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Study of heat and fluid flow during melting of PCM inside vertical cylindrical tube

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ABSTRACT

This paper presents numerical investigation to study the melting of Phase Change Material (PCM) partially filled in a vertical cylindrical tube. The top space of tube was filled with air to take into account the volumetric expansion of PCM. The natural convection inside PCM liquid phase was considered via the temperature dependency of density and gravitational force. The finite-volume method was adopted to discretize the conservation equations of mass, momentum, and energy. The enthalpy porosity formulation was employed to solve the energy equation in both regions of PCM, liquid and solid. In this multiphase system, the Air-PCM interactions have been treated using the Volume of Fluid model (VOF). The mathematical model is based on conjugate heat transfer in PCM subjected to a constant temperature at the external surface of cylindrical shell. The obtained results have been analyzed and compared with literature, and a good agreement was showed. Then, a parametric study was carried out to establish correlations for the liquid fraction and time of complete melting as a function of all dimensionless parameters that governing this problem, such as Fourier number, Grashof number, Stefan number, wall to PCM thermal diffusivity ratio, tube aspect ratio, shell-to-tube diameter ratio and dimensionless initial temperature. The results show that all parameters of the problem can really affect the phase change phenomena and consequently, affect the melting time.

1. Introduction

The use of latent heat of Phase Change Materials (PCM) in the energy storage systems has attracted a lot the attention of researchers interested in renewable energies field. Usually, the PCM can be encapsulated in containers of cylindrical or spherical geometries. In literature, a large number of available works present experimental, numerical and analytical research investigating the PCM melting within a cylindrical tube. The PCM can be filled in open or closed containers that can be placed in vertical, horizontal or inclined position. Some researchers have been inspected the effects of the rotating shell on the phase change process. The shell-and-tube configuration, in vertical or horizontal direction, has been widely studied as latent heat storage systems. The melting of PCM in vertical tube configuration has attracted, for the first time, the attention of Sparrow and Broadbent [1], where the heat transfer and transient evolution of the liquid-solid interface during the melting of a PCM was experimentally investigated. This study is continued by Sparrow et al. [2] to investigate the melting of pure and impure PCM. The time-dependent melting results for the substances were correlated as a function of some dimensionless parameters. The melting of the paraffin RT27 as phase change material filled in open vertical tubes of different diameters was experimentally analyzed by Katsman [3]. The effect of internal longitudinal fins in the tubes was investigated, and a correlation relates the dimensionless melting time to Stefan number and Raleigh number was developed. It was found that the liquid fraction and the heat flow during melting process can be significantly affected by the natural convection within the liquid phase of PCM. The natural convective motion during PCM solidification and melting in vertical cylindrical was visually followed in the experiment conducted by Menon et al. [4]. Shmueli et al. [5] studied numerically the same geometries as [3] to investigate the effect of various parameters, such as the mushy zone, pressure–velocity coupling and pressure discretization schemes on the simulation results. Benjamin et al. [6] obtained experimental measurements during the melting of the n-eicosane, as PCM with a moderate-Prandtl-number, in an upside-heated cylinder; the melting front was captured photographically and its location determined using digital image processing techniques. Ebadi et al. [7,8] investigated numerically and

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Nomenclature

cp	specific heat ($Jkg^{-1}K^{-1}$)
D	diameter of tube (m)
fr	liquid fraction
Fo	Fourier number [$Fo = t\alpha_l/D^2$]
g	gravitation (ms^{-2})
H	PCM height inside tube (m)
L	height of tube (m)
k	thermal conductivity ($Wm^{-1}K^{-1}$)
P	Pressure (Nm^{-2})
q	latent heat (Jkg^{-1})
r	radial coordinate (m)
R	radius of cylindrical tube (m)
Gr	Grashof number [$g\beta(T_w - T_m)D^3\rho_l^2/\mu_l^2$]
Gr_H	H-Grashof number [$g\beta(T_w - T_m)H^3\rho_l^2/\mu_l^2$]
Ste	Stefan number [$cp_l(T_w - T_m)/q$]
Ste_s	solid Stefan number (or sub-cooling parameter) [$cp_l(T_m - T_i)/q$]
t	time (s)
T	dimensional temperature (K)
u	Velocity (ms^{-1})
z	axial coordinate (m)

Greek symbols

α	thermal diffusivity (m^2s^{-1})
β	thermal expansion coefficient of PCM (K^{-1})
γ	porosity
δ	shell thickness (m)
ζ	volume fraction
μ	dynamic viscosity ($kgm^{-1}s^{-1}$)
ρ	density (kgm^{-3})
σ	dimensionless shell thickness[$\sigma = 2\delta/D$]
χ	dimensionless height of PCM [$\chi = H/L$]
ψ	wall to PCM thermal diffusivity ratio[$\psi = \alpha_w/\alpha_l$]

Subscripts

s, l	solid and liquid phase
i, m	initial and melting
w	phase change material, wall

experimentally the effects of nano-particles volume fraction on the melting process in a vertical cylindrical tube, used like thermal energy storage system.The PCM solidification in an open horizontal tube found its application in the study of Vu [9].

