



Solidification enhancement in a triplex-tube latent heat energy storage system using nanoparticles-metal foam combination



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ABSTRACT

Thermal storage systems utilizing Phase Change Materials (PCMs) are known to exhibit slow thermal response. This is mainly due to the relatively low thermal conductivity of most PCMs used in the systems. Thus packing the PCMs in better performing containment vessels and/or employing heat transfer enhancement additives is required for improved performance of these systems. Nanoparticle-metal foam combination as a compound enhancement approach along with triplex-tube heat exchanger as a modified exchanger design were used in this study to improve the PCM solidification rate. A mathematical model based on the thermal equilibrium assumption which takes into account the non-Darcy effects of porous foam and the Brownian motion of nanoparticles was formulated and validated with previous related experimental studies. The influence of nanoparticle volume fraction and metal foam porosity on the evolution of the solid-liquid interfaces, distribution of isotherms, and liquid-fraction profile over the whole solidification process was studied. Results show that dispersing nanoparticles in the presence of metal foams results in total time saving up to 96% depending on foam structure and volumetric nanoparticle concentration.

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1. Introduction

Promotion of renewable energy sources like solar, wind, geothermal, etc. to more effectively contribute in energy markets requires a means to correct their intermittent nature. Development of more efficient energy storage technologies is one path for making renewable energy systems to be cost competitive with conventional fossil fuels. Storage of energy in thermal form which is known as thermal energy storage (TES) has been considered the best-suited option for broad applications, ranging from solar water heaters to building air conditioning systems [1].

Thermal energy can be stored in the form of sensible heat, latent heat, and thermochemical energy. Among these three methods, latent looks more attractive than others because of the relatively high storage density and the nearly isothermal nature of the storage process. Latent TES systems utilizing Phase Change Materials (PCMs) can store 5–14 times more energy than those of sensible storage materials under the same volume requirements [2]. This makes integration into small-scale portable systems to be more

possible. However, most PCMs suffer from the undesirable property of relatively low thermal conductivity. This strongly limits the functionality of latent TES systems because it prolongs the energy charging/discharging process and makes the system response time to be too long for meeting the desired results. In some cases, serious safety issues may emerge. One way to correct the limitation is to enhance the thermal conductivity through some modifications of the structure of the PCM container such as introduction of fins [3,4], insertion of heat pipes [5,6], inclusion of metal foams [7–12], and dispersion of highly conductive nanoparticles [13–19].

The existence of convective movement of the liquid PCM is desirable because it motivates better heat transport during the phase change of the PCMs. However, the use of fixed enhancement structures like fins, heat pipes etc. to offset the poor thermal conductivity of the PCM hinders the flow of the melting PCM and negatively affects convection. Thus, with regard to convection, nanoparticles are preferred because they don't resist the PCM-melt movement as much as fins, heat pipes etc. Nanoparticles would be able to move with the PCM melt. Generally speaking, the use of nanoparticles results in more fluid-like behavior during the PCM phase-transition. This induces better convection contribution. However, a better choice is the one which results in the best overall

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Nomenclature	
A_m	mushy zone constant
A_{sf}	interfacial surface area (m^{-1})
C_f	inertial coefficient (m^{-1})
C_p	specific heat (J/kg K)
d_l	ligament diameter (m)
d_p	pore size (m)
g	gravity acceleration (m/s^2)
h_{sf}	interfacial heat transfer coefficient ($W/m^2 K$)
k	thermal conductivity ($W/m K$)
K	Permeability of porous foam (m^{-2})
L	latent melting heat (J/kg K)
P	pressure (Pa)
r	tube radius (m)
t	time (s)
T	temperature (K)
T_l	liquidus temperature of the PCM (K)
T_s	solidus temperature of the PCM (K)
u	velocity component in r-direction (m/s)
v	velocity component in θ -direction (m/s)
HTF	heat transfer fluid
PCM	phase change material
PPI	pore number per inch
TES	thermal energy storage
LTE	local thermal equilibrium
LTNE	local thermal non-equilibrium
<i>Greek letters</i>	
ρ	fluid density (kg/m^3)
ϕ	nanoparticles volume fraction
λ	liquid fraction
β	thermal expansion coefficient (K^{-1})
μ	dynamic viscosity ($kg/m s$)
ζ	correction factor
ε	porous foam porosity
ω	pore density (PPI)
<i>Subscripts</i>	
np	nanoparticle
e	effective value
f	liquid nanoPCM
i, o	inner, outer tube
int	initial
s	porous foam
w	wall

improvement when the effect of convection and conduction are combined.

