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Solidification of fluid saturated in open-cell metallic foams with graded morphologies

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A B S T R A C T

Solidification of distilled water saturated in open-cell metallic foams with graded morphologies was investigated experimentally. Open-cell foams having different morphological properties including porosity, pore density (PPI) and materials for the porous matrix were cut into pieces and stacked up, forming a whole porous layer with gradient morphological features. Systematic measurements of temporal solidification front and full solidification time for distilled water saturated in the morphology gradient foams were carried out. Meanwhile, numerical simulations of solidification in fluid-saturated metallic foams with uniform morphological properties were performed. It was found that the presence of gradient in foam properties affect significantly the solidification rate and full solidification time. The results showed that compared to the single-layered foam with fixed morphology, the stacked foams with properly designed morphology gradient would reduce more effectively the full solidification time, due to the enhanced heat transfer.

1. Introduction

Thermal energy storage (TES) and phase change materials (PCMs) have become a main research topic in the energy application engineering [1]. Charge and discharge of heat/cold through latent heat of the PCMs are involved in a multitude of applications such as heat/cold storage, thermal protection in aerospace engineering, and central air-conditioning systems [2–4]. In these applications, PCMs undergo a change of phase either from solid to liquid for heat storage, or from liquid to solid for cold storage. During the process of phase change, the phase change rate as well as full solidification/melting time are always of great significance. Nonetheless, the relatively low thermal conductivity of typical engineering-facilitated PCMs deteriorates the thermal efficiency for heat/cold storage.

To enhance the phase change process, the main approaches may be summarized into two categories [5,6]: (a) improve directly the thermal conductivity of PCMs through adding moving heat spreader, e.g. micro/nano particles with higher thermal conductivity; (b) insert non-moving metallic matrix into PCMs, forming PCM–matrix composites. Liu et al. [7] found that the suspension of TiO_2 nano particles in saturated $BaCl_2$ aqueous solution exhibited excellent phase change performance, significantly increasing both the cold storage/supply rate and the cold storage/supply capacity. Kumaresan et al. [8] fabricated a novel PCM consisting of multi wall carbon nanotubes (MWCNT) suspended in water, and their experimental results showed that a maximum reduction of 20.1% was achieved in the full solidification time. In addition, it has been demonstrated that CuO, Al_2O_3 and Cu nanoparticles can directly enhance the effective thermal conductivity of PCMs and therefore promote the phase change process [9,10].

Compared with the attainable enhancement with moving micro/nano particles, adding non-moving metallic matrices into PCMs poses increasing promise for low cost, structural controllability and satisfactory thermal enhancement [5,11–13]. Tong et al. [14] numerically examined the enhancement of solidification by inserting Al foam into pure water. Lafdi et al. [15] and Zhao et al. [11] experimentally investigated the phase change process of paraffin filled with metal foams, and found that the use of metal foam can dramatically reduce the time for thermal storage. Xiao et al. [16] described in detail how to prepare a PCM–foam composite experimentally. Feng et al. [17] both experimentally and numerically examined the solidification behavior of water saturated with open-cell metallic foams under constant temperature

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Nomenclature

e	dimensionless node size
c_p	specific heat at constant pressure, (J kg^{-1} K^{-1})
f_s	solid fraction
H	total thickness (or length) of PCM parallel to heat flow, (m)
$\hat{H}$	enthalpy, (J)
$\hat{h}$	sensible enthalpy, (J)
k_s	thermal conductivity of solid phase of PCM, (W m^{-1} K^{-1})
k_f	thermal conductivity of liquid phase of PCM, (W m^{-1} K^{-1})
k_{eff}	effective thermal conductivity of foam-PCM composite, (W m^{-1} K^{-1})
L	latent heat of PCM, (J kg^{-1})
PCM	phase change material
q	heat flux conducted through the solidified layer, (W m^{-2})
$S(t)$	location of phase interface front, (m)
Ste	Stefan number defined as $Ste = c_p(T_0 - T_m)/L$ with constant temperature boundary
t	time, (s)
T_m	melting temperature of PCM, (K)
$T_{solidus}$	solidus temperature of PCM, (K)
$T_{liquidus}$	liquidus temperature of PCM, (K)
T_w	boundary wall temperature of PCM, (K)
T_{in}	temperature of inside wall of the container, (K)
T_{out}	temperature of outside wall of the container, (K)
z	axis coinciding with solidification

Greek symbols

α	dimensionless ligament length
ε	void fraction (porosity) of heterogeneous material
ρ	density of PCM, (kg m^{-3})
τ	thermal tortuosity

thermal boundary. It was shown that the thermal contact resistance can be readily neglected during the freezing process of water filled in open-cell foams.

