



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 finite-volume method was adopted to discretize the conservation equations of mass, momentum, and energy. The enthalpy 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 subject to constant temperature at the external surface of cylindrical shell. The obtained results have been analysed and compared with literature, and a good agreement was showed. Then, a parametric study was carried out to establish correlations for liquid fraction and the time of complete melting as a function of the main dimensionless parameters that governing this problem, such as Grashof number, Stefan number and wall-to-tube diameter ratio.

Keywords—Phase change material, Melting, heat storage, Numerical resolution, Cylindrical tube.

I. INTRODUCTION

The use of latent heat of Phase Change Materials (PCM) in the energy storage systems has attracted a lot the attention of researcher 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 [1-3], numerical [4, 5] and analytical [6, 7] research investigating PCM melting within a cylindrical tube.

Sparrow et al. [1] studied by experiments the melting of two types of paraffin, as pure and impure PCM, in a closed vertical tube. The time-dependent melting results for the investigated substances were correlated as a function of pertinent dimensionless parameters. Sparrow and Broadbent [2] experimentally investigated the heat transfer and transient evolution of the melting interface during the melting of a phase-change material in a vertical tube. It was found that the natural convection within the liquid phase of PCM, could affect significantly the liquid fraction and the heat flow during melting process. Benjamin et al. [3] obtained an experimental measurements during the melting of the n-eicosane, as a moderate-Prandtl number material, in a cylindrical enclosure

heated from the side. The melting front was captured photographically and its location ascertained using digital image processing techniques.

Wu and Lacroix [4] conducted a numerical study of natural convection melting of a phase change material within an isothermal vertical cylinder. The continuity, momentum and energy equations with the corresponding boundary conditions are solved with the finite difference method. The effect of various parameters of the numerical solution, such as the mushy zone, pressure-velocity coupling and pressure discretization schemes, on the results is examined by Shmueli et al. [5].

Bechiri and Mansouri [6] developed an analytical solution to study volumetric heat generation effects during melting and solidification of nano-enhanced phase change material, encapsulated in horizontal cylindrical container of thermal energy storage. Kalaiselvam et al. [7] 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,

In this work, we take into account the thickness of the tube wall to improve our understanding of the PCM melting phenomenon, inside vertical cylindrical tubes.

II. PROBLEM STATEMENT

A. Physical model

As shown in Fig. 1, we consider a vertical tube of internal radius R_0 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_0 , which could be greater than the melting temperature of PCM. The tube is open from the above and isolated from the bottom side. The phase change process was studied as unsteady, laminar, incompressible, axisymmetric and two-dimensional problem.

In this study, we investigating 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 $H = 10$ cm, and fills 67 % of the tube volume at the initial temperature of 5°C below the PCM melting temperature. The heat and fluid flow is axisymmetric around the vertical axis of the tube and conduction is the lone mode of heat transfer through the solid shell material. The following assumptions are considered:

- Both air and PCM are homogeneous and isotropic.
- The liquid phase is a Newtonian fluid.
- The flow is laminar and has no viscous dissipation.

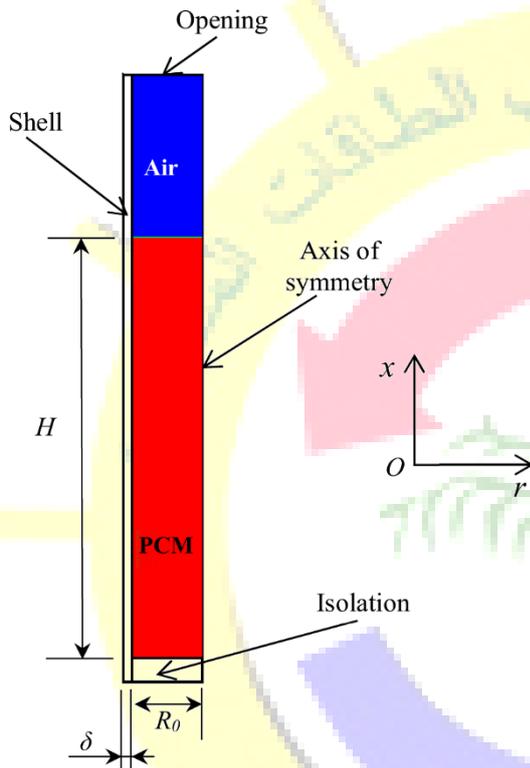


Fig. 1. Schematic of the considered geometry.

