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Solidification analysis of a single particle with encapsulated phase change materials

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HIGHLIGHTS

- Inward solidification model of a sphere for a single encapsulated phase change material particle is built.
- An effective numerical method is developed and validated by an iterative analytical series solution.
- The evolution of solidification and the moving front surface are predicted for different size particles.
- The model explains the rapid solidification of microencapsulated Paraffin particles under small Stefan numbers.

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ABSTRACT

The melting or solidification behavior of a single particle with encapsulated phase change material (PCM) is essential in analyzing the heat transfer effect of encapsulated PCM suspension slurries, particularly in mini-channels or high flow speed applications. Accordingly, the heat diffusion equation of a sphere with a liquid–solid moving interface model is used to analyze the solidification of PCM within a single encapsulated particle. The nonlinearities associated with a moving boundary problem are simplified via the transformation of dimensionless variables of equations. A technique which combines Explicit Euler method and Implicit Euler method in finite difference scheme is thus developed to solve the Stefan problem. The result is compared with an iterative analytical series solution and a good agreement is obtained. The evolution of solidification and the moving front surface are predicted for different size particles with core paraffin encapsulated, and the solidified volume fraction as a function of time is also determined.

1. Introduction

Latent heat storage is particularly attractive, since it provides a high energy storage density and can store the energy as the latent heat of fusion at a constant temperature (phase change temperature of the corresponding PCM). Notably, the use of PCMs for thermal energy storage in solar heating system has received considerable attention. The heat storage capacities of different PCMs were investigated theoretically and experimentally in a cylindrical energy storage tank linked to a solar powered heat pump system by Esen et al. [1–3]. In recent years the micro or even nanoscale encapsulated PCMs can be produced in a large quantity thanks to the rapid development of the manufacturing techniques. This can not only thoroughly solve the leakage problem (occurred in solid/liquid phase change of PCMs), but also the shell of the micro/nano-capsules can provide the protection of PCMs by avoiding the direct contact between the PCMs and heat transfer media.

For microencapsulated PCM slurries, the heat transfer or storage performance depends on the heat release or absorption rate per particle and the particle concentration (the number of particles per unit volume of the slurry) [4]. The factors influencing the heat transfer for a single particle are the liquid–solid interface location and the phase change rate. Moreover the microencapsulated PCM slurries are often used in mini-channels for cooling purpose, but it is unknown whether or not the melting process of the particles has been completed at the channel exit for such a short distance, particularly at a high flow speed. Therefore it is important to study the mechanism of heat transfer in phase change stage of a single encapsulated PCM particle.

Among various shapes of encapsulated particles, spherical particles are the most preferred as it can store a larger amount of

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Nomenclature

T^*	temperature of solid
t^*	time
r^*	radial coordinate of solid region ($R^* < r^* < R^*_{max}$)
T^*_b	boundary temperature of a particle
T^*_f	freezing temperature
R^*	position of liquid–solid interface
k	thermal conductivity of solid
c	specific heat capacity of solid
L	latent heat of PCM
T	dimensionless temperature of solid
r	dimensionless radial coordinate of solid region
R	dimensionless position of liquid–solid interface
t	dimensionless t
$u(r,t)$	new defined variable from $T(r,t)$
$\varphi(x,y)$	new transformed variable from $u(r,t)$
x	new defined variable from dimensionless radial variables
y	new defined variable to represent R
$\hbar$	variable in finite difference solution
cof_1, cof_2, cof_3	intermediate variable in discretized equation of Implicit Euler method
a_i, b_i, c_i	coefficients in discretized equations of Implicit Euler method
$A_n(x)$	coefficients in the expression of the iterative analytic series solution
$f_1(\delta)$, $\varpi(\delta)$, $A_{11}(x)$, $A_{12}(x)$,$C_{12}(x)$	variables in the iterative analytic series solution

Greek symbols

α	thermal diffusivity in the solid phase, $\alpha = k/\rho c$
ρ	density of solid
ζ	Stefan number
γ, σ	parameters in the iterative analytic series solution

energy due to a more favorable ratio of volume to heat transfer surface area [5]. For this reason the heat conduction or diffusion equation of a sphere with a liquid–solid moving interface model is investigated in this paper, and a method is proposed to describe the solidification process (Stefan problem) of a single encapsulated PCM particle.

