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A state-space based method to predict thermal performance of pipe-embedded double skin façade: case study in Guangzhou

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ABSTRACT
Pipe-embedded double skin facade, which arranges pipes in shading device, is an alternative to reduce indoor demand and save energy. To simulate annual performance of this system, a simplified approach based on optical and thermal property is proposed at first, in which dynamic performance is acquired through state-space method. Then the model is validated with former investigation and shows good accuracy. Indoor room temperature with the pipe-embedded double skin façade is analyzed under different types of room in Guangzhou at last. Results show that the pipe-embedded double skin façade could guarantee a barely satisfactory indoor environment where indoor heat gain is small in most time. Besides, superiority would be obvious when solar radiation is strong, indicating the applicability in some typical region with abundant sunshine.

KEYWORDS
natural energy, pipe-embedded window, double skin facade, heat gain, free-running temperature

NOMENCLATURE

DSF	double skin façade
PDSF	pipe-embedded double skin façade
CFD	computational fluid dynamics
LMTD	logarithmic mean temperature difference

INTRODUCTION
Glass curtain has been widely applied in recent years. Nevertheless, heat transfer through transparent envelope is significant, which would lead to the increase heating and cooling load in building. To be specific, large amount of solar radiation transmitted directly into the room in summer while the heat dissipated through glass is remarkable in winter owing to its poor thermal insulation. Many researches concentrated on the thermal performance improvement of glass envelope consists:1) substitution of high thermal performance glazing such as triple glazing (Manz et al.,2006), 2) development of high-efficiency shading devices (Cheng et al., 2013), 3) double skin façade(DSF) with ventilation. Better glazing aims to reduce heat dissipation in winter however better shading aims to decrease solar transmittance in summer, in other words, both the first and second approach is not designed for annual performance. By contrast, double skin façade could be of benefit for both heating and cooling.

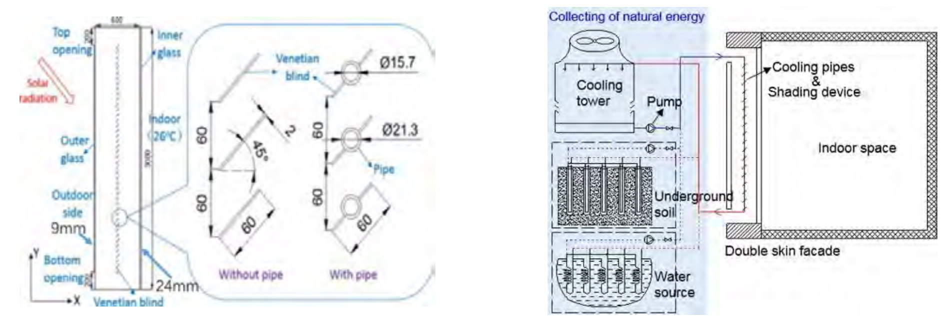
Traditional DSF combined with ventilation is made up of the external glass, shading device and internal glass. Researches shows that the outlet air temperature could reach up to 50℃ when solar radiation is strong, that is, conventional double skin façade combined with ventilation can't remove heat absorbed by venetian blinds efficiently in some cases. Thus, Shen and Li (2016) proposed the idea to arrange pipes in the shading device and simulated the performance by CFD method. Results shows that inner surface temperature can be reduced dramatically compared with traditional DSF, benefitting not only energy consumption but also thermal comfort.

Hourly indoor temperature prediction plays an important role in thermal comfort and energy saving. It is difficult to get the hourly indoor temperature in the whole year by CFD method due to its complication and time-consuming character. Therefore, a state-space method based on optical and thermal property is proposed to calculate the hourly indoor temperature at first. Then thermal performance of pipe-embedded double skin façade(PDSF) in Guangzhou under two different types of room is analyzed.

