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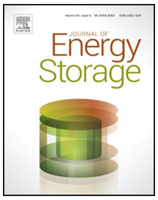

Studies on the inward spherical solidification of a phase change material dispersed with macro particles

N. Lakshmi Narasimhan*, V. Veeraraghavan, G. Ramanathan, B. Sanjay Bharadwaj, M. Thamilmani

Department of Mechanical Engineering, SSN College of Engineering, OMR, Kalavakkam 603110, Tamil Nadu, India

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ABSTRACT

This paper investigates numerically the solidification of a phase change material (PCM) dispersed with high conductivity macro particles inside a spherical container. The formulation takes into account the addition of particles invoking an effective thermal conductivity model. A case study has been made comparing the experimental results available in the open literature for the solidification of a pure PCM case (without particles) to investigate the influence of particles. The results show that the addition of particles between 10 and 50% by volume, enhances the heat transfer rate by about 13.5 and 59% respectively. Parametric studies have been carried out to investigate the influence of relevant dimensionless numbers such as Biot number (Bi) and Stefan number (Ste) on the solidification characteristics of the PCM for different particle fractions. The role of particles was found to be significant at lower Ste compared to Bi. It has been concluded that the effect of particle fraction on the solidification is more compared to that of particle-PCM thermal conductivity ratio. It was found that there is no restriction on the choice of particle material for a given PCM, as long as the particle-PCM thermal conductivity ratio considered remain larger than 5.

1. Introduction

Studies on phase change problems involving freezing/melting of materials have always been interesting due to their relevance to several practical applications involving thermal storage using phase change materials (PCMs). Practical applications of PCMs are many and wide spread. To cite a few are space based power generation, building cooling, electronic cooling, textiles, HVAC, solar thermal, etc. A detailed review on PCMs and their applications is available elsewhere [1–3] in the open literature.

PCMs are materials capable of releasing/absorbing heat in the form of latent heat while undergoing freezing/melting at a nearly constant temperature or at a small temperature range. Systems employing PCMs are referred to as latent heat thermal storage (LHTS) systems. In a real situation, the melting and freezing of PCMs happens alternately in a cyclic manner enabling repeated charging and discharging of LHTS systems. In many cases, a heat transfer fluid (HTF) is employed to aid heat transfer from/to the PCMs.

1.1. Drawback of PCMs and need for thermal conductivity enhancement

The advantages that PCMs offer are (i) high energy storage density (ii) nearly uniform temperature of operation and (iii) system compactness. In spite of the advantages, a major drawback with PCMs is their low thermal conductivity in both solid and liquid phases. The thermal conductivity of a majority of PCMs lies between 0.2 and 0.6 W/mK [4] that obviously is very low from a heat transfer point of view. The low thermal conductivity of PCMs results in a poor thermal response especially during the energy retrieval process (referred to as discharging process). In applications where there is a need for faster discharging owing to limitations in the duration of availability of HTF, a delay in the energy retrieval process affects the system's overall performance/efficiency. Therefore, from a practical point of view, there is a need for enhancement of thermal conductivity of PCMs to improve the overall performance of LHTS systems.

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* Corresponding author.
E-mail address: lakshminaras74@gmail.com (N. L. Narasimhan).