B. Computational procedures

The fluid flow and temperature evolution during the phase change process were described by Navier-Stokes and thermal energy equations. In order to simulate the phase change process, enthalpy-porosity formulation and control volume technique were used. The computational domain of the axisymmetric model is shown in Fig. 1. The Volume-of-Fluid (VOF) model is used to describe the PCM–Air interactions with a moving interface and without interpenetration of the two media. The volume fraction of the n th fluid (α_n) is defined as:

$$\alpha_n = \frac{\text{volume of the } n^{\text{th}} \text{ phase in a cell}}{\text{volume of the cell}} \quad (1)$$

where:

$$\begin{aligned} \alpha_n &= 0 && \text{if the cell is empty of the } n^{\text{th}} \text{ fluid} \\ \alpha_n &= 1 && \text{if the cell is full of the } n^{\text{th}} \text{ fluid} \\ 0 < \alpha_n < 1 && \text{if the cell contains the fluid interface} \end{aligned} \quad (2)$$

Consequently, the governing equations can be expressed as follows:

- Continuity:

$$\frac{\partial(\alpha_n \rho_n)}{\partial t} + \nabla \cdot (\alpha_n \rho_n \mathbf{u}_n) = 0 \quad (3)$$

- Momentum:

$$\frac{\partial(\alpha_n \rho_n \mathbf{u}_n)}{\partial t} + (\mathbf{u}_n \cdot \nabla)(\alpha_n \rho_n \mathbf{u}_n) = -\alpha_n \nabla P + \alpha_n \rho_n \mathbf{g} + \alpha_n \mu (\nabla \cdot \nabla) \mathbf{u}_n \quad (4)$$

- Energy:

$$\frac{\partial(\alpha_n \rho_n \bar{H})}{\partial t} + \nabla \cdot (\alpha_n \rho_n \mathbf{u}_n \bar{H}) = \alpha_n \nabla \cdot (k_n \nabla T) \quad (5)$$

In the above equations, \mathbf{u}_n is the n th fluid's velocity vector, \bar{H} is the sensible enthalpy and H is the specific enthalpy which is defined as the sum of sensible heat " $cp \times T$ ", and latent heat " $\gamma \times q$ ", as:

$$\bar{H} = cp T + \gamma q \quad (6)$$

the porosity γ , can be defined as below:

$$\begin{aligned} \gamma &= 0, && \text{if } T < T_{\text{solidus}} \\ \gamma &= 1, && \text{if } T > T_{\text{liquidus}} \\ \gamma &= \frac{T - T_{\text{solidus}}}{T_{\text{liquidus}} - T_{\text{solidus}}}, && \text{if } T_{\text{solidus}} < T < T_{\text{liquidus}} \end{aligned} \quad (7)$$

The above mathematical system was numerically resolved using the control volume technique. The pressure-velocity coupling was treated by employing an implicit scheme based on the SIMPLE algorithm. The PRESTO scheme was adopted for the pressure correction equation. A second order upwind scheme was employed to discretise the momentum and energy equations. The under relaxation factors for pressure, density, velocity, and liquid fraction were 0.2, 0.7, 0.4, and 0.9, respectively. The convergence criteria for continuity, velocity, and energy equations was checked at each time step, and it was chosen as absolute residuals of 10^{-7} , 10^{-7} and 10^{-10} ,



respectively. To ensure independency of solution, different cases were tested; and it was found that a grid size of 0.5mm, time step of 0.01s and number of iterations for every time step of 50 were sufficient to satisfy the convergence criteria.

