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Simulation on melting processes in a vertical rectangular enclosure with a free-moving ceiling

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ABSTRACT

Transport processes associated with melting of a phase change material (PCM) placed inside a vertical rectangular enclosure with a free-moving ceiling are simulated numerically. The enclosure is side-heated isothermally. Buoyancy-induced flow in the melt region is modeled utilizing the Boussinesq approximation. The effect of solid–liquid density change upon melting is accounted that liquid density of the PCM is assumed to be lower than the solid density and as a result, the melt bulk expands while melting, transmitting a linear motion of the free-moving ceiling of the enclosure. Numerical simulations for the two-dimensional melting process using a finite-difference method on a fixed grid are undertaken to delineate the motion characteristics of the ceiling related to the melting process of solid PCM inside the enclosure with the relevant dimensionless parameters in the following ranges: the enclosure aspect ratio $Asp = 2$–12; the Stefan number $Ste = 0.1$, 0.3, and 0.5; the Rayleigh number $Ra = 10^3$–10^6; and the Prandtl number $Pr = 41.7$. Simulation results clearly reveal the influence of the Rayleigh number on the displacement of movable ceiling of the enclosure and the average Nusselt number over the isothermally heated wall of the enclosure tend to degrade greatly with the increase of the aspect ratio.

1. Introduction

The present article presents a numerical simulation of melting process in a vertical rectangular enclosure with a free-moving ceiling, as depicted in Fig. 1. The physical configuration considered is of fundamental interest in connection with the problem concerning a thermally-activated actuator or switch utilizing the volume expansion (solid–liquid density change) associated with the thermally induced melting of paraffin [1,2]. The aim of this study is to elucidate the motion characteristics of the ceiling induced by the volume expansion associated with melting of the paraffin inside the enclosure due to isothermally heating on the vertical walls.

A substantial body of numerical and experimental studies has been dedicated to the problem of buoyancy-driven melting from a vertical wall in a rectangular enclosure, as revealed in the review articles [3,4]. Representative works are chronically listed in Refs. [5–8]. In these previous studies, the volume (or density) change inherent in the solid–liquid phase change processes was not taken into account. Relatively little attempts have been made to address the effects of volume change upon melting process in enclosure. Ho and Viskanta [9] observed the influence due to the density-change-induced fluid motion in the early stage of melting in a rectangular enclosure. The effect of the density change on the buoyancy-driven melting behavior in a rectangular enclosure was further examined numerically by Yoo and Ro [10] employing the body-fitted coordinate transformation. Ho and Chu [11–13] presented a series of numerical simulations of multiple moving solid–liquid interfaces during natural-convection-dominated melting of a pure material contained in enclosures imposed with various wall temperature conditions. The numerical results unveil that there may coexist three solid–liquid interfaces during the sustained periodic solid–liquid phase change process inside the enclosure. Accordingly, a complicated cyclic variation of the melting rate and the heat transfer characteristics arises as a result of the periodic occurrence of multiple moving boundaries inside the enclosure. It should be noticed that the configuration considered in the early studies concerning the density change effect upon melting features a free surface over the un-melted solid PCM in the enclosure.

Binet et al. [14] developed a 2-D mathematical model for simulating the thermal behavior of a rectangular enclosure used for cooling management of flush mounted heat sources. The predicted results

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Nomenclature

Asp	aspect ratio, *H*/*W*
c_p	specific heat
D_p^+	displacement of enclosure ceiling
D_p	dimensionless displacement of enclosure ceiling, D_p^+/H
Fo	Fourier number, $\alpha_\ell t/H^2$
g	gravitational acceleration
H	height of enclosure
k	thermal conductivity
L	latent heat of fusion
Nu_h	local Nusselt number along heated wall
$\overline{Nu}_h$	average Nusselt number along heated wall
P	dimensionless dynamic pressure, $(p^+ - p_o^+)H^{+2}/(\rho_\ell \alpha_\ell^2)$
P^+	pressure
Pr	Prandtl number, ν_ℓ/α_ℓ
q''	heat flux at vertical wall
Q	dimensionless heat transfer rate
Ra	Rayleigh number, $g\beta(T_h - T_f)H^3/(\alpha_\ell \nu_\ell)$
S	dimensionless position of solid-liquid interface
Ste	Stefan number, $c_{p,\ell}(T_h - T_f)/L$
t	time
T	temperature
v_n	normal interface velocity
v_p	moving velocity of top enclosure ceiling
V_m	volume of liquid PCM
V_o	total volume of PCM
V^*	volumetric fraction of liquid PCM, V_m/V_o
W	width of enclosure
x^+, y^+	Cartesian coordinates
x, *y*	dimensionless coordinates,$x^+/H, y^+/H$

