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Numerical analysis of the influencing factors on the performance of a pipe-embedded window operated in summer

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ABSTRACT
The pipe-embedded window is a double window structure with pipes embedded inside the cavity to adjust the temperature. The preliminary studies showed that it can significantly reduce the cooling load of buildings with natural cooling sources such as the water from cooling towers in summer. However, the research on the influencing factors of the pipe-embedded window is insufficient. In this paper, the numerical calculation models are established for a pipe-embedded window and a traditional window. The influence of climatic factors, such as the natural cooling source temperature and outdoor air temperature on the thermal performance of the pipe-embedded window are studied. Based on these, the building energy efficiency is analysed. The results show that the thermal resistance of the pipe-embedded window is basically constant. A linear relationship has been found between the inner surface heat flux, pipe heat flux, interlayer mean air temperature and the outdoor air temperature, mean water temperature or solar radiation intensity. The solar radiation intensity, water temperature, outdoor air temperature is ranked from most to least influence. The location of pipe has little effect on the temperature field and heat transfer of a pipe-embedded window. In summer, the difference between inner-glass and outer-glass insulation is small.

KEYWORDS
Space cooling, Pipe-embedded window, CFD, Cooling load, Building energy efficiency

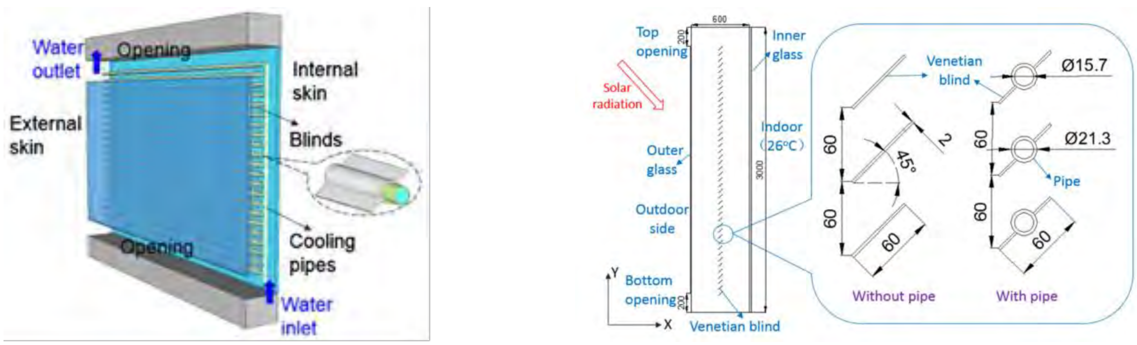
INTRODUCTION
It is crucial to reduce the cooling load caused by glass envelope. Double Skin Façade (DSF) is able to utilize the dry bulb temperature of outdoor air to improve its own thermal performance, so it has a very large energy-saving potential. However, some problems of the DSF have been exposed with the research and application going in deep. As the two main problems, under summer solar radiation, it is prone to the interlayer greenhouse effect because of the interlayer overheat (Gratia and De Herde, 2007); in winter, strengthening insulation can only be achieved by closing the passageway. The external environment is underutilized in regulating temperature as in summer.

To further reduce the cooling load from window, Shen and Li (2016a) proposed a system that embedding water pipes in the venetian blinds of a double glass window utilizing cooling water and studied the system performance under the design condition. Their results showed the effectiveness of the pipe-embedded window. However, the system performance under different weather conditions and water temperatures wasn't studied; Shen and Li (2016b) also studied the performance of the pipe-embedded window they proposed applying it to different regions and orientations. It showed that the above pipe-embedded window had a great energy saving potential in most climatic regions of China. However, the influence of different types of window structures wasn't considered. Overall, at present, the influencing factors on the heat transfer of this kind of window are rarely studied. The analysis of the relevant energy efficiency and heat transfer mechanism is also insufficient, which also restricts the popularization and application of this kind of window to a certain extent.

In this paper, a numerical model is built for a pipe-embedded window. The influences of the climatic influencing parameters, such as the natural cooling source temperature, outdoor air temperature and solar radiation intensity, as well as the geometrical influencing parameters, such as the pipe and insulating layer location on the thermal performance of this kind of window are systematically studied in order to provide reference for engineering practice.