Upon systematically reviewing existing literature on cold storage enhancement, we noted several issues that are yet fully addressed. For example, while the concept of using graded porous matrix to enhance heat transfer was proposed and verified in terms of forced convection [18] and pool boiling [19], how it would affect solid–liquid phase change is unclear. We speculated that through proper structural design, e.g. gradient configuration, the propagation of phase interface could be promoted. Therefore, in the present study, we aim to experimentally investigate the effect of gradient in foam morphological parameters on transient phase interface as well as full solidification time of water saturated in open-cell metallic foams, as illustrated schematically in Fig. 1. The distilled water saturated in open-cell foam had an initial temperature of T_i, higher than its freezing temperature T_m. At time $t > 0$, the temperature of the cold wall was suddenly reduced to T_w ($<T_m$) and subsequently held constant. Copper, aluminum and Nickel foam samples with different pore morphologies were tested with different packing

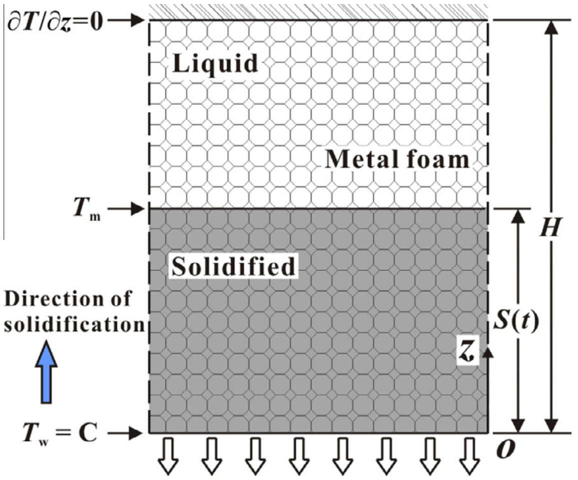

Fig. 1. Schematic of one-dimensional solidification along the z-direction with a constant temperature (lower than the freezing point) imposed on the bottom wall boundary with the thermally insulated top surface and side walls.

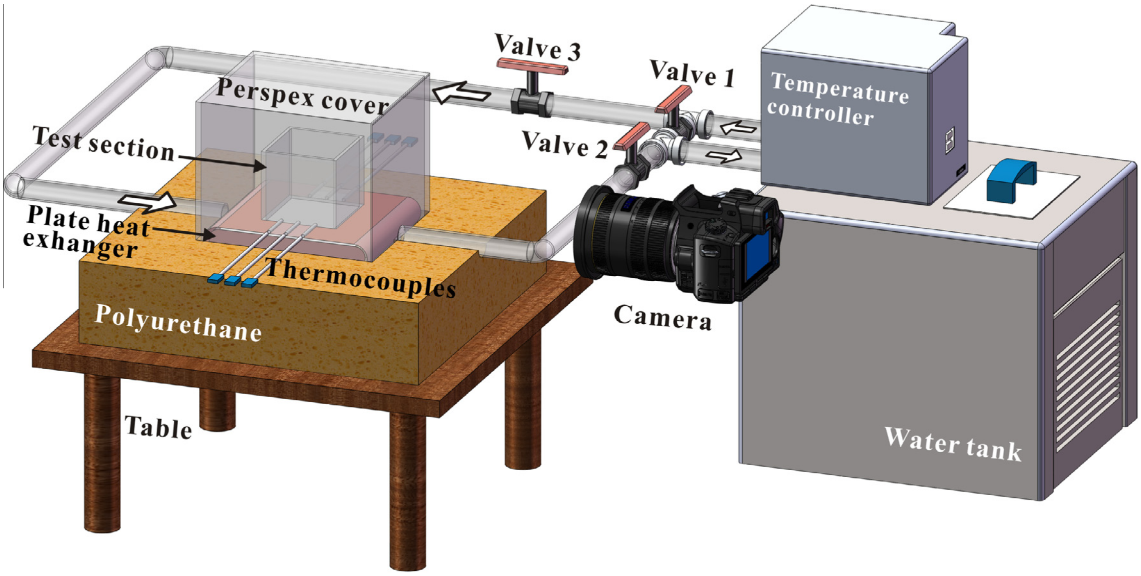

Fig. 2. Schematic of the test rig for studying solidification of water saturated in open-cell metallic foam with gradient morphology.