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Solar heat gain reduction of double glazing window with cooling pipes embedded in venetian blinds by utilizing natural cooling

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ABSTRACT

Although numerous technologies – such as double skin façade (DSF), double glazing window (DGW), etc. – have been applied in the glass envelope, the heat transfer of the glass envelope is still considerable. Cooling pipes embedded in the venetian blinds of a double-skin envelope are presented in this study as a system for reducing the heat transfer of the glass envelope in summer. Solar radiation is taken away directly by pipes through which cooling water is circulated, and the water can be produced from natural cooling. CFD software is employed in this paper to simulate the conjugated heat transfer in the double-skin envelope and the numerical model has been validated. The effect of embedded pipes is numerically investigated based on DGW. Different DGW structure and glass assemblies are taken into consideration. The results show that the cooling pipes can significantly reduce the temperature of the venetian blinds and air cavity, which will in turn lower heat transfer and improve thermal comfort. With pipe embedded, cooling water averagely takes away about 60% of the solar radiation directly and the average solar energy transmittance is only 13%. In addition, cheap glass can be employed to the pipe-embedded DGW with only small negative influence.

1. Introduction

Due to its distinctive transparency and esthetic features, glass is widely used in modern buildings. However, the popular application of the glass envelope in architecture is often accompanied by high energy consumption from air-conditioning because of the glass envelope's heat transfer characteristics [1]. On the one hand, the thermal insulation performance of glass is generally poor. On the other hand, considerable solar radiation can transfer to the room directly. Thus, it is crucial to reduce heat gain through glass in summer months, especially solar energy transmittance.

Numerous investigations have been conducted to improve glazing technology. The development of aerogel glazing [2], vacuum glazing [3], gas-filled glazing and multilayer glazing has significantly promoted thermal insulation performance. Even a triple vacuum glazing with thermal transmittance of less than 0.2 W/(m^2 K) was achieved in a study [4]. Solar heat gain can also be controlled with various coating techniques. Currently, low emissivity (low-e) coatings have been widely adopted in energy-saving glass envelopes [5]. However, the substantial cost of coating materials (e.g., silver) greatly limits their application [6]. In addition, unilateral improvement in glazing is not adequate for dealing with both winter and summer, because the effects of solar radiation vary in different seasons. For example, the excellent shading performance of glazing is beneficial in summer but negative in winter. Smart glazing [7], such as electrochromic windows [8], is able to change the visible and thermal transmittance characteristics in different conditions, but the technology is still in the initial stages of research and far from being put into practice [9].

Based on the development of glazing technology, many investigators have addressed the solutions provided by glass envelope systems. Glass envelope system is a kind of glass envelope which consists of one or more glazing units or even an integrated shading device. Double skin façade (DSF) and double glazing window (DGW) are the most popular types of energy-efficient glass envelope systems. They are both made of an external glass surface and an internal skin (a so-called double skin glass envelope), and are usually combined with shading blinds in the cavity [10]. They are favored by architects, developers, and owners due to their fantastic esthetic value [11]. Compared with DSF, the external skin of DGW is sealed and cannot be ventilated in summer months. This design makes DGW much simpler and cheaper to install and operate, but also results in the cavity overheating in summer. Another difference between DSF and DGW is that DGW is typically small, that is, closer to the size of a traditional window, whereas DSF is taller and wider to acquire a better stack effect. Both DSF and DGW have

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Nomenclature

a	absorption coefficient (m^{-1})
f_d	diffuse fraction
I	radiation intensity (W/m^2)
n	refractive index
q	heat flux (W/m^2)
q_V	heat generation rate (W/m^3)
Re	Reynolds number
$\vec{r}$	location vector
$\vec{s}$	main direction vector
$\vec{s}'$	diffusion direction vector
S_Φ	the source term
T	absolute temperature (K)
t	temperature in Celsius (°C)
u	thermal conductivity coefficient (W/(m K))
$\vec{U}$	velocity vector
y^+	dimensionless wall distance
z	distance to the wall

Greek symbols

α	expansion coefficient
Γ	diffusion coefficient
ε_w	wall emissivity
η	effectiveness of pipe
μ	effectiveness of DGW
κ	turbulence kinetic energy (m^2/s^2)
λ	wavelength
ν	kinematic viscosity (m^2/s)
ξ	solar energy transmittance
ρ	density (kg/m^3)
σ	Stephen–Boltzmann constant
σ_s	scattering coefficient (m^{-1})
τ	time (s)
Φ	common variable
Ω'	solid angle

Subscripts

ab	absorption
conv	convected
em	emission
di	diffusely
k	wavelength band number
in	incident
rad	radiated
re	reflection
sp	specularly
w	wall

already gained some popularity for their ability to reduce solar heat gain in buildings [12].

