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# Melting and solidification behaviour of phase change materials with cyclic heating and cooling

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ABSTRACT

The present study deals with the investigation of melting behaviour of phase change materials (PCMs) during the cyclic heating. For this work, a computational fluid dynamic (CFD) study of heat and mass transfer during melting and solidification of PCM is carried out for the constant and variable (sinusoidal) heat supply. For the constant heat flux a step function ranging from 500 W/m$^2$ to −500W/m$^2$ and for variable heat flux, a sine function having a similar area as step function was considered at one wall of the container to provide heating and cooling of the PCMs. The results are reported in terms of melting interface, melt fraction during melting and solidification, temperature variation, the variation of melted PCM velocity, and rate of energy storage and release. From the results, it is observed that the melting time is reduced with variable heat flux as compared to constant heat flux and it is also pointed out that the melting time of PCM is lower as compared to solidification time.



## 1. Introduction

Thermal energy storage applications using phase change materials (PCMs) are quite attractive due to high storage density and their economic viability [1]. Several researchers have investigated the viability of different PCMs as thermal energy storage for different applications [2–7]. The PCMs used to store thermal energy during the melting process and release it during the solidification process. During melting and solidification of PCMs, the melting interface changes, moving away and then reverse with respect to the heated surface respectively [8–10]. The problem in solving phase change process in the presence of a moving boundary or region in which heat and mass transfer conditions are to be satisfied is very important. The problem can be solved numerically by using finite element analysis or finite difference techniques[11,12]. This way, the material's temperature variation and melting interface can be predicted in two dimensions. Heat and mass transfer during the phase change is very important in latent heat thermal energy storage systems, such as ice formation, food preservation, metallurgy, castings, crystal growth and numerous other solidification methods. The prediction of melting interface, temperature distribution and rate of melting and solidification are critical in order to evaluate the effect of constant and variable heat supply.

The interest of studying cyclic heating and cooling is due to the application of energy storage materials used in passive solar energy devices, which get affected by the variation in the solar radiation. Hence, there is a need to study the cyclic heating and cooling of PCMs, which will, in turn, affect the performance of solar energy applications. Various researchers have carried out the study of melting and solidification of PCMs separately but not as a continuous process. *Kant* et al. [1] investigated the performance of different fatty acids for thermal energy storage applications. The melt fraction, the energy stored and the melting interface of fatty acids was predicted using finite element analysis and the effective thermal conductivity of melted PCM [13]. The latent heat of fusion was modelled using a Delta Dirac function of the temperature and solved with the commercial package COMSOL Multi-Physics 5.0 version. The time-dependent calculation was carried out to see the effects of wall temperature and energy storage during melting of fatty acids. The effect of the wavy surface at bottom subjected to constant heat flux, on the melting of PCMs in the rectangular enclosure was carried out by *Kousksouet al.* [14]. A numerical program was developed to solve the natural convection combined with solid-liquid phase transition process using an unstructured finite-volume method and an enthalpy-porosity technique. The detailed investigation was conducted to see the effect of the wavy

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**Nomenclature**

$C_p$ *Specific heat (J/kg K$^{-1}$)*
$g$ *Gravitational acceleration (m s$^{-2}$)*
$k$ *Thermal conductivity(W/m K$^{-1}$)*
$L_f$ *Latent heat of fusion (J/kg)*
$P$ *Pressure (Pa)*
$q_w$ *Heat flux(W/m$^2$)*
$T$ *Temperature (T)*
$t$ *Time(s)*
$u$ *Velocity(m s$^{-1}$)*
$v$ *Velocity in y direction(m s$^{-1}$)*
$\rho$ *Density (kg/m$^3$)*
$\Delta T$ *Transition temperature (K)*
$\mu$ *Dynamic viscosity (Pa s)*
$\beta$ *Thermal expansion coefficient of PCM*

Subscript
*PCM* *Phase change materials*
*s* *Solid state*
*l* *Liquid state*

surface amplitude on heat transfer characteristics and flow behaviour. It was reported that with an increase in the magnitude of the amplitude value of the wavy surface, the rate of the melting upsurges. *Pakrouh* et al. [15] carried out a numerical study by the application of Taguchi method to optimise heat sinks with pin fin. The study was carried out with the effect of natural convection and PCM volume variation during the melting process. *Biwole* et al. [16] carried out computational fluid dynamics (CFD) modelling of heat and mass transfers in a system composed of an impure phase change material to improve solar panel's performance. An approximate analytical model was developed by *P. Lamberg* [10] in finned PCM storage for two-phase solidification. The analytical and numerical results were compared using the heat capacity method and it was found that both are in good agreement with each other.

