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Energy and exergy analysis of different Trombe walls

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ABSTRACT

This study aims to compare the thermal performance of two different types of Trombe wall: one with the absorber plate pasted on the thermal storage wall (Type I) and one with the absorber plate placed between the glass cover and the thermal storage wall(Type II). The glass cover is double glazed. The energy and exergy efficiencies of the Trombe walls are evaluated for various air channel depths, solar radiation intensities and the emissvities of the glass cover. The energy and exergy efficiencies, the airflow rate and air temperature rise in the air channel in the Trombe wall with the absorber plate placed between the glass cover and the thermal storage wall(Type II) are higher than those in the Trombe wall with the absorber plate pasted on the thermal storage wall(Type I). In addition, it is found that the particular exergy destruction due to absorption of the absorber plate is the largest and that a higher absorber plate temperature is preferable in decreasing the total exergy destruction and increasing exergy efficiency.

1. Introduction

One of the classical passive solar systems is the Trombe wall. A Trombe wall, which is also known as a thermal storage wall and solar heating wall [1,2], reduces a building's energy consumption by up to 30% [3] and provides thermal comfort in winter and intermediate seasons [4]. A Trombe wall is an important green architectural feature that aides the ventilation, heating and cooling of buildings.

Many theoretical and experimental studies on the performance of Trombe walls have been carried out. Khedari et al. investigated the performance of a modified Trombe wall, named the partially-glazed modified Trombe wall, which aimed to induce higher natural ventilation and provide daylight for housing [5]. The thermal performance of two types of solar facade: flat and transpired aluminum plates were compared and it was found that the transpired design was able to reduce heat losses [6]. The thermal performance of a classical Trombe wall and a composite Trombe–Michel wall was also studied [7]. It showed that the composite wall had better energy performance than the classical wall in cold and/or cloudy weather. Ryan et al. reported on test rigs resembling lightweight passive solar air-heating collectors. The thermal efficiency was shown to be a function of the heat input and the system height, but not of the channel depth [8]. The thermal performance of five different passive solar test-cells (Direct-gain, Trombe-wall, Water-wall, Sunspace, and Roofpond) was reported [9]. A research project was conducted to investigate the performance of a coupled novel triple glass and PCM wall as a solar space heater [10]. The energy performance comparison of single glass, double glass and a semi-transparent PV module integrated on the Trombe wall façade of a model test room built in Izmir, Turkey has been carried out [11]. The efficiency of the modified Trombe wall with forced convection that could be operated in four different modes was analyzed [12]. A PV-Trombe wall, installed in a fenestrated room with heat storage, was investigated to approach the practical application of this type of solar wall [13].

Most of the studies on Trombe walls were based on the energy balance equations. However, the energy balance equations alone do not consider the internal losses, and the energy efficiency is not an adequate criterion for Trombe walls. Exergy analysis can reflect the quality change of solar energy transfer process, use and consumption through Trombe walls. Exergy analysis is more informative with regard to the optimum operating zone, quantifying the inefficiencies, their relative magnitudes and locations [14–16]. Exergy is the maximum work potential that can be obtained from a form of energy [17]. Exergy efficiency is more realistic than energy efficiency, and exergy analysis should be considered in the evaluation and comparison of solar thermal systems [18]. Therefore, the main consideration in this study will be on the detailed energy and exergy analysis of two types of Trombe walls, one of which has the absorber plate pasted on the thermal storage wall (Type I) and the other of which has the absorber plate placed between

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the glass cover and the thermal storage wall (Type II). These are for evaluating the performance and optimizing the designed Trombe walls with the maximum exergy efficiency under given operating conditions.

2. The description of Trombe walls

In Fig. 1, the physical model for the two types of Trombe walls is divided as follows: the glass cover, the absorber plate, the air channel, the thermal storage wall and two openings. Two openings are respectively located on the upper and lower part of the thermal storage wall. In Fig. 1(a), the absorber plate is pasted on the thermal storage wall (Type I) and there exists an air channel between the glass cover and the absorber plate. In Fig. 1(b), the absorber plate is placed between the glass cover and the thermal storage wall (Type II) with the air channel between the absorber plate and the thermal storage wall, so there is an air gap between the glass cover and the absorber plate. The glass cover is double glazed in Fig. 1. Solar radiation penetrates through the glass cover and is absorbed by the absorber plate which results in a temperature rise of the absorber plate. Colder air from indoor enters the air channel through the lower opening, and is heated by the hot absorber plate and rises and then enters indoors through the upper opening. The heat transfer modes and heat exchange in the system are shown in Fig. 1.

3. Energy analysis

While the energy balance equations are derived, some assumptions have been made:

(1) The systems operate under steady state conditions.
(2) The air temperature in air channel changes only in the direction of the flow.
(3) Heat transfer through the glass cover, the absorber plate, and the thermal storage wall is 1-D and in the direction perpendicular to the air flow.
(4) The heat loss of the lateral walls is neglected due to its small effect.

For the studied Trombe walls shown in Fig. 1, the energy balance equations are written as below.

