International Communications in Heat and Mass Transfer 88 (2017) 269–276

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Numerical simulation of modified Trombe-Michel Walls with exergy and energy analysis

Sandra Corasaniti, Luca Manni, Flavia Russo, Fabio Gori*

Department of Industrial Engineering, University of Rome "Tor Vergata", Via del Politecnico 1, 00133 Rome, Italy

A R T I C L E I N F O

Keywords:
Modified Trombe-Michel Wall
Sharp edges
Rounded edges
Guided flow
Exergy and energy analysis

A B S T R A C T

Numerical simulations of three configurations of a modified Trombe-Michel Wall (TMW) are carried out and the numerical results are employed to carry on the energy and exergy analyses. The three configurations of the modified Trombe-Michel Wall (TMW) investigated are with sharp edges, with rounded edges and with the guided flow. For each configuration and glaze spacing, spanning from 0.1 m up to 0.5 m, the velocity and the mean air temperature in the channel, the heat flux, the exergy gain and the conductive heat transfer through the massive wall are evaluated numerically. The comparison among the three configurations shows that the guided flow presents the highest energy and exergy efficiency.

1. Introduction

The global energy consumption for the building sector in the European Union is nowadays around 40%, with about two-thirds due to heating, ventilating and air conditioning (HVAC). A Directive of the European Union suggested in 2010 that all EU members should approve energy policies to promote very low energy consumption "passive" buildings, [1].

The use of Double Skin Facades (DSF) attracted the interest of the researchers because of their capability to store solar energy and to release it gradually by keeping the internal temperature within the comfort range. One of the oldest and cheapest ways to realize a DSF is the Trombe-Michel Wall (TMW), based on a special type of envelope, where the second layer is a transparent glazing (made of glass or of a high transparent polymer). The aim of the TMW is to exploit solar energy, to storage it during peak-use periods using the heat capacity of the building materials, and to supply energy. In a typical TMW configuration, solar energy is absorbed on the black-painted south-facing wall, which increases its temperature until natural convection occurs. The density changes drive the flow through the narrow gap between the massive wall and the glazing, and the chimney effect causes the cooler air from the room to be drawn in through the bottom vent. Even if a correct configuration of the wall provides a natural convection transport mechanism, the installation of a mechanical device, such as a blower, allows the air circulation to achieve a better control of the heat transfer. Moreover, the incident energy is also transferred to the internal conditioned space by conduction through the storage wall, with a delay function of the thermal properties of the wall material and its thickness.

Analytical techniques were developed in [2–3] to predict the hydrodynamic characteristics of a TMW, and compared with the numerical results of the same authors. The effect of the variable properties on natural convection inside an asymmetrically heated vertical channel was investigated in [4] with the numerical simulation of the recirculation patterns. It was found that the recirculation zone decreases due to the variable properties, while the mass flow rate increases and the Nusselt number is influenced until reversal flow exists.

As far as the turbulence modeling in natural convection problems is concerned, low Reynolds $k-\varepsilon$ model was used in [5], founding that the turbulence intensity at the channel inlet influences the location of the transition point from laminar to turbulent flow. The influence of the channel width of a TMW on the air flow rate, as far as pressure losses are concerned, was investigated in [6]. The study pointed out that the increase of the channel width, over a certain value, does not lead to a greater air flow rate because losses are mainly located in the orifices. The same conclusion was found on the mass flow rate, which increases until a maximum value and then decreases, [7].

The shape and arrangement of the absorbing surfaces of the collectors to provide greater heat transfer, suitable for the passive heat transfer augmentation techniques, were investigated experimentally in [8]. The performance of air solar collectors, with staggered absorber sheets and attached fins on absorber surface, were tested. The efficiency of the solar collector increases approximately of 10% to 30% in comparison with the conventional solar collector. Even though scientific literature exhibits a certain shortage of experimental data, some transient results are reported in [9]. A numerical model for a composite

* Corresponding author.
E-mail address: gori@uniroma2.it (F. Gori).

http://dx.doi.org/10.1016/j.icheatmasstransfer.2017.09.005

TMW was validated experimentally in [10], showing that the composite TMW has better energy performances than the classic one in cold and/or cloudy weather.

Several researchers focused their studies on smaller and cheaper modifications, such as the shape of the channel. Plates with optimized spacing in the channel can maximize the induced mass-flow rate, within C-shaped channels with a TMW configuration, by assuming isothermal walls [11]. Smaller channel depth presents significant friction losses, while larger channel depth increases the heat losses in solar air heaters [12]. A non-symmetrical heated vertical plane, representative of several geometries, from chimney to Trombe wall, was investigated experimentally in [13]. The appearance of the flow regime is dependent on the Rayleigh number, since, at high values, the boundary layer is always present and a reverse flow is close to the unheated wall.