For solidification within a sphere containing molten PCM inside, solid transformation starts from the outer shell due to the wall temperature being below the freezing point, and develops inward to the center until all the liquid changes into solid [5,6]. Accordingly the solidification of a PCM particle can be simply described by inward solidification model of a sphere. However, it is difficult to analytically calculate the inward solidification of a sphere due to the moving liquid–solid interface existed in phase change stage. In the previous research, Shih et al. [7,8] obtained an analytical solution for the solidification of cylinders and spheres with constant heat transfer coefficient by using an analytical iteration technique. The success of this method lies in transforming the diffusion equation from cylindrical coordinates or spherical coordinates into a form of rectangular configuration with position dependent coefficients. Moreover, perturbation approach has been applied to obtain the analytical solution for spherical solidification. Due to the divergence of the regular perturbation solution when the freezing front approaches to the center, the method of strained coordinates was used by Pedroso and Domoto [9]. The treatment which assumed that the parameter β, the ratio of the latent heat to the sensible heat of the substance is large, was adopted in the analytical solution by Riley et al. [10]. Another semi-analytical technique which simplifies the non-linearity associated with the moving boundary and enables an iterative analytic series solution was proposed by Davis and Hill [11] and the technique was further developed in Ref. [12] to give successive estimates of the time for complete solidification of a sphere.

However, the analytical solution is not able to solve more complicated thermophysical problems which are sometimes encountered. Therefore, the numerical methods are also appropriate for solving the Stefan problems. The numerical methods were reported to effectively work out the general one-dimensional Stefan problems in Refs. [13–19]. At first, the Explicit FD method was used for the Stefan problem with time-dependent boundary conditions and compared with the nodal integral method. The high accuracy and agreement can be obtained for both solutions [13]. The variable space grid method based on finite differences was further used by Savovic and Caldwell [14] and the result exhibited good agreement with the exact solution. In addition, the finite difference was also used to solve one-dimensional Stefan problem with periodic boundary conditions [15]. The weak or Galerkin formulation of the initial-boundary value problem was used to derive a system of initial value problems in ordinary differential equations by Asaithambi in a one-dimensional Stefan problem [18,19]. Furthermore, the full two-phase Stefan problem was considered by applying a small-time perturbation scheme and by presenting numerical results calculated using an enthalpy method [20]. The method of matched asymptotic expansions and a finite difference scheme based on the enthalpy method were used by Tabakova et al. for the freezing of a supercooled spherical droplet [21].

In this paper, a convenient and feasible technique which combines the numerical calculation and the transformation of dimensionless variables in equations is developed. The purpose of variables transformation is to simplify the moving boundary problem to one with a fixed boundary for the diffusion equation of a sphere. Based on the transformed dimensionless variables and the new boundary conditions, a finite difference method is developed and the result is compared with the iterative analytical series solution [11]. The evolution of the solidification and the temperature profile in the solidified region is also predicted and discussed. In addition, the solidification of different-sized particles with a core of encapsulated paraffin PCM is analyzed in details.

2. The spherical solidification model

As shown in Fig. 1, the radius of the sphere is R^*_{max}. During the solidification stage, the two phases including the liquid and solid coexist in this area. Conduction in solid is the sole transport

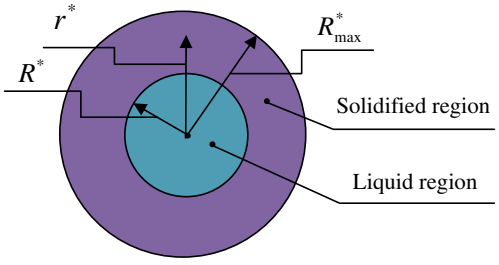

Fig. 1. Inward solidification of a sphere.