METHODOLOGY

Description of PDSF

The detailed structure together with schematic diagram of the PDSF are shown in Figure 1. Compared with traditional DSF, cooling pipes are embedded into the shading device for the case of PDSF. Water flows inside pipes to take away the heat absorbed. On one hand, heat transfer coefficient of water to blinds is much larger than air to blinds, so PDSF would remove the radiation more efficiently. On the other hand, natural cooling source such as direct evaporative cooling, ground source heat exchanger is feasible and of low-cost according to the climate feature.



a) b)

Figure1. description of PDSF system. a)structure, b) schematic diagram.

Solar radiation distribution

The dynamic optical properties of glazing should be calculated at first, then the overall optical character of DSF could be obtained including reflection, transmission and absorption. Solar radiation consists of two parts, namely direct fraction and diffuse fraction, whose optical character should be calculated separately (Wang et al.,2016)

$$\alpha_{eg}^{dir} + \alpha_{bl}^{dir} + \alpha_{ig}^{dir} + \rho^{dir} + \tau^{dir} = 1 \quad (1)$$

$$\alpha_{eg}^{dif} + \alpha_{bl}^{dif} + \alpha_{ig}^{dif} + \rho^{dif} + \tau^{dif} = 1 \quad (2)$$

where α, ρ and τ represents absorptivity, reflectivity and transmittance respectively; subscript eg, bl, ig represents external glass, blind and internal glass; superscript dir, dif represents direct radiation and diffuse radiation.

Optical property of diffuse fraction equals to that of direct radiation whose incidence angle is 60 degrees. Thus solar distribution in each layer is acquired, which is the fundamental to thermal performance calculation.

Energy balance equation

Thermal stratification in the cavity is neglected according to the CFD results (Shen and Li, 2016). Since heat transfer coefficient of water side is much larger than air side, we make the assumption that blind temperature is 0.5°C higher than water temperature, which corresponds to our previous study (Shen and Li, 2016). Thus, surface temperature can be calculated based on thermal network, as shown in Figure.2.

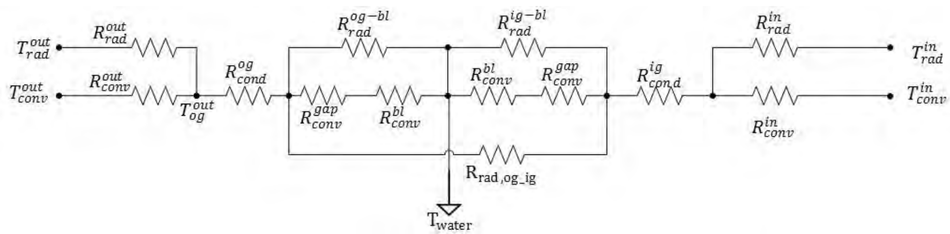


Figure 2. Thermal network of PDSF

where R represents thermal resistance($m^2 \cdot K/W$); subscript conv, cond and rad indi cates convective, conductive and radiative heat transfer respectively.

LMTD model (Utamura et al., 2008) is utilized to simulate the inlet and outlet water temperature difference.

Dynamic simulation based on state-space method

State space method, where space is discretized while time is continuous, was widely used (Parker and Bowman, 2012) and adopted in this study. Compared with conventional window, thermal performance of PDSF is related with not only meteorological parameter but also water temperature. That is, temperature of PDSF and other node temperature of room should be solved through two matrices below respectively.

$$M\overrightarrow{T_{glass}} = \vec{b} \tag{3}$$

where T_{glass} is node temperature of glass, M is the matrix based on thermal network, b is a vector related to climate data.

$$C\dot{\vec{T}} = A\vec{T} + B\vec{u} \tag{4}$$

where T is node temperature, C represents heat capacity, A is a matrix related to heat transfer between different node, u is a vector of thermal disturbance and B is its' distribution on each node.

By the thermal network in figure 2, there are only four nodes in state-space method, thus it is easier to describe the thermal character than conventional CFD approach.

