



Melting and solidification enhancement using a combined heat pipe, foil approach



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ABSTRACT

Melting and solidification of a phase change material (PCM) is investigated, experimentally and computationally, using a novel heat pipe–metal foil approach. By embedding a PCM within a metal foil matrix, and delivering (or extracting) thermal energy to (or from) the matrix with a vertically-oriented heat pipe, overall thermal resistances between a working fluid and the PCM solid–liquid interface can be reduced. This leads to increased phase change rates relative to configurations involving only the heat pipe, or only a solid rod of the same physical dimensions as the heat pipe. For a small (approximately 1%) volume fraction of foil in the PCM–foil matrix, measured and predicted melting (solidification) rates associated with heat pipe–foil configurations are increased by approximately 300% (900%) relative to configurations involving the rod with no foil. Melting and solidification rates relative to configurations involving the heat pipe with no foil, are increased by approximately 200% and 600%. The influence of the heat pipe evaporator-to-condenser length ratio, as well as the overall temperature difference between the working fluid and the PCM fusion temperature, is also reported.

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1. Introduction

Latent heat thermal energy storage (LHTES) is considered to be more advantageous than sensible TES for many applications because of its high energy density [1–6]. Also, because of the nature of phase change, the energy storage and delivery can occur with minimal temperature differences within a LHTES system. However, the low thermal conductivity of most inexpensive phase change materials (PCMs) is a drawback, potentially limiting the heat transfer rates within, and phase change rates of the PCM.

Various strategies to overcome the large PCM thermal resistance have been proposed, including but not limited to use of high thermal conductivity porous matrices filled with PCM [7,8], dispersion of high thermal conductivity particles within the PCM [9,10], micro-encapsulation of the PCM [11,12], use of extended surfaces [13–19], and use of heat pipes (HPs) which are capable of passively transferring large amounts of heat efficiently over considerable distances through small cross-sectional areas [20].

1.1. Heat pipe-assisted phase change (HP-PCM)

Two patents involving the integration of HPs with PCMs are held by Faghri [21,22]. In related research, Horbaniuc et al. [23]

analytically investigated the solidification of PCM surrounding a longitudinally-finned HP. It was shown that, as expected, addition of more fins to the HP increases PCM solidification rates. Similarly, incorporation of a HP heat exchanger in a LHTES system was investigated experimentally by Liu et al. [24] in which a circumferentially-finned, acetone-charged copper thermosyphon was considered, with stearic acid as the PCM. Water was the heat transfer fluid (HTF) used to, ultimately, melt or solidify the PCM. The influence of the HTF inlet temperature and the HTF mass flow rate on the heat transfer and phase change rates was of particular interest.

Motivated by applications involving concentrating solar power, Shabgard et al. [25] developed a thermal network model to simulate both charging (melting) and discharging (solidification) a high temperature LHTES system. Multiple HPs were positioned between the HTF and PCM in two distinct geometrical configurations; one with PCM surrounding a tube through which flowed HTF, and the other involving PCM housed inside a tube across which the HTF flowed. The HPs increased the heat transfer rates to and from the PCM, and the improvement in phase change rates was quantified in terms of an effectiveness. The benefits associated with exploiting HP-assistance for LHTES were experimentally confirmed by Robak et al. [26] using an apparatus that consisted of a vertical cylindrical enclosure filled with n-octadecane. HPs were inserted between the HTF and the PCM, providing an effective thermal