C. Validation

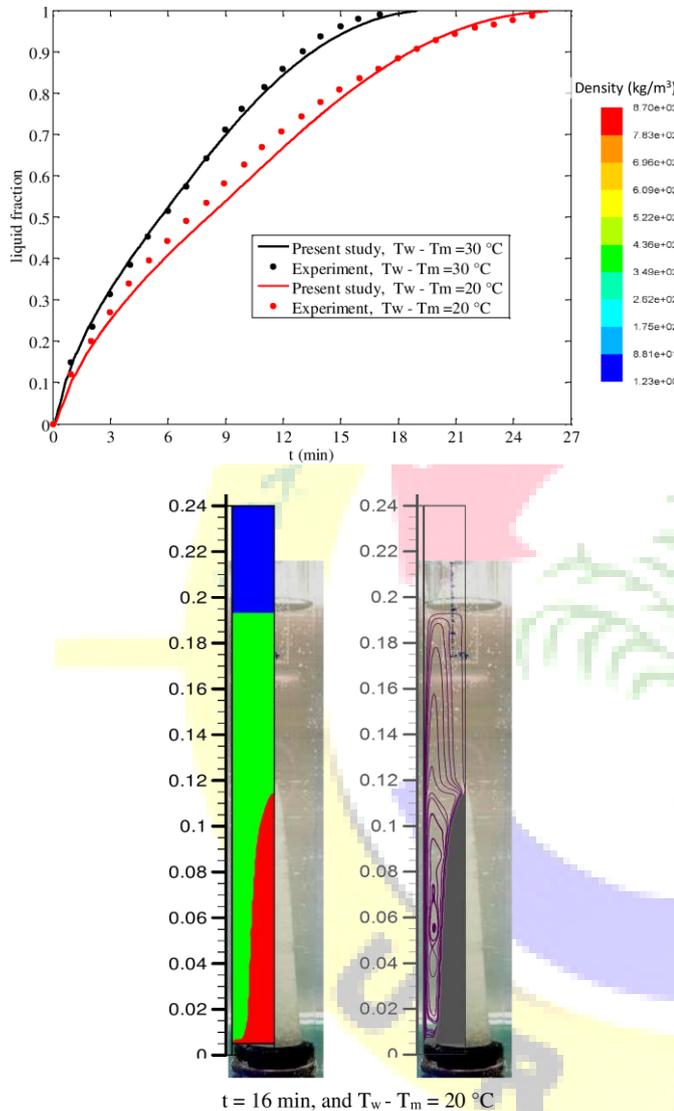


Fig. 2. Validation of numerical results with experiment [8].

In order to validate the developed numerical model, a comparison with available experimental results presented by Katsman [8], was performed. In his work, the author conducted an experimental investigation to study the melting of RT27 as phase change material, filled in vertical tubes of different diameters, and the same height. The investigation has

been extended to study the effect of internal longitudinal fins in the tubes. For comparison purpose, we adopted the same characteristics of materials used in experiment. It can be seen from the comparative results plotted in Fig. 2, that presents the contour of density, the streamlines and the timewise liquid fraction evolution for two values of outer wall temperatures, that the two methods are in good agreement.

III. RESULTS AND COMMENTS

The effects of the tube inner diameter, outer surface temperature, wall thickness, Grashof number and Stefan number have been analyzed by considering the seven cases summarized in Table 1. In this numerical simulation, the commercial parafin RT27 (Rubitherm GmbH), was used as phase change material with a melting temperature interval of 28–30 °C. The properties of all materials used in this study are cited in Réfs [5, 8-9].

Table 1. Different cases analyzed.

Case number	D (mm)	T ₀ - T _m (K)	δ mm	Gr _D	Ste	Γ
1	15	15	1	6.48 × 10 ³	0.2095	0.1333
2	25			2.99 × 10 ⁴		0.08
3	35			8.23 × 10 ⁴		0.0571
4	25	5	1	8.23 × 10 ³	0.0698	0.08
5		25		6.02 × 10 ⁴	0.3492	
6	25	15	0.5	2.99 × 10 ⁴	0.2095	0.04
7			1.5			0.12

In Fig. 3, the transient evolution of the liquid fraction was presented for different values of cylinder diameter defined by the cases 1-3, with constant outer wall temperature, Tw = 316 K. As can be seen, low cylinder diameter reduces the complete melting time. The variation of cylinder diameter from 15 to 35 cm increases the melting time around 20 minutes. Indeed, the increasing in the cylinder diameter affects two parameters, namely: the mass of PCM that must be melted, and the second is the natural convection in the PCM liquid phase. The increasing in the PCM amount leads to extend the time of complete melting, and the natural tends to accelerate melting process so, decreases the total melting time. Therefore, the PCM amount is more affecting than the natural convection, on the melting time.

The effect of the shell outer surface temperature on the timewise variation of the liquid fraction during melting of PCM, was studied by examining the cases 2, 4 and 5. The inner diameter and shell thickness were fixed at 25 mm and 1 mm, respectively. The Fig. 4 shows the liquid fraction evolution as function of time for different boundary condition values above the PCM melting temperature. The increasing of outer wall temperature from 306 to 326 K reduces the melting time approximately 23 minutes. Therefore, higher values of



shell outer wall temperature lead to a short melting time. In addition, the increase in the sensible heat effects the Grachof Number, and consequently, enhances the natural convection heat transfer.

material wall, which will participate to slow down the heat transfer between PCM and tube. This reduction in heat exchange leads to increase the melting time.

