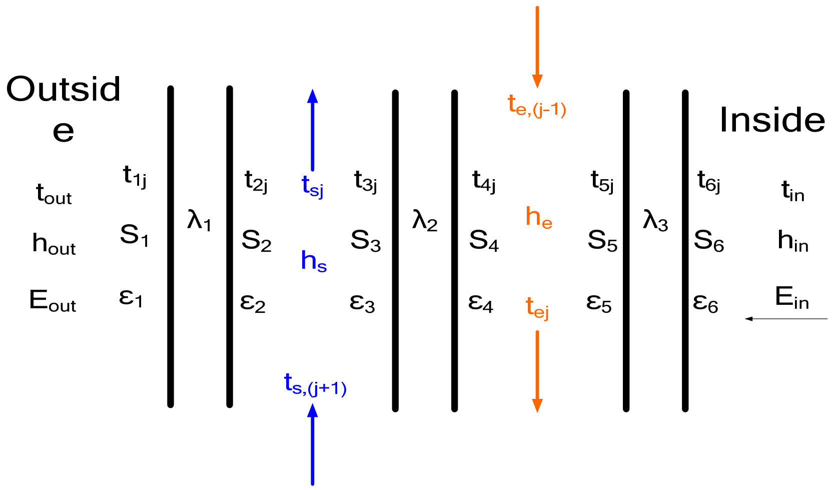
Fig. 3. Schematic of window network models for EnergyPlus

2.1. Implementation of the network model into EnergyPlus

More specifically, our modifications were implemented by a new network model. The model was based on the energy balance for each section, which considers convection, conduction, and solar radiation through the glass panes, and radiation exchange between the glass panes and the interior and exterior spaces as shown in Fig. 4(a). For the section, the existing equations in EnergyPlus can be used. The energy and mass balance between sections were only considered in the two cavities. The heat transfer along the glass height was neglected. This investigation also did not consider the heat and mass transfer in the third direction. Thus, this study had implemented two additional flow equations for the cavities. Fig. 4(b) shows further the parameters used in this study. Please refer to the nomenclature for the explanation of the parameters. Please note that most of the parameters were variables.



(a) Energy balance in a section



(b) Parameters used for the section

Fig. 4. Schematic of heat and mass flow through section j of the dual airflow window

Fig. 4(a) shows that the dual airflow window has eight nodes in a section. For node 1, the energy balance equation is

$$E_{out}\varepsilon_1 - \varepsilon_1\sigma T_{1j}{}^4 + \lambda_1(T_{2j} - T_{1j}) + h_{out}(T_{1j} - T_{out}) + Q_{solar1} = 0 \tag{1}$$

Similarly, the equation for node 2 can be written as

$$\lambda_1(T_{1j} - T_{2j}) + h_s(T_{sj} - T_{2j}) + \sigma\frac{\varepsilon_2\varepsilon_3}{1-(1-\varepsilon_2)(1-\varepsilon_3)}\left(T_{3j}{}^4 - T_{2j}{}^4\right) + Q_{solar2} = 0 \tag{2}$$

For the air layer in the outer cavity (node 3), one can establish its energy balance equation to be

$$h_s(T_{sj} - T_{2j}) + h_s(T_{sj} - T_{3j}) + \rho V_s c_p(T_{sj} - T_{s,(j+1)}) = 0 \tag{3}$$

For the mid-pane, the energy equations for nodes 4 and 5 are similar. They are

$$h_s(T_{3j} - T_{sj}) + \lambda_2(T_{4j} - T_{3j}) + \sigma\frac{\varepsilon_2\varepsilon_3}{1-(1-\varepsilon_2)(1-\varepsilon_3)}\left(T_{2j}{}^4 - T_{3j}{}^4\right) + Q_{solar3} = 0 \tag{4}$$

$$\lambda_2(T_{3j} - T_{4j}) + h_e(T_{ej} - T_{4j}) + \sigma\frac{\varepsilon_4\varepsilon_5}{1-(1-\varepsilon_4)(1-\varepsilon_5)}\left(T_{5j}{}^4 - T_{4j}{}^4\right) + Q_{solar4} = 0 \tag{5}$$

Easily, one can find the energy balance equations for the inner cavity (node 6) to be:

$$h_e(T_{5j}-T_{ej})+\lambda_3(T_{6j}-T_{5j})+\sigma\frac{\varepsilon_4\varepsilon_5}{1-(1-\varepsilon_4)(1-\varepsilon_5)}\left(T_{4j}^{\ 4}-T_{5j}^{\ 4}\right)+Q_{solar5}=0 \tag{6}$$

Finally, we can establish the energy balance equations for the inner glass-pane (nodes 7 and 8) to be:

$$h_e(T_{ej}-T_{4j})+h_e(T_{ej}-T_{5j})+\rho V_e c_p(T_{ej}-T_{e,(j-1)})=0 \tag{7}$$

$$E_{in}\varepsilon_6-\varepsilon_6\sigma t_{6j}^{\ 4}+\lambda(T_{5j}-T_{6j})+h_{in}(T_{in}-T_{6j})+Q_{solar6}=0 \tag{8}$$

The eight equations are for the eight unknown temperatures. But, many of the parameters shown in Fig. 4(b) are temperature dependent and the air temperatures along the cavity height are related. Thus, iteration between sections and among the eight equations is needed to obtain a converged solution.

2.2. Experiment setup for obtaining data to validate EnergyPlus

Since the network model use assumptions, it is essential to validate the modified EnergyPlus program by experimental data. The validation is to estimate the impact of two dimensional assumptions for the three-dimensional window on the energy demand and temperature distributions. Gosselin and Chen [9] conducted experimental measurements of the dual airflow window without solar radiation. Should the data be used, the validation would be incomplete. Therefore, this investigation conducted experimental measurements of airflow and heat transfer through the window in a room under actual weather conditions, which was with solar radiation, convection, and conduction. Since such experiment was for the program validation, it is unnecessary to conduct the experiment for a long period of time. The data for one or two days would be sufficient. Then the validated program could be used to compare the energy performance of the three windows in different climates.