METHODS

Physical model



a) b)

Figure 1. Pipe-embedded double window system. a) Structures, b) Dimensions

Fig. 1 provides the structures and dimensions of a pipe-embedded double window system. Water pipes are embedded into the venetian blinds of the double window. Actually, the differences between the traditional window and the pipe-embedded window only exist in sunshade structures. The dimensions of the studied pipe-embedded window are 3 m (height, Y) × 0.6 m (width, X). In total, 44 cooling pipes are embedded into the venetian blinds with an interval of 60 mm. The outside diameter of each cooling pipe is 21.3 mm. The thermal parameters of materials are determined by referring to the references (Iyi et al. 2014; Zeng et al. 2012). The working conditions about the climatic influencing factors in this paper are divided into three groups: Different water temperatures (A); Different outdoor air temperatures (B); Different solar radiation intensities (C). The working conditions about the geometrical influencing factors are divided into two groups: Different pipe locations (D); Different insulating layer locations (E). The details are summarized in Table 1 and Table 2.

Table 1. The settings of the working conditions (Climatic influencing factors)

Working condition	Water temperature(℃)	Outdoor temperature(℃)	Solar radiation(W/m^2)
A	24/26/28/30	34	500
B	28	32/34/36/38	500
C	28	34	125/250/375/500

*The pipes are located in the middle of interlayer. The insulating layer closes to the indoor side.

Table 2. The settings of the working conditions (Geometrical influencing factors)

Working Condition	Water temperature(℃)	Pipe location	Insulating layer location
D	28	left/middle/right	right
E	22/26/30	middle	left/right

*The outdoor air temperature is 34 ℃. The solar radiation intensity is $500W/m^2$.

Numerical method

A CFD model is established in this paper. The κ-ε turbulence model is adopted in this paper (Iyi et al, 2014). A two-dimensional simplification is adopted in this paper (Manz, 2004; Saelens et al, 2008). The heat transfer is considered to be a steady process. Discrete ordinate (DO) method is adopted for simulating the radiation heat transfer. The commercial CFD software ANSYS Fluent is employed to solve all the numerical equations in this paper. Structured quadratic meshes are divided in the main domain except for a small part near venetian blinds; the mesh with 35,000 cells is eventually employed. The numerical simulation methods in this section have been validated successfully (Shen and Li, 2016b).

Energy efficiency analysis method

The electricity consumption of delivery for a pipe-embedded window system (P_{pipe}, W/m^2) is made up of the electricity consumption of indoor pumps and outdoor heat rejection equipment (such as cooling tower), it can be calculated as:

$$P_{pipe} = \frac{Q_{pipe}}{WTF_{pipe}} + \frac{Q_{pipe}}{EER_{out}} \tag{1}$$

where Q_{pipe} is the heat flux of water pipes, W/m^2. WTF_{pipe} is the transport factor (ratio of transferred heat energy to the electricity consumption of pumps) of the pipe-embedded water system. EER_{out} is the energy efficiency ratio of outdoor unit, the NDRC (2008) recommends the values.

The electricity consumption of delivery for a traditional air conditioning system (P_{room}, W/m^2) is made up of the electricity consumption of indoor pumps, outdoor heat rejection equipment and indoor heat exchangers (such as fan-coil unit), it can be calculated as:

$$P_{room} = \frac{Q_{room}}{WTF_{room}} + \frac{Q_{room}}{EER_{in}} + \frac{Q_{room}}{EER_{out}} \tag{2}$$

where Q_{room} is the indoor air conditioning load caused by the window (equal to the inner surface heat flux), W/m^2. WTF_{room} is the transport factor of the indoor air conditioning water system. EER_{in} is the energy efficiency ratio of indoor unit, the NDRC (2008) recommends the values.

The electricity consumption of the traditional air conditioning system (E_{trad}, W/m^2) can be calculated as:

$$E_{trad} = \frac{Q_{room}}{COP} + P_{room} \tag{3}$$

where COP is the coefficient of performance of the chiller system.

