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Double-skin façade optimization design for different climate zones in China

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ABSTRACT

While the natural ventilation double-skin façade is a widely-used technology, its thermal performance is not yet fully understood. Hence, this paper investigates the thermal performance and optimization of double-skin façades. Previous studies focused on typical moments or standard days to evaluate the thermal performance of a double-skin façade. The current study adopts a simplified method based on Computational Fluid Dynamics (CFD) to obtain the hourly heat gain and total heat gain of a double-skin façade for an entire cooling season. The data is then used to evaluate thermal performance. Finally, based on the total heat gain of the double-skin façade with different structural parameters for an entire cooling season, this paper proposes optimization parameters for different climate zones in China.

1. Introduction

In recent years, the double-skin façade (DSF) has been widely applied in modern high-rise buildings due to its 'high-tech' appearance and energy-saving capacity. DSF serves as a kind of envelope structure of buildings, which composes inner glass, outer glass and an air cavity in between for ventilation. Per the ventilation pattern, DSF can be divided into external and internal circulation types, with a further sub-division of external types into natural and mechanical ventilation. The natural ventilation external circulation DSF (with openings on outer glass for natural ventilation) is frequently used in China due to its simple control strategy and energy-saving capacity. Compared with traditional single-skin facades, DSF provides better heat preservation in winter (Gratia and Herde, 2007b) as well as reducing indoor heat gain via cavity ventilation in summer (Poirazis, 2004; Hendriksen and Sørensen, 2007; Colak and Fulli, 2015; Ghaffarianhoseini and Ghaffarianhoseini, 2016). Previous studies show that the DSF structure significantly influence the DSF thermal performances (Jiang and Long, 2006; Gratia and Herde, 2007c; Zeng and Li, 2012a). In Belgium, Gratia and Herde (2007c) used the DSF module of an office building to study thermal performance. The results showed that the energy consumption of buildings with a ventilated DSF were less than that of buildings with a non-ventilated DSF. The blind size and location also influenced the reduction of cooling consumption for high-temperature summer days. Jiang (2006) found that the heat discharge from cavity openings significantly influenced DSF heat transfer. Here, the cavity temperature tended to be higher than the outer temperature. Furthermore, he found that short-wave radiation transmittance of the blinds also influenced DSF thermal performance. However, other studies have shown that the outer environmental parameters also affect DSF thermal performance (Haase and Amato, 2006; Torres and Escalona, 2007; Shameri and Alghoul, 2011; Reith, 2015). Different types of DSF are suitable for different climate zones (Saelens, 2002), which indicates that DSF optimization should consider climate factors. Moreover, study has been done on the impact of DSF orientation in Europe, showing that different DSF orientations affected the indoor heat gain (Gelesz and Reith, 2015). It has been found that climate conditions affected the thermal performance of a south-facing DSF; as such, dynamic operation of DSF should be applied (Gratia and Herde, 2004b). Given that the costs for dynamic operation are relatively high, DSF structural optimization for different climates is a more economically viable solution. To achieve this solution, further study is required into DSF thermal performance evaluation and design optimization in different climate zones.

This study conducts experiments and simulations to investigate DSF thermal performance. Previous studies have also investigated

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Nomenclature

q	heat gain, kW/m^2
H	height of DSF, m
H_{dir}	height of the outer glass region receiving direct radiation, m
H_{re}	height of the outer glass region receiving once-reflected radiation, m
A'	solar altitude angle, °
$J_{s,diff}$	diffusion radiation intensity, W/m^2
$J_{s,dir}$	direct radiation intensity of DSF, W/m^2
J_s	total radiation intensity of DSF outer glass, W/m^2
R	reflectance of the base material of the DSF
τ	transmittances
ε	emissivity
λ	thermal conductivity, W/(m K)
δ	thickness of DSF, m
δ_i	thickness of DSF inner glass, m
U	overall heat transfer coefficient, W/(m^2 K)
$h_{ig,is}$	natural convective heat transfer coefficient between indoor air and inner glass surface of DSF, W/(m^2 K)
h_{lr}	long-wave radiation heat transfer coefficient between the indoor air and inner glass surface, W/(m^2 K)
t_{out}	outdoor air temperature, K
t_{in}	indoor air temperature, K
RCI	Radiation Conversion Index of DSF, (W/m^2)$^{1/3}$
D	cavity width of DSF, m
x	distance between the blind and outer glass of DSF, m
h	ventilation opening width of DSF, m

