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Dynamic modeling of the ventilated double skin façade in hot summer and cold winter zone in China

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ABSTRACT

An improved zonal approach with a dynamic optical model of the venetian blind and airflow network model is proposed to model the mechanical ventilated double skin façade (DSF) in hot summer and cold winter zone in China. It is validated by the experiment in both cooling and heating season cases. The comparison results show that the simulated results fit well with the measured results. The effects of the ventilation rate and slat angle on the inner glass temperature and heat gains through the DSF are discussed. Both increase ventilation rate and slat angle can decrease the inner glass temperature and heat gains through the DSF, but the decrease range is greater by increasing the slat angle. Compared to the slat angle at 0°, heat gains can be reduced by 63% when the slat angle at 60°. The proposed method can not only meet the requirements of engineering application, but also spend less computational time in modeling DSF dynamically in hot summer and cold winter zone in China. It can be used to evaluate the thermal performance and simulate the annual energy consumption of DSF.

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1. Introduction

Double skin façade (DSF) consists of two or three glasses and an air cavity becomes more and more popular in commercial buildings for its good aesthetics, super visual comfort, and good acoustic. Nevertheless, the complex thermal and energy performance are not clearly known by building designers and owners [1–5].

The thermal and energy performance of the DSF not only involves the thermal properties of glasses but also involves the optical properties of the shading device and glasses and the airflow regime, which is a complex heat transfer process. Scholars have devoted themselves to adopting a proper method to investigate the complex performance of it for a long time. Firstly, analytical and non-dimensional methods [6–10] are used to analyze the thermal behavior of the DSF, especially, the effect of the interactive parameters. These methods can quickly obtain the results without consuming large time. However, it is not suitable for the dynamic modeling of the DSF. Lumped model is another simple method which lumps the temperature in the vertical direction of each layer in the DSF [11,12]. Grabe [13] adopted this method to predict the airflow and temperature of the DSF. In his model, parameters of the DSF were treated as a point, and the Bernoulli equation was used to analyze the air flow in the cavities. The results illustrated that using the traditional resistance factor for analyzing the flow characteristics of the natural ventilation of the DSF may lead to wrong results without considering the turbulent flow. Panão et al. [14] proposed a lumped RC model to predict the room air temperature of a building with a DSF. It was found that this method don't reduce the overall accuracy with approximately 1 °C mean absolute error for the room air temperature. This method can provide some useful information in the design phase and can largely simplify the mathematical descriptions in the heat transfer process without high computational resources. However, it cannot describe the vertical temperature gradient of the glass and airflow concretely, that is, some deficiencies exist in the thermal performance estimation of the DSF.

Air flow property is a significant influence factor in the thermal performance of DSF. Compared with the lumped method, airflow network model is a relative detailed method in the air flow description. Hensen et al. [15] indicated that the airflow network model treats each air space as a node and some relevant laws are established, e.g., the equation of mass conservation. Tanimoto and Kimura [16] used thermal and airflow network model to study the performance of a DSF with venetian blind and an integrated roll screen. This method can provide information of the final state of the

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Nomenclature

T	temperature, K
A	area, m^2
h	heat transfer coefficient, W/(m^2K)
d	thickness, m
m	mass flow rate, kg/s
c	specific heat capacity, J/(kg K)
Q	heat flux, W/m^2
v	air flow velocity, m/s
Nu	Nusselt number
Ra	Rayleigh number
H	height, m
D	cavity width, m
ΔP_t	total pressure, Pa
ΔP_{fan}	negative pressure caused by the exhaust fan, Pa
ΔP_{th}	thermal pressure, Pa

Greek symbols

λ	thermal conductivity, W/(m K)
ε	emissivity
σ	Stefan–Boltzmann constant, 5.67×10^{-8} W/(m^2K^4)
β	ratio of the exhaust air rate of the outer cavity to the exhaust air rate of the fan
ρ	air density, kg/m^3
φ	slat angle, °
μ	flow coefficient

