International Communications in Heat and Mass Transfer 88 (2017) 211–219

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

# Numerical simulation and experimental verification of constrained melting of phase change material in inclined rectangular enclosures

Babak Kamkari[a,*], Hamid Jahedi Amlashi[b]

[a] Department of Mechanical Engineering, Yadegar-e-Imam Khomeini (RAH) Shahre-Rey Branch, Islamic Azad University, Tehran, Iran
[b] Department of Mechanical Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran

ARTICLE INFO

*Keywords:*
Phase change material
Inclination
Constrained melting
Lauric acid

ABSTRACT

In the present study, melting of phase change material (PCM) in vertical and inclined rectangular enclosures is numerically investigated. Comparison of the numerical and experimental results reveals that the two-dimensional numerical simulations of PCM melting in vertical enclosures can accurately predict both the liquid fraction and the temporal evolution of the solid-liquid interface. Also, it well predicts the instantaneous values of liquid fractions for inclined enclosures (45° and 0°) with a maximum deviation less than 6.5%. Regardless of the Stephan number, the complete melting time in 0° and 45° inclined enclosures are respectively about 52% and 37% shorter as compared to the vertical enclosure. Heat transfer enhancement and consequently melting rate augmentation in inclined enclosures are found to be the result of the intensification of natural convection flows and formation of thermal plumes originating from counter-rotating vortices. Moreover, to generalize the results, a group of dimensionless numbers is introduced and used to develop three new correlations for prediction of the instantaneous liquid fraction, energy storage and time-averaged Nusselt number in inclined enclosures.

## 1. Introduction

The latent heat thermal energy storage systems based on phase change material (PCM) have gained increasing interest due to the advantages of high thermal energy storage density and small temperature change during the melting and solidification processes. PCMs have great potential for integration with different thermal systems such as solar thermal collectors, solar cells, building air conditioning and electronics. Besides the advantages of PCMs, the main drawback of these materials is their inherently low thermal conductivity decreasing the rate of heat transfer during the melting and solidification processes. In order to overcome this shortcoming of PCMs, various heat transfer enhancement techniques have been proposed. These methods include the use of fins [1], metal/graphite matrices [2], heat pipes [3,4], dispersed high-conductivity nanoparticles in the PCM [5], and micro-encapsulation of PCM [6].

It has already been proven that melting of PCM in an enclosure is a transient process controlled by two heat transfer mechanisms, heat conduction and natural convection [7]. The dominance of each of the mentioned heat transfer mechanisms depends on the melting method of the PCM. Melting of PCM in enclosures can be categorized as unconstrained (close-contact or unfixed) and constrained (fixed), depending on the position of solid PCM in the container. During the unconstrained melting, the solid PCM descends to the bottom of the container and heat transfer to the PCM occurs by both heat conduction and natural convection. Heat conduction is the dominant mode of heat transfer through the thin film of liquid between the solid PCM and heat transfer surface while natural convection exists at the bulk of the liquid PCM in the upper part of the enclosure [8–12]. During the constrained melting, the solid PCM is restrained from settling down to the bottom of the container and heat conduction plays a significant role only during the initial stage of melting while natural convection becomes the dominant mode of heat transfer as the gap between the solid PCM and container wall increases [13–15]. The strength of natural convection flows in the liquid PCM depends on the geometry of the container and a group of nondimensional numbers, namely Rayleigh, Stefan, and Fourier. Also, the inclination of the container with respect to the gravitational field affects the formation of natural convection flows and consequently changes the melting rate of the PCM [16,17]. One of the earliest studies addressing the melting of PCM in inclined enclosures was conducted by Webb and Viskanta [17]. They experimentally investigated melting of PCM in a rectangular enclosure at inclinations of 0°, 30° and 60° with a fixed Stefan number. The results revealed that the melting rate of PCM is strongly dependent on the inclination angle of the enclosure. Sharifi et al. [18] examined the effect of tilting on melting behavior of PCM in a cylindrical enclosure. The experimental

* Corresponding author.
*E-mail addresses:* kamkari@ut.ac.ir, kamkari@iausr.ac.ir (B. Kamkari), h.amlashi@srbiau.ac.ir (H.J. Amlashi).

http://dx.doi.org/10.1016/j.icheatmasstransfer.2017.07.023

**Nomenclature**

| | |
|---|---|
| $C_p$ | specific heat capacity, J/(kg K) |
| $e$ | thermal energy storage per kilogram of PCM, J/kg |
| $Fo = \frac{\alpha t}{H^2}$ | Fourier number |
| $g$ | gravity acceleration, m/s$^2$ |
| $H$ | height of the enclosure, m |
| $h_{SL}$ | latent heat of fusion, J/kg |
| $k$ | thermal conductivity, W/(m K) |
| $\langle \overline{Nu} \rangle$ | time-averaged Nusselt number |
| $Ra = \frac{g\beta(T_w - T_m)H^3}{\nu\alpha}$ | Rayleigh number |
| $Ste^*$ | modified Stefan number |
| $t$ | time, s |
| $T$ | temperature, °C |
| $u$ | horizontal velocity component, m/s |
| $v$ | vertical velocity component, m/s |
| $x$ | horizontal Cartesian coordinate, m |
| $y$ | vertical Cartesian coordinate, m |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | thermal diffusivity, m$^2$/s |
| $\beta$ | thermal expansion coefficient, 1/s |
| $\gamma$ | liquid fraction |
| $\mu$ | dynamic viscosity, kg/(m s) |
| $\rho$ | mass density, kg/m$^3$ |
| $\theta$ | angle of inclination, degrees |
| $\Delta H$ | latent heat, J/kg |