RESULTS AND DISCUSSIONS

Influences of the climatic influencing factors

By calculating the inner surface heat flux, pipe heat flux, interlayer mean air temperature in every case, the relevant fitting formulas can be obtained ($R^2 \approx 1$):

$$Q_{room} = 0.9964 \cdot t_{air} + 3.3456 \cdot t_{water} + 0.07889 \cdot R_{solar} - 86.25 \tag{4}$$

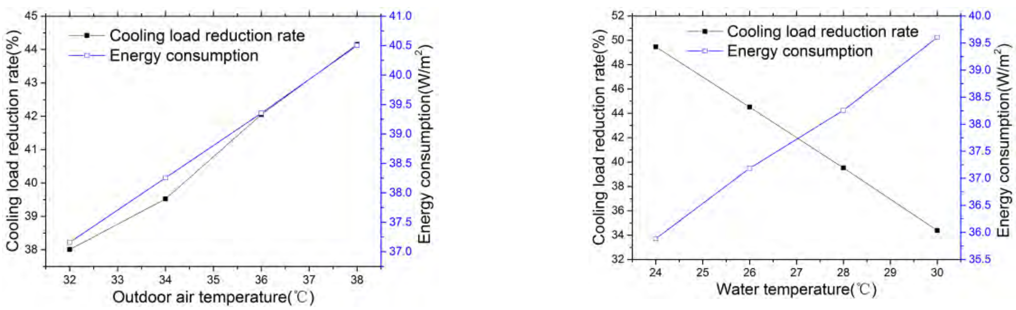
$$Q_{pipe} = 4.7091 \cdot t_{air} - 9.5898 \cdot t_{water} + 0.60877 \cdot R_{solar} + 60.22 \tag{5}$$

$$t_{aver} = 0.1954 \cdot t_{air} + 0.6761 \cdot t_{water} + 0.00413 \cdot R_{solar} + 3.18 \tag{6}$$

where T_{aver} is the interlayer mean air temperature, ^oC. t_{air} is the outdoor air temperature, ^oC, and t_{water} is the water temperature, ^oC. R_{solar} is the solar radiation intensity, W/m^2.

The above formulas with a very high linearity show that the thermal resistance of the pipe-embedded window will be basically constant if the structure of a pipe-embedded is defined. The convective and radiant heat transfer coefficients are basically unaffected by the climatic influencing parameters such as outdoor air temperature. The influence of the water temperature on the inner surface heat flux is significantly higher than that of the outdoor air temperature. However, the pipe heat flux will increase by 50 W/m^2 if the solar radiation intensity increases by 60 W/m^2. The fluctuation range of the solar radiation intensity in one day is often at the order of several hundred W/m^2, so the solar radiation intensity is the most significant influencing factor. The water with a higher temperature can also take away effectively solar radiation heat energy because of the solar radiation heating source with a very high temperature, so the influence of the water temperature is slightly smaller.

Fig 2 and Fig 3 show the influences of the outdoor air temperature, water temperature and solar radiation intensity on the cooling load reduction rate of the embedded window (compared with the traditional DSF) and electricity consumption.



a) b)

Figure 2. Influences of outdoor air and water temperature. a) Outdoor air temperature, b) Water temperature

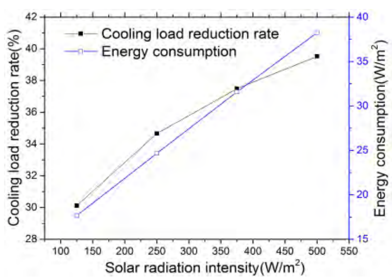
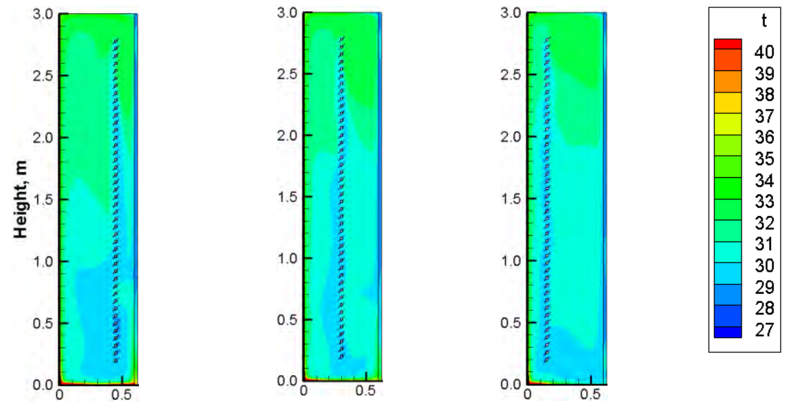


