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Study on a high-performance photocatalytic-Trombe wall system for space heating and air purification

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HIGHLIGHTS

- A solar photocatalytic-Trombe wall for space heating and formaldehyde degradation.
- A day experiment was conducted to test air heating and purification performance.
- A coupled kinetic, thermal and mass model was built and experimentally confirmed.
- A seasonal energy saving of 309.9 MJ/m^2 and total clean air of 4764.9 m^3/m^2 in Hefei.
- 12.1 years to recoup investment only consider saving electricity by space heating.

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ABSTRACT

This article proposes a novel solar gradient-utilization photocatalytic-Trombe wall system that can realize the dual functions of space heating and removal of indoor formaldehyde. A photocatalytic layer is coated on the internal surface of the glazing cover in conventional Trombe wall system. Under solar radiation, ultraviolet light is absorbed by the photocatalytic layer to activate the photocatalytic oxidation of formaldehyde, and the rest of visible and infrared parts are collected by the absorber plate to heat indoor environment. In this article, firstly, an experimental testing set-up of photocatalytic-Trombe wall was constructed and a full-day experiment was conducted to investigate the performances of air heating and formaldehyde degradation. Secondly, a coupled kinetic, thermal and mass model was derived and verified by the experimental data. Finally, adopting the established model, the seasonal energy saving analysis and economic analysis in Hefei were conducted. Results are: (1) Based on the experimental results, the daily air heating efficiency was 0.351, and daily generated clean air and degradation mass of formaldehyde were 164.0 $m^3/(m^2\,day)$ and 100.0 $mg/(m^2\,day)$, respectively; (2) Experimental results confirmed the model accuracy within 8%; (3) Compared with the total thermal load reduction of 246.9 MJ/m^2 in heating seasons for conventional Trombe wall, photocatalytic-Trombe wall not only has a higher value of 309.9 MJ/m^2, but also an additional valuable total generated clean air of 4764.9 m^3/m^2; (4) Photocatalytic-Trombe wall system takes about 12.1 years to recoup the initial investment only considering the saving electrical by indoor space heating.

1. Introduction

The global environmental problems have been more and more serious due to the large-scale use of fossil fuel in recent years [1]. The utilization of renewable energies such as solar energy is a promising way to solve this contradiction between energy and environment. Solar-direct heating technologies [2] or solar-aided heat pump technologies such as solar-aided latent heat store heat pump [3] and solar-assisted ground source heat pump [4] for reducing the building heat load are a potential and clean way to lower the electricity consumption. Trombe wall system, as a simple and sustainable passive solar heating design, has been widely investigated in recent years [5]. The basic elements for

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Nomenclature

T	temperature, °C
I	solar radiation intensity, W/m^2
c	specific heat capacity, J/(kg K)
t	time, s
h	heat transfer coefficient, W/(m^2 K); mass transfer coefficient, m/s
δ	thickness, m
u	air or water flow velocity, m/s
A	area, m^2
q	heat flow rate, W/m^2
E	reaction activation energy, J/mol
R	thermal resistance, (m^2 K)/W
L	thermal load, MJ
C	formaldehyde concentration, ppb
j	the mass transfer rate, ppb m/s
r	reaction rate, ppb m/s
k	reaction rate coefficient, m/s
K	adsorption equilibrium constant
q	thermal flux, W/m^2
Re	Reynolds number
Pr	Prandtl number
Nu	Nusslet number
Ra	Rayleigh number
Sh	Sherwood number
Le	Lewis number
D	HCHO diffusion coefficient, m^2/s

Greeks

λ	thermal conductivity, W/(m K)
ε	formaldehyde once-through conversion
σ	Stefan-Boltzmann constant, W/(m^2 K^4)
α	absorptivity
β	coefficient of thermal expansion, K^{-1}
ν	dynamic viscosity, m^2/s
ρ	density, (kg/m^3); reflectivity

Subscripts

g	glass plate
PC-g	photocatalytic-glass
a	air
p	absorber plate
w	wall
amb	ambient
sky	sky
$HCHO$	formaldehyde
app	apparent
in	inlet
out	outlet
red	reduction

Abbreviation

UV	ultraviolet
Vis	visible
IR	infrared
PC	photocatalytic
PCO	photocatalytic oxidation
CADR	clean air delivery rate, m^3/h
TC	thermal-catalytic
PCM	phase change materials
DWVG	delta winglet vortex generator
PV	photovoltaic
ppb	parts per billion

a conventional Trombe wall system are a glazing cover, a massive wall, an air flow channel between the glazing cover and the massive wall, and upper and lower vents. Normally, the external surface of the massive wall is painted black to enhance the surface absorptivity. The solar rays penetrate the glazing cover and are absorbed by the black surface of the massive wall. Then the air in the air flow channel is heated by the massive wall and the warm air flows into the room. At the same time, the solar heat is stored by the massive wall due to its high thermal mass. While in the nighttime, the massive wall heats the indoor environment. The integration of Trombe wall system in a house is an effective way to reduce build heating load by sent the heat from the air channel to the room in daytime [6] and conducting the heat from the massive wall to the room in nighttime [7]. However, conventional Trombe wall system has the inevitable drawback of single-function. Also, thermal energy is a kind of low level energy. Therefore, to enhance the thermal performance and functionality of conventional Trombe wall system, many modifications to conventional Trombe wall system have been carried out by many researchers.

Bellos et al. [8] designed an innovative Trombe wall system with an extra window in the massive wall and made the comparisons of this novel system with the conventional Trombe wall, and the dependent insulated wall. Results showed that the proposed system created a warmer indoor profile than the other systems and could solve partially the aesthetics problem of conventional Trombe wall. To improve the status of only receiving sunlight from one direction (normally the south direction) for conventional Trombe wall system, Rabani et al. [9,10] proposed a Trombe wall system with a new channel design that the glasses replaced the solid lateral surfaces of the air flow channel, which could make the solar rays penetrate by three directions (South, East, and West). Moreover, to enhance the cooling effect in summer, they combined the solar chimney and water spraying systems with this new designed Trombe wall system [11]. Experimental results showed the indoor temperature decreased by about 8 °C and the indoor relative humidity increased by about 17% after the adding of the water spraying system, which indicated that the water spraying system increased the thermal efficiency of 30%.

In order to avoid the overheating in summer, Chen et al. [12] proposed a novel Trombe wall system with a porous absorber that could avoid the over irradiation under the solar radiation or the significant losses in the nighttime. Accordingly, our group proposed a novel Trombe wall system with the adjustable venetian blind structure, with a high absorptivity layer and a high reflectivity layer on each side [13]. A series of experiments on the thermal performance of Trombe wall system with the venetian blind structure in summer and winter were conducted. Results showed that the slat angle of 45° made the indoor temperature approach the highest value compared to the other slat angles (0° and 90°) in winter and the maximal heat gains from the south wall reached to 3.66×10^3 kJ in summer. Accordingly, the numerical analyses in terms of the air heating performance in winter and the air cooling performance in summer were also conducted, respectively [14,15]. The simulation results showed that a building with Trombe wall system with the venetian blind structure could achieve the better thermal comfort compared with a room with conventional Trombe wall system in cold weather [14]. In addition, the blind tilt angle had a significant effect on the cooling load while the air gap width affected slightly [15].

The application of phase change materials (PCMs) in the building envelopes can decrease the indoor air temperature fluctuations and the