This investigation used the heat box facilities at the Harbin Institute of Technology in China to obtain reliable experimental data to validate the modified EnergyPlus program. The facilities were on the roof of a four-storey building and no taller buildings were in the nearby area that eliminated the potential effect of the nearby buildings on the wind conditions around the facilities. This study used six test cells from the facilities: three of them south-facing and the other three north-facing, as shown in Fig. 5. The three south- and three north-facing cells had the dual airflow window, the low-e window, and the blinds window, respectively. The walls with the windows were the only exterior ones, and the rest were interior ones that were controlled to be adiabatic. The control was achieved by exposing all the interior walls, roofs, and floors in a large interior air-conditioned space that had the same air temperature as that of the six cells. Fig. 4 shows the dimension of the cells and the windows. The exterior walls were constructed with 490 mm brick and 100 mm benzene board for insulation. The airflow rate through the dual airflow window was 40 m^3/h, and drawn by fans installed in the window.

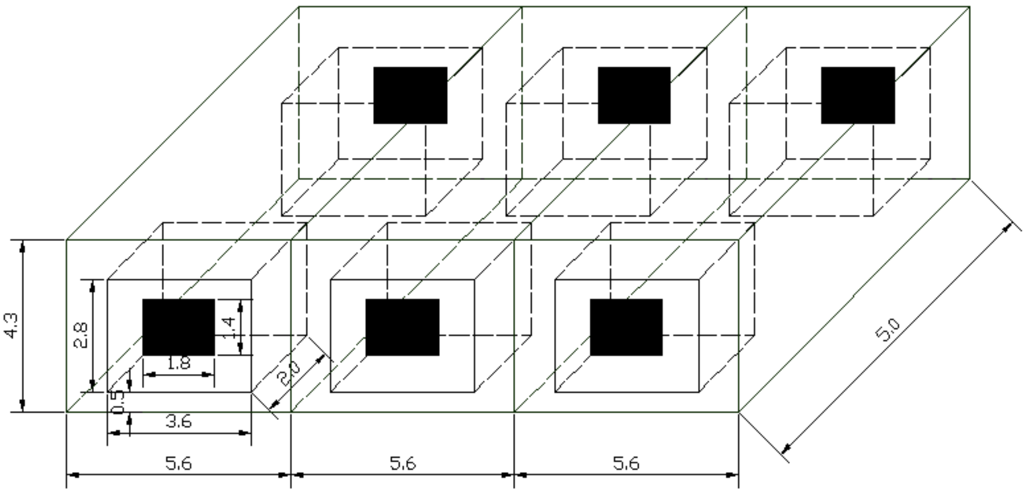


Fig. 5. Sketch of the facilities with six cells installed with the windows (black area) (m)

Each cell used an air conditioner in cooling season and an electric heater in heating season to control the cell air temperature. The indoor air temperature in each cell was measured by HOBO temperature sensors and data loggers. The energy demand by the air conditioners and heaters was also measured. A series of thermocouples were used to measure glass pane temperatures and air temperatures in the window systems. This investigation installed a HOBO Micro Weather Station to collect local weather data at the facilities, such as outdoor air temperature, dew point temperature, wind speed, wind direction, solar radiation, and relative humidity. The data was used in EnergyPlus as input weather data. This paper used the weather data during the one week experiment and only the glass pane temperatures and energy demand data of the last day of the experiment to validate the modified EnergyPlus program. It is important to use one week weather data to eliminate the impact of large thermal inertial of the facilities on the energy demand and temperatures calculated.

From the schematic of the window structure shown in Fig. 6, the flow in the window system should be three-dimensional. As the modified EnergyPlus program simplified the heat and mass transfer in the dual airflow window to be two dimensional, it is essential to study their impact on temperature along the third dimension by comparing the calculated temperature with the data measured with the 16 thermocouples on the surface of both the inner and outer glass panes.

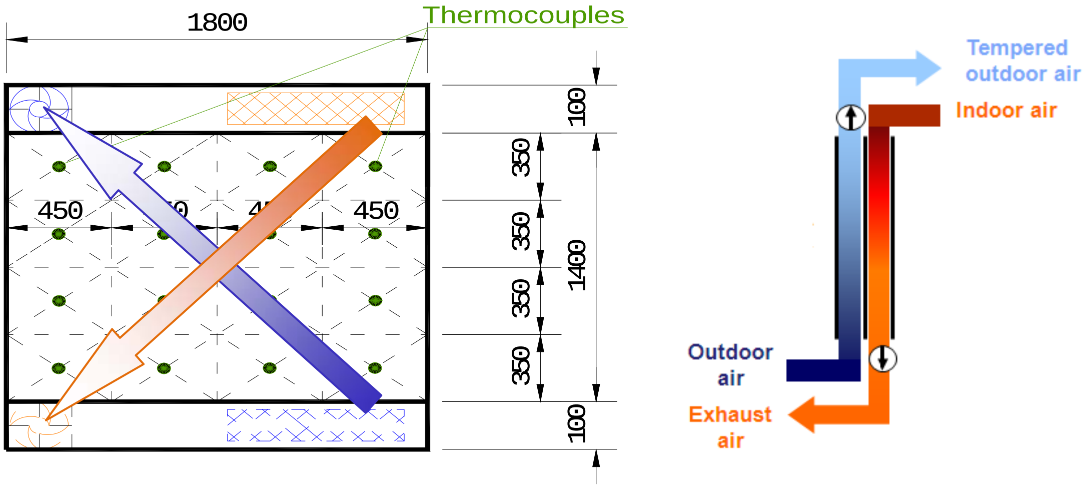


Fig. 6. Locations of the thermocouples and inlet and outlet of the two flow streams on the dual airflow window

3. Results

3.1. Validation of the modified EnergyPlus program

The experiment for validating the assumption used in the third dimension was conducted on a sunny day in Harbin, August 2, 2007. Table 1 shows the temperature distributions at 12:00 pm on that day. The data shows that the temperature difference on the vertical direction ranged from 2.2 to 9.4 K and that on the horizontal direction 0.1 to 1.4 K. The temperature difference between the outdoor and indoor air was 44.8 K. Clearly, the temperature difference along the horizontal direction (the third dimension) was much smaller than that in the other two directions. Therefore, the two-dimensional approximations used in EnergyPlus seem reasonable.

