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Heat transfer analysis of an integrated double skin façade and phase change material blind system

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ABSTRACT

In this study, the heat transfer in an integrated double skin facade (DSF) and phase change material (PCM) blind system has been theoretically analysed. Both heat transfer and airflow models with CFD methods have been developed for the integrated DSF and PCM blind system. Data from an existing typical DSF building have been obtained in order to define input parameters for the simulation exercise and validate the numerical models. The temperature and velocity fields in DSF with the PCM blind system has been predicted under overheating scenario using the ANSYS Workbench FLUENT software and been compared with case of conventional aluminium blind system. This study has shown that the integrated PCM blind system was able to reduce the average air temperature and outlet temperature of the DSF while improving the convective heat transfer between the cavity air and the blades. Compared with the aluminium blind, the PCM blind can absorb large amount of excessive heat in the cavity. Overall the integrated PCM blind system has the potential to be used as an effective thermal management device for minimising the overheating effect in DSFs.

1. Introduction

The building sector is responsible for approximately 40% of the world's total annual energy consumption [1]. This situation has therefore raised the need for applying various sustainable design concepts for reducing energy consumption in buildings [2]. As a form of envelope in modern buildings, double skin façade (DSF) has already become a common architectural design feature around the world with great potential in energy saving [3]. DSFs are types of building envelopes consisting of external and internal skins with intermediate space between them. The DSFs have advantages such as providing natural ventilation, natural daylight, and acoustic barrier to buildings [4]. Kim et al. [5] also proved that DSFs can be used to reduce energy consumptions in buildings during both heating and cooling seasons while maintaining indoor comfort levels. However, studies conducted by Tascon [6] revealed that DSFs tend to experience overheating problems during warm seasons.

To this end various methods have been studied as possible solutions for minimising the overheating problems. For instance Jager et al. [7] indicated that the overheating problem can be avoided by ensuring a minimum distance between the internal and external panes of a DSF due to greater stack effect and adequate air flow in wider cavities. Wigginton et al. [8] stated the sizes of ventilation openings are crucial parameters influencing the cavity temperature since they determine the efficiency of air exchange between DSF and external environment. Fallahi et al. [9] demonstrated that utilisation of concrete slats as thermal mass in mechanically ventilated DSF can help to decrease the risk of overheating. Recent studies have further reported that the effectiveness of concrete can be enhanced by incorporating phase change materials (PCMs) [10]. Gracia et al. [11,12] integrated a PCM system into the air channel of a ventilated facade and observed reduction of overheating effect during the PCM solidification and melting periods. Even though the above highlighted studies have provided possible solutions to the overheating effect in DSFs, it is clear that there are still some technical and scientific barriers that need to be overcome.

The focus of this paper is on the development of a physical–mathematical model of an integrated DSF and PCM blind system by using CFD methods. The numerical results are validated

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Nomenclature

A	area (m^2)
C_p	specific heat (kJ/kg·K)
Q	heat (W)
E	total energy
H	enthalpy (kJ/kg)
ΔH	latent heat (kJ/kg)
T	temperature (K)
ΔT	temperature difference
T_0	operating temperature/surface temperature of objective
T_s,T_∞	temperature on surface/of fluid far from surface
S_φ	user-defined source term
Γ_φ	the diffusion coefficient
φ	a common variable that refers to the continuity equation, temperature, and velocity
$\vec{U}$	velocity vector
G_{sol}	Solar irradiance
$\vec{J_j}$	diffusion flux of species j
h	convective heat transfer coefficient (W/m^2K)/sensible enthalpy (kJ/kg)
k, k_{eff}	thermal conductivity/effective conductivity (W/mK)
t	time (s)
ρ, ρ_0	density/reference density
ν	kinematic viscosity
μ	molecular viscosity
μ_t	turbulent viscosity
s	path length
α	absorption coefficient/expansion coefficient of air
β	thermal expansion coefficient/liquid fraction
τ	transmittance of the DSF outer glass skin
ε	emissivity
σ	Stefan-Boltzmann constant/solid angle/turbulent Prandtl number
δ	characteristic length of geometry

Subscripts

net	net heat gain of DSF
sol	total solar radiation on the DSF
refl	reflected solar radiation
ref	reference value
abs	absorbed solar radiation
tra	transmitted solar radiation
1	external glass skin of the DSF
2	internal glass skin of the DSF
conv	convective heat transfer
rad	radiative heat transfer
a	cavity air
b	blind
k	turbulence kinetic energy
i	indoor
o	outdoor
p	PCM layer of the blind
s	substrate of the blind
ε	dissipation rate
x, r, z	axial/radial/swirl coordinate

by comparing with experimental measurements. The heat transfer behaviour of the integrated system under overheating scenario is then evaluated and compared with conventional aluminium system.

2. Background

Double skin facades have been widely applied in different climatic area around world [13,14]. This study mainly investigates the hot summer and cold winter regions where DSFs are favourable applications in winter and mid-season [15], but face a major challenge of overheating in summer which tend to result in unpleasant indoor environment and increase the cooling loads in buildings [16,17]. Previous researchers have raised the overheating problems associated with DSFs and come up with several solutions to dispel the problems. Tascon [5] raised that the main causes of overheating in DSF which included ineffective removal of heat stored within the DSF system, inappropriate location and size of shading devices, and inadequate operations of the DSF for specific thermal environmental conditions. Jager et al. [6] and Wigginton et al. [7] reported physical considerations at design stage of DSFs such as ensuring a minimum distance between the outer and inner skins and adjusting the sizes of openings for better ventilation in the cavity. Other flexible methods such as utilisation of shading devices (venetian blind as the commonest one [15]), integration of thermal mass (Fallahi et al. [8]), application of energy storage materials such as phase change materials (De Gracia et al. [10]), and thermal control strategies (Haase et al. [18,19]) have also been investigated to assess their effectiveness in removing excess heat gains in DSFs.

Even though the above methods may be adopted in DSF systems as solutions to overheating effect, there are some barriers to be overcome and improvements to be made. For instance, extensive research have been conducted on venetian blinds and prove that factors such as blind position [20–22], slat tilt angle [10,22], and colour and size of the blind [21] can influence the DSF performance. The main problem of the existing venetian blind systems for DSFs is the high surface temperature caused by solar absorption on the blinds [23]. The consequences are that the blinds may act as solar heaters which radiate heat and contribute to overheating in adjacent space. Fallahi et al. [8] investigated different integrations of concrete materials and DSFs and revealed limitations of the thermal mass system included comparably low energy storage capacity of the concrete and sacrifice of natural illumination through the DSF.

Phase change material (PCM), as a thermal energy storage medium, can increase the thermal capacity of the building components and thus contribute to reducing heating and cooling loads in buildings [24]. Since PCMs have high energy storage capacity over a narrow temperature, large amount of heat can be stored during the melting processes. De Gracia et al. [10,11] adopted PCM in DSF system and found it can prevent the overheating effect between the PCM solidification and melting periods. However, it is necessary to optimise the PCM-DSF system for achieving certain level of natural illumination and flexible operation under various weather conditions. By incorporating proper PCMs into the blind system, it is possible to embody the advantages and overcome the operational limitations of the currently existing thermal management strategies and systems the limitations of conventional venetian blind and thermal mass system can be eliminated. Weinlaeder et al. [25] monitored an integrated PCM solar blind system in a building and achieved some level of temperature reduction in comparison with a conventional blind. However, the systems which consisted of