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Melting over a wavy surface in a rectangular cavity heated from below

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ABSTRACT

The current numerical study is conducted to analyze melting in a rectangular closed enclosure by subjecting the bottom wavy surface to a uniform temperature. The cavity vertical walls and the top wall are insulated while the bottom wall is maintained at temperature $T_B = 38.3\ ^\circ$C. The enclosure was filled by solid Gallium initially at temperature $T_i = 28.3\ ^\circ$C. A numerical code is developed using an unstructured 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 amplitude of the wavy surface on the flow structure and heat transfer characteristics is investigated in detail. It is found that the rate of the melting increases with the elevation in the magnitude of the amplitude value of the wavy surface.

1. Introduction

The problem of solid–liquid phase change with natural convection in the liquid phase has continued to be an important research area for several decades, due to its application in many technologically important processes such as metal casting, food freeze drying, electronics cooling, and in particular, thermal energy storage [1–7]. The solid–liquid transition provides also a suitable technique for controlling temperature in systems, which are subjected to periodic heating. This process allows, for periodic heating, the conversion of temperature oscillations into oscillations of the melting interface, with a significant damping of the perturbation. Furthermore, the energy stored during melting can be recovered during freezing, with significant energetic opportunities.

Although many experimental and numerical studies have been dedicated to convection-dominated melting of PCMs (Phase Change Materials) for various geometry configurations, e.g., along a vertical wall, inside as well as around a horizontal cylinder, etc. [8–11], little effort has been reported on the melting of a PCM heated from below [8,10,12–17]. It is well known that when a horizontal layer of fluid is heated from below, a cellular form of natural convection may occur inside the liquid, similar to that observed during classical Rayleigh–Bénard convection. As a result of the interaction between the cellular convection and the melting process, the phase-change interface, which is assumed to be at the equilibrium temperature, tends to get wavy. For the melting from below, few works exist in the literature. Yen and Galea [17,18] and Seki et al. [19] experimentally studied the melting of a horizontal ice slab heated from below. Hale and Viskanta [20] performed experiments for melting from below and solidification from top of n-octadecane in a rectangular cavity. They did not present flow patterns and phase change interface shapes, however, Gau et al. [21] presented flow visualization for melting from below of an n-octadecane slab in a rectangular cavity. Diaz and Viskanta [22] extended the experiments of Gau et al. [21] to morphology observation of the liquid–solid interface. Prud'Homme et al. [14] studied numerically the melting of a pure substance within a vertical cylindrical enclosure heated isothermally from below and assuming adiabatic conditions at the vertical side. The governing equations for the convective flow in the melt are solved using computer generated body-fitted curvilinear coordinates. In their study, the authors found that the critical Rayleigh number for the onset of convection based on the melt layer thickness is 2197. The flow patterns show that the initial multicellular regime is replaced ultimately by a single Bénard cell. Lacroix [12] performed a series of numerical simulations using a variable grid method for the melting of a low Prandtl substance. The author analyzed the effect of the temperature difference between the bottom wall and the initial temperature of the solid. The effect of the Rayleigh number, on the flow patterns during the melting of a pure phase change material in square cavity isothermally heated from below and which is adiabatic at the rest of the walls, is studied numerically by Gong and Mujumdar [13]. The governing equations for the convective flow in

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Nomenclature

a	amplitude of the wavy surface (m)
A_P	linearized coefficient
b	number of undulation
c	specific heat capacity (J kg^{-1} K^{-1})
f	liquid fraction
$\vec{g}$	acceleration of gravity vector (m s^{-2})
L_F	melting heat (J kg^{-1})
L	length (m)
Nu	Nusselt number
p	pressure (Pa)
Pr	Prandtl number
Ra	Rayleigh number
S	heat source (W m^{-3})
Ste	Stefan number
T	temperature (°C)
t	time (s)
$\vec{u}$	Vitesse vector (m s^{-1})
V	control volume (m^3)
W	width (m)
x	coordinate (m)

