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# Melting processes of phase change materials in an enclosure with a free-moving ceiling: An experimental and numerical study

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## ABSTRACT

This work aims to examine, via a complementary approach of experimental measurement and numerical simulation, transient transport processes associated with melting of a phase change material (PCM) placed inside a vertical rectangular enclosure with a free-moving ceiling. The core phase change material is *n*-octadecane with melting temperature about $T_m = 28\ °\mathrm{C}$. The vertical side walls of the enclosure were differentially heated isothermally while the remaining side walls were thermally insulated. Experiments have been undertaken for the air-saturated enclosure filled with MECPCM particles with the relevant parameters in the following ranges: the enclosure aspect ratio $Asp = 24$; the subcooling number $Sc = 1.06–11.5$; Stefan number $Ste = 0.179–0.370$; and the Rayleigh number $Ra = 0.897–8.60 \times 10^8$. Meanwhile, numerical simulations have been performed based on a mathematical modeling mimicking the experimental configuration considered to further elucidate the transient transport processes of the free-moving ceiling of the enclosure. Finally, the formula of the dimensionless displacement of the top ceiling subjected to various thermal conditions are proposed and correlated with the related parameters, including the Stefan number *Ste*, the subcooling parameter *Sc*, Rayleigh number *Ra* and the Fourier number *Fo*.

## 1. Introduction

In the present study, the melting transport phenomena in a vertical rectangular enclosure with a free-moving ceiling, as schematically illustrated in Fig. 1, are explored via a combined experimental and numerical approach. Primarily motived by its applications concerning a thermally-activated actuator or switch utilizing the volume expansion (solid–liquid density change) connected with the thermally induced melting of paraffin [1,2], experiment and simulation have been conducted for the motion and heat transfer characteristics of the ceiling induced by the volume expansion related to melting of the paraffin inside the enclosure due to isothermally heating on the vertical walls.

The phenomena associated with buoyancy-driven melting initiated from isothermal heating from one or more sides of enclosures are covered by a great number of analytical, numerical, and experimental studies [3–13]. These studies clearly point to the eventual significant role of buoyancy-driven convection, while diffusion dominated thermal transport was important at early stages of melting. Among these previous studies, relatively little attempts have been made to address the effects of volume change upon melting process in enclosure. The density-change-induced fluid motion in the early stage of melting in a rectangular enclosure was experimentally observed and examined by Ho and Viskanta [14]. Yoo and Ro [15] presented a numerical method using the body-fitted coordinate transformation to examine the melting process in the presence of solid–liquid density change and natural convection in a two-dimensional rectangular enclosure filled with phase-change material. The presence of the density change brings no change into the basic form of governing equation, so it is considered through the reformulation of boundary conditions. Ho and Chu [16] simulated numerically using the finite difference method the transient heat penetration through a vertical rectangular composite cell filled with a solid–liquid PCM and an air layer. Mbaye and Bilgen [17] examined numerically fusion mechanism of a pure substance (gallium) in a rectangular enclosure which is was subjected to a constant heat flux on its left vertical wall, constant temperature on its right wall, whereas adiabatic condition was maintained on its two horizontal walls. They reported that an important parameter controlling heat transfer and melting velocity was the applied heat flux. The melting of an organic phase change

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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, $\nu_\ell/\alpha_\ell$ |
| $q''$ | heat flux at vertical wall |
| $Ra$ | Rayleigh number, $g\beta(T_h - T_f)H^3/(\alpha_\ell \nu)$ |
| $Ste$ | 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* | |
| $\alpha$ | thermal diffusivity |
| $\theta$ | dimensionless temperature, $(T - T_m)/(T_h - T_m)$ |
| $\nu$ | kinematic viscosity |
| $\rho$ | density |
| $\psi^+$ | stream function |
| $\psi$ | dimensionless stream function, $\psi^+/\alpha_\ell$ |
| $\omega^+$ | vorticity |
| $\omega$ | dimensionless vorticity, $\omega^+ H^2/\alpha_\ell$ |
| *Subscripts* | |
| $h$ | hot wall |
| $ini$ | initial-state value |
| $\ell$ | liquid phase |
| $m$ | melting point |
| $s$ | solid phase |
| $ss$ | steady-state value |
| *Superscripts* | |
| $*$ | ratio of quantity for solid to that for liquid phase |
| $-$ | averaged or mean value |