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Nomenclature

A	Area (m^2)
Bi	Biot number
C	Specific heat (J kg^{-1} K^{-1})
C_l	Specific heat of liquid PCM (J kg^{-1} K^{-1})
C_{ls}	Ratio of specific heat of liquid and solid PCM
C_s	Specific heat of solid PCM (J kg^{-1} K^{-1})
h_o	Convective heat transfer coefficient(W m^{-2} K^{-1})
h	Enthalpy (J kg^{-1})
i	I^{th} node
k	Thermal conductivity (W m^{-1} K^{-1})
k_l	Thermal conductivity of liquid PCM (W m^{-1} K^{-1})
k_p	Thermal conductivity of PCM (W m^{-1} K^{-1})
k_s	Thermal conductivity of solid PCM (W m^{-1} K^{-1})
$\overline{k}$	Effective thermal conductivity of PCM-particle mixture(W m^{-1} K^{-1})
$\overline{k_l}$	Effective thermal conductivity of liquid PCM-particle mixture (W m^{-1} K^{-1})
$\overline{k_s}$	Effective thermal conductivity of solid PCM-particle mixture (W m^{-1} K^{-1})
$\overline{k_p}$	Effective thermal conductivity of either liquid or solid PCM-particle mixture (W m^{-1} K^{-1})
k_{par}	Thermal conductivity of particle (W m^{-1} K^{-1})
$\overline{k_{ps}}$	Thermal conductivity ratio of PCM-particle mix to solid PCM
$\overline{k_{pw}}$	Thermal conductivity ratio of PCM-particle mix to capsule wall
m	Mass (kg)
m_s	Mass of solid PCM (kg)
Q	Heat (J)
Q_i	Total heat released by sensible cooling of liquid PCM (J)
Q_l	Total sensible heat of liquid PCM (J)
Q_λ	Total heat released during phase change (J)
$Q_{\lambda_{max}}$	Maximum latent heat stored by the PCM (J)
Q_s	Total heat released by sensible cooling of solid PCM (J)
Q_{tot}	Total heat released over a time period (J)
Q_i^+	Nondimensional total sensible heat released by liquid PCM
Q_1^+	Nondimensional total sensible heat of liquid PCM
Q_λ^+	Nondimensional heat released during phase change
Q_s^+	Nondimensional total sensible heat released by solid PCM
Q_{tot}^+	Nondimensional total heat released over a time period
r	Radial coordinate (m)
r_f	Interface location (m)
r_i	Inner radius of shell (m)
r_e	Outer radius of shell (m)
R	Nondimensional radial coordinate
R_e	Nondimensional external radius
R_i	Nondimensional internal radius
R_f	Nondimensional interface position
Ste	Stefan number
t	Time (s)
t1	Time domain - 1 (s)
t2	Time domain - 2 (s)
t3	Time domain - 3 (s)
T	Temperature (K)
T_f	Melting temperature (K)
T_{ini}	Initial temperature of PCM (K)
T_l	Liquid PCM temperature (K)
T_o	Temperature of HTF (K)
T_s	Solid PCM temperature (K)

Greek symbols

α	Thermal diffusivity (m^2 s^{-1})
α_l	Thermal diffusivity of liquid PCM (m^2 s^{-1})
α_s	Thermal diffusivity of solid PCM (m^2 s^{-1})
$\overline{\alpha}_p$	Effective thermal diffusivity of PCM-particle mixture (m2 s−1)
Δm_i	Instantaneous elemental mass between nodes i and i + 1 (kg)
Δm_{Rf}	Instantaneous elemental mass surrounding interface node (kg)
ε	Particle volume fraction
ϕ	Nondimensional temperature
ϕ_{ini}	Nondimensional initial temperature of PCM
λ	Latent heat of fusion of PCM (J kg^{-1})
ρ	Density (kg m^{-3})
ρ_l	Density of liquid PCM (kg m^{-3})
ρ_p	Density of PCM (kg m^{-3})
ρ_s	Density of solid PCM (kg m^{-3})
ρ_{ls}	Ratio between the density of liquid and solid PCM
τ	Nondimensional time
Ψ	Nondimensional enthalpy

Subscripts

l	Liquid PCM
s	Solid PCM
p	PCM
par	Particle
ini	Initial
w	Wall

1.2. Performance enhancement methods

Several methods have been proposed in the past on performance enhancement of LHTS units. Methods proposed can be classified under different categories viz. (i) employing fins [5,6] (ii) employing multiple PCMs [6,7] (iii) dispersion of high conductivity macro particles to PCMs [8,9] (iv) embedding PCMs in shape stable structures [10] and (v) dispersion of nanoparticles to PCMs [11–14]. Of the methods mentioned above, only the last three methods address the low thermal conductivity issues of PCMs whereas the rest focus on heat transfer enhancement without altering the PCM's thermal conductivity. Studies have shown that the dispersion of particles is a promising method for thermal conductivity enhancement of PCMs [8,9,11–15]. Recent studies have explored in detail the hydrodynamic and thermal interaction of nanoparticles for several interesting cases [16–18].

1.3. Drawback of nanoparticle additions

The addition of particles can be of macro/micro or nano scales. Many researchers have found that the addition of particles at nano scales (nanoparticles) could affect the thermophysical properties of the base PCM [11–15]. The technical issues associated with nanoparticle additions are i) the reduction of PCM's latent heat of fusion and ii) increase in viscosity beyond certain concentrations thereby lowering the natural convection heat transfer. In a real scenario, the advantage due to increase in PCM's thermal conductivity with nanoparticle addition is offset by the issues mentioned above. On the otherhand, macro particles do not encounter such issues and appear to be a promising option for performance enhancement of LHTS units.