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Nomenclature

<i>acc</i>	accuracy	<i>Subscripts</i>	
c_p	specific heat at constant pressure (J/kg K)	<i>a</i>	adiabatic
D	diameter (m)	<i>air</i>	air
f_f	foil volume fraction	<i>b</i>	bottom
f_ℓ	volumetric liquid fraction	<i>cell</i>	computational unit cell
g	gravitational acceleration (m/s ²)	<i>e</i>	enclosure
h_{fg}	latent heat of vaporization (kJ/kg)	<i>f</i>	foil
h_{se}	latent heat of fusion (kJ/kg)	<i>g</i>	gap
HP	heat pipe	<i>hp</i>	heat pipe
HTF	heat transfer fluid	<i>htf</i>	heat transfer fluid
k	thermal conductivity (W/m K)	<i>i</i>	inner, initial
L	length (m)	<i>in</i>	inlet
m	mass (kg)	ℓ	liquid phase of PCM
p	pressure (Pa)	<i>m</i>	melting
r, z	coordinate directions (m)	<i>o</i>	outer
R	gas constant (J/kg K)	<i>out</i>	outlet
<i>res</i>	resolution	<i>PCM</i>	phase change material
t	time (s or min), thickness (m)	r, z	coordinate directions
T	temperature (K), thermocouple	<i>ref</i>	reference
u	uncertainty	<i>rod</i>	rod
V	volume (m ³)	<i>s</i>	solid phase of PCM, solidification
<i>Greek</i>		<i>sat</i>	saturation
β	thermal expansion coefficient (K ⁻¹)	<i>t</i>	top
ε	effectiveness	ν	vapor phase of heat pipe working fluid
μ	dynamic viscosity (Pa s)	<i>w</i>	wall
ρ	density (kg/m ³)		

pathway to drive phase change. The measured thermal performance with HPs was compared to cases without HPs (i.e., transferring heat between the PCM and HTF through a plane wall) and again quantified in terms of an effectiveness. Melting rates for the HP configuration were approximately 60% higher than for the non-HP case, while solidification rates were approximately doubled relative to the plane wall case. The detailed numerical investigation of Sharifi et al. [27] provided additional insight into the heat transfer mechanisms responsible for the impressive thermal performance of the HP-PCM concept.

1.2. Foil-assisted phase change (Foil-PCM)

Melting and solidification rates can also be increased by adding high-thermal-conductivity material, such as metal foil, to a PCM. A representative numerical study considered the effect of integrating thin aluminum foils, arranged orthogonally with respect to the axis of a steam tube, within a PCM [28]. The PCM (a KNO₃/NaNO₃ eutectic mixture) filled the spaces between individual foils, as well as between the foils and the tube. Predictions showed that the solidification time could be decreased by approximately 25% by either increasing the foil thickness or decreasing the foil pitch. In related work, Bayón et al. [29] experimentally tested a high temperature LHTES system charged by steam flowing from a parabolic-trough solar collector. Expanded graphite foils were arranged on tubes in a sandwich configuration to increase the effective thermal conductivity of the PCM. The temporal variation of the outlet steam quality, along with the corresponding PCM (a KNO₃/NaNO₃ eutectic mixture) temperature–time behavior showed that the complete charging time could be reduced significantly by incorporating the foils with the PCM. In a similar study, Sugawara et al. [30] investigated freezing of water around a horizontal copper tube, through which flowed a cold HTF. Copper foils of thickness 0.03 mm were positioned around the tube to increase the freezing rate. It was

found that by using only 0.025 foil volume fraction, the solidification rate could be increased by a factor of four, relative to the case without foils.

In addition to increasing phase change rates for LHTES systems involving a HTF, use of foils offers other advantages relative to, for example, conventional finned heat transfer surfaces. First, foils are typically flexible because of their relatively small thickness compared to fins (or the interconnecting solid structures of metal porous foams) which are rigid. Structural flexibility is desirable, in that it can minimize the propensity for material damage or failure associated with the expansion and contraction of the PCM upon phase change, especially in high temperature applications where the metal itself may undergo considerable expansion from its initial cool state. Also, as will become evident, foils do not need to be physically attached to heat transfer surfaces by welding or fusion in order to increase, significantly, the thermal performance of a HTF-LHTES system. Finally, foils are typically inexpensive relative to conventional fins or metallic porous materials, in terms of both raw material and manufacturing costs.

Building on literature that has quantified the benefits of both (i) the HP-PCM and (ii) the Foil-PCM approaches, a novel concept (HP-Foil-PCM) is presented here that involves the integration of HPs with foils as a means to enhance the thermal performance of LHTES systems. The objective is to experimentally and analytically determine the thermal performance of the HP-Foil-PCM concept.

2. Experimental apparatus

As shown in Fig. 1, a PCM is contained within an upright cylindrical enclosure that is formed by an acrylic tube of $D_{e,i} = 41$ mm inner diameter, $L_e = 125$ mm height, and 4.6 mm wall thickness. The bottom of the enclosure consists of a 5 mm thick acrylic disk of 50.2 mm diameter, while the top of the enclosure is a 10 mm thick aluminum plate. A compartment of air overlies the PCM to

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