The glass cover is double glazed which has four surfaces and one air layer. The energy balance equations for the first and second surfaces of the glass cover are:

$$h_{cga}A_g(T_{g1}-T_a)+h_{rgs}A_g(T_{g1}-T_a)+\frac{\lambda_g}{\delta_g}A_g(T_{g1}-T_{g2}) = \alpha_g A_g I \tag{1}$$

$$(h_{rgg}+\frac{\lambda_{fg}}{\delta_{fg}})A_g(T_{g2}-T_{g3})+\frac{\lambda_g}{\delta_g}A_g(T_{g2}-T_{g1})=0 \tag{2}$$

where T_{g1}, T_{g2}, T_{g3} are respectively the temperatures of the first, second and third surfaces of the double glazing shown in Fig. 1 (°C), T_a is the outdoor temperature (°C), A_g is the area of the double glazing (m^2), I is the solar radiation intensity(W/m^2), α_g is the absorptivity of the glass cover, λ_g, λ_{fg} are respectively the thermal conductivity of the glass and air in the air layer(W/m·K), δ_g, δ_{fg} are respectively the thicknesses of the glass and the air layer(m).

The convection heat transfer coefficient due to wind h_{cga} is given by W.H. Mcadams as [19]:

$$h_{cga}=5.7+3.8u_w$$

where u_w is the wind speed.

The radiation heat transfer coefficient h_{rgs} from the outside surface of the double glazing to the sky referred to the ambient temperature is obtained from

$$h_{rgs}=\frac{\sigma_b\varepsilon_{g1}({T_{g1}}^4-{T_s}^4)}{T_{g1}-T_a}$$

where σ_b is Stefan–Boltzmann constant (5.67 × 10^{-8}W/m^2·K^4), and ε_{g1} is the emissivity of the first surface of the glass cover.

The sky temperature T_s is given by Duffie and Beckman [20] as

$$T_s=0.0552T_a^{1.5}$$

The radiation heat transfer coefficient h_{rgg} from the third surface to the second surface of the double glazing can be derived as

$$h_{rgg}=\frac{\sigma({T_{g3}}^2+{T_{g2}}^2)(T_{g3}+T_{g2})}{\frac{1}{\varepsilon_{g3}}+\frac{1}{\varepsilon_{g2}}-1}$$

where ε_{g2}, ε_{g3} are respectively the emissivities of the second and third surfaces of the double glazing.

The energy balance equations for the third and fourth surfaces of the double glazing are:

$$(h_{rgg}+\frac{\lambda_{fg}}{\delta_{fg}})A_g(T_{g3}-T_{g2})+\frac{\lambda_g}{\delta_g}A_g(T_{g3}-T_{g4})=\alpha_g A_g\tau_g I \tag{3}$$

$$(h_{rpg}+\frac{\lambda_{fp}}{\delta_{fp}})A_p(T_{g4}-T_p)+\frac{\lambda_g}{\delta_g}A_g(T_{g4}-T_{g3}) +h_{cg}A_g(T_{g4}-T_f)=0 \tag{4}$$

where T_{g4} is the temperature of the fourth surface of the double glazing, T_p,T_f are respectively the temperatures of the absorber plate and air in air channel (°C), A_p is the area of the absorber plate (m^2),τ_g is the transmissivity of the double glazing, λ_{fp} is the thermal conductivity of air in air layer between the absorer plate and the glass cover (W/m·K), δ_{fp} is the thickness of the air layer (m).

The radiation heat transfer coefficient h_{rpg} from the absorber plate to the fourth surface of the double glazing can be obtained from

$$h_{rpg}=\frac{\sigma({T_p}^2+{T_{g4}}^2)(T_p+T_{g4})}{\frac{1}{\varepsilon_p}+\frac{1}{\varepsilon_{g4}}-1}$$

where ε_p, ε_{g4} are respectively the emissivities of the fourth surface of the double glazing and the absorber plate.

The convection heat transfer coefficient h_{cg} between the air in the air channel and the fourth surface of the double glazing can be defined as

$$h_{cg}=Nu\lambda_f/\delta$$

where λ_f is the heat conduction coefficient of air in air channel (W/m·K), δ is the thickness of the air channel (m). Nu is Nusselt number.

In Eq. (4), $\lambda_{fp}/\delta_{fp}=0$ for the first type of Trombe wall shown in Fig. 1(a); $h_{cg}=0$ for the second type of Trombe wall shown in Fig. 1(b). The heat balance equation for the absorber plate is:

$$h_{cp}A_p(T_p-T_f)+(h_{rpg}+\frac{\lambda_{fp}}{\delta_{fp}})A_p(T_p-T_{g4})+U_pA_p(T_p-T_n) +h_{rpw}A_p(T_p-T_w)=\alpha_p\tau_g A_p I \tag{5}$$

where T_w is the temperature of the thermal storage wall (°C), T_n is the indoor temperature (°C).

The radiation heat transfer coefficient h_{rpw} from the absorber plate to the thermal storage wall can be obtained from

$$h_{rpw}=\frac{\sigma({T_p}^2+{T_w}^2)(T_p+T_w)}{\frac{1}{\varepsilon_p}+\frac{1}{\varepsilon_w}-1}$$