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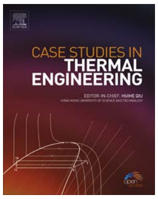

Effect of inclination angle on the melting process of phase change material

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ABSTRACT

A two-dimensional numerical simulation of the melting process in a rectangular enclosure for different inclination angles, has been carried out. Galium as a phase change material (PCM) with low Prandtl number is used. A numerical code is developed using an unstructured mesh, finite-volume method and an enthalpy porosity technique to solve for natural convection coupled to solid–liquid phase change. The validity of the numerical code used is ascertained by comparing our results with previously published results. The effect of the inclination angle on the flow structure and heat transfer characteristics is investigated in detail. It is found that the melting rate inside the rectangular cavity increases by decreasing the inclination angle from 90° to 0°.

1. Introduction

Latent energy storage (LES) is required to ensure the continuity of a thermal process in energy systems where a temporal difference exists between the supply of energy and its utilization [1–3]. Certainly, LES is of particular interest and significance in using this essential technique for solar thermal applications such as heating, hot water, cooling, air- conditioning, etc., because of its intermittent nature. In these applications, a LES system must be able to retain the energy absorbed for at least a few days in order to supply the energy needed on cloudy days when the energy input is low. Good understanding of heat transfer during melting process is essential for predicting the storage system performance with accuracy and avoiding costly system overdesign [4,5]. Natural convection heat transfer around and within cylindrical capsules finds various practical applications in space heating, heat exchangers, solar energy collectors, energy storage systems, and electronic devices. During the solidification process, conduction is the sole transport mechanism but in the case of melting natural convection occurs in the melt region and this generally enhances the heat transfer rate compared to the solidification process.

Various investigations have been performed to analyze the effect of the natural convection on the melting process of the PCM [6–10]. These investigations can be classified into categories based on the Prandtl number of the PCM: low Prandtl number ($Pr < 1$) and high Prandtl number ($Pr \geq 1$).

The influence of the inclination angle on melting process of PCM in an enclosure has been studied by few investigators [11–13]. Webb and Viskanta [11] investigated the melting heat transfer of n-octadecane in an inclined rectangular enclosure. During the experiments the only recorded parameter was the interface shapes which were then used to infer the flow structure. It was found that decreasing the inclination angle increases the three-dimensionality of the flow field and results in non-uniform melting of the solid

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Nomenclature

A_P	the linearized coefficient
c	specific heat capacity (J kg^{-1} K^{-1})
f	liquid fraction
$\vec{g}$	the acceleration of gravity vector (m s^{-2})
H	the height of the rectangular cavity (m)
L_F	melting heat (J kg^{-1})
Nu	Nusselt number
p	pressure (Pa)
Ra	Rayleigh number ($Ra = \frac{\rho\, c\, \beta\, H^3\, (T_H - T_m)}{\mu\, \lambda}$)
S	surface (m2)
T	temperature (°C)
t	time (s)
$\vec{u}$	vitesse vector (m s^{-1})
V	control volume (m3)
x	coordinate (m)

Greek symbols

$\bar{\bar{\tau}}$	the viscous stress tensor
λ	thermal conductivity (W m^{-1} K^{-1})
φ	scalar
Γ	diffusion coefficient
μ	dynamic viscosity (kg m^{-1} s^{-1})
ρ	density (kg m^{-3})
β	the coefficient of volumetric thermal expansion (K^{-1})

Subscripts

i	initial
m	melting
nb	neighboring

PCM.

Akgu et al. [12] experimentally investigated the melting and solidification process of paraffin in a vertical annular enclosure. It was found that the melting time can be decreased by 30% when the enclosure is tilted 5° from its vertical position. Sharifi et al. [13] investigated the effect of tilting during the outward melting from a vertical warm cylinder. Experiments were performed for small inclination angles of 5° and 10°. It was observed that modest tilting of the enclosure significantly affects the temperature distribution within the PCM, as well as the temporal evolution of the solid–liquid interface with a three-dimensional shape. This is a result of the interaction between 3D convection currents in the liquid PCM with the solid interface.

Jourabian et al.[14] performed a numerical analysis of the melting process with natural convection in an inclined cavity using the enthalpy-based lattice Boltzmann method. The study was carried out for Stefan number of 10, Rayleigh number ranging from 10^4 to 10^6, and inclination angle ranging from −30° to +30°. The predicted results indicated that an increase in Rayleigh number leads to intensifying the melting rate at each inclination angle.

Recently Kamkari et al. [15] investigated experimentally the heat transfer process and melting behavior during the solid–liquid phase change of lauric acid (as a high Prandtl number PCM) in a rectangular enclosure at different inclination angles. They founded that the heat transfer enhancement ratio for the horizontal enclosure is more than two times higher than that of the vertical enclosure.

This paper investigates the heat transfer process and melting behavior during the solid–liquid phase change of galium (as a low Prandtl number PCM) in a rectangular enclosure for different inclination angles. The problem of the melting process is formulated using the enthalpy-porosity based method. A numerical code is developed using an unstructured mesh and a finite-volume method.

2. Physical model and basic equations

The general assumptions considered in this work include transient formulation and two dimensional Newtonian incompressible fluid where the natural convection effects are considred. The thermophysical properties of the PCM are assumed to be constant but may be different for the liquid and solid phases. The Boussinesq approximation is valid, i.e., liquid density variations arise only in the buoyancy source term, but are otherwise neglected. Since the present formulation deals with solutions on unstructured grids, it is essential to represent the conservation laws in their respective integral forms.

With the foregoing assumptions, the conservation equations for mass, momentum and energy may be stated as

$$\int_S \vec{u}\,.\,\vec{n}\;dS = 0 \tag{1}$$

$$\frac{d}{dt}\int_V \rho\,\vec{u}\;dV + \int_S \rho\,\vec{u}\,\vec{u}\,.\,\vec{n}\;dS = -\int_V \vec{\nabla}p\;dV + \int_S \bar{\bar{\tau}}\,.\,\vec{n}\;dS + \int_V \overrightarrow{A_U}\,dV \tag{2}$$

$$\frac{d}{dt}\int_V \rho\,c_pT\;dV + \int_S \rho\,c_pT\;\vec{u}\,.\,\vec{n}\;dS = \int_S \lambda\vec{\nabla}T\,.\,\vec{n}\;dS + \int_V \rho L_F\frac{\partial f}{\partial t} \tag{3}$$

where $\vec{u}$ is the velocity vector, p the pressure and T the temperature. $\bar{\bar{\tau}}$ is the viscous stress tensor for a Newtonian fluid:

$$\bar{\bar{\tau}} = \mu\,(\bar{\bar{\nabla}}u + (\bar{\bar{\nabla}}u)^T) \tag{4}$$

The integration occurs over a control volume V surrounded by a surface S, which is oriented by an outward unit normal vector $\vec{n}$. The source term in Eq. (2) contains two parts:

$$\overrightarrow{A_U} = \rho\,\beta\,(T - T_m)\vec{g} + A\,\vec{u} \tag{5}$$