Greek symbols

α	thermal diffusivity
θ	dimensionless temperature, $(T - T_f)/(T_h - T_f)$
ν	kinematic viscosity
ρ	density
ψ^+	stream function
ψ	dimensionless stream function, ψ^+/α_ℓ
$\Delta\psi$	fluctuation amplitude of dimensionless stream function
ω^+	vorticity
ω	dimensionless vorticity, $\omega^+ H^2/\alpha_\ell$

Subscripts

f	fusion point
h	hot wall
ini	initial-state value
ℓ	liquid phase
s	solid phase
ss	steady-state value

Superscripts

$*$	ratio of quantity for solid to that for liquid phase
$-$	averaged or mean value

showed that enclosures with high aspect ratio can control better heat sources temperature and offer relatively extended melting durations. The numerical investigation of the natural convection heat transfer during the melting of phase change materials contained in a rectangular enclosure was carried out by Qarnia et al. [15]. The correlations encompassing a wide range of parameters were proposed in terms of the dimensionless secured operating time and the corresponding liquid fraction. Recently, Kamkari et al. [16] investigated the heat transfer process and melting behavior during the solid–liquid phase change of lauric acid in a rectangular enclosure at different inclination angles. Qualitative and quantitative studies are performed by visualizing the solid–liquid interface patterns and temperature distribution within the enclosure.

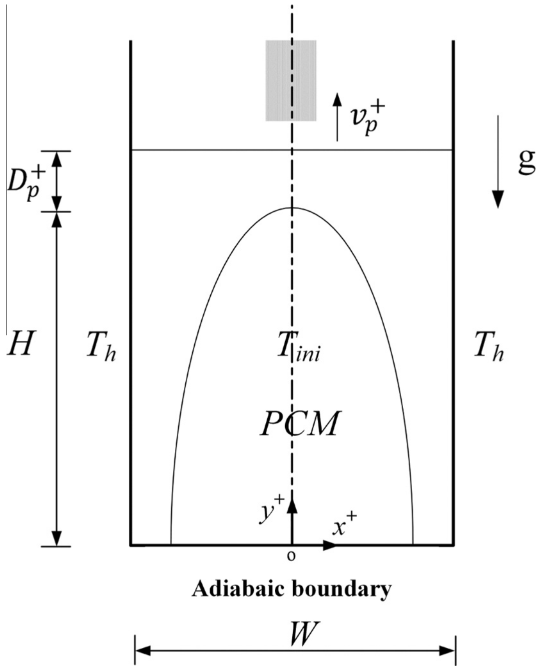

Fig. 1. Schematic diagram of physical problem and coordinate system.

It should be noticed that the configuration considered in the early studies concerning the density change effect upon melting features a free surface over the un-melted solid PCM in the enclosure. To the best knowledge of the authors, there exists no previous study dealing with the melting process in the presence of the solid–liquid density change in a rectangular enclosure with a free-moving ceiling, instead of a free surface.

1.1. Formulation of problem

The physical configuration considered is a two-dimensional melting process of a solid PCM (paraffin) from two vertical wall of a vertical rectangular enclosure as depicted schematically in Fig. 1. The enclosure walls are considered stationary except for the upper wall (ceiling), which is assumed to be movable freely with negligible inertia of momentum. Initially, the solid PCM contained in the enclosure is maintained at its fusion temperature,$T_{ini} = T_f$. The ceiling and bottom walls of the enclosure are assumed to be thermally adiabatic. At a certain instant of time, *t* = 0, the vertical walls of the enclosure are instantaneously heated symmetrically and thereafter maintained at a constant temperature T_h ($>T_f$). The effect of solid–liquid density change upon melting is accounted that liquid density of the PCM is assumed to be lower than the solid density and as a result, the melt bulk expands and overflows forming a melt layer above the solid PCM while melting, transmitting a linear motion of the free-moving ceiling which is denoted by a displacement D_p^+ above the original height of the enclosure H^+. The dimensionless governing equations, which