In the present paper, a two-dimensional numerical study is carried out to investigate the effect of cyclic heating and cooling on charging and discharging of n-octadacane, a widely used PCM for thermal energy storage. The properties of n-octadacane are presented in Table 1 [17]. The same amount of energy is supplied to the PCM with constant and variable heat flux at a wall of the PCM container to see the melting effect of PCM. During the cooling, the same amount of energy is extracted as supplied during the heating. The calculation is carried out for the variation of melting interface, melt fraction, temperature variation, velocity field etc.

**Table 1**
Material properties [17].

| Material/properties | | n-Octadecane | Aluminum |
|---|---|---|---|
| Melting Point(°C) | | $28.2 \pm 1$ | NA* |
| Latent heat of fusion (kJ/kg) | | 245 | NA* |
| Thermal Conductivity (W/m K) | Solid | 0.35 | 179.96 |
| | Liquid | 0.149 | |
| Density (kg/m$^3$) | Solid | 814 | 2712.6 |
| | Liquid | 775 | |
| Specific heat(kJ/kg K) | Solid | 1.934 | 0.96 |
| | Liquid | 2.196 | |
| Kinematic viscosity (m$^2$/s) | | $5 \times 10^{-6}$ | NA* |
| Thermal expansion coefficient(1/°C) | | $9.1 \times 10^{-4}$ | NA* |

* Not applicable.

## 2. Mathematical formulations

Numerical heat and mass transfer simulation have been carried out using conjugate heat transfer in the solid aluminium wall and in the PCM. The following assumptions are made to carry out the present study.

i Thermophysical properties of the aluminium wall are independent of temperature.
ii he melted PCM is Newtonian, flow is incompressible, thermal radiation, viscous dissipations and three- dimensional convection are negligible.
iii Properties of PCMs are different in solid and liquid phase.
iv The PCM is homogeneous and isotropic.

It is important to mention that only a two-dimensional model is used and three-dimensional convection is neglected, for the sake of avoiding mathematical complexity. Furthermore, the effect of the three-dimensional natural convection during melting of PCMs is very limited [18] when compared with the whole melting process, consequently, the two-dimensional simulation can be considered quite realistic in rectangular enclosures.

### 2.1. Heat transfer

The heat transfer diffusion equation (Eq. (1)) has been applied to the PCM and the aluminium container. The velocity field $u$ in Eq. (1) is given by Navier-Stokes equations for incompressible fluids. The velocity field of in the solid state of PCM is nearly equal to zero.

$$\rho C_p \frac{\partial T}{\partial t} + \nabla.(-k\nabla T) + \rho C_p \vec{u}.\nabla T = 0 \tag{1}$$

The density variation of PCM can be given as

$$\rho_{pcm}(T) = \rho_s + (\rho_l - \rho_s).\lambda(T) \tag{2}$$

where the liquid fraction λ, is the function of temperature and can be given by

$$\lambda(T) = \begin{cases} 0, & T < (T_m - \Delta T) \\ (T - T_m + \Delta T)/(2\Delta T), & (T_m - \Delta T) \leq T < (T_m + \Delta T) \\ 1, & T > (T_m + \Delta T) \end{cases} \tag{3}$$

Eq. (3) shows that $\lambda$ is zero when the PCM is in solid phase and 1 when it is in the liquid phase. $\lambda$ linearly grows from zero to 1 between the two states [16]. The value of transition temperature is taken 2 °C [19]. The specific heat of the PCM can be written as

$$C_{ppcm}(T) = C_{ps} + (C_{pl} - C_{ps}).\lambda(T) + L_f D(T) \tag{4}$$

Where $L_f$ is the latent heat of fusion and

$$D(T) = e^{\left(\frac{\frac{-(T-T_m)^2}{\Delta T^2}}{\sqrt{\pi.\Delta T^2}}\right)} \tag{5}$$

Function $D$ is a smoothed Delta Dirac function which is zero everywhere except in interval $[T_m - \Delta T, T_m + \Delta T]$. It is centred on the melting temperature of PCM ($T_m$) and its integral is equal to 1. Its main role is to distribute the latent heat equally around the mean melting point. The thermal conductivity of the PCM depending on its phase is:

$$k_{pcm}(T) = k_s + (k_l - k_s).\lambda(T) \tag{6}$$

### 2.2. Mass and momentum transfer

It is assumed that the PCM in the liquid phase is a Newtonian fluid. The mass, momentum and energy conservation equations