Table 1

Temperature distributions on the glass panes of the dual airflow window at 12:00 noon on August 2, 2007

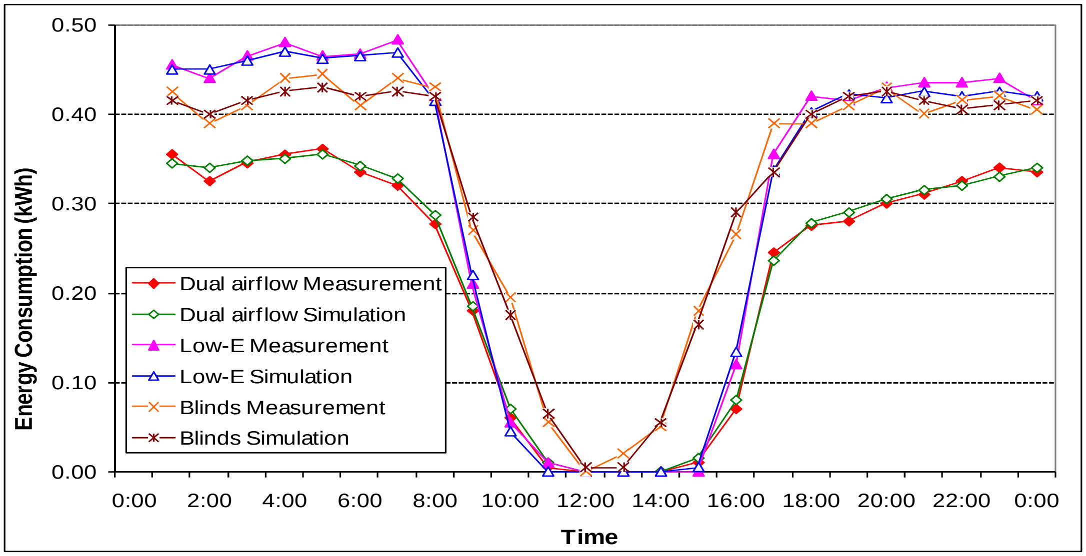
(a) Inner glass pane

23.36	23.03	21.54	22.93
23.19	22.78	22.66	23.24
25.85	24.56	24.25	27.09
26.06	25.21	26.80	27.45

(b) Outer glass pane

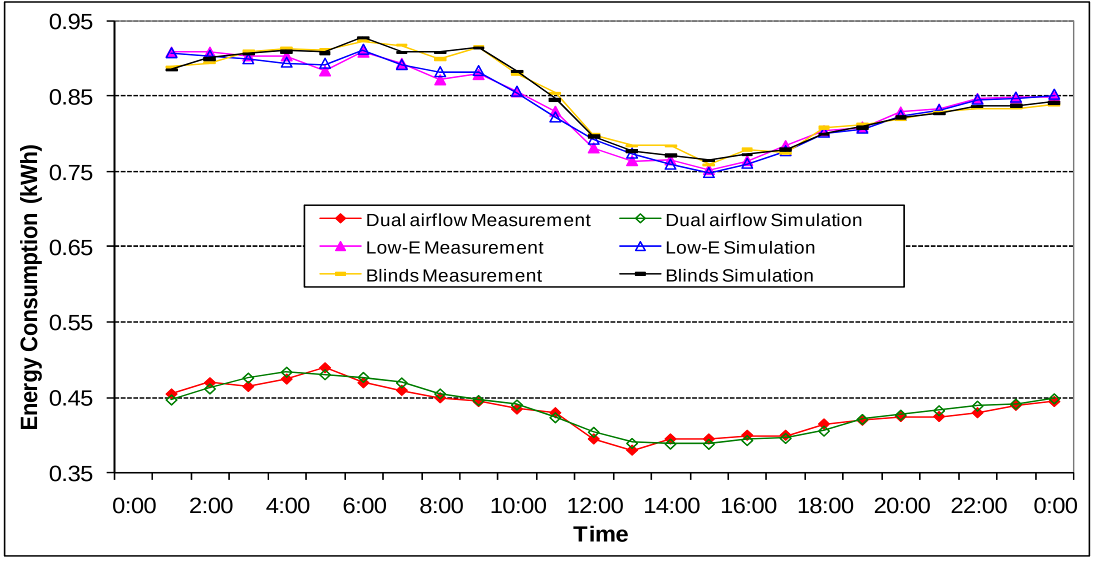
25.35	26.39	26.79	26.60
27.96	28.07	27.72	27.56
35.03	33.04	32.51	33.18
33.78	33.48	33.92	34.20

The validation of the network model used in the modified EnergyPlus program used the energy demand measured from the experimental facilities. The weather data used was measured from February 17 to 23, 2007 when it was sunny. This period was almost the coldest days in Harbin in 2007. The validation is to compare the computed energy demand with the corresponding measured data for the cells installed with the three types of windows for February 23, 2007. Fig. 7 shows that the simulated energy demand profiles of the cells agree well with the measured data with a difference mostly less than 0.01 kW. The difference between the measured and computed results is equivalent to the energy loss due to 0.9 m^3/h (0.045 ACH) infiltration under a temperature difference of 40 K between the indoor and outdoor air. One can imagine that the uncertainties in predicting infiltration could be larger than 0.045 ACH. The difference is acceptable. The simulated curves are smoother than the measured ones, which is another possible evidence of the fluctuated infiltration.