Verification with CFD results

Total indoor cooling load simulated by this state-space based method in five typical cities were verified with that by CFD method (Shen and Li, 2016). Standard κ-ε turbulence model and DO radiation model were adopted in the CFD simulation. Results show that the simplified method can achieve the accuracy within 15 percent in all cases. The detailed information can be seen from Figure. 3. Nevertheless, computing time can be reduced from 2 days to 1 hour for each simulation.

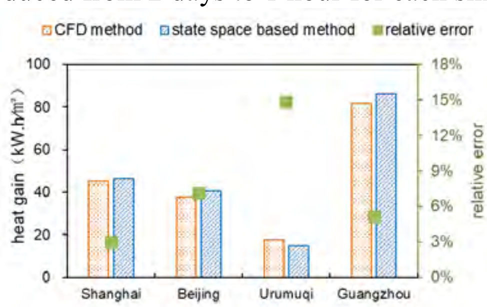


Figure 3. Validation with CFD results

CASE STUDY IN GUANGZHOU

Description of case setup

A typical room in Guangzhou which belongs to hot summer and warm winter zone was selected to investigate thermal improvement by PDSF. Hourly outdoor climate parameter including solar radiation, dry bulb temperature etc. can be obtained from China climate database and it is shown in Figure. 4. The dimension of the room is 5.0 m (length) × 5.0 m (width) × 3 m (height). All of the building envelope was designed according to the design standard GB 50189-2015. A PDSF, whose size is 5.0 m (length) × 3.0 m (height), is installed at south orientation. This room locates in middle floor and the east wall is the external wall. Heat transfer through other internal structure is neglected. Thermal and optical properties of the pipe-embedded double skin façade is described as Table 1.

Table 1. Thermal properties of the PDSF

	External glass	Venetian blinds	Internal glass
Material	stalinite	aluminum	Double glazing
Thickness(mm)	9	2	6+12(air)+6
Heat conductivity Coef-ficient(W/(m·k))	0.28	180	0.09
Density (kg/m3)	2200	2700	1000
Specific heat (J/kg·K)	840	100	880
Refractive index	1.4	/	1.4
Absorptivity(1/m)	5	/	20
Transmissivity	/	0.1	/

Two types of room, namely office room and residential room, in which indoor heat gain are different, are adopted in this study for the applicability discussion. Detailed information of these two rooms is listed in Table 2.

Table 2. Indoor heat gain and occupancy of office and residential room

<table>
<tr><th></th><th colspan="2">Office room</th><th colspan="2">Residential room</th></tr>
<tr><td></td><td>Power(W/m2)</td><td>Occupancy(hour)</td><td>Power(W/m2)</td><td>Occu-</td></tr>
<tr><td>Occupant</td><td>8</td><td rowspan="3">7:00-19:00</td><td>3</td><td>All-time</td></tr>
<tr><td>Equip-</td><td>18</td><td>5</td><td>7:00-22:00</td></tr>
<tr><td>Lighting</td><td>8</td><td>3</td><td>18:00-22:00</td></tr>
</table>

Cooling water produced by cooling tower is analysed in this study. The temperature of cooling water is assumed to be considered 3℃ higher than wet bulb temperature(Klimanek et al., 2015).

In this study, a triple glazing DSF whose external and internal glass are the same as pipe-embedded DSF was simulated as baseline.

Outdoor climate is described as figure 4. The average outdoor temperature hit the peak at July while solar radiation hit the peak at November.

