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Experimental and numerical performance analysis of a TC-Trombe wall

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HIGHLIGHTS

- A novel zero-energy TC-Trombe wall was introduced.
- Experimental testing platform and numerical model were built.
- The air heating and HCHO degradation performance were analyzed experimentally.
- A photothermocatalytic synergetic effect existed in the solar driven TCO.
- The total saving energy of 97.4 kW h/m^2 be obtained in heating seasons in Hefei.

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ABSTRACT

The present paper proposes a novel zero-energy solar application system combining the thermal catalytic technology with Trombe wall (TC-Trombe wall), which could realize indoor air purification and space heating simultaneously fully driven by solar energy. A full-day experiment was conducted to study the air heating performance and formaldehyde degradation performance of TC-Trombe wall. Results showed that the daily air heating efficiency was 41.3%. In our experiments, the generated total volume of fresh air and total formaldehyde degradation amount by TC-Trombe wall were 249.2 m^3/(m^2 day) and 208.4 mg/(m^2 day), respectively. In addition, a photothermocatalytic synergetic effect exists in the solar light driven thermocatalytic oxidation process over MnO_x-CeO_2 catalysts. A dynamic numerical model was developed to predict system thermal properties. Based on the simulation results, the effects of the solar radiation intensity, ambient temperature and air layer thickness on the system thermal efficiency were discussed. Furthermore, the energy saving performance of TC-Trombe wall was evaluated in heating seasons in Hefei based the established system thermal model. Results showed that the total saving energy of up to 97.4 kW h/m^2 could be obtained. The saving energy for space heating and formaldehyde degradation were 64.3 kW h/m^2 and 33.1 kW h/m^2, respectively.

1. Introduction

Parallel to the high speed development of economy and rapid growth of human population, the environmental pollution and lack of energy are two main problems in the new century. The building energy consumption for the heating, ventilating and air conditioning (HVAC) occupies 30–40% of the total energy consumption in the world to maintain a comfortable and health indoor environment [1]. The ratio of building energy consumption for space heating should not be ignored. Therefore, it is potential to use the renewable energy such as solar energy for building space heating.

Trombe wall (TW) has been popularized as one kind of solar space heating methods in the past few decades because it delivers some advantages such as simple configuration, low running cost and using the storing solar energy of the wall during daytime to heat room overnight [2–4]. Typical Trombe wall consists of a glass plate, massive wall, air channel and vents [5]. The high thermal mass wall can store solar heat in the day and release it into the room in the night. And the energy stored performance of wall is a very important parameter to a Trombe wall system for night heating. Hassanain et al. [6] found that the

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Nomenclature

G	solar radiation intensity, W/m^2
H	height, m
A	area, m^2
c	specific heat capacity, J/(kg K)
T	temperature, °C
d	hydrodynamic diameter, m
Pr	Prandtl number
Ra	Rayleigh number
Nu	Nusslet number
Re	Reynolds number
E	electricity
Ra	rayleigh number
m	mass, kg; mass flow, kg/s
Q	volumetric flow rate of gas, m^3/h
f	resistance factor
h	heat transfer coefficient, W/(m^2 K)
C	formaldehyde concentration, ppb
R	thermal resistance
F	view factor
t	time, s
V	air flow velocity, m/s; volume, m^3

Greeks

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

Subscripts

th	thermal
a	air
HCHO	formaldehyde
cata	catalyst
eq	equivalent
in	inlet
out	outlet
ti	heat insulating material
conv	convective heat transfer
rad	radiation heat transfer
g	glass plate

Abbreviation

TCO	thermal catalytic oxidation
TW	Trombe wall
VOCs	volatile organic compounds
PCO	photocatalytic oxidation
RSMD	root mean square deviation
CADR	clean air delivery rate, m^3/h
IAQ	Indoor Air Quality
ppb	parts per billion
HVAC	heating, ventilating and air conditioning

average indoor air and soil temperature increased 1.1 °C and 4 °C during winter nighttime in the greenhouse when Trombe wall was used for the solar heat storage. Hernandez et al. [7] found that storage wall could supply the maximum energy stored of about 109 MJ and 70 MJ to the room in nighttime during the warmest day and the warmest day in Mexico, respectively. Liu et al. [8] investigated the heat storage and release of Trombe wall in the fully day based on the numerical analysis. Results showed that the massive wall released heat from 15:00 PM to 7:30 AM and stored heat from 7:30 AM to 15:00 PM. A balance between heat storage and heat release was achieved at about 7:30 AM. Rabani et al. [9] compared the energy storage rate and time duration of room heating during the non-sunny periods using four different materials of the Trombe wall such as concrete wall, brick wall, hydrated salt wall and paraffin wax. Results showed that the Trombe wall made of paraffin wax could keep the room more warm in comparison with other materials for about 9 h. The influencing factors such as the thickness of the core layer [10], the massive wall thickness and the existence of a ventilation system [11], integrating phase change materials [12], and the shading effect of the side walls [13], on the heat release performance were investigated in night time in Trombe wall system.

However, it exists several inevitable shortcomings such as the low thermal resistance [14], single-function [3], and some aesthetical problems because the wall is colored black to increase the absorptivity of wall [15] in Trombe wall system. Furthermore, the paint layer might release the volatile organic compounds (VOCs) when it reached high temperature under solar radiation. Therefore, many improved Trombe wall systems have been developed [15–18].

The adding of another insulation layer or closed air layer leads to the increase of the thermal resistance of the composite TW [16,19]. The amplitudes of the indoor temperature for the composite TW are smaller than that of the classical TW. Tunc et al. [18] filled the air cavity with the high-absorptivity and low-density particles in TW. Results showed that the heat collecting efficiency got the great improvement because the air in air cavity was in contact with the fluidized particles directly.

The modifications to TW such as Trans-wall and photovoltaic TW make itself be more multifunctional. More high value-added products such as electricity, thermal comfort and aesthetic enjoyment are produced. Trans-wall provides not only heat but also illumination of the room [17]. Another novel design is photovoltaic TW (PV-TW) that simultaneously realizes both space heating and electricity generation [15,20,21]. The generated electricity is the high value-added product compared with thermal energy. In general, the air flow behind the PV panels has a cooling effect on the PV cells, which is beneficial to the electrical performance of PV cells [22]. Moreover, PV-TW solves aesthetic problem of traditional TW perfectly because the deep blue color of PV cells makes the external facade more appealing [15]. Ji et al. [15,23–25] proposed PV-TW and conducted a series of investigations including experiments and models on the performance of space heating and electricity generation. Various factors such as south facade designs [15], PV coverage ratio [23], areas and climatic conditions [26–28], and ventilation modes including natural ventilation and mechanical ventilation [29], affecting thermal and electrical efficiency were discussed in detail. However, compared with the conventional TW, the thermal efficiency of PV-TW reduces due to the opaque nature of PV cells. Sun et al. [15] pointed out the thermal efficiencies of PV Trombe wall reduced by 7% and 17% for the different fractions of PV coverage of 33.4% and 100%, respectively. And the replacement of PV cells by semi-transparent amorphous silicon solar cell would decrease the daily average electrical efficiency of the system greatly [30]. Another novel designs including PV blinds-Trombe wall [31] and PV thermoelectric-Trombe wall [32] were studied to improve the functionality, thermal and electrical efficiency.

As mentioned, nowadays, human beings have put more and more focus on the Indoor Air Quality (IAQ) of dwelling buildings and public