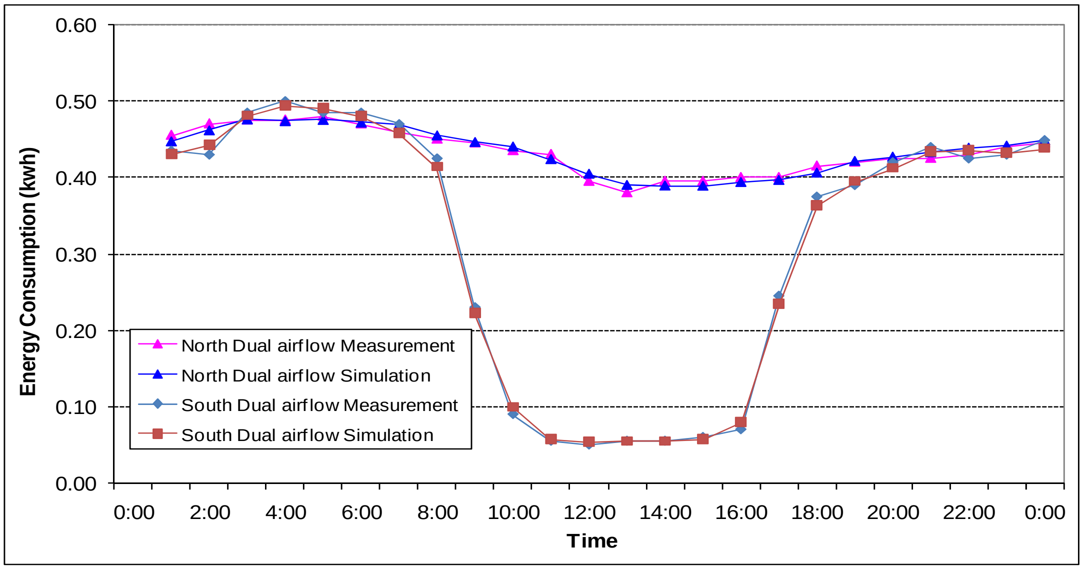


(a) Windows without ventilation in the south-facing cells

(b)



(b) Windows with ventilation in the north-facing cells



(c) Dual airflow window with ventilation in both north-facing and south-facing cells

Fig. 7. Comparison of computed energy demand by the cells with the three types of windows with the experimental data of February 23, 2007

Fig. 7(a) shows the energy demand of the three south-facing cells without window ventilation. The cell with the dual airflow window demanded the least energy because it had the best insulation due to the three glass-panes construction. The energy demand for all the cells with the three types of window became smaller from 9:00, reached to zero in the noon time, and then turned larger again in the afternoon. The change should be due to the heat gain from solar radiation. The cell with the blinds window demanded more energy than that with the low-e and dual airflow windows between 9:00 and 17:00 since the reflection of blinds decreased the heat gain from the solar radiation. The validation shows the modified EnergyPlus can simulate correctly the dual airflow window without ventilation.

Fig. 7(b) shows the energy demand for the three cells with north-facing windows and 40m^3/h supply air rate. The low-e and blinds window were assumed to be able to supply outdoor air directly to the cells via a supply fan. The measured data was modified to factor the impact of the ventilation on energy demand. The figure depicts that the cell with the dual airflow window required only about a half of the energy compared with that for the cells with the other two windows. The significant reduction on energy demand in this case is due to heat recovery between the two streams of flows in the window cavities in the dual airflow window. The energy demand for all the cells with the three types of window changed little during the day due to little solar radiation from the north and very large temperature differential between indoor and outdoor air. The validation concludes that the modified EnergyPlus can simulate correctly the heat exchange between supply airflow and exhaust airflow in the dual airflow window.

Fig. 7(c) depicts the difference of energy demand between the cell with the dual airflow window facing south and that facing north. In the night, the difference was small since the radiation was similar. In the day time, the cell with the south facing window required much less energy than that with the north facing one. Clearly, solar radiation played a very important role here. The modified EnergyPlus program can also simulate accurately the solar radiation.

These efforts have demonstrated that the modified EnergyPlus can be used to calculate energy demand for a room with the dual airflow window.

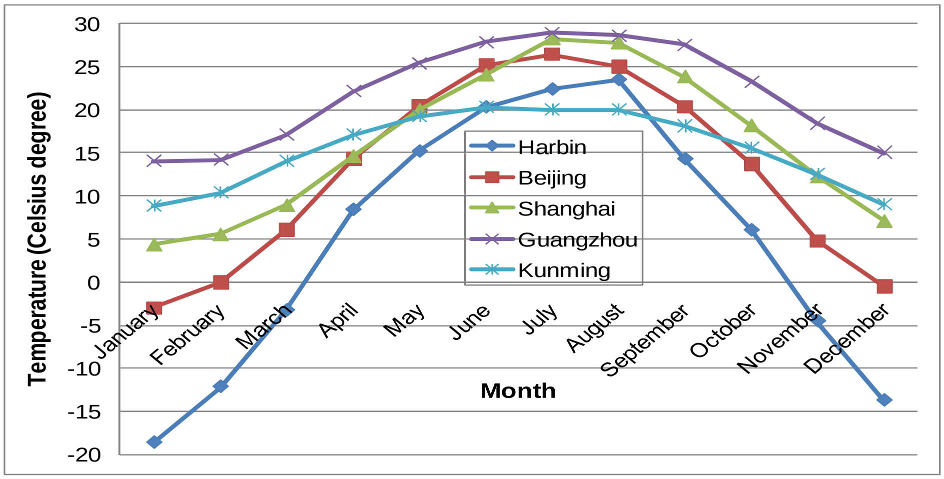
3.2. Analysis of annual energy demand for an apartment with the dual airflow window using the modified EnergyPlus program

The validated EnergyPlus program was then used to simulate energy demand for an apartment with the three different types of window for five climate zones in China. This investigation chose one representative city from each climate zone. The cities are Harbin (severe cold), Beijing (cold), Shanghai (hot in summer and cold in winter), Guangzhou (hot in summer and mild in winter), and Kunming (mild). Table 2 and Figure 8 present the detailed climate information of the five cities.