The 3D analysis is avoidable and the variations of the thermal properties with the temperature are negligible, [14]. The RNG version of the $k-\varepsilon$ turbulence model was preferred, rather than the $k-\omega$ family of models, because of the better accuracy for the heat transfer prediction, even though only few experimental data are available to validate turbulence models. Numerical 2D simulations of the TMW performance and indoor air environment were investigated in unsteady state condition for a room located in Iran [15]. The results showed that a Trombe wall, made of paraffin wax, can keep the room warmer for about 9 h.

The energy efficiency of finned double-pass solar collectors was evaluated in [16]. Some turbulence models were considered in a 3D problem, [17], where solar load was taken into account. The results indicated that the low Reynolds shear stress model is a better turbulent model, even though it requires the solution of the whole Reynolds stress tensor. As far as the performance is concerned, the exergy analysis can play an important role in the investigation. Exergy performance of plate solar collectors was investigated in [18]. The optimum values of the collector inlet temperature, mass flow rate, absorber plate area, and fluid outlet temperature were obtained for the maximum exergy inflow from the system.

The thermal behavior of a new TMW configuration, employed in the Mediterranean region, was investigated in [19]. The comparison of the results with a classic TMW showed that thermal fins contribute to the increase of the internal room temperature rise and the decrease of the external temperature, allowing a significant improvement in the thermal efficiency. A TMW with venetian blind was studied to predict its thermal behavior [20]. The numerical results demonstrated that the average temperature of the air in the room was about 5 K higher than in a classic TMW. The penetration of the natural convection in vertical parallel plates with an asymmetrically heated wall was investigated numerically in [21], with the flow reversal caused by buoyancy.

The present work is motivated by the shortage of exergy analysis of the Trombe-Michel Wall (TMW) in the literature. The principal aim is to perform an exergy analysis, which requires the numerical investigation of the thermal and fluid dynamics characteristics of the TMW. Three new configurations are investigated in order to reduce losses, increase the mass flow rate and the heat transfer, for several channel widths and a given heat flow on the irradiated surface.

Nomenclature

Latin symbols

c_p	specific heat of air, J/(kg K)
$\dot{E}x$	exergy, W/m
L	glaze spacing, m
$\dot{m}$	mass flow rate, kg/(s m)
p	pressure, Pa
$\dot{Q}$	heat power, W/m
T	temperature, K
u	velocity, m/s
$u^* = \sqrt{\frac{\tau_w}{\rho}}$	friction velocity, m/s
y	distance from wall, m
$y^+ = \frac{u^* y}{\nu}$	dimensionless wall distance

Greek symbols

δ_{ij}	Kronecker delta
Δ	difference
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
τ	shear stress or Carnot Factor, N/m^2

Subscripts

am	ambient
d	destroyed
des	desired
inl	inlet
m	mean
out	outlet
p	constant pressure
rad	radiation
s	sun
t	turbulent
w	wall

2. Trombe-Michel Wall configurations

Fig. 1 reports the three configurations of the TMW investigated. Fig. 1a is the basic one, named “sharp edges”. Fig. 1b is the configuration named “rounded edges” on the inlet and the outlet vents. Fig. 1c is the configuration named “guided flow”, which is derived from the second one by adding the guide vanes on the bottom of the channel to limit the flow detachment from the heated wall.

The first configuration is the classic TMW; a vertical channel between the irradiated surface of the massive wall and the glaze covering, usually made of transparent material, as glass or polycarbonate. Most of the solar energy is out of the visible band, and the choice of the material could strongly affect the overall performance of the system. The configuration with “sharp edges” has two orifices of the same height. Losses of efficiency are mostly due to the shape of the orifices and their dimensions. Since one purpose of this study is to reduce losses, the inlet and outlet vents are modified with the configurations with “rounded edges” and “guided flow”. The “guided flow” configuration should avoid the flow detachment with the use of four blades downwind the bottom vent. The heat transfer over the irradiated vertical surface is assumed as an average value over the whole day. The heat transfer is the same for all the geometries, because the aim of the present work is to highlight the effect of the channel depth and the shape of the orifices.

3. Numerical analysis

3.1. Computational modeling

The numerical simulations are carried out with several spacing between the cover glazing and the irradiated wall. For each of the three configurations, the interspace thickness (L) is increased from 0.10 m to 0.50 m, with a step of 0.02 m. The total height is 3 m, the wall thickness 0.4 m, as the length of the inlet and outlet vents. The boundary conditions at the orifices are selected as pressure outlet, with inflow temperature of 20 °C on the lower vent. A temperature of 0 °C is imposed on the cover glazing, in order to overestimate the thermal losses of the whole heating system. The irradiated wall heat flux is assumed as 300 W/m^2. Top and bottom sides of the massive wall allow the heat transfer with the airflow. The other side of the massive wall has a heat transfer coefficient of 5 W/m^2 K, with 20 °C of room temperature. The radiated wall has a constant heat generation rate, since the aim of this