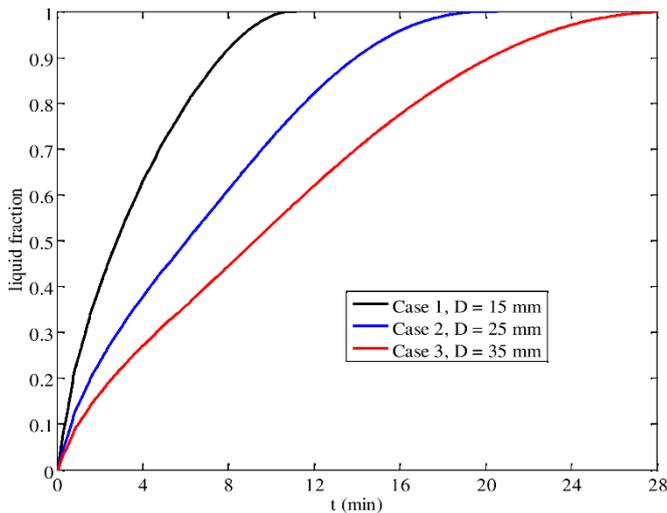


Fig. 2. Effect of the tube diameter on the liquid fraction.

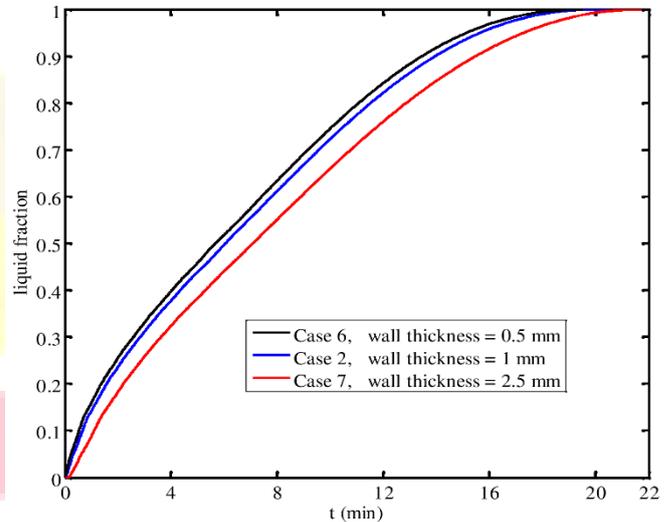


Fig. 3. Effect of the wall thickness on the liquid fraction.

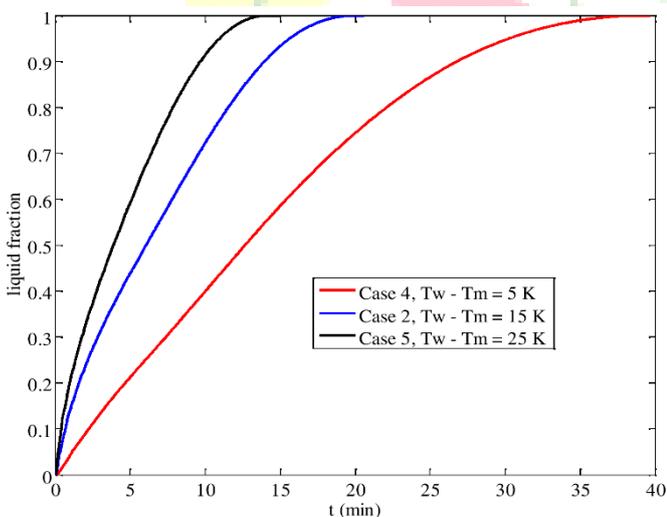


Fig. 4. Effect of the outer wall temperature on the liquid fraction.

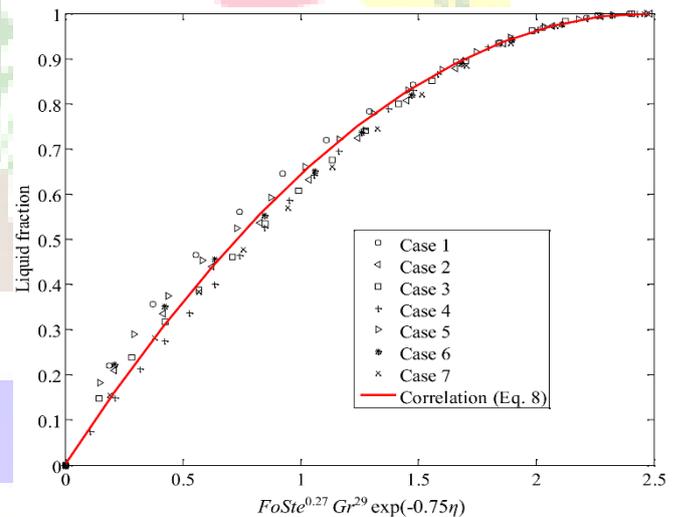


Fig. 6. Liquid fraction as a function of pertinent parameters.