Due to their high thermal conductivity, large area-to-volume ratio, and strong mixing capability, metal foams (e.g. copper and aluminum) have also been a subject of interest for many studies [20]. Metal foams offer remarkable solutions for phase-change enhancement in PCMs. For instance, Zhao et al. [8] reported that phase-change rate can be increased by up to 10 times with the use of metal foams. But because they reduce the available PCM volume and consequently cause a less overall storage capacity, only metal foams with high porosity (≥ 0.90) are recommended for PCM-based TES applications. Metal foams are porous metallic structures with small openings called pores or voids. The ratio of the void volume to the total volume is the porosity. High porosity makes the metal foam light in weight and larger in void space, which in turn aids the formation of thin boundary layers that lead to an enhanced interstitial heat transfer. However, further heat transfer enhancement is possible through incorporation of high-conductive nanoparticles. This study attempts to combine advantages of using nanoparticles and high-porosity metal foams together to enhance the solidification of PCMs in latent TES applications.

Much of the work in the literature pertaining to implementation of metal foams in PCM-based applications has focused on heat transport characteristics during energy charging (i.e. melting) and energy discharging (i.e. solidification) but the solidification has received less attention. Since the scope of the present work is on solidification, we note that Siahpush et al. [7] investigated the melting and solidification of eicosane as a PCM saturated in 0.95-porosity copper foam contained in an isothermally-cooled vertical cylinder. The study found that the use of metal foam significantly enhanced the phase-change rate by increasing the effective thermal conductivity of the composite. The scale analysis done, confirmed the experimental results within 10% discrepancy in the worst case. Zhao et al. [8] studied the effects of embedding metal (copper) foam on thermal performance of solid-liquid phase change process of RT58 as a PCM. Results revealed that 3 to 10 times better melting rate can be achieved and more than half

solidification time can be reduced depending on the metal foam structures and materials. Zhao et al. [9] inserted copper foam and expanded graphite into two different PCMs: paraffin RT 27 and calcium chloride hexahydrate. The study discovered that both approaches enhance the heat transfer but the metal foams achieved better heat transfer performance than the expanded graphite especially in the solid zone where natural convection is almost absent. Zhang et al. [10] used metal (copper and nickel) foams to enhance the low thermal conductivity of pure molten salt ($T_m = 220^\circ C$) and found that the metal foam significantly weakens the natural convection during the heat storage process; while the heat retrieval process which is dominated by the heat conduction is largely enhanced by the presence of the metal foam. The report recommended the use of thermal non-equilibrium in heat transfer modeling due to the high-temperature difference recorded between the salt and the metal foam. Atal et al. [11] tested the effectiveness of 0.95- and 0.77- porosity aluminum foam on paraffin wax (PCM 58P) phase-change process and developed a simplified numerical model without the non-Darcy effects. The results showed that the use of metal foams with PCMs significantly reduced the charging/discharging time.

The concept of incorporating nanoparticles to enhance the thermal response of PCMs was first proposed by Khodadadi and Hosseinizadeh [13]. The study showed through numerical simulation that the enhanced functionality of the PCMs by nanoparticle dispersion is promising for utilization in thermal energy storage applications. Wu et al. [14] experimentally investigated melting/solidification characteristics of copper/paraffin composite as a nanoparticle-enhanced PCM. The results revealed that with copper nanoparticles of 2% by weight the thermal conductivity of paraffin can be enhanced by 14% in the solid phase and 18% in the liquid phase. Furthermore, adding copper nanoparticles of 1% in weight can save the melting and freezing times by about 33 and 32%, respectively. Fan and Khodadadi [15] presented a study on expedited unidirectional freezing of cyclohexane (C_6H_{12}) with copper oxide (CuO) nanoparticles as a nanostructure-enhanced PCM. The numerical predictions based on one-dimensional Stefan model

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