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PCM addition inside solar water heaters: Numerical comparative approach

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ABSTRACT

The aim of this paper is to highlight the design of solar storage tank integrating PCM modules for solar hot water production. The objective is to simulate working cycle of solar thermal energy storage systems with encapsulated PCM operating under realistic environmental conditions (Marrakech, Morocco) and typical consumption load profile. Thus, two numerical codes were built to predict the temperature evolution in a storage tank simulation filled by PCM. This research aims to compare two numerical procedures: the technique of apparent specific heat capacity (C_p^{app}) and the Enthalpy method, basically used to simulate the phase change phenomena for latent storage inside a solar tank integrating spherical PCM capsules. Effects, advantages and limits of these numerical methods were examined via various numerical observations as well as a set of system thermal performance indicators. The assumptions, equations used in numerical modeling, the temperature profiles and the PCM liquid fraction evolution are presented and discussed as well. It was found that the time required for a complete melting inside the storage tank for the considered PCMs is 2.5 h and the increase in PCM amount decreases the melting velocity and enhance the heat losses to surrounding in dynamic mode. Results also show that the choice of a numerical method plays an important role in describing efficiently the phase change phenomena and system thermal performance. Based on the design and parameter studies performed, other suggestions and several numerical model improvements for further studies are as well addressed.

1. Introduction

Currently, solar water heaters intended to produce hot water are the subject of great interest, especially the assessment of their overall efficiency that depends not only on environmental climatic conditions, but also on the efficiency of other determinant devices such as the storage tank. The introduction of Phase Change Materials (PCMs) provides a solution by using latent heat instead of sensible heat to store thermal energy, as evidenced by the abundant literature in the domain [1,2]. Furthermore, in the last decades, one of the actual issues is the improvement of solar energy technologies [3,4], particularly solar water heater systems intended to store domestic hot water whether for individual [5,6] or collective applications [7].

Nowadays, PCMs have become a potential contender used to improve the thermal inertia of the storage tank [8,9]. In fact, miscellaneous CFD studies have been conducted to assess solidification and melting of PCMs through two-dimensional [10] and three-dimensional numerical simulations [11]. Relevant studies have been identified that are presented as follows. First, Sattari et al. [12] investigated the melting process of phase change materials (PCMs) in a spherical capsule through CFD simulations. Their results showed that the surface temperature of the spherical capsule could have a significant effect on the heat flux and the melting rate, compared to other parameters such as geometrical parameters and other operational conditions. Moreover, the modeling and development of a novel heat exchanger with spiral-wired tubes which integrates phase change material (PCM) has been performed by Youssef et al. [13] using a detailed 3D CFD simulations that were validated against experimental measurements. The energy performance of the exchanger with PCM has been improved and its integration with the solar system remains a possible option.

Recently, Kasibhatla et al. [14] modeled two immiscible fluids: PCM and air using a continuum surface force (CSF) model which is available in OpenFOAM CFD software, in order to assess the Wetting Phenomena During Melting (WPDM) of PCM. Their results showed that the numerical modeling could be considered as a potential tool to optimize the efficiency of thermal storage units even if several small deviations occur in the achieved results. Furthermore, Laaouatni et al. [15] studied the technological feasibility and proposed a solution based on the

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Symbols

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U_z	water velocity [m/s]
T_{ini}	initial temperature [K]
T_{in}	inlet temperature [K]
T_S	solidus temperature [K]
T_L	liquidus temperature [K]
L	length of the tank [m]
D	diameter of the tank [m]
$\dot{m}_{load}$	mass load flow rate [kg/s]
$\dot{m}_{coll}$	collector mass flow rate [kg/s]
a_0	zero loss efficiency [–]
a_1	first order heat loss coefficient [W/K m^2]
a_2	second order heat loss coefficient [W/K^2 m^2]
h_a	ambient heat transfer coefficient [W/K m^2]
N	number of tank layers [–]
L_f	latent heat capacity [J/kg]
Pr	Prandtl number [–]
I_c	solar radiation [W/m^2]
h_g	global heat transfer through shell of capsule [W/K m^2]
Nu	Nusselt number [–]
R_i	thermal resistance [K/W]
ρ	density [kg/m^3]
β	thermal expansion coefficient [1/K]
μ	dynamic viscosity [Pa s]
λ	thermal conductivity [W/K m]
ϵ	proportion of PCM [%]
C_p^{app}	apparent specific heat capacity [J/K kg]
Re	Reynolds number
f	liquid fraction [–]
Δz	space step [m]
S_c	surface of the PCM capsule [m^2]