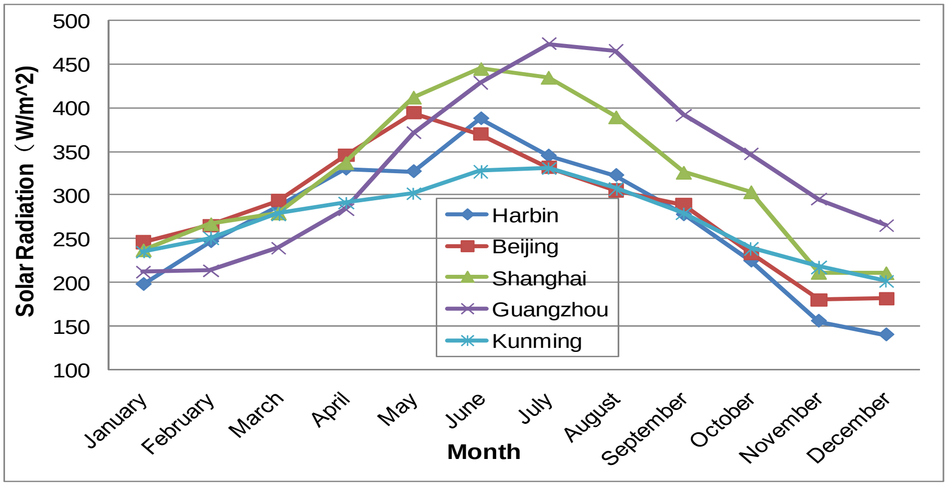
Table 2

Location and design day climate conditions in the five different cities

	Location			**Summer/Winter design day**	
City name	Longitude	Latitude	Elevation (m)	Maximum/Minimum dry bulb temperature (°C)	Daily temperature range (°C)
Harbin	N45.72	E126.68	126.62	30.3/ -29	8.3
Beijing	N39.79	E116.46	31.1	33.2/ -12	8.8
Shanghai	N31.16	E121.43	4.6	34/ -4	6.9
Guangzhou	N23.04	E116.67	6.7	33.5/ 5	6.5
Kunming	N25.02	E102.68	1891.3	25.8/ 1	6.9



(a) Monthly average outdoor dry bulb temperature (^{o}C)



(b) Monthly average solar radiation
Fig. 8. Climate conditions in the five different cities

Fig. 9 shows the layout of a generic apartment with a 60 m^2 floor area. It was on a middle floor of an apartment building and neighbored with other apartments. Therefore, only the south and north walls that were with the windows were the exterior ones. The rest walls, roof, floor were interior envelope. Since its neighboring rooms were assumed to have the same air temperature, the interior walls could be considered as adiabatic. The balcony was enclosed so the window between the kitchen and the balcony was an interior window. The balcony space was treated as a room without heating or cooling. The exterior walls were constructed with 360 mm brick and 80 mm benzene board of insulation. In the figure, W-1 and W-2 were two different sizes of windows, which can be the dual airflow window, low-e window, or blinds window. When W-1 and W-2 were the dual airflow windows, only the fixed panels (800 mm wide) were three layers and the operable parts were conventional double-pane.

This investigation assumed that there were two persons in the apartment. The airflow rate through each of the W-1 window and the W-2 window was 24 m^3/h. This made a total of 72 m^3/h of fresh outside air entering the apartment through the three windows. The flow rate met the ASHRAE Standard of 10 L/s per person for providing acceptable indoor air quality in the apartment. The fan power consumption for all the three windows was estimated to be 50 W. Our simulations considered two scenarios: one with the 72 m^3/h ventilation all the time and the other no ventilation at all. This study further assumed that the total electric load was 100W from lighting and equipments. The indoor air temperature was allowed to swing between 20 and 26 ^{o}C. Within this temperature range, no heating or cooling was needed.

Due to the limited space available, this paper presented detailed results only for Harbin with the severe cold winter climate and Guangzhou with the hot summer mild winter climate. For other cities, only the summary results were presented.

