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Unidirectional freezing of phase change materials saturated in open-cell metal foams

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HIGHLIGHTS

- Unidirectional freezing of water as a PCM embedded in metal foams was studied.
- Local thermal equilibrium between a metal foam and PCM was experimentally observed.
- The one-equation model suffices to model the PCM-saturated metal foams.
- Thermal contact resistance has negligible influence on freezing rates.
- Thus, one can simply embed metal foams into PCMs with no need for interface bonding.

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ABSTRACT

An experimental and theoretical study of the unidirectional freezing of water as a PCM filled in metal foams has been carried out. Particular concern is placed upon determining how the contact conditions between the metal foam and the cold wall influence the freezing process, as well as exploring the local thermal equilibrium between the metal foam and the PCM. To address these questions, three contact conditions were considered, *i.e.*, natural contact, applied pressure, and bonding with a high thermal conductivity adhesive. To explore the local thermal equilibrium, temperatures on foam ligaments and within the pores were measured individually using thermocouples. For the current copper foam/water PCM system, the three different contact conditions were found to have similar freezing rate. This indicates that in practice one can simply embed metal foam blocks into PCMs with no need of bonding them to the cold wall *via* sintering, thermal adhesive or other methods, thereby reducing the costs of devices in thermal energy storage systems. Effects of foam properties, including porosity and pore density on the freezing rate, were also discussed.

1. Introduction

Phase change materials (PCMs) have the capability of storing and releasing sizeable latent heat upon solid–liquid phase transition. They have been widely used in many applications such as thermal management of electronics, heat protection systems in aerospace applications, and thermal energy storage. Various organic and inorganic materials with a wide range of melting temperatures can be used as potential PCMs for different applications. PCMs with a low melting temperature (less than 20 °C) are mainly used for *cold energy storage*, e.g., food storage and air conditioning [1], while PCMs with a higher melting temperature can be used for *heat energy storage*, e.g., waste heat recovery systems, buildings, and solar power plants [2]. However, most PCMs suffer from low thermal conductivity, which limits attainable heat transfer rates thus prolonging energy charging and discharging periods. Thermal conductivity enhancement of PCMs has therefore been studied extensively, as documented in several recent review papers [1,3,4].

Existing methods for enhancing the thermal conductivity of PCMs may be divided into two broad categories: 1) dispersing nano-sized additives into PCMs to produce *free-form and fluid-like composites* and 2) introducing *fixed high-conductivity inserts*. Various nanoparticle-enhanced PCMs such as CuO-cyclohexane [5], Cu-paraffin [6] and Al_2O_3–H_2O [7] have been studied and have

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Nomenclature

c_s	heat capacity of copper (J/kg K)
$c_{PCM,l}$	heat capacity of water (J/kg K)
$c_{PCM,s}$	heat capacity of ice (J/kg K)
H	height of metal foams along freezing direction (m)
$k_{ef,l}$	effective thermal conductivity of foam/water composite (W/mK)
$k_{ef,s}$	effective thermal conductivity of foam/ice composite (W/mK)
$k_{PCM,l}$	thermal conductivity of water (W/mK)
$k_{PCM,s}$	thermal conductivity of ice (W/mK)
L	latent heat (J/kg)
s	growth of ice thickness (m)
T_i	initial temperature (K)
T_m	freezing temperature (K)
T_0	cold wall temperature (K)

Greek symbols

ρ_s	density of copper (kg/m^3)
$\rho_{PCM,l}$	density of water (kg/m^3)
$\rho_{PCM,s}$	density of ice (kg/m^3)
ε	porosity
δ	thickness of sub-layer PCM (m)

shown reduced freezing/melting times relative to those of the pure base material. However, the phase change process is not enhanced monotonously by an increase in the concentration of nanoparticles due to precipitation of particles [5]. The problem of particle precipitation can be alleviated by using *fixed high-conductivity inserts*. Copper, aluminum, nickel, stainless steel and carbon in various forms (e.g., fins [8], honeycomb [9], brush [10], foam [2], and graphite [11]) have been utilized as fixed inserts. Upon extensive review of state of the art enhancement methods, Fernandes et al. [4] argued that embedment of open-cell metal foams in PCMs is one of the most promising approaches to enhancing thermal conductivity and heat transfer rates, as metal foams prove to be a non-expensive, easy to handle and are abundantly available. Zhao et al. [2] experimentally investigated the melting and solidification processes of paraffin wax RT 58 embedded in copper foams and found that the addition of metal foams can increase the overall heat transfer rate by 3–10 times during the melting process and reduce the solidification time by more than half. The feasibility of using metal foams and graphite to enhance the heat transfer of $NaNO_3$ as a PCM for high temperature solar thermal energy storage was experimentally studied by Zhao and Wu [12], and the overall performance of metal foam inclusion was found to be superior to expanded graphite inclusion.

