International Journal of Heat and Mass Transfer 120 (2018) 241–249

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Theory and experiment of contact melting of phase change materials in a rectangular cavity at different tilt angles

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ARTICLE INFO

Article history:
Received 11 April 2017
Received in revised form 6 September 2017
Accepted 1 December 2017

Keywords:
Phase change materials
Contact melting
Boundary layer theory
Tilt angle
Image digital processing

ABSTRACT

During the heat transfer of phase change materials in a closed cavity, natural convection and contact melting play important roles in heat transfer enhancement. An improved Nusselt boundary layer model is proposed to describe the contact melting process of phase change material in a rectangular cavity at different tilt angles. A 2-dimensional visualization experimental set for contact melting process of phase change material is put up. The melting process of n-octadecane in a rectangular cavity at 7 different tilt angles (0°, 15°, 30°, 45°, 60°, 75°, 90°) is recorded by digital camera. The liquid fraction, dimensionless height and the total melting time of the phase change materials in the tilted rectangular cavity are obtained through digital image processing mothed. The dimensionless height of solid phase change materials and liquid fraction are consistent with the theoretical solution. And the shortest total melting time is when the tilt angle is 60°.

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1. Introduction

Phase change materials play more and more important roles in energy storage because of their good thermal stability, the larger latent heat, the smaller volume change. But there are many shortcomings, such as super cooling in the crystallization process [1], small thermal conductivity. In order to overcome the shortcomings, many measures are taken to improve the thermal conductivity to enhance heat transfer, such as setting metal model with a high thermal conductivity, mixing with metal powder, and increasing the metal surface area [2–8].

To improve the effect of heat transfer enhancement for phase change, the heat transfer theory of solid-liquid phase change should be discovered. The research on solid-liquid phase change research can be divided into two stages [9]. The first stage is before the 1970s, while the heat transfer of solid-liquid phase change is only considered as heat conduction and the natural convection that may exist in the liquid phase is ignored. Since the late 1970s, the influence of the flow of liquid phase on heat transfer has been gradually recognized [10]. The existence of natural convection, Movement of solid phase and mushy region results in that the movement of the solid-liquid interface and the heat transfer of phase change process become complicated. In order to investigate the complex theory of the phase change heat transfer to enhance phase change heat transfer, a lot of research has been conducted. Different models of the phase change heat transfer are proposed, including the simple plate [11–15], vertical wall, circular inside and outside, spherical inside and outside to the cylindrical and rectangular cavity and some special shapes [16–20].

The rectangular cavity is widely researched because of the simple shape can help us to expose the heat transfer theory of phase changing easily.

In 1980, Nicholas and Bayazitoglu [21] studied the contact melting characteristics and mechanism by using the methods of numerical analysis and experimental study. The disadvantage is that the experimental data are so rough that can only be used for the comparison, and failed to consistent with the theoretical results. In 1985, the melting of a phase-change medium encapsulated in a circular tube was investigated experimentally by Sparrow and Myrum [22]. It is found that repeatable and continuous direct contact of the melting solid with the tube wall was established at tilt angle. And direct contact gave rise to substantial enhancements in the amount of melted mass and in the energy transfer. In 1982, contact melting of a phase change material within a spherical enclosure is considered by Moore and Bayazitoglu [23], and the solid continually drops toward the bottom of the shell as melting progresses. A mathematical model is developed and confirmed by experimental evidence. In 1986, the contact melting process of solid materials on circular and rectangular

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https://doi.org/10.1016/j.ijheatmasstransfer.2017.12.006
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Nomenclature

B	aspect ratio
μ	dynamic viscosity, kg/(ms)
L	latent heat of melting, kJ/kg
ρ^*	dimensionless density
Ste	Stephen number
T_f	melting temperature, °C
T_w	wall temperature, °C
Pr	Prandtl number
a, b, c	constant
α	tilt angle
S	side melting width
U	velocity components on the X axis
V	velocity components on the Y axis
υ	kinetic viscosity, m^2/s
F_o	Fourier number, $a_L\ t/w^2$
Ste*	equivalent Stephen number, $Ste^* = Ste{\cdot}L/L_m$
L_m	equivalent latent heat of melting
τ	dimensionless time, $\tau = F_o\ Ste^*$
H*	dimensionless height
V*	liquid fraction
V	volume, m^3
λ	thermal conductivity, W/m/K
S_h	melting height at the top
S*	dimensionless number of melting rate at the side, $S^* = S/H$

