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Technical Note

A similarity solution to unidirectional solidification of nano-enhanced phase change materials (NePCM) considering the mushy region effect

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ABSTRACT

In this Technical Note, we report on the similarity solution to a one-dimensional, two-phase, three-region Stefan problem, with application to unidirectional solidification of nano-enhanced phase change materials (NePCM) in a semi-infinite domain accounting for the presence of a mushy region. The NePCM were considered as homogeneous mixtures with effective thermophysical properties by neglecting diffusion of the nano-additives. As an example, NePCM consisting of dodecanol and graphene nanoplatelets, as the base PCM and nano-additives respectively, were studied. Instead of using predicted values from existing models/correlations, the effective thermophysical properties of the model NePCM at various loadings were measured experimentally, which were substituted directly into the similarity solution. It was shown that a mushy region appears and gradually develops as solidification proceeds with its thickness being non-monotonously changed with increasing the loading, in consistent with the variations of the measured solidus and liquidus temperatures. The relative solidification rate was compared quantitatively, showing that solidification is greatly accelerated up to a factor of 34% at the highest loading of 1.0 wt%. Based on the similarity solution, thermal conductivity enhancement of the NePCM was interpreted to be the major cause leading to expedited solidification.

1. Introduction

Thermal energy storage is deemed to be an effective means to improve energy efficiency of renewable energy conversion systems, industrial processes, commercial and residential buildings, etc. Latent heat storage by materials upon phase change, e.g., melting of a solid material into liquid in most cases, has long been studied and utilized [1]. In practice, thermal conductivity enhancement of phase change materials (PCM) is one of the crucial issues to be addressed toward performance improvement of PCM-based thermal energy storage systems [2]. Recently, in contrast to the adoption of convectional extended surfaces at meso-scale, the concept of nano-enhanced PCM (NePCM) has been proposed to enhance the effective thermal conductivity of PCM by introducing highly thermally conductive nano-additives [3].

Understanding of solid–liquid phase change of NePCM, in the form of colloidal suspensions at liquid phase, has since stimulated increasing research interests to revisit the classical melting and solidification problems with complexities in the presence of nano-additives. As opposed to melting with possibly intensive natural convection effect, the conduction-dominated formulation is well justified for solidification. Unidirectional solidification of NePCM, treated as effective media with homogeneous thermophysical properties, was studied by solving a one-dimensional, two-phase, two-region Stefan problem in a finite slab via a combined analytical and integral method [4], and the effective media assumption was verified qualitatively by experimental results [4,5]. However, the sharp-phase-interface formulation may be inappropriate in view of the fact that numerous PCM candidates, especially organic PCM for medium-to-low temperature applications, will develop mushy regions over extended temperature ranges during solidification [6]. By describing the mushy region as a binary mixture [7], a one-dimensional, two-phase, three-region Stefan problem was solved exactly in an semi-infinite domain [8].

In this Technical Note, an extension of the existing mathematical modeling of unidirectional solidification of NePCM will be undertaken by seeking a similarity solution to the three-region Stefan problem considering the mushy region effect. Quantitative results will be presented and discussed with model NePCM at various loadings of the nano-additives.

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Nomenclature

c	specific heat capacity at constant pressure (kJ/kg K)	η	similarity variable
E	expediting factor	λ	non-dimensional constant
f	phase fraction	ρ	density (kg/m^3)
k	thermal conductivity (W/m K)	ϕ	loading of nano-additives (wt%)
L	latent heat of fusion (kJ/kg)		
Ste	Stefan number	*Subscripts*	
T	temperature (°C)	0	initial condition
t	time (h)	C	at cold boundary
X	location of phase front (mm)	L	liquid phase
x	coordinate (mm)	M	mushy region
		S	solid phase
Greek symbols			
α	thermal diffusivity (m^2/s)		

2. Physical model

Unidirectional conduction-dominated solidification of NePCM in an semi-infinite domain is considered in order to make the problem explicitly solvable. Despite a lack of practical utility, the slow phase change rates encountered in most actual solidification processes make the semi-infinite formulation a rational approximation to the case of slabs with finite thickness [6]. As illustrated in Fig. 1, the entire domain is initially kept at a temperature T_0 that is higher than the solidus temperature T_S of the NePCM, which is suddenly (at $t = 0$) dropped to and then (for $t > 0$) maintained at a temperature T_C that is lower than the liquidus temperature T_L on the left boundary ($x = 0$). A solidification layer initiates from the left cold boundary with a mushy region developing ahead of it. As solidification proceeds, the two phase interfaces separate the three regions, i.e., the solidus and liquidus temperature lines, move toward the positive x direction. The liquid region far from the left boundary remains at the initial temperature T_0.