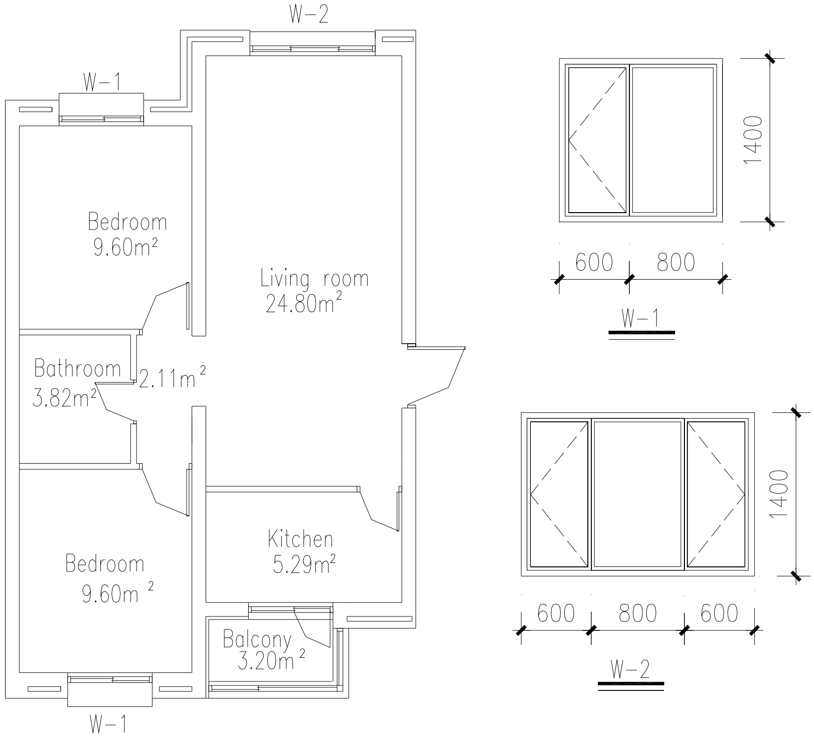
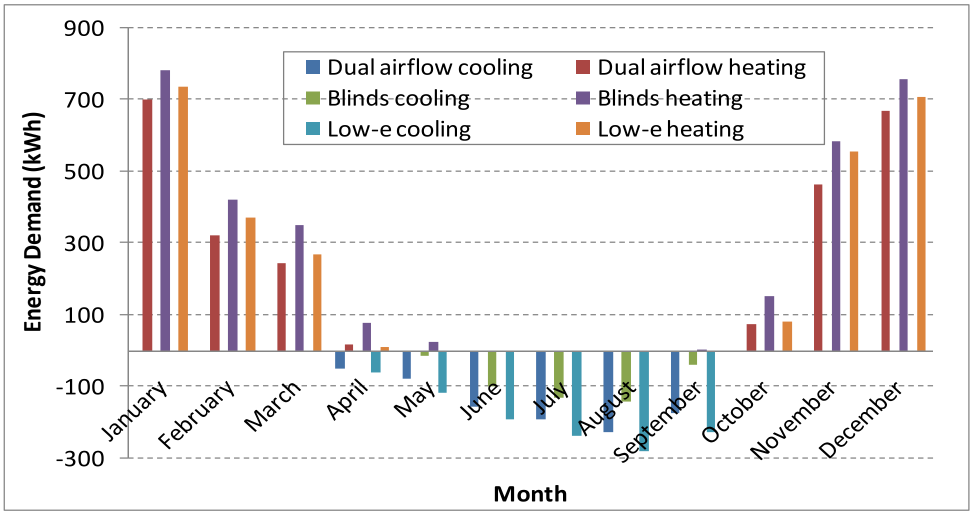


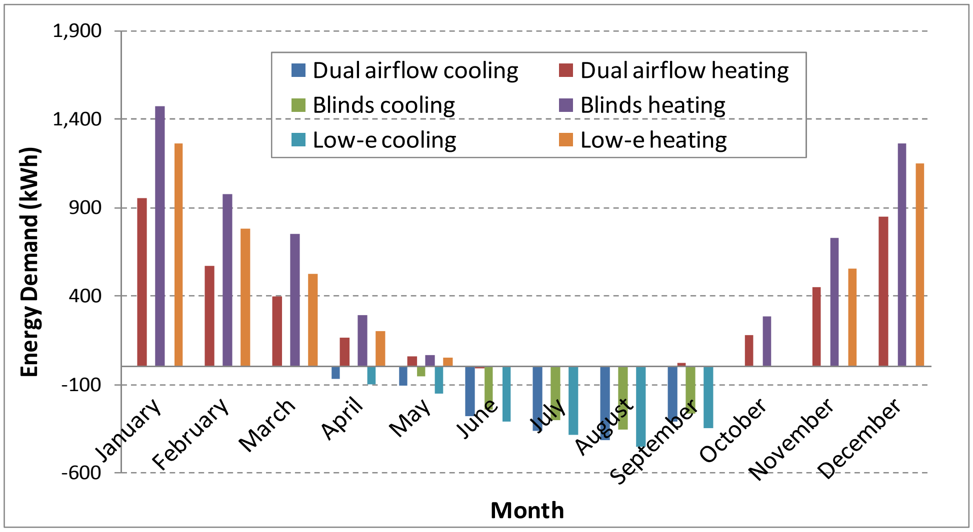
Fig. 9. Layout of the house installed with the windows (W-1 and W-2)

Fig. 10 shows the monthly energy demand for Harbin with and without window ventilation. The figure shows that heating was required for the apartment from October to May and cooling from April to September.

Without window ventilation, the case with dual airflow windows demanded the least heating energy and that with the blinds windows required the most. Clearly, the insulation of the dual airflow windows was the highest and that of the blinds windows the lowest. The dual airflow windows benefited from the three-layer glazing construction. The low-e window had a better insulation than the blinds window due to the low emissivity coating on the inner pane, which can decrease infrared radiation heat loss from the inner space to outer space. The difference in heating demand is small among the three types of windows. In the cooling season, the case with the low-e windows needed most cooling energy and the one with the blinds windows the least. The cooling energy demanded by the case with the dual airflow windows was slightly less than that with the low-e windows. This is because the low-e windows and the dual airflow windows allowed the solar to be transmitted into the apartment due to no shading device, while the blinds windows can reflect solar back to the outdoor space. The solar reflection decreased the solar heat gain and cooling demand. Figure 8(a) shows Harbin has a cool summer, even in the hottest month, the average temperature is lower than 26 °C. Thus, the total cooling energy demand was small.