Subscripts

l	liquid state
s	solid state
g*	dimensionless gravity

Superscript

*	dimensionless
'	experiment value

heated plates is analyzed for by Moallmi, Webb et al. [24]. In 1991, Close-contact melting characteristics of phase change materials (PCM) inside horizontal rectangular capsules are examined experimentally by Hirata, Makino et al. [25]. A method of analysis applying Nusselt liquid film theory to the close-contact melting heat transfer in the rectangular capsule is presented. The analytical results show good agreement with the experimental data. Close-contact melting processes of phase change material (PCM) inside a horizontal rectangular capsule are studied by Chen [26,27] using the theoretical analysis method of Nusselt liquid boundary layers, conducted a theoretical analysis of the contact melting in the asymmetric heating rectangular cavity. The theoretical formulas of the dimensionless melting rate and the thickness of the liquid layer during the heat transfer process are obtained, which is convenient for engineering predictions. In 1996, Chen et al. [28] gives a comprehensive review on the advances in the study of contact melting of the solid, with respect to the following aspects: the contact melting of the solid within the enclosure capsules, the contact melting around a moving heat source as well as under other force and thermal conditions.

At the same time, the influence of natural convection on the heat transfer in the liquid phase has attracted more and more attention.

Three-dimensional unsteady natural convections in a tilted porous cavity are numerically studied by Wang and Yang et al. [29]. It is revealed that, when the porous cavity is moderately inclined, the natural convections inside are stable. With proper selection of tilt angles and oscillation frequency, the natural convection heat transfer will be significantly improved. The melting process of solid phase change materials is investigated theoretically by Hamdan and Elwerr [30]. In this study natural convection mode was considered to be the dominant mode of heat transfer within the melted region, except within the region very close to the solid surface at the bottom where conduction mode was only taken into considerations. It was found that the obtained results are in good agreement with previous ones. And the analysis is used to predict the melted fraction of the phase change material and the amount of stored energy. Cheong et al. [31] numerically studied the natural convection flow and heat transfer in a tilted rectangular enclosure with sinusoidal temperature profile on the left wall. The finite difference method is used to solve the governing equations with a range of inclination angles, aspect ratios and Rayleigh numbers. The fact that the heat transfer increases first then decreases with increasing the tilt angles of the enclosure for all aspect ratio and Rayleigh number was found. Bondareva et al. [32–34] numerically studied the natural convective heat transfer combined with melting in a cubical cavity filled with a pure gallium under the effects of inclined uniform magnetic field and local heater. It is revealed that the Hartmann number, magnetic field inclination angle and dimensionless time on streamlines, isotherms, profiles of temperature and velocity as well as mean Nusselt number at the heat source surface. And a growth of magnetic field intensity reflects the convective flow suppression and heat transfer rate reduction. High values of Hartmann number homogenize the liquid flow and heat transfer inside the melting zone.

On the other hand, tilt angle has become one of the important factors that affect the melting process of phase change materials.

Lu et al. [35] viewed the transient performance of a phase change material (PCM)-based heat sink may be affected by its inclination angle because natural convection usually occurs and dominates melting during the operation of the heat sink. The results of experiment showed that the transient performance of the heat sink is able to be improved by simply increasing its inclination angle which then facilitates the natural convection during melting. The optimal tilt angle was found to lie between 60° and 75°. Kamkari et al. [36] investigate the dynamic thermal behavior of phase change material melting in a rectangular enclosure at various inclination angles. Image processing of melt photographs along with recorded temperatures were used to calculate the melt fractions, Nusselt numbers and the local interfacial heat transfer rates at the solid–liquid interface. The results reveal that the enclosure inclination has a significant effect on the formation of natural convection currents and consequently on the heat transfer rate and melting time of the phase change material.

In summary, the closed cavity of the phase change can be divided into a circular tube, a spherical shape and a rectangular cavity. The solid phase descending speed changes linearly with time and is independent of the shape of the cavity. The influence of the cavity on the melting process lies in the concave convex form of the contact surface, the melting of the phase change material in the cylinder and the rectangular cavity is related to the aspect ratio, and the influence factors of the two kinds of cavity are similar. Most investigations focused on cylindrical model, and the influence of the tilt angle has been studied. The research on the tilted rectangular cavity model has not been conducted fully. In previous studies, it is proved that the applicability of Nusselt

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