Since the attention of this work is mainly on heat transfer of NePCM at meso-scale, the nano-additives are assumed to be always uniformly distributed in base PCM by ruling out any micro-scale mechanisms of particle diffusion during solidification, although the foreign particles actually diffuse (re-distribute) and interact with the developing phase interface. Solidification of NePCM (or colloidal suspensions) is analogous to that of binary alloys/mixtures. In this work, the latent heat of fusion of NePCM is considered to be released gradually within the mushy region, similar to the formulation in case of binary alloys/mixtures [7]. However, as the nano-additives are always in solid phase that do not experience solidification, the so-called constitutional supercooling for binary alloys/mixtures is not present for NePCM.

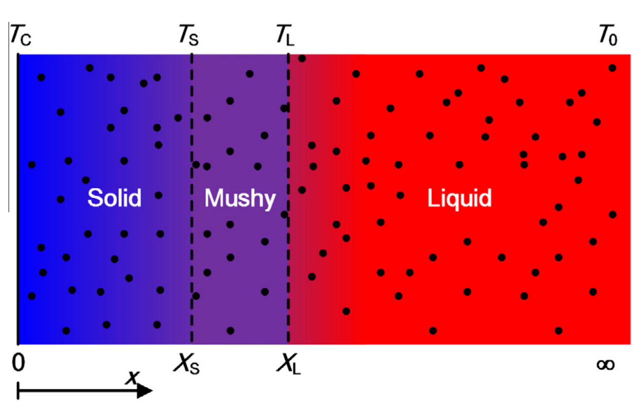

Fig. 1. Physical model of the unidirectional solidification problem of NePCM.

3. Mathematical formulation

The major assumptions invoked for simplicity of analysis are: (a) heat conduction is the only mechanism of heat transfer, (b) the problem is uncoupled for heat and mass transfer, i.e., the particle diffusion is neglected as compared to heat conduction, (c) the thermophysical properties, except for density, are independent of temperature and they may differ in each phase, (d) the properties within the mushy region are interpolated by the values for solid and liquid phases, and (e) density is constant within all the regions so that the volume change is negligible. Based on the above assumptions, a one-dimensional, two-phase, three-region Stefan problem is formulated to describe the unidirectional solidification of NePCM accounting for the mushy region effect.

In the solid region, where $0 < x < X_S$, the energy equation reads

$$\frac{\partial T}{\partial t} = \alpha_S \frac{\partial^2 T}{\partial x^2}. \tag{1}$$

In the mushy region, where $X_S < x < X_L$, the energy equation may be written as

$$\frac{\partial T}{\partial t} = \alpha_M \frac{\partial^2 T}{\partial x^2} + \frac{L}{c_M} \frac{\partial f_S}{\partial t}, \tag{2}$$

where the heat source term accounts for the transient release of latent heat within the mushy region that is represented by the time rate change of solid fraction f_S, which is usually considered as a known function of temperature or location. A simple expression of the solid fraction as a linear function of location may be given by

$$f_S = \frac{X_L - x}{X_L - X_S}. \tag{3}$$

It is noted that this expression is modified based on the one proposed in the literature for eutectic alloys/mixtures [7], where the critical solid fraction at eutectic, with a value being less than unity, is omitted. This modification is necessary in that NePCM are not eutectic mixtures.

In the liquid region, where $x > X_L$, the energy equation is similar to that in the solid region

$$\frac{\partial T}{\partial t} = \alpha_L \frac{\partial^2 T}{\partial x^2}. \tag{4}$$

The boundary conditions for the three regions at $t > 0$ are given by