(a) Without window ventilation



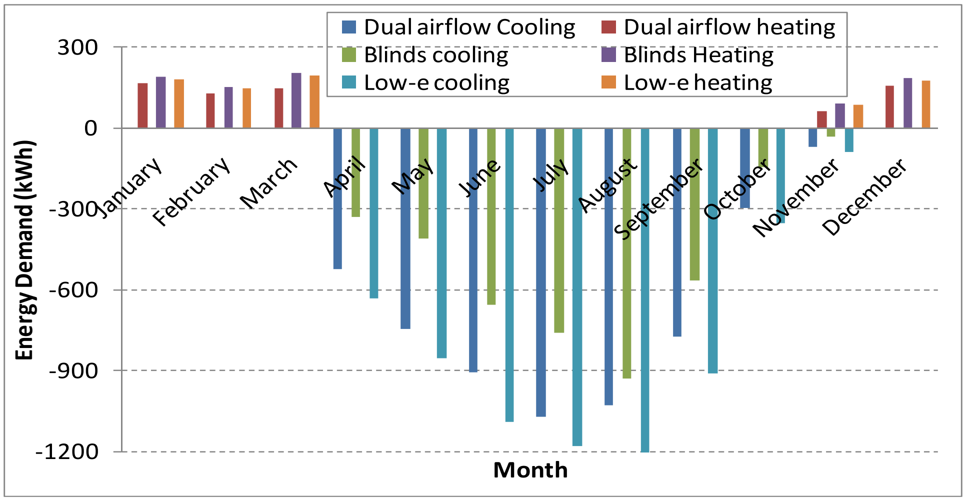
(b) With window ventilation

Fig. 10. Monthly energy demand for the apartment with the three types of windows in Harbin (severe cold climate)

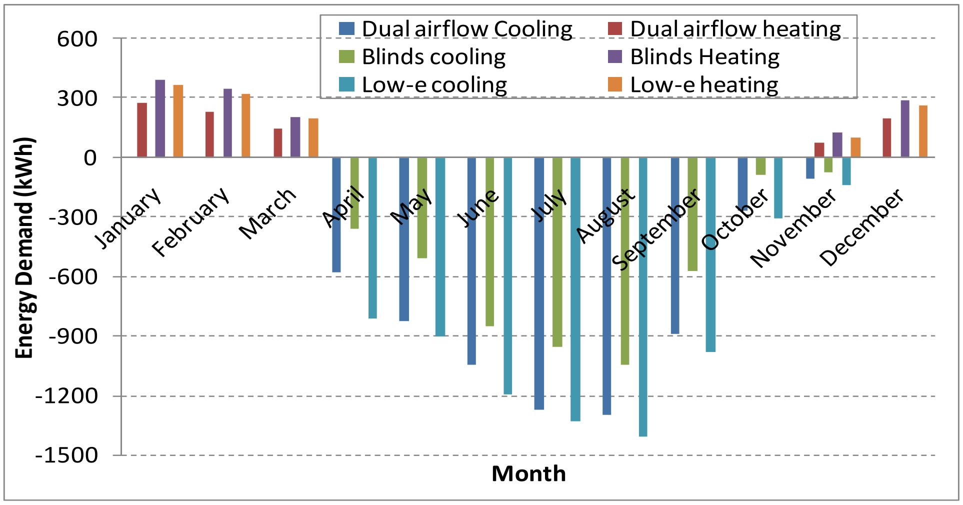
With window ventilation, Fig. 10(b) depicts that the heating load increased for all the cases because the outdoor air temperature was low in Harbin. In the coldest month, the average temperature difference between indoor and outdoor was almost 40 K. Thus the heating load is very high. The increase was especially evident for the cases with low-e and blinds windows because they did not have any heat recovery capability. Compared to the apartment with the same windows without ventilation, the increased energy demand for the apartment was 87% and 63% for the low-e and blinds windows, respectively. The heating energy demand of the case with the dual airflow windows was also increased but only by a moderate rate of 39%, due to the heat recovery by the windows. Overall, the apartment with dual airflow windows demanded 36% lower energy than that with the low-e windows and 48% lower energy than that with the blinds windows in the heating season. On the other hand, the cooling load of the apartment with the window ventilation decreased a little in the cooling period, compared to that without the window ventilation. This is because, even in the hottest month (July) in Harbin, the air temperature in the night was lower than that indoors. This can be seen from Figure 8(a), in July and August, the average monthly temperature is less than 26^{o}C, while the daily high temperature can be higher than 26^{o}C in most days. The ventilation in the night can effectively cool down the building structure (especially the exterior wall with heavy thermal mass) that reduced the cooling demand. The dual airflow window can make the air temperature in the outer cavity higher that can further reduce the heat transfer to the room through the window. The heat recovery from the dual airflow windows was low since the air temperature difference between the two cavities was small. From energy demand point of view, the dual airflow window should be recommended in the heating season not in the cooling season in Harbin. However, the main drive to use the dual airflow window is to improve indoor air quality by bring outdoor air to indoor.

Fig. 11 shows the monthly energy demand for the apartment with the three types of windows in Guangzhou (hot summer and mild winter climate). The results show that heating was needed only from November to March but cooling from April to November. This corresponds to Fig. 8. Only when the averaged monthly temperature is lower than 20^{o}C, the apartment with these windows needs heating. By contrast, when the averaged monthly temperature becomes higher and with solar radiation, it needs cooling.

Fig. 11(a) illustrates the heating and cooling demand for the cases without ventilation. The trend is similar to that for Harbin so the explanation for Harbin can be applied here as well. Fig. 11(b) shows the energy demand for the apartment with window ventilation. In the heating season, the case with the dual airflow windows demanded the least energy and that with blinds windows demanded the most, which is in consistence with that found in Harbin. The winter was mild in Guangzhou so the energy demand for heating was small. In the cooling season, the case with the blinds windows demanded the lowest energy, since only the blinds window can reflect solar heat gain back to the outdoor space in the daytime. The case with the low-e windows demanded the highest energy. This is because the dual airflow windows can cool down the hot supply airflow and can reduce the heat transfer from the outdoor air to the window as explained for the case in Harbin. Compared to the cases without window ventilation, the cases with window ventilation increased the energy demand by 19% for the dual airflow windows, 21% for the blinds windows, and 26% for the low-e windows, respectively. This is because in the cooling season the ventilation by the warm outdoor air would significantly increase the cooling demand. In addition, the heat recovery capacity of the case with the dual airflow windows was low because the temperature difference between the two air streams in the window was small. Overall, the case with the dual airflow windows ventilation required 27% more cooling energy than that with the blinds windows. Thus, shading was more important than heat recovery in summer in Guanzhou.



