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Thermal energy storage and losses in a room-Trombe wall system located in Mexico

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ABSTRACT

A thermal evaluation of a R-TW system (room with a Trombe wall) is presented. Hourly climatic data of the coldest and the warmest days of 2014 was used to assess the behavior of the R-TW in two cities of Mexico with cold climate (Huitzilac and Toluca). The simulations were done with an in-house code based on the Finite Volume Method. It was found that thermal energy losses through the semitransparent wall are about 60% of the solar radiation incident on the system (G_{sol}). Despite of the thermal losses, the system gets enough energy to keep the air inside the room with a temperature above 35 °C. For both cities during the coldest day, the maximum energy stored is about 109 MJ and during the warmest day is about 70 MJ. This energy is supplied from the storage wall to the air inside the room during periods without insolation.

1. Introduction

Energy efficiency is one of the big challenges for today engineers since most of the energy generated comes for the burning of fossil fuels. In buildings, there are several options to achieve an efficient energy consumption. Solar energy is the most popular option because it is free and it can be used for diverse purposes such as production of photovoltaic and photothermal energy, solar distillation and heating or cooling of buildings via passive solar systems. Particularly, in the latter purpose, the Trombe wall system has demonstrated to be a suitable solution for heating buildings.

The TW (Trombe wall) is an indirect gain passive solar system which was designed and patented by Edward Morse with the purpose of supply heating and ventilation in buildings using solar radiation [1]. Between 1964 and 1967, this concept was used by Felix Trombe and Jacques Michel in a house located in Odeillo, France [2] where the system showed good results for heating. Since then, TW has been the subject of several studies aiming to improve its thermal performance. In the literature, there are theoretical studies that have predicted the behavior of the system considering several parameters. Some of these studies used the TNA (thermal network approach) to model the TW system [3–8], while others have used CFD (Computational Fluid Dynamics) [9–17].

Although TNA does not consider possible multidimensional effects due to the fluid flow in the channel, there are important results obtained with this method. Balcomb et al. studied the thermal performance of a Trombe wall considering three thicknesses of the wall (15, 30 and 60 cm) [3]. They found that a thickness of 15 cm is very sensitive to the changes of solar radiation, on the contrary a thickness of 30 cm is enough to damp this changes in an acceptable way. Later, Utzinger et al. compared a one-dimensional and two-dimensional model to determine the effects of the non-uniform heat flux on the wall. They observed that the one-dimensional model yields similar results to the two-dimensional when considering an exponential air temperature profile in the gap [4]. In subsequent studies it was determined that the energy inefficiencies in TW mainly occur by losses to the outside through the glass [18–20]. Then, it is necessary to quantify this parameter and to search possible solutions to minimize the energy losses. In a recent work, Fares reported that for economic

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Nomenclature

$C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$, C_μ	empirical coefficients of the turbulence model
c_p	specific heat (J/kgK)
dF	differential view factor
g	acceleration due to gravity (9.81 m/s^2)
G_{sol}	solar radiation (W/m^2)
H	height of cavity (m)
h_{ext}	outdoor convective heat transfer coefficient (W/m^2 K)
H_v	height of vents (m)
k	turbulent kinetic energy (m^2/s^2)
L	length of cavity (m)
L_c	width of the channel (m)
L_g	thickness of the glass (m)
L_r	length of room (m)
L_w	thickness of the storage wall (m)
p	pressure (N/m^2)
q	heat flux (W/m^2)
T	temperature (°C)
T_{amb}	ambient temperature (°C)
T_o	average fluid bulk temperature, °C
T_{sky}	sky temperature (°C)
u, v	components of velocity (m/s)
V_{wind}	wind velocity (m/s)
x, y	coordinates (m)
Greek	
α^*	absorptivity
β	volumetric thermal expansion coefficient (K^{-1})
β_g^*	extinction coefficient of the glass (m^{-1})
ε^*	emissivity
λ	thermal conductivity of the air (W/mK)
λ_s	thermal conductivity of the wall (W/mK)
μ	dynamic viscosity (Ns/m^2)
μ_t	turbulent viscosity (Ns/m^2)
ρ	density (kg/m^3)
$\rho*$	reflectivity
σ^*	Stefan–Boltzmann constant ($\sigma^* = 5.67 \times 10^{-08}$ W/m^2 K^4)
ε	rate dissipation of k (m^2/s^3)
Subscripts	
cond	conduction
conv	convection
rad	radiation
g	glass
s	solid

purposes, it is possible to use a 20–45 cm thick storage wall [21]. However, he recommended to use a thickness of 45 cm when is desired to store energy for nocturne warming. But if warming during the day is the priority, a thickness of 20 cm is the best choice.

