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Effect of inclination angle during melting and solidification of a phase change material using a combined heat pipe-metal foam or foil configuration

Michael J. Allen [a], Nourouddin Sharifi [a], Amir Faghri [a,*], Theodore L. Bergman [b]

[a] Department of Mechanical Engineering, University of Connecticut, 191 Auditorium Road, Storrs, CT 06269-3139, USA
[b] Department of Mechanical Engineering, University of Kansas, Lawrence, KS 66045, USA

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ABSTRACT

Experiments are performed to analyze the impact of system inclination (ranging from 0° to 90°) on the melting and solidification of a phase change material (PCM) in a cylindrical enclosure. Heat transfer occurs through a concentrically located heat pipe (HP) or solid copper rod and an underlying copper disc. The HP may also be combined with aluminum foils and foam. Six configurations are investigated: HP-Foil-PCM, HP-Foam-PCM, HP-PCM, Rod-PCM, Foam-PCM and non-enhanced PCM. The PCM liquid fraction histories, temperature distributions and photographs provide insight into the influence of the inclination angle, as well as the three-dimensional melting phenomena. Experimental measurements indicate that the system orientation has a minimal effect on the solidification rates for nearly all case studies due to conduction-dominated heat transfer. However, during melting, the presence of natural convection may significantly alter the liquid fraction histories for systems without foam or foils. For the HP-PCM and Rod-PCM configurations with a horizontal orientation, the liquid fraction may be increased by up to 0.09 and 0.20 compared to a vertical orientation for a system with and without heat transfer through the base, respectively. For the HP-Foil-PCM and HP-Foam-PCM configurations, a vertical orientation achieved a slightly higher liquid fraction by approximately 0.03 and 0.05, respectively, relative to horizontal orientation. This may be attributed to the flow of the HP's internal working fluid, in which gravity assists the return of the liquid working fluid to the HP evaporator in a vertical orientation. The time for complete melting and solidification for the HP-Foil-PCM configuration was reduced to 11% and 3% of that for a non-enhanced system, respectively, regardless of orientation. Overall, the combination of a HP with foils or foam may achieve much higher melting and solidification rates with respect to a non-enhanced system.

1. Introduction

The utilization of energy storage may allow for renewable energy power systems, such as solar-thermal, to increase in efficiency as well as become economically competitive with traditional power plants. While various energy storage methods are available, latent heat thermal energy storage (LHTES) using a phase change material (PCM) is attractive for thermal systems. Currently, sensible heat thermal energy storage is more common, yet, LHTES may have a higher potential for utilization due to its higher energy density, nearly isothermal operation and reduced size [1]. However, most PCMs have low thermal conductivities which has limited the use of LHTES systems in the past [2]. Therefore, various heat transfer enhancement approaches have been proposed and implemented such as: heat transfer fins [3,4], foils (fin thickness less than 0.2 mm) [5], micro-encapsulation [6], macro-encapsulation [7], nanoparticles [8], porous media (such as metal foams and expanded graphite) [9] and heat pipes (HPs) [10,11].

The implementation of HPs into PCMs has been patented by Faghri [12,13], as they can efficiently transfer large amounts of heat passively through small cross-sectional areas [14]. The incorporation of HPs into a PCM to increase melting and solidification rates has been investigated [1,10,11,15–18]. As enhancers, HPs allow for deeper thermal penetration into the PCM. Other approaches, such as embedding foam or foils into the PCM, increase the effective thermal conductivity of a PCM-enhancer composite. For example, Zhao et al. [19] reported that the overall

* Corresponding author. Tel.: +1 860 486 0419.
E-mail address: faghri@engr.uconn.edu (A. Faghri).

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Nomenclature

c_p	specific heat (J/kg K)
f_l	liquid fraction
Δf_l	difference in liquid fraction
h_{sl}	latent heat of fusion (kJ/kg)
k	thermal conductivity (W/m K)
m	mass (g)
r	radial coordinate (mm)
r_m	melting rate (g/min)
T	temperature (°C)
$\lvert\Delta T\rvert$	driving temperature: the temperature difference between the heat transfer fluid and the phase change material (°C)
t	time (min)
t_m	time for 95% complete melting (min)
t_s	time for 95% complete solidification (min)
V	volume
z	axial coordinate (mm)

Greek symbols

α	inclination angle measured from vertical (°)
φ	porosity
ε_m	melting effectiveness at $f_l = 0.95$
ε_s	solidification effectiveness at $f_l = 0.05$
θ	polar coordinate angle (°)
ρ	density (kg/m^3)