*Subscripts*

| | |
|---|---|
| $l$ | liquid phase |
| $m$ | melting temperature |
| $o$ | initial |
| $s$ | solid phase |
| $w$ | wall |

measurements showed that tilting the enclosure induces three-dimensional convection currents in the liquid PCM. Allen et al. [19] experimentally analyzed the melting and solidification of PCM in a cylindrical enclosure with different combinations of heat transfer promoters including heat pipe, copper rod, aluminum foil, and foam. It was observed that the orientation of the container significantly alters the liquid fraction histories during the melting process. However, during solidification, orientation has a minimal effect on the solidification rates due to conduction-dominated heat transfer. Kousha et al. [20] studied the effect of inclination angle (0° to 90°) on the thermal performance of a shell and tube heat storage unit. Results indicated that the melting rate in horizontal position is higher than the other inclinations.

The effect of inclination on thermal performance of PCM-based heat sinks has also been explored by several researchers. Fok et al. [21] experimentally showed that thermal behavior of heat sink is slightly affected by its inclination at low heating powers (less than 0.5 W/cm$^2$). However, they declared that the angle of inclination may become significant at higher power levels. Similar findings were also observed by Wang et al. [22] and Yang and Wang [23]. Lu et al. [24] reported that the thermal performance of PCM-based heat sink varies by inclination angle when it is operating under intense heat loads (about 2.5 W/cm$^2$). Baby and Balaji [25] experimentally studied the influence of orientation on thermal performance of a metal foam heat sink filled with PCM. The results showed that the orientation has a marginal effect on the heat transfer performance of heat sink but according to an investigation conducted by Lafdi et al. [26] it was found that orientation of heat sink can greatly alter the heat transfer performance of the metal foam heat sink saturated with PCM.

The preceding review shows that studies on the effect of inclination angle on melting of PCM in rectangular enclosures are scarce. To the authors' knowledge, the only detailed experimental study on the constrained melting of PCM in an inclined enclosure (0° to 90°) under constant wall temperature has been conducted by Kamkari et al. [16]. The motivation of the present investigation is to simulate the constrained melting of Lauric acid in an inclined rectangular enclosure to further study the effect of natural convection flow structures on the evolution of solid-liquid interface, heat transfer rate, and energy storage. Moreover, a group of dimensionless numbers is proposed and correlations for prediction of instantaneous melt fraction, energy storage and time-averaged Nusselt number are developed.

## 2. Problem statement and mathematical formulation

### 2.1. Physical model

A schematic view of the physical model is illustrated in Fig. 1. The

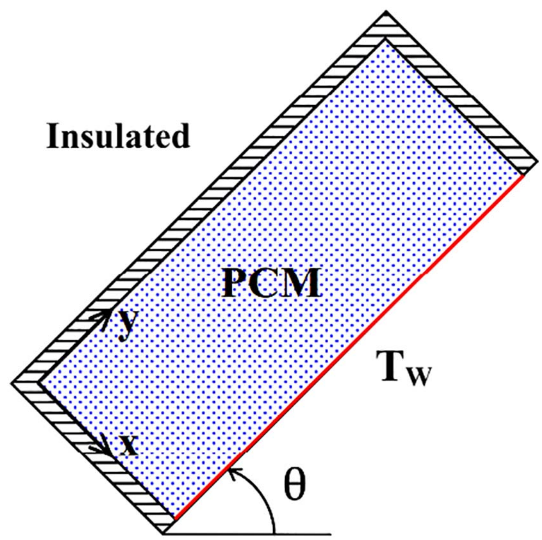


**Fig. 1.** Schematic view of PCM enclosure.

computational domain is a rectangle with a width of $W = 5$ cm and a height of $L = 12$ cm filled with Lauric acid as PCM. The right wall of the cavity is set at a constant temperature ($T_w$) and the other walls are adiabatic. The simulations are conducted at three different inclination angles of 90°, 45° and 0° for three different wall temperatures of 70, 60 and 55 °C. Table 1 presents the thermophysical properties of Lauric acid [27].

### 2.2. Mathematical formulation

The liquid PCM is assumed to be Newtonian and incompressible. The volume change during melting is neglected and thermophysical properties for each of the solid and liquid states are constant. The

**Table 1**
Thermophysical properties of lauric acid [27].

| | |
|---|---|
| Specific heat capacity solid/liquid (kJ/kg K) | 2.18/2.39 |
| Melting temperature range (°C) | 43.5/48.2 |
| Latent heat of fusion (kJ/kg) | 187.21 |
| Thermal conductivity solid/liquid (W/m K) | 0.16/0.14 |
| Density solid/liquid (kg/m$^3$) | 940/885 |
| Kinematic viscosity (m$^2$/s) | $6.7 \times 10^{-6}$ |
| Prandtl | 100.7 |