The PCM expansion is an important factor during the phase change process, and must be taken into account during experimental studies. Then, the closed containers must be partially filled with PCM and the void space will be used for the dilated liquid [10,11]. For analytical and numerical simulations, this factor can de neglected for most cases [12,13]. Kalaiselvam et al. [14] developed an analytical solution for particular quasi-steady regime (low Stefan number) to study the PCM melting within cylinder with a constant temperature imposed on external surface. Hlimi et al. [15] developed a numerical code basing on the finite volume method and an enthalpy porosity technique to investigate the effects of natural convection during constrained melting within a horizontal cylindrical capsule. The constrained melting of PCM within horizontal cylindrical capsule was also studied numerically and experimentally in Refs. [16,17]; the nanoparticles was dispersed within the phase change material.

The shell-and-tube latent heat thermal energy storage systems (LHTES) are a promising technique in renewable energy filed; and its application was considerably adapted to storing the solar heat energy [18–23]. Akgun et al. [24] conducted a series of experiments to design and build a novel storage unit used as shell-and-tube heat exchanger system. The effect of geometric design on vertical shell-and-tube latent heat storage systems was investigated by Seddegh [25], using cylindrical and conical shapes. Ait Adine and El Qarnia [26] studied numerically a latent heat storage unit consisting of two coaxial tubes. In order to enhance the thermal performance of the latent heat storage unit, two phase change materials (paraffin P116 and n-octadecane) were used to fill the space between tubes. Cao et al. [27] combined experimental research and numerical simulation to examine the heat transfer enhancement due to the eccentricity ratio. It was found that the natural convection in the eccentric horizontal shell-and-tube unit is more important, and can increases significantly the melting performance in the storage unit. Tao and He [28] designed a local enhanced fin-tube to eliminate the larger non-uniformity for the solid–liquid interface caused by the natural convection during the PCM melting in a horizontal shell-and-tube storage unit. Liu and Groulx [29] used central and longitudinal fins with two orientations, straight fins and angled fins, to enhance the overall heat transfer rates during the phase change processes inside a shell-and-tube latent heat energy storage system. Chabot and Gosselin [30] studied the constrained PCM melting around a hot cylinder in horizontal cavity in transient regime; and Jourabian et al. [31] investigated the same problem with cyclic heating.

Some works studied the melting in rotating tubes, Chaboki and Sparrow [32] performed an experiment in which the melting of PCM occurred in close rotating tube. It was found that the rotation improves the melting process compared with the static case. The coupling between rotation and melting indicates that, when $Pr \geq 1$, the secondary flow induced by rotation within the cavity plays a similar role to natural convection in a non-rotating tube [33]. The unconstrained case, the shape of the solid was substantially affected by rotation than the constrained case [34].

Regarding the above mentioned works, we noted that Sparrow et al. [2] and Katsman [3] correlated the transient melting fraction evolution with considering only a few parameters, like Stefan number and Grashof number. The numerical simulation performed in the current work, takes into account all pertinent parameters governing the phase change process, to elaborate two correlations: the first to evaluate the liquid fraction evolution and the second correlation to determine the complete melting time inside an open vertical cylindrical tubes.

2. Problem statement

2.1. Physical model

As shown in Fig. 1, we consider a vertical tube of internal radius *R* and wall thickness δ, partially filled with solid phase change material at initial temperature T_i. To considering the volumetric expansion during the melting of PCM, the remaining volume of tube is occupied by air at one bar. The external surface of the wall is subject to a constant temperature T_w, which could be greater than the melting temperature of PCM. The tube is open from the above and insulated from the bottom side. The phase change process was studied as unsteady, laminar, incompressible, axisymmetric and two-dimensional problem.

In current study, we investigated the melting of PCM in a vertical cylindrical tube of 0.5, 1 and 2.5 mm in shell thickness and 15, 25, and 35 mm in inner diameter, at the outer wall temperatures of 5, 15, and 25 °C above the melting temperature of PCM. In the initial state, the height of solid PCM is $H = 7.5$, 10 and 12.5 cm, that fills 50, 67 and 83.3% of the tube volume at the initial temperature of 0.01, 6 and 26 °C below the PCM melting temperature. The full length of tube was fixed at $L = 15$ cm in all studied cases. The heat and fluid flow is