Subscripts

bc	base case
l	liquid
m	melting
me	metal enhancer
pcm	phase change material
s	solidification, solid
total	total
void	void

Acronyms

HP	heat pipe
HTF	heat transfer fluid
LHTES	latent heat thermal energy storage
PCM	phase change material

heat transfer rates can be increased by up to 10 times with the inclusion of metal foam, depending on the choice of foam and PCM. Similarly, Sugawara et al. [5] reported that installing copper foils (0.03 mm thickness, 5% foil volume fraction) onto a heat transfer fluid (HTF) tube surrounded by PCM can reduce the complete melting (solidification) time to a tenth (eighteenth) of that for a case without foils. Other studies involving metallic heat transfer enhancers have shown comparable results which will not be discussed here.

Embedding metal enhancers, such as foam or foils, into PCMs may significantly suppress the positive contribution of natural convection during melting. Therefore, the improvement in conduction within a PCM should outweigh the suppression of natural convection. Since many studies of Foam-PCM systems have been focused towards electronic cooling, length scales typically in the range of approximately 15–50 mm have been considered [19–24]. However, as the distance between the solid–liquid interface and the heat transfer surface increases for larger scale systems, foams or foils may be ineffective, hence the need to increase the thermal penetration depth within the metal enhancer.

The combination of HPs and aluminum foils was first proposed by Sharifi et al. [25]. The authors experimentally and numerically investigated the solidification and melting in a vertical cylindrical enclosure heated/cooled by a concentric HP which penetrated an array of horizontal foils within the PCM enclosure. Heat transfer rates were increased with a HP-Foil-PCM configuration by 3 and 9 times compared to a similar Rod-PCM system during melting and solidification, respectively, with a foil volume fraction of 1.2%.

A similar system was investigated by Allen et al. [26] which included the combination of a HP and aluminum foam, where the foam porosities ranged from 0.870 to 0.987. The HP-Foil-PCM configuration was reported to have improved performance relative to the HP-Foam-PCM configuration. The HP-Foil-PCM configuration was capable of reducing the complete melting and solidification times from 200 min and 150 min for a Rod-PCM configuration to 13 min and 11 min, respectively. The HP-Foil-PCM and HP-Foam-PCM configurations increased the heat transfer rates by nearly 15 and 7 (8 and 6) times, respectively, relative to the Rod-PCM configuration during melting (solidification) with a porosity of approximately 0.957 for the foil-PCM and foam-PCM composites.

In the past, the combined HP and foam or foil systems were only studied in the vertical orientation [25,26]. However, if an enhancement technique is to be implemented into systems which experience various inclination angles, such as portable electronics, it must operate regardless of its orientation. For example, the time varying performance of a HP assisted LHTES has been investigated for an emerging application involving a dish-Stirling system for solar power production [27,28]. The authors proposed that the LHTES be attached directly onto the dish which will impose a varying inclination angle with the time of day, as the dish is designed to follow the trajectory of the sun.

In conduction-dominated systems, orientation is mainly insignificant. However, for systems involving HPs, the internal evaporation and condensation processes vary depending on the HP orientation. Also, natural convection within the PCM strongly depends on the location of the hot surface relative to the solid PCM. Therefore, system orientation may alter the melting rates.

Ye et al. [29] numerically investigated the effect of system inclination angle on the melting of a paraffin ($T_m \approx 27$ °C) in a quadrantal cavity heated from the curved wall. Without any heat transfer enhancement within the PCM, the complete melting time for the system when the heated curved surface was at bottom of the system and the gravity vector bisects the quadrantal cavity was approximately 13% of that when it was rotated 180°. In a related study, Kamkari et al. [30] experimentally melted a lauric acid ($T_m \approx 45$ °C) in a rectangular enclosure with varying tilt angles, with 0° corresponding to heating from below. The complete melting time was reduced by approximately 53% and 35% for the 0° and 45° orientations, respectively, relative to 90° with side wall heating. Hence, orientation alone may significantly alter the heat transfer rates in PCM systems due to changing natural convection flow patterns. Similar observations have been reported elsewhere [31–34].

With regard to HP-PCM systems, few have considered HP orientation with the exception of Nithyanandam and Pitchumani [35–38] and Shabgard et al. [16]. These works numerically investigated the effects of the orientation and number of HPs in a shell and tube PCM system. In [35], the effectiveness for a case with