Greek symbols

β	coefficient of volumetric thermal expansion (K^{-1})
λ	thermal conductivity (W m^{-1} K^{-1})
ϕ	transport variable
Γ	diffusion coefficient
μ	dynamic viscosity (kg m^{-1} s$^{-1)}$
ρ	density (kg m^{-3})
ψ	stream function (m^2 s^{-1})
ω	under-relaxation factor

Subscripts

C	cold
H	hot
i	initial
m	melting
nb	neighboring

the melt are solved using the Streamline Upwind/Petrov Galerkin finite element method in combination with a fixed grid primitive variable method. More recently, Fteiti and Nasrallah [10] investigated the melting process in rectangular enclosure heated from below and cooled from above. The authors used the enthalpy–porosity method to track the motion of the solid–liquid interface and the governing equations are numerically solved using the control volume based finite element method. They concluded that the melting process is more rapid as the aspect ratio of the enclosure is small, but the volume fraction melted at the steady state is less important.

It is interesting to note that, flow and heat transfer from irregular surfaces are often encountered in many engineering applications to enhance heat transfer such as micro-electronic devices, flat plate solar collectors and flat-plate condensers in refrigerators, etc. Roughened surfaces could be used in latent storage systems where the wall heat flux is known. One of the reasons why a roughened surface is more efficient in heat transfer is its capability to promote fluid motion near the surface; in this way a complex wavy surface is expected to promote a larger heat transfer rate than a flat plate. This complex geometry will promote a correspondingly complicated motion in the fluid near the surface; this motion is described by the nonlinear boundary-layer equations. A vast amount of literature about convection along a sinusoidal wavy surface is available for different heating conditions and various kinds of fluids [23–25]. The major conclusion is that the total heat-transfer rate for a wavy surface of any kind is, in general, greater than that of the corresponding flat plate, and may be a function of the ratios of amplitudes to wavelengths of the surface. On the other hand, the result that the average heat-transfer rate per unit of wetted surface for a wavy surface is less than that of a flat plate is confirmed. The total heat-transfer rate is the more important factor in designing a heat-transfer surface.

To the best of the authors' knowledge, no attention has been paid to the problem of the heat transfer during melting in a rectangular cavity that is heated from a horizontal wavy surface. The objective of the present study is to examine the melting process in a rectangular cavity by subjecting the bottom wavy surface to a relatively higher temperature than the melting temperature of the PCM. We aim to investigate the impact of the wavy surface amplitude on the kinetics melting of the PCM inside the enclosure. The results are shown in terms of parametric presentations of streamlines and isotherms.

2. Mathematical formulation

2.1. Physical model and basic equations

Unsteady two-dimensional melting of PCM is governed by the basic laws represented by the continuity, momentum and energy equations and by the following assumptions:

- The thermophysical properties of the PCM are 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.
- The liquid is Newtonian.
- Viscous dissipation is neglected.
- Fluid motion in the melt is laminar and two-dimensional.

Since the present formulation deals with solutions on unstructured grids, it is essential to represent the conservation laws in their respective integral forms.

$$\int_S \vec{u}.\vec{n}\,\mathrm{d}S = 0 \tag{1}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\int_V \rho\,\vec{u}\,\mathrm{d}V + \int_S \rho\,\vec{u}\vec{u}.\vec{n}\,\mathrm{d}S = -\int_V \vec{\nabla}\,p\,\mathrm{d}V + \int_S \bar{\bar{\tau}}.\vec{n}\,\mathrm{d}S + \int_V \vec{B}_{\mathrm{u}}\mathrm{d}V \tag{2}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\int_V \rho\,c_{\mathrm{p}}T\,\mathrm{d}V + \int_S \rho\,c_{\mathrm{p}}T\,\vec{u}.\vec{n}\,\mathrm{d}S = \int_S \lambda\vec{\nabla}\,T.\vec{n}\,\mathrm{d}S + \int_V \rho L_{\mathrm{F}}\frac{\partial f}{\partial t} \tag{3}$$

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 :

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