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Energetic study of a Trombe wall system under different Tunisian building configurations

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ABSTRACT

In order to take advantage of the local climate many passive solar design techniques were applied to reduce buildings energy demands.

In term of reducing heating demands, the Trombe wall system appears as one of these effective passive techniques providing that it was properly conceived.

In this study a numerical model of a Trombe wall system was developed using TRNSYS software and validated by a small scale experimental prototype, located at the Laboratory of Thermal Processes of the Research and Technology Center of Energy (CRTEn) of Borj Cedria. This model was then adopted for the numerical investigation of Tunisian typical buildings.

The results of the simulation show that approximately 77% of the total heating demand of a 16 m^2 non-insulated simple typical Tunisian building, can be realized by a vented Trombe wall of 8 m^2.

A 97% reduction of the annual heating loads was attained by a 6 m^2 Trombe wall area when the external walls of the considered simple building were double walls insulated by 5 cm of expanded polystyrene.

1. Introduction

According to the World Energy Council, primary energy demand will double by 2050 due to the global population growth, global economic growth, continued urbanization, and other energy dependent services [1].

The building sector is a big consumer of energy, this is mainly due to the large amount of energy used in building, cooling and heating so as to achieve an optimal thermal performance and an acceptable condition of comfort.

This sector was identified to be one of the most cost-effective sectors for reducing energy consumption by the progress and the use of efficient technologies.

In Tunisia the energy consumption associated with the residential building sector has continuously increased over the last three decades [2].

Indeed, the energy use for heating and cooling equipment has jumped from 20% in 1989 to 26% in 2004 in the Tunisian residential building sector and it is still increasing [3].

In the objective of designing high performance buildings targeting net-zero energy use in terms of heating, many effective solutions have been applied. These solutions consist especially in the use of renewable and sustainable energy like solar energy which is the most abundant Tunisian renewable resource, given that solar radiation varies from 1800 kWh/m^2/year (North) to 2800 kWh/m^2/year (South) [4].

The Trombe wall system is one of these solutions, it is regarded as a sustainable architectural technology for heating and ventilation [5].

Many theoretical and experimental studies have focused on this system and discussed the various accessories of the Trombe walls that help to increase the efficiency of this system, such as configurations [6–8], size [9], vent effects [10,11], fans [12,13], insulation [14] and construction material [15].

But, like all bioclimatic techniques, the efficiency of this system is directly affected by the specificity of the climate where it will be built and the configuration and composition of the building in which this system will be implemented.

So, in this paper we will examine the energetic performance of this system under Tunisian climate for various wall areas, according to different typical Tunisian buildings.

2. Trombe wall description

2.1. Functioning principle

The Trombe wall consists of a massive wall, generally made of stone, brick, or concrete, with high inertia and black color installed at a small distance from a glazing (Fig. 1). The wall absorbs solar radiation and transmits part of thermal energy into the building

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Nomenclature

A	Trombe wall area (m^2)
a	thermal diffusivity (m^2/s)
A_g	air gap area (m^2)
A_o	vent area (m^2)
C_d	discharge coefficient
C_p	specific heat of wall (kJ/kg K)
C_{pa}	specific heat of air (kJ/kg K)
e	wall thickness (m)
g	gravity acceleration (m/s^2)
Gr	Grashof number
H	wall height (m)
h_c	air gap heat transfer coefficient ($kJ/m^2\,^\circ C$)
K_a	air thermal conductivity (W/m K)
L	distance between glass and Trombe wall (m)
$\dot{m}$	air mass flow rate in the gap (kg/s)
Nu	Nusselt number
Pr	Prandtl number
Q_{cond}	conductive flux (W)
Q_v	convective flux by ventilation (W)
Re	Reynold's number
R	thermal resistance between the air gap and the room
T	temperature (°C)
t	time (s)
T_m	mean air temperature in the gap (°C)
T_r	room temperature (°C)
$T_{w.e}$	external wall temperature (°C)
$T_{w.i}$	internal wall temperature (°C)
w	wall width (m)
λ	thermal conductivity of the wall (W/m K)

by natural convection through the solar chimney formed by the glazing on one side and the wall on the other. The heat absorbed from the sun by the external surface of the wall is conducted slowly through the massive wall to the inner surface and then to the room by radiation and convection [16].