Subscripts

eg	exterior glass of the outer double glazing
am	ambient
gap	air gap of the outer double glazing
eg-am	between the exterior glass and the ambient
ig	interior glass of the double skin façade
eg-ig	between the exterior glass and interior glass
ca1	outer cavity
ca2	inner cavity
bl	venetian blind
ing	inner glazing of the double skin facade
ig-ca1	between the interior glass and the outer cavity
ig-bl	between the interior glass and the blind
bl-ca1	between the blind and the outer cavity
bl-ca2	between the blind and the inner cavity
ing-ca2	between the inner glazing and the inner cavity
in-ing	between the interior glass and the inner glazing
bl-ing	between the blind and the inner glazing
room	room
ing-room	between the interior glass and the room
sol	solar energy
ex/in	exterior glass and/or inner glass
mean	mean (average)
air	air
cc	convective heat transfer coefficient of the closed cavity
(ca1,ca2)	between outer and inner cavity
O	outdoor
o,ca1	from outdoor to the outer cavity
o,ca2	from outdoor to the inner cavity
fan	exhaust fan
h	heat gain
t,sol	total solar gains
i	serial number

airflow quickly without consuming large computational resources. Nevertheless, the airflow network model should combine with the proper thermal model, optical model, and thermal buoyancy effect in the DSF. Control volume model is an alternative method in the numerical simulation of DSF. Faggembauu et al. [17,18] employed this method to study the thermal performance of DSF without venetian blind in Mediterranean climates. The same method was also used by Gracia et al. [19] to study the thermal performance of ventilated façade with phase change material. Actually, this method aims to obtain an accurate simulation result so that adequate small control volumes are required. In other words, it is a complex and time-consuming work to model the dynamic thermal performance and simulate the annual energy consumption, especially for a DSF with large size. Another limitation of this method is the airflow problem, that is, the pressure distribution of the airflow for the cavity should be known before the calculation.

Zonal method is a good choice to establish the heat and mass relationship of each zone for the building environment simulation [20,21]. In each zone, thermophysical parameters are regarded as uniform. This method is an intermediate one between the lumped method and control volume method. Jiru and Haghighat [22] used this method to investigate the DSF. It was found that the zonal model can be used to assess the performance of the DSF system with venetian blind. Also it can provide more detailed information, which cannot be realized by lumped and control volume methods. In their study, the mass flow rate is calculated by the power law model and formed a complex non-linear equations system and Newton-Raphson algorithm is repeatedly used in the iteration process. Moreover, the dynamic optical properties of the glass and venetian blind are not considered, but they have significant effect on the accuracy of the simulation results. To obtain an overall and accurate simulation result of the air flow for the DSF, computational fluid dynamics (CFD) method is the best choice. It not only can accurately describe the flow regime, velocity, and vertex of the airflow in the cavity, but also can determine the heat transfer coefficient of the DSF system [23–29]. However, it is not a perfect method in the thermal and energy performance simulation of a long time such as one year, and the complex optical properties cannot be obtained directly. Also the venetian blind model could be a problem in the simulation process. Due to the small thickness and large number of the blind slats, the number of the meshes in the CFD model is extremely large. For this reason, a porous media model was used in the CFD model to study the airflow of the venetian blind by Zeng et al. [30]. Therefore, the CFD model is not suitable for the dynamic modeling and simulating the annual energy consumption of the DSF.

Some scholars attempt to develop simplified methods to model the DSF quickly. A fast assessment method based on the CFD approach for DSF in cooling season was proposed by Xue and Li [31]. It mainly focuses on the static energy performance assessment of the DSF with a *RCI* indexes related to energy flow, solar gains, and *U* value rather than the dynamic modeling. Another simplified model based on the RC method was proposed by Elarga et al. [32]. This model was implemented in a Microsoft Excel sheet without any complex mathematical expressions and high computational resources and it was validated by the more detailed model DIGITHON. It was found that this model can be used to predict the thermal performance of the DSF, despite some discrepancies exist.

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