The wall thickness effects have been examined by analyzing the cases 2, 6 and 7, where the inner diameter and outer wall temperature were fixed at 25mm and 316 K, respectively. The predicted transient liquid fraction evolution for the aforementioned cases is depicted in Fig. 5. The decreasing in wall thickness from 2.5 to 0.5mm reduces the melting time roughly 142 s. The increase in wall thickness value is interpreted as an elevation in the thermal resistance of

Fig. 6 presents the evolution of melting fraction as function of pertinent dimensionless parameters that controlling the melting process. The Fourier number, Stefan number, Grashof number and dimensionless thickness wall have been placed in the X-axis to substitute the dimensional time, as the following form: $FoSte^a Gr^b \exp(c\eta)$. It's clear that the values of $a = 0.27$, $b = 0.29$ and $c = -0.75$ lead to merge all the curves into a single curve, which can be fitted by the following correlation:



$$fr = 0.807 X - 0.162 X^2 \quad (8)$$

where

$$X = FoSte^{0.27}Gr^{0.29} \exp(-0.75\eta)$$

Based on this equation, the correlation that fits the complete melting time as function of the dimensionless parameters, can be obtained by imposing $fr = 1$, and we obtain:

$$Fo_{complete\ melting} = \frac{2.482}{Ste^{0.27}Gr^{0.29} \exp(-0.75\eta)} \quad (9)$$

In Fig. 7, this correlation is compared to the numerical simulation results. It can be concluded that this correlation fits perfectly the complete melting time of the numerical simulation.

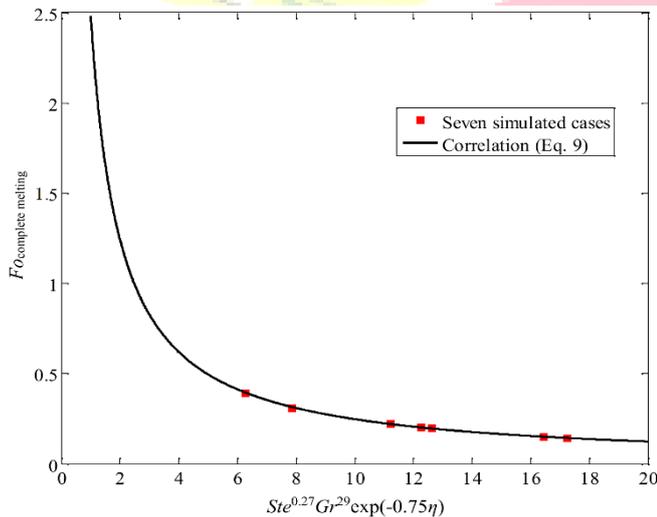


Fig. 4. Dimensionless complete time as a function of pertinent parameters.

IV. CONCLUSIONS

A numerical simulation of phase change process of commercial paraffin RT27 has been performed and examined. The PCM is encapsulated in a cylindrical vertical tube exposed to constant temperature at the tube outer wall. The following conclusions were obtained:

- The numerical solution developed in this study was validated by comparing the obtained results with literature, and it can be used to validate other methods.

- The natural convection in the liquid PCM and the temperature of outer wall surface can significantly affect the melting process.
- The correlations proposed for the liquid fraction and complete melting can be used with good confidence only for fixed $H = 10$ cm, $T_m - T_i = 5$ K and $\zeta_l / \zeta_w = 0.3061$.

NOMENCLATURE

cp	specific heat (Jkg ⁻¹ K ⁻¹)
D	diameter of tube
fr	liquid/solid fraction
g	gravitation (ms ⁻²)
k	thermal conductivity (Wm ⁻¹ K ⁻¹)
q	latent heat (Jkg ⁻¹)
r	radial coordinate (m)
R0	radius of cylindrical tube (m)
Gr	Grashof number [$g\beta(T_0 - T_m)D^3\rho l^2/\mu l^2$]
Ste	Stefan number [$cpl(T_0 - T_m)/q$]
t	time (s)
T	dimensional temperature (K)

Greek symbols

β	thermal expansion coefficient (K ⁻¹)
γ	porosity
δ	wall thickness (m)
η	dimensionless thickness [$2\delta/D$]
ρ	density (kgm ⁻³)
ζ	thermal diffusivity (m ² s ⁻¹)
μ	dynamic viscosity (kgm ⁻¹ s ⁻¹)
χ	PCM to wall thermal diffusivity [$\chi = \zeta_l/\zeta_w$]
Fo	Fourier number [$Fo = t\zeta_l/D^2$]

Subscripts

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

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