Figure 3. Influence of solar radiation intensity

It can be seen that all the influence relations are approximately linear. The load reduction rate increases with the outdoor temperature and solar radiation intensity, decreases with the water temperature. The water temperature has a greater influence than the outdoor air temperature. It shows that when the outdoor air temperature or solar radiation intensity rise or the water temperature reduces, the pipes can take away not only more heat energy but also a greater proportion of heat energy because of the increase of difference between the water temperature and solar-air temperature. When the outdoor air temperature is 38 ^{o}C, the inner surface heat flux is 84.7 W/m^2 and the load reduction rate is up to 44%; when the water temperature is 24 ^{o}C, the inner surface heat flux is 67.4 W/m^2 and the load reduction rate is up to 49%; when the solar radiation intensity is 125 W/m^2, the inner surface heat flux is 80.7 W/m^2 and the load reduction rate is up to 40%.The electricity consumption increases with the outdoor air temperature, water temperature and solar radiation intensity. However, it doesn't change much around 38 W/m^2 when the outdoor air temperature and water temperature change. The solar radiation intensity has the most significant impact on electricity consumption. When the solar radiation intensity is 125 W/m^2, the electricity consumption reduction rate is up to 25%.

Influences of the geometrical influencing factors

Fig 4 shows the comparison of the temperature fields with different pipe locations. It can be seen that the temperature fields are basically the same. When the pipes are near the indoor side, the overall air temperature between the pipes and outer glass is slightly higher because of more direct radiation hitting the bottom surface. The pipe location almost has no effect on the electricity consumption (around 39 W/m^2) and the heat transfer of the window.



a) Right b) Middle c) Left

Figure 4. Comparison of the temperature fields with different pipe locations (The left boundary direct contacts with the outdoor environment). a) Right, b) Middle, c) Left

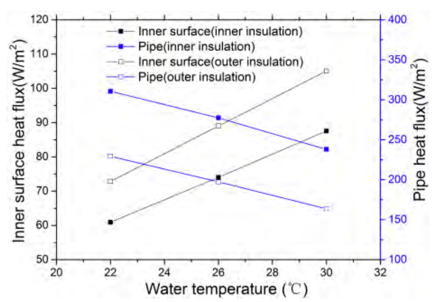


Figure 5. Influences of insulating layer with different locations

Figure 5 shows the influences of insulating layer with different locations. It can be seen that the weights between the inner surface and pipe heat flux with different insulating layer locations are different. When the insulating layer is located near the indoor side, the heat flux passing the inner surface is very little but the heat flux passing the pipe wall is very much. On the contrary, when the insulating layer is located near the outdoor side, the no-water interlayer air temperature is higher, the inner surface heat flux will increase and pipe heat flux will decrease with the decrease of the difference between the interlayer air temperature and water temperature. When the insulating layer location changes, the change range of the pipe heat flux is about 2.5 times that of the inner surface heat flux. In other words, if the cooling efficiency of the pipes is 2.5 times higher than that of indoor heat exchangers, the way of inner-glass insulation will be more energy-saving. However, the pipes are mainly used to remove the solar radiation energy instead of the thermal conduction and convection in summer. Besides, the difference between the water temperature and outdoor air temperature is usually little, so the difference of the electricity consumption between the inner-glass and outer-glass insulation is very small.

CONCLUSIONS

A linear relationship was found between the inner surface heat flux, pipe heat flux, interlayer mean air temperature and the outdoor air temperature, mean water temperature or solar radiation intensity. The solar radiation intensity, water temperature, outdoor air temperature is ranked from most to least influence.

The cooling effect of the pipe-embedded window is significant even if the water temperature is higher than the indoor air temperature. For example, When the water temperature is 28 ^{o}C, the interlayer mean air temperature of the pipe-embedded window is 5.5 ^{o}C lower than that of traditional DSF. The inner surface heat flux of the pipe-embedded window is 52.7 W/m^2 lower than that of tradition DSF, the load reduction rate is nearly 40%; when the water temperature is equal to the indoor air temperature, the load reduction rate can be up to 45%.

In summer, the pipe location almost has no effect on the temperature field and heat transfer of the pipe-embedded window. The performance of glass is not the decisive factor in the overall performance of the pipe-embedded window. The difference between inner-glass and outer-glass insulation is small.

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