Corresponding to CFD modeling, the first studies only considered heat convection in the channel [9,10]. Later, Ormiston et al. conducted the first numerical prediction of the thermal interaction between the Trombe wall and the room [11]. They concluded that is important to consider the coupling between the channel and the room because this interaction reduces the heat transfer by 30% compared to case when the coupling is not considered. In a posterior study, Ben Yedder and Bilgen studied the effect of the size of the vents [12]. It was observed that the system with vents performs better than the system without vents by about 25% at low Rayleigh number (*Ra*) and 10% at high *Ra*; thus, the thermal losses from the glazing are higher in the system without vents during the day. However, in the night, the system unvented is preferable because the massive wall prevents losses by convection from the room through the system. These studies made important contributions to the science of the Trombe wall system, nevertheless, they did not consider the thermal radiation. Mezrhab and co-workers were the first to consider the surface thermal radiation in the TW system (channel-storage wall-room) [22,23]. Results showed that thermal radiation considerably increases the heat transfer mainly for $Ra > 10^7$. It implies that thermal radiation must be considered when turbulent regime occurs. The same results were found by Tadrari et al., who studied the conjugate heat transfer in a TW system, but the coupling with the room was not considered [13]. From the results, the authors reported that thermal surface radiation contributes about 75% of the total heat transfer in the system.

Regarding to transient or pseudo transient numerical studies, Hami et al. conducted a transient numerical study for the climate data of Bechar, Algeria [24]. The authors considered laminar natural convection in the fluid and heat conduction in the storage wall. They found that the system efficiency can reach up to 48%. Rabani et al. made a pseudo transient prediction of the storage energy by the wall considering different materials in Yadz, Iran from the 07:00 h to 17:00 h [16]. Laminar flow regime and convective losses to the exterior were considered. From the results the authors concluded that Phase change materials are better to store energy than conventional ones.

Few CFD studies of the TW system that consider thermal radiation and turbulent regime are available [15,17,25,26]. One of these studies was developed by Kundakci and Yilmaz who compared a simulation model with experimental results of a TW façade of a model test in Izmir, Turkey for two days [15]. They found that the simulation model tends to overpredict the outlet air temperature in the channel when the solar radiation is weak. Liu et al. investigated the storage behavior of the TW by experimental and numerical prediction [25]. Authors observed that the thermal storage wall begins to store heat at about 07:30 h and at about 15:00 h, the energy storage reaches its maximum: 10.6 MJ/m^2 (72.82 MJ for the case of a surface of 6.9 m^2), then the storage wall releases its energy until at 07:30 h on the next day. Recently, Bajc et al. simulated a 3-dimensional TW system for Belgrade, Serbia weather [17]. Nevertheless, thermal losses through the glazing were not considered. Rabani et al. studied a new designed TW for Yadz, Iran in winter [26]. From the comparison of numerical and experimental results the authors concluded that the new design TW is able to keep the room warm.

From the above review, it can be observed that studies based on TNA do not consider the multidimensional effects and this way, CFD methods are preferable. In addition, many CFD studies have used laminar formulation to predict the thermal performance of the TW system and most of them do not consider the thermal radiation which contributes greatly to the total heat transfer in the system [13,22,23]. Moreover, according to the experimental evidence, the fluid flow in the channel is completely turbulent [27], hence the simulation must be performed considering both thermal radiation and turbulence regime. Those studies that use commercial software, do consider the thermal radiation and the turbulent regime, but they have not quantified the thermal energy losses through the