(a) Without window ventilation



(b) With window ventilation

Fig. 11. Monthly energy demand for the apartment with the three types of windows in Guangzhou (hot summer and mild winter climate)

Table 3 gives a summarized comparison of the total energy demand of the apartment in the five climate zones studied. The table compares the energy demand of the apartment with the dual airflow windows to that with the blinds and low-e windows. The analysis for Harbin and Guangzhou can be used for other climate zones. In the heating season, the case with the dual airflow windows used the lowest energy, and that with the blinds windows used the highest. The heat recovery of the dual airflow window can effectively reduce the energy demand. The annual energy demand shows that the efficiency of the dual airflow windows in conserving energy becomes higher as the climate gets colder. In the cooling season, the case with the blinds windows required the least energy, but that with the low-e windows needed the most. Thus it is important to shade the windows. If the dual airflow window can be shaded from solar radiation, the cooling energy demand could be reduced to be smaller than that with the blinds window. The energy recovery by the dual airflow window in summer was not very effective.

However, the dual airflow window can bring outdoor fresh air to indoor and can filter the outdoor air if necessary. The dual airflow window can be used in all the climate regions.

Table 3
(a) Annual energy demand for heating by the apartment with the three types of windows

Typical city in each climate zone	**Heating demand (kWh)**			**Relative energy reduction compared with the dual airflow window (%)**	
	Dual airflow	Blinds	Low-e	Blinds	Low-e
Harbin	3253	4815	4424	48	36
Beijing	2630	3761	3525	43	34
Shanghai	1698	2394	2258	41	33
Guangzhou	843	1154	1105	37	31
Kunming	1512	1816	1753	21	16

(b) Annual energy demand for cooling by the apartment with the three types of windows

Typical city in each climate zone	**Cooling demand (kWh)**			**Relative energy reduction compared with the dual airflow window (%)**	
	Dual airflow	Blinds	Low-e	Blinds	Low-e
Harbin	1356	1130	1492	-16	11
Beijing	2421	1889	2735	-22	13
Shanghai	3614	2497	4372	-31	21
Guangzhou	5163	3884	5878	-27	14
Kunming	321	266	379	-17	18

4. Discussion

The above results demonstrate that the dual airflow window can reduce significantly energy demand in heating season, but its heat recovery capacity in cooling season is limited. However, it does not mean that the dual airflow window should only be used in cold climate. This study assumed that the dual window worked in all the year round and it had no blinds or shades. The performance of the dual airflow window can be improved by only operating it when the temperature differential between the two cavities is high and overhang shading device and blinds could be added to the outside, inside or outer cavity of the window.

Note that a major function of the dual airflow window is to supply fresh outdoor air to the apartment for improving indoor air quality. Energy demand may not be the only concern. The benefits of the window should take the indoor air quality improvement into consideration. Although the other two windows can be opened for fresh air, the fresh air is not stable and can cause severe draft in cold winter.

5. Conclusions

This investigation developed a network model for calculating the complex heat transfer through the dual airflow window. The model could consider the heat transfer in the two cavities along the window height. The model has been successfully implemented into EnergyPlus, a building energy analysis program.

The network model implemented neglected the heat transfer in the third direction. The measured window surface temperatures show that the temperature variation in the third direction were small compare with that in the vertical and the cross sectional direction. Therefore, the heat transfer in the third direction is not important, although the airflow in the window was indeed three dimensional.

The two-dimensional network model has been further validated by using the energy demand measured from a test facility with the dual airflow window. The computed energy demand is nearly the same as the measured one. This indicates that the two-dimensional approximations used in the dual airflow window are acceptable. The validated EnergyPlus program can be used to analyze energy in buildings with the dual airflow windows.

The validated EnergyPlus was then used to compare the annual energy demand of a small apartment of 60 m^2 floor area with the dual airflow, low-e and blinds windows in five Chinese cities with different climates. The cities are Harbin (severe cold), Beijing (cold), Shanghai (hot in summer and cold in winter), Guangzhou (hot in summer and mild in winter), and Kunming (mild). Without window ventilation, the energy demand of the apartment with the three types of windows was similar. The energy demand of the apartment with the dual airflow window was the lowest for heating, and that with the blinds window was the lowest for cooling. When the window was assumed to supply a total of 72 m^3/h airflow to the apartment through the windows, the trend of the energy demand looks similar to that without ventilation but the differences become very significant. Table 4 concludes that the apartment with the dual airflow windows could reduce the heating energy by 16-48% depending on the climate, compared with that with the other two types of windows. However, the cooling energy demanded by the apartment with the dual airflow windows can be higher than that with the blinds windows because the later can effectively shade the solar radiation. When compared with the low-e windows, the cooling energy reduction of the apartment with the dual airflow windows was only 11 to 21% because of low temperature differential between the two flow streams in the window cavity.

From energy demand point of view, the dual airflow window should be installed in buildings in cold climate. However, if improving air quality is a major consideration for a building, the window can be used in any climate.

Table 4
Relative energy saving by the apartment with dual airflow windows

Typical city in each climate zone	**Heating demand**		**Cooling demand**	
	Blinds Low-e		Blinds	Low-e
Harbin	48	36	-16	11
Beijing 43		34	-22	13
Shanghai 41		33	-31	21
Guangzhou 37		31	-27	14
Kunming 21		16	-17	18

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