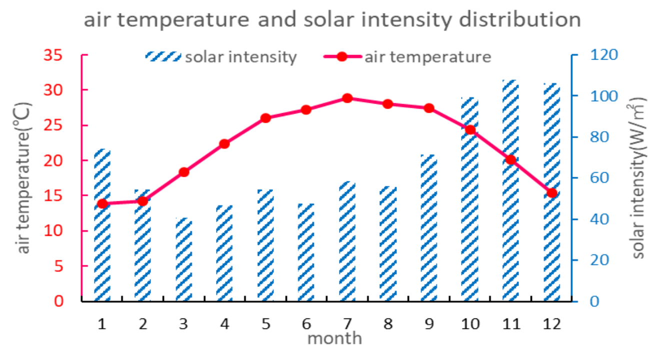
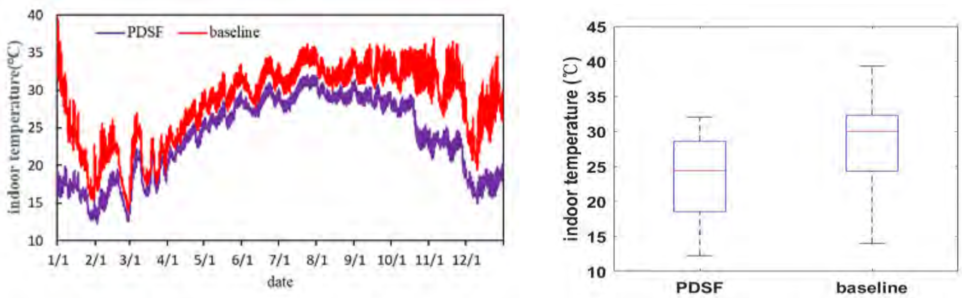


Figure 4. Monthly average outdoor temperature and solar radiation of Guangzhou

Performance of decreasing average indoor temperature

Cooling water provided by water pipes can decrease external glass temperature as well as block solar radiation, therefore room temperature can be reduced. Since heating is not required in Guangzhou, the PDSF is operated all-year around.



a) b)

Figure 5. results of residential room. a) hourly indoor temperature, b)distribution

With built-in pipes in venetian blinds, room temperature can be decreased about 5°C for both office and residential room. Although with pipe-embedded, room temperature would still exceed 30°C in office for some time due to large indoor heat gain.

Superiority of PDSF is significant in spring and autumn when solar radiation is the strong while outdoor air temperature is not so high. What's more, average indoor temperature difference between office and residential rooms is only 3°C, approving that transmitted solar radiation has a tremendous impact on indoor temperature.

Effect of extending non-air-conditioning period

Accumulated satisfactory hours when indoor room temperature is below 25°C and 28°C, which can guarantee a barely satisfactory environment (Okuma et al., 2007) as to save energy, are utilized for the determination of non-air-conditioning period. From Figure. 6, we can conclude that hours when indoor temperature is within 25°C can be increased from 1000 to 3000 hours by applying PDSF in office room. If a broad range of indoor room temperature is acceptable, the accumulated time can reach more than 4000 hours.

Compared with office room, performance in residential room is more promising. There are 5900 hours when room temperature is under 28°C. It means that the pipe-embedded double skin façade is considerably efficient under this circumstance.

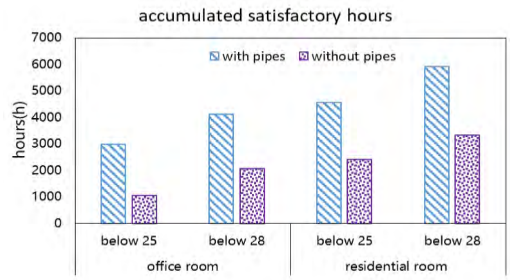


Figure 6 Satisfactory hours in different criteria

CONCLUSION

PDSF integrated with natural energy is a new approach to reduce heat gain. A state-space based method to evaluate dynamic thermal performance of PDSF is proposed in this paper. Performance of two typical rooms with different indoor heat gain in Guangzhou is analysed as a typical case. The main conclusions are as follows.

1) PDSF combined with cooling tower can reduce indoor room temperature significantly in Guangzhou. The average room temperature can be decreased about 5℃.
2) Accumulated hour when indoor temperature is within 28℃ accounts for 5900 hours for residential room, indicating room temperature can meet the basic requirement in most time with the assistance of PDSF if indoor heat gain is small.
3) Performance in October is the most efficient when solar radiation is strong because shading blind embedded with water-pipes can block solar radiation and take it away directly, which indicates that PDSF could be promising in regions with strong solar radiation such as western china.

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