Modelling heat transfer in a porous medium, e.g., a PCM-metal foam composite, can be performed with either a one- or two-equation model, depending on whether local thermal equilibrium is assumed between the two phases of the filled porous medium. A one-equation model assumes local thermal equilibrium, i.e., the foam and the fluid have an identical temperature. The two-equation model assumes local thermal non-equilibrium, i.e., the foam and the fluid have different temperatures, and each constituent is characterized with a separate equation. Based upon the assumption of local thermal non-equilibrium, Mesalhy et al. [13] numerically studied the melting process of PCMs saturated in metal foams within an annular space. Tian and Zhao [14] and Li et al. [15] also adopted the two-equation model to simulate the melting process of paraffin/metal foams composite under horizontal and vertical positions, respectively. By comparing the prediction results from the one-equation model and the two-equation model, Krishnan et al. [16] revealed that when the interstitial Nusselt number between the foam and the solid-/fluid-layer of PCM exceeds a certain value, the local thermal equilibrium assumption is valid. Recently, Hu and Patnalk [17] applied two different simulation methodologies for paraffin-embedded aluminum foam: one was direct numerical simulation (DNS), which makes no assumptions regarding local thermal equilibrium; the other was a volume averaged simulation using both one- and two-equation models. Upon comparing results from the two methodologies, the volume averaged simulation was found to be sufficient for modelling the paraffin/aluminum foam composite.

Although solid–liquid phase change in metal foams has been extensively studied, there are still several areas that need to be addressed. First, there is no experimental investigation on the local thermal situation between metal foams and PCMs. A two-equation model, which was used in most previous studies, involves empirical parameters (e.g., an interstitial heat transfer coefficient), which introduce uncertainties into model predictions. Meanwhile, if the actual thermal situation is close to local thermal equilibrium, a one-equation model, requiring no interstitial heat transfer coefficients for closure, is more adequate and simple. Therefore, a proper understanding of local thermal equilibrium is needed to select the appropriate model to achieve accurate model prediction. Furthermore, the influence of the contact condition between a metal foam and a heat transfer surface on phase change heat transfer has not been covered in previous studies.

To address the above issues, unidirectional freezing of water (a common phase change material in cold energy storage [1,11]) embedded in open-cell copper foams was investigated both experimentally and theoretically. The problem is depicted in Fig. 1. The distilled water had an initial temperature of T_i, higher than the freezing temperature T_m. At time $t = 0$, the temperature of the cold wall ($x = 0$) was suddenly reduced to T_0 ($<T_m$) and subsequently held constant. At $x = H$, the boundary condition was assumed adiabatic. Three copper foam samples were tested with three different contact conditions between the foam and the cold wall: natural contact, applied pressure, and bonding with a high thermal conductivity adhesive. Propagation of the freezing front in different test cases was recorded using a digital camera. To explore local thermal equilibrium between the foam and the PCM, temperatures of the foam ligaments and within the pores were separately recorded with thermocouples. The effects of foam properties upon freezing were also analysed in detail.

2. Experimental setup and procedures

A test rig was designed and built to investigate quasi one-dimensional freezing of PCMs saturated in open-cell copper

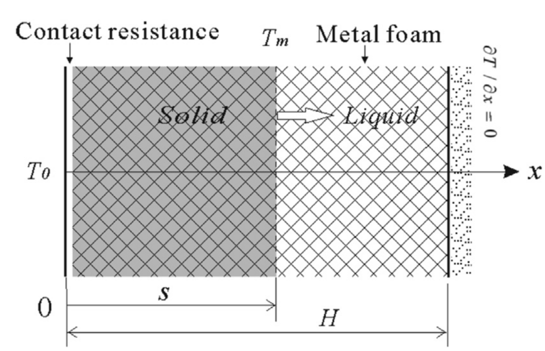

Fig. 1. Unidirectional freezing of PCMs saturated in metal foams.

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