material ($n$-triacontane) in a tall enclosure with an aspect-ratio of 10 was investigated numerically and experimentally by Pal and Joshi [18]. They indicated that natural convection plays a dominant role during the initial stages of melting. The transport processes associated with melting of a phase change material (PCM) placed inside a vertical rectangular enclosure with a free-moving ceiling were studied numerically by the present authors [19]. In Ref. [19], the effects of solid–liquid density change upon melting are

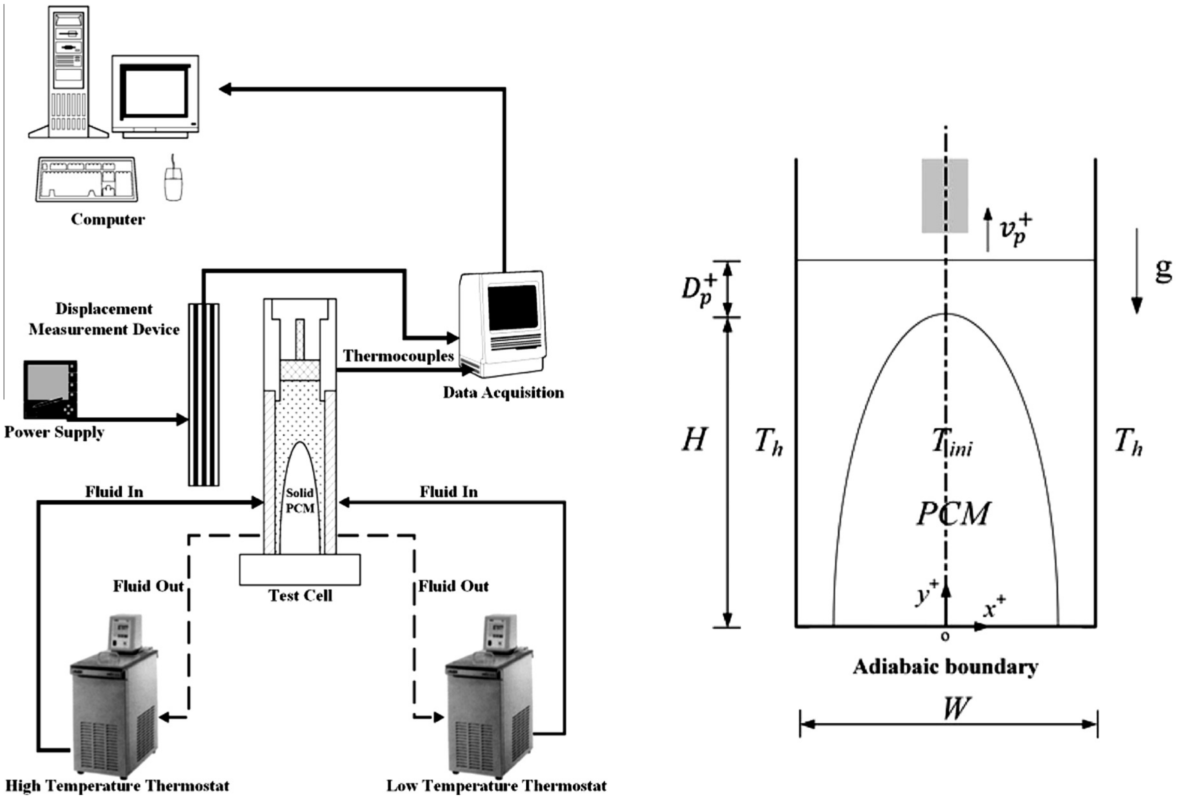

**Fig. 1.** The physical system. (a) Experimental setup, (b) numerical modeling.