Abbreviations

PCM	phase change material
DHW	domestic hot water
in	injection
adv	advection
cd	conduction
cv	convection
cw	cold water
hw	hot water

integration of PCM with ventilation tubes in buildings in order to improve their thermal inertia. They performed two studies: an experimental assessment, besides to a 3D numerical simulation investigation. They showed through their results that a large thermal inertia of a building could be reached using this novel potential solution. Last but not least, the melting of a PCM using a simplified model in presence of natural convection and radiation has been carried out by Souayfane et al. [16]. They showed that their proposed simplified model is simple to implement and the computation time is reduced compared to CFD models and Discrete Ordinate Models (DOM) related to radiation heat transfer. The major importance of this simplified model lies in the fact that it can be easily integrated into an energy simulation tool for yearly performance evaluation. Moreover, they found that heat transfer by radiation enhances the average liquid fraction, while natural convection has a remarkable effect as it enhances the average liquid fraction and the position of the melting front during PCM melting process.

Due to the variation in solar insolation, thermal energy storage using PCMs is typically used in solar hot water systems to improve the system performance and particularly by improving the solar collector and heat exchanger efficiency [17] or by improving the performance of the storage part [18]. On the other hand, it is noted that considerable studies released in the literature are addressing solidification and melting of PCMs via different approaches and by means of CFD simulations as it was reported in the last paragraphs. Indeed, numerical methods such as the enthalpy method and the specific heat capacity method can be used to model solidification and melting. Panoply of these studies is presented through the following bibliographic research. For instance, Tabassum et al. [19] investigated 2D transient numerical study based on a boundary-fitted coordinate (BFC) technique to model the melting of an impure PCM in the arbitrary-shaped annular gap and various shaped inner tubes. In fact, they developed a code to solve the conservation equations for mass, momentum, and energy based on a finite difference method. In addition, they used the enthalpy-porosity scheme to model the mushy region melting. Moreover, Kozak et al. [20] developed a novel enthalpy method to model the melting of PCM which is accompanied by sinking of the solid phase. Their proposed model solved all the relevant conservation equations besides to the force balance for the solid bulk and a coupling between the solid phase motion and the melting taking into account the effect of natural convection. Furthermore, Joybari et al. [21] developed a simplified front tracking method to assess natural convection during melting of PCM based on two numerical models, because generally the upper half of the system is affected by the upward buoyancy-driven melted PCM motion. The first model is the pure conduction model, while the second one is the combined conduction and natural convection model.

It was also reported that the comparison between two numerical heat transfer models for phase change material namely: the effective heat capacity method and the enthalpy method were investigated by Jin et al. [22], because they are considered as the two most common methods used to build the numerical heat transfer models for phase change material (PCM) board. The main results of [22] have shown that the accuracy of those two models depends on the phase change temperature range. For instance, the capacity method could be efficient, if the phase change temperature range is small. However, the effective heat capacity method requires less computing time than the model with the enthalpy method.

Many numerical studies have investigated the addition of PCMs to increase the efficiency of thermal energy storage for sevral systems such as electronic cooling, batteries, etc used the overall system performance as a metric of evaluation. For instance, Wei et al. [23] released a review to depict the multiple investigations on selection principles, innovation, and thermophysical properties of high temperature PCM used for thermal energy storage. In fact, this review could be considered as a helpful reference for the design of high temperature Thermal Energy Storage systems (TES). Besides, investigations of a horizontal PCM that assists a heat pipe system for electronic cooling incorporated in higher-power computer chips through CFD numerical simulations has been carried out by Behi et al. [24]. Indeed, they found that the PCM-assisted heat pipe could provide up to 86.7% of the required cooling load in the working power range of 50-80 W. This contribution has been assessed equal to 11.7%. Furthermore, Yang et al. [25] performed numerical analysis besides to experimental visualization of PCM melting process for thermal management of cylindrical power battery. They found that the unmelted PCM instead adheres to the inner wall of housing and the melting at the rate slower than the metal housing case and the isothermal temperature plateau phenomena occurs when the latent heat and natural convection are sufficiently strong for the metal housing. In addition, Elarga et al. [26] carried out a multi-objective optimization through the development of a genetic algorithm, in order to study the integration of forced ventilated PV-PCM modules in glazed facade