The advantage of the important heat capacity of the wall, is storing heat from the sun during the day and releasing it into the building space during the night [17,18].

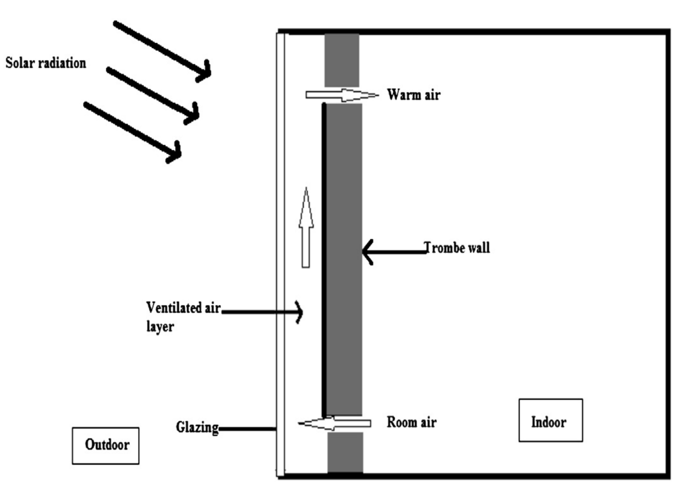

Fig. 1. Functioning principle of the Trombe wall.

2.2. Modelisation used for the thermal exchange

By applying Bernoulli's equation, the mean air velocity in the gap is determined by [19]:

$$V = \left[\frac{2gH\cdot(T_m - T_r)}{(C_1(A_g/A_o)^2 + C_2)\cdot T_m}\right] \quad (1)$$

where H is the wall height (m), T_m is the mean air temperature in the gap (°C), g is the acceleration of gravity (m/s^2), T_r is the room air temperature (°C), A_g is the air gap area (m^2), A_o is the vent area (m^2).

The expression $C_1(A_g/A_o)^2 + C_2$ represents the pressure drop in the gap and vents, where C_1 and C_2 are dimensionless empirical constants which have been determined by Utzinger to be, respectively, equal to 8 and 2 [20].

The mass flow rate is naturally driven by air temperature differences and is given by:

$$\dot{m} = \rho V A_g \quad (2)$$

In this case the rate of energy flux by ventilation incoming from the air gap can be calculated by the following equation:

$$Q_v = 2\dot{m}C_{pa}(T_m - T_r) \quad (3)$$

The rate of energy flux by conduction through the wall is calculated from the Fourier's law:

$$Q_{cond} = \frac{T_{w.e} - T_{w.i}}{e/\lambda A} \quad (4)$$

where $T_{w.e}$ is the external wall temperature, $T_{w.i}$ is the internal wall temperature, e is the wall thickness (m), λ is the thermal conductivity of the wall (W/m K).

The thermal resistance to the energy flux between the gap and the room when the mass flow rate of the air in the gap is finite, is given by [21]:

$$R = \frac{A[(\dot{m}C_p/2h_cA)(\exp(-(2h_cA/\dot{m}C_p)) - 1) - 1]}{\dot{m}C_p(\exp(-(2h_cA/\dot{m}C_p)) - 1)} \quad (5)$$

where C_p is the specific heat of air (kJ/kg °C), h_c is the air gap heat transfer coefficient ($kJ/m^2\,^\circ C$), A is the Trombe wall area (m^2).

The heat transfer coefficient in the air gap can be calculated according to the mass flow rate of air in the gap [22] such as:

- If $\dot{m} = 0$

$$h_c = \frac{k_a}{L}(0.01711(Gr\cdot Pr)^{0.29}) \quad (6)$$

- if $\dot{m} \neq 0$ and $Re > 2000$

$$h_c = \frac{k_a}{L}(0.0158\cdot Re^{0.8}) \quad (7)$$

- if $\dot{m} \neq 0$ and $Re \leq 2000$

$$h_c = \frac{k_a}{L}\left(4.9 + \frac{0.0606(x^*)^{-1.2}}{1 + 0.0856(x^*)^{-0.7}}\right) \quad (8)$$

where

$$x^* = \frac{h(1+w)}{Re\cdot Pr\cdot 2\cdot A_g} \quad (9)$$

3. Numerical model validation using a small scale prototype

3.1. Experimental set-up

The experiment has been carried in a test room with a Trombe wall located at the Laboratory of Thermal Processes of the Research