However, the reduction of solar heat gain by the current double-skin glass envelopes still has sufficient room to be promoted in summer months [13]. On the one hand, the thermal convection on the internal glass is considerable. It is common that the air temperature in the upper zone of cavity in DSF is about 4–10 °C higher than the outdoor temperature [14], which is extremely unfavorable for the indoor environment (the situation of DGW is even worse as the air in cavity cannot be ventilated). On the other hand, the shading device itself becomes another heat radiation source. As the shading device absorbs most solar radiation through the window, it can easily be heated to over 60 °C [15]. It then radiates heat into the indoor space and affects both energy consumption and thermal comfort. Various studies have been conducted to improve the performance of double skin with shading blinds, although most of them have been based on the optimization of the location or angle of the blinds [16–21], which were not capable of mitigating the inherent drawbacks of shading. Double glazing with a circulating water chamber is another innovative glass envelope that has been proposed in recent years [9,22–24]. Though its feasibility has been validated, improvements in this technology are still limited because the thin layer of water film present in the process cannot absorb sufficient solar energy. The high cost of the corresponding coating and the high risk of water leakage also make it hard to popularize. Thus, it would be very favorable to develop a simple method for effectively blocking solar radiation in the summer months.

Due to their high surface temperature, current shading devices are the main reasons for high heat gain through double skin glass envelope. However, they also offer the possibility of removing the heat by high temperature natural cooling water, for example, the cooling water produced from cooling tower, underground soil, etc. Xu et al. [25] and Zhu et al. [26,27] have conducted a series of studies on the effect of cooling pipes embedded in the brick wall of a building envelope and outstanding performance has been obtained. It seems even more promising to embed cooling pipes in the shading device of a glass envelope (e.g., DGW and DSF), though the relative investigation on the matter is insufficient. Thus, the method for embedding cooling pipes in the shading blinds of a glass envelope and taking away the heat directly by utilizing low-grade cooling water is proposed in this paper.

Nevertheless, the heat transfer in a glass envelope is very complex due to the conjunction of conduction, convection, and radiation. CFD is no doubt the most widely used computing approach in this area, but it is difficult to accurately predict the performance of double skin glass envelope with some simple assumptions [28]. For example, in most studies the radiation from the glass envelope to the indoor and outdoor environment has been ignored [29] and the simulation of radiation and flow has been separated [30]. Many investigators have neglected the effect of the blinds or only considered their resistance characteristics (as porous medium) instead of taking the radiation into account [31,32].

Hence, in this study, a comprehensive numerical modelling technique is developed and validated to simulate the conjugated heat transfer in a double skin envelope. DGW, compared with DSF, is more convenient to install and operate, and the effect of ventilation can be avoided. Thus, to purely understand the effect of cooling pipes, DGW is selected as the typical double skin glass envelope in this preliminary study. Comparative analysis of a DGW with pipes, DGW with blinds, and a naked DGW is conducted to evaluate their performance. Based on this, the energy saving potential of pipe-embedded DGW in different glass assembly conditions is investigated.

2. Description of the pipe-embedded DGW

Fig. 1 provides a sketch of the principle of the pipe-embedded double glazing system. Pipes are embedded into the venetian blinds of a DGW. And there are many alternative arrangement types for the pipes, e.g. horizontally or vertically arranged with parallel or series connections. Cooling water is circulated in the pipes and most solar radiation can be taken away before transferring to air or affecting the indoor environment. Because the original temperature of the venetian blinds is high, the heat gain in the blinds can be removed directly by relatively warmer cooling water, for example, low-grade natural energy provided by cooling tower, underground soil, rivers, lakes, etc. Since this system only consumes energy through pumps or fans instead of chillers, it is capable of reducing the heat transfer through the glass envelope with far less energy consumption.