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CFD thermal energy storage enhancement of PCM filling a cylindrical cavity equipped with submerged heating sources

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ABSTRACT

In this paper, two-dimensional CFD simulations were performed to simulate the melting process of a phase change material (PCM) filling a cylindrical cavity which includes heating sources. A CFD model based on the physical enthalpy-porosity formulation was used to simulate the phase change of the solid Gallium and to optimize the geometry of the heating sources according to the operating conditions in terms of the applied temperatures. The geometric effect of the heating sources, as well as the boundary conditions on the heat transfer characteristics are investigated in detail. In fact, the evolution of the temperature, liquid fraction and streamlines contours for the studied configurations, namely the cylindrical heating sources and the heating source with fins for two applied temperatures (T_h = 40 °C) and (T_h = 45 °C) were carried out. Temperature and liquid fraction measurement were assessed numerically for some specific points located inside the studied configurations for determining the redesign effect of the heating sources. Finally yet importantly, the heat transfer coefficient at the heating sources has been defined as indicator of performance to measure the contribution of the fins in the improvement of the melting time within the cylindrical cavity. It has been found that the cylindrical cavity where four fins are integrated at each heating source have enhanced the heat transfer in the PCM and improved its melting time from 18.35 min to 13.35 min while applying a hot temperature (T_h = 40 °C). Furthermore, the configuration with fins enhanced the heat transfer and improved the melting time of the PCM.

1. Introduction

Thermal energy storage (TES) improvement using phase change materials (PCMs) has become a highly topical issue of major importance in the scientific research community, because the released works with regard to this field have increased [1,2] during the last 20 years. It must be emphasized that research on the theory and application of phase change materials (PCM) in storage systems was undertaken extensively after 1970s [3]. In fact, the number of numerical and experimental studies has increased considerably. For instance, Diarce et al. [4] developed a two-dimensional CFD model for a new active type of ventilated facade integrating PCMs in their outer layer. They have shown that it is possible to consider a PCM as a solid material with a variable specific heat under the assumption of a negligible convective effects or thermal hysteresis phenomena. The expensive time of their numerical simulations was decreased using their developed melting and solidification model.

In the literature reports, Tay et al. [5] validated their CFD melting model against experimental results of a PCM encapsulated inside a cylindrical tank which is intended for thermal energy storage applications. They concluded that the CFD developed model is predicting with accuracy the behavior of the storage system during the thermal storage and release energy phases. While Sattari et al. [6] simulated the melting process of PCMs within a spherical capsule. Furthermore, Liu et al. [7] have studied the integration of phase change materials into concrete through microencapsulation using cenospheres.

Kumarasamy et al. [8] developed new CFD numerical schemes to model the dominant heat transfer by conduction of PCMs, which are encapsulated. Moreover, investigating the heat transfer of a building brick that includes PCMs has been presented in [9]. Saffari et al. [10] released a review on passive cooling of buildings which are actually using PCMs. While Wang et al. [11] have conducted a study to enhance heat transfer using phase change composite material with copper, foam and paraffin. In addition to this, Kuznik et al. [12] have studied the impact of the enthalpy function on the simulation of a building with phase change material wall.

Park et al. [13] have performed a numerical model and simulation of a vehicular heat storage system with PCMs. Furthermore, Zhou et al.

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Nomenclature

T_h	hot temperature (K)
T_c	cold temperature (K)
t	time (s)
$\vec{u}$	velocity vector (m/s)
g	gravity (m/s^2)
T	temperature (K)
T_m	mean temperature (K)
H	enthalpy (J)
h	sensible enthalpy (J)
h_{ref}	reference enthalpy (J)
C_p	specific heat capacity (J/K kg)
T_s	solidus temperature (K)
T_l	liquidus temperature (K)
L_F	latent heat of melting (K)
S	source term
A_{mush}	mushy zone constant
$\vec{u_p}$	solid velocity (m/s)
Ra	Rayleigh number

Greek symbols

ϕ_{int}	internal diameter (m)
ϕ_{ext}	external diameter (m)
ρ	density (kg/m^3)
$\bar{\bar{\tau}}$	viscous stress tensor (Pa)
β	thermal expansion coefficient (1/K)
μ	viscosity (Pa s)
α	liquid fraction
λ	conductivity (W/K m)

Abbreviations

PCM	phase change material
CFD	computational fluid dynamics
H.S	heat source

[14] have conducted a dynamic measurement of the thermal conductivity of phase change materials in the liquid phase near the melting point. Besides, Browne et al. [15] have investigated the corrosive properties of phase change materials in contact with metals and plastic. The thermal performance of an integrated collector storage solar water heater (ICSSWH) with phase change materials (PCM) has also been investigated [16]. The modeling and analysis of phase change materials for efficient thermal management strategy has been carried out in [17].