Subscripts

tot	total
trans	shortwave radiation transmission
conv	convection
td	temperature difference
rad	solar radiation
lr	long-wave radiation
sr	short-wave radiation

DSF performance. Wang and Huang (2006) studied the energy-saving performance of double-skin and single-skin façades alongside ventilated DSF and non-ventilated DSF. However, only the inner glass temperature under different conditions was measured, which does not represent DSF thermal performance. Zeng and Li (2012a) studied the impact on thermal performance of DSF shading, ventilation, and heat insulation, then summarized the ventilation rate and temperature distribution in the cavity under different solar altitude angles. However, the experimentation was only conducted under typical conditions. Experimentation costs for the heat gain data of an entire cooling season are relatively high. As such, a simulation method is better suited to the study of DSF thermal performance where measurements are required for an entire cooling season.

The following models have previously been used to analyze DSF thermal performance: Airflow Network Model, Zonal Approach, and Computational Fluid Dynamics (CFD). The Airflow Network Model was used to study the impact of double-skin orientation and wind orientation on DSF thermal performance (Gratia and Herde, 2004a). The Zonal Approach was used to determine the impacts of height, airflow rate, and venetian blinds on DSF thermal performance (Jiru and Haghighat, 2008). While each of the above-mentioned models have the advantage of offering simple calculations, they lack the accuracy required in that the complex airflow in the cavity is not taken into account in the calculation. To address this issue, CFD can simulate complex airflow in the cavity and calculate basic parameters involving velocity, consistency, and pressure for each position in the cavity. Therefore, CFD is more accurate and, hence, more commonly used in the study of DSF.

Based on CFD, other studies have also considered the meteorological data to investigate the thermal performances of different types of DSF (Safer and Woloszyn, 2005; Popovici and Cirlan, 2016). However, the results of these studies only represented the DSF thermal performance of ‘typical moments’. To obtain more reliable results, some studies have adopted a ‘standard day’ to investigate DSF thermal performance (Jiru and Tao, 2011; Parra and Guardo, 2015). There have also been studies that obtained data based on several standard days (Gratia and Herde, 2007c; Zeng and Li, 2012b). In general, previous studies have mainly focused on typical moments or several standard days to evaluate the thermal performance of DSF. Here, the CFD modeling and simulation processes are relatively complex and the dynamic modeling calculations place high demands on computing and time resources.

Both former studies using experimental or simulation-based methods have applied the DSF heat gain of typical moments or several standard days to evaluate DSF thermal performance. However, the thermal performance of DSFs cannot be properly evaluated using typical moments or several standard days. To obtain greater accuracy, total heat gain for the entire cooling season must be used to evaluate DSF thermal performance. This study conducts simulations using a simplified method proposed by Xue and Li (2015) based on CFD to calculate the hourly heat gain of DSF for an entire cooling season. The total heat gain of a DSF with different structural parameters for an entire cooling season are then used to determine the optimal DSF parameters for different climate zones in China.

2. Methodology

2.1. Calculation of DSF heat gain

The total DSF heat gain can be divided into three parts:

$$q_{tot} = q_{trans} + q_{conv} + q_{lr}$$

where q_{tot} is the total DSF heat gain; q_{trans} is the heat gain from the shortwave radiation transmission; q_{conv} is convective heat transfer between DSF inner glass and indoor air; and q_{lr} is long-wave radiation heat transfer between DSF inner glass and indoor objects (see Fig. 1).

Compared with q_{trans} and q_{conv}, q_{lr} only comprises a small portion of q_{tot}; as such, it can be neglected (Gratia and Herde, 2007a).

And q_{conv} is caused by the temperature difference between the inner glass and indoor air. The temperature of the inner glass can be divided into two parts: outdoor temperature and rising temperature caused by solar radiation.

Hence, heat gain from convective heat transfer is:

$$q_{conv} = q_{conv,td} + q_{conv,rad}$$

where $q_{conv,td}$ is heat gain from the convective heat transfer caused by the temperature difference between outdoor and indoor air; $q_{conv,rad}$ is heat gain from the convective heat transfer caused by solar radiation.