Recently, Ma et al. [18] have conducted a review and outlook on the use of phase change materials in photovoltaic systems for thermal regulation and electrical efficiency improvement. Besides, Muhammad et al. [19] have performed the validation of a CFD melting and solidification model for phase change in vertical cylinders. Moreover, Sharma et al. [20] have presented a numerical study to enhance the solidification of phase change materials using trapezoidal cavity. In addition, Pielichowska et al. [21] have investigated the phase change materials for thermal energy storage. Temirel et al. [22] have studied the solidification of additive-enhanced phase change materials in spherical enclosures with convective cooling. Other interesting studies can be found in the literature treating the incorporation and heat transfer optimization of PCM modules. In fact, Cano et al. [23] have investigated experimentally the thermal storage system using phase change materials. Zhao et al. [24] have proposed a passive thermal management system for electronic device using low-melting-point alloy as phase change material. Furthermore, Kapsalis et al. [25] have studied the solar thermal energy storage and heat pumps with phase change materials. Last but not least, Zhao et al. [26] have studied the heat transfer analysis of encapsulated phase change materials.

It should be noted that PCMs could be integrated inside stratified horizontale storage tanks [27], which include heat pipes [28] or verticle solar tanks [29] storage tanks to enhance their efficiency. Bouhal et al. [30] have already performed CFD parametric studies to optimize the energy efficiency of solar horizontal storage tanks and circulation pipes integrating evacuated tube collectors (ETC), by changing the number of the integrated heat pipes also their shape. It can be suggested as further studies to this thermal storage enhancement the integration of PCM within the tank, and to assess their effect on its overall efficiency such as the MIX number or the discharging yield. Further, PCMs can also be used to increase the efficiency of solar tanks liked to solar collectors for individual [31] or collective [32] applications of solar hot water production.

From our literature review and according to the best of the authors' knowledge, little attention has been paid to the heat transfer problem during the melting of the PCM heated from the outer surface of a closed cavity and from discrete sources with different shapes (internal heated cylinders with and without fins configurations) put at its inside. In this vision, this paper focuses on the melting process inside a cylindrical cavity, where a relatively higher temperature than the melting temperature of the PCM is applied. The effect of the internal heated source geometries, which are with and without fins on the kinetics of the

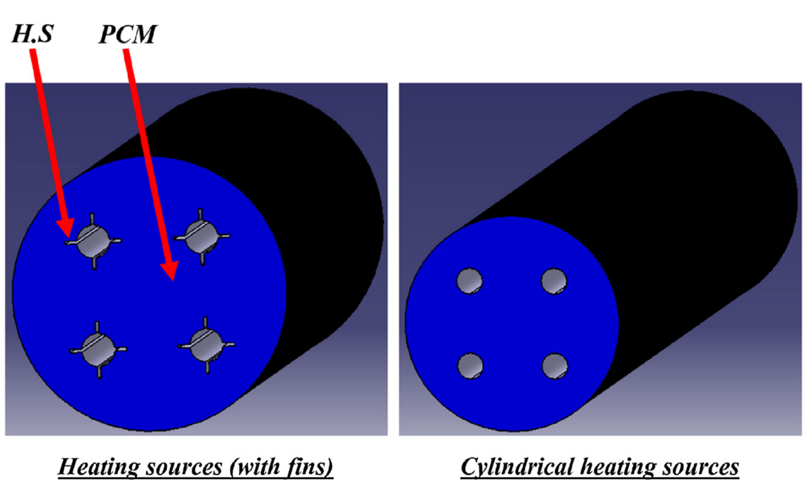

Fig. 1. Layout of the cylindrical cavity including heating sources with and without fins.