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Segregation due to motion of front of solidification in phase change materials systems and dependence with shape and dimension factors

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HIGHLIGHTS

• Additional segregative mechanism for phase change materials.

• Behavior particles into phase change materials.

• Segregation particles low Stokes number.

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ABSTRACT

The present work investigates the segregation of particles due to the motion of front of solidification in phase change materials (PCMs) and its dependence with shape and dimension factors adjustable by design. It is shown that for particle diameters <10 μ m this kind of segregation is the dominant mechanism overcoming the gravitational settling. Utilizing a simplified geometrical model on from the solution of Stephan problem, an analytical expression for the dependence of segregation on such factors was derived. The results show that shape and dimension factors profoundly affect the segregation which implies that the particle segregation can be controlled in great extent through system modeling and design optimization.

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1. Introduction

Solidification of colloidal suspensions is of great importance in phase change materials for thermal energy storage systems [1]. Colloidal suspensions can appear from semi or incongruent melting due to density difference, for example, in salt hydrates the lower hydrate (or anhydrous salt) settles down at the bottom of the container [2]. Also segregation can occurs in colloidal suspensions composed by nanoparticles used for thermal conductivity enhancement [3]. Finally, precipitation of impurities by degradation of materials after several charging/discharging cycles can appears into the PCM. Particle segregation of colloidal suspensions has a large impact on the performance of thermal storage systems since the thermophysical and transport properties, as well as the freezing temperature of the PCMs are

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http://dx.doi.org/10.1016/j.applthermaleng.2014.10.082 1359-4311/© 2014 Elsevier Ltd. All rights reserved. strongly affected by the volume fraction of particles [3,4]. Therefore, it is important to have a deep understanding on particle segregation and factors that substantially affect the particle segregation.

PCM energy storage has received increasing attentions in recent years [5–10]. The particle segregation in PCM colloidal systems during the solidification process has been widely studied analytically and numerically [11–16]. The typical segregation mechanism in literature was based on the concept of critical velocity which was firstly proposed by Uhlmann et al. [11]. Most of the studies were concerned with the interaction of a single particle with the solid--liquid interface which helped to understand the basic physics behind the phenomenon. In order to study the colloidal suspension involving a large number of particles, recently, Peppin et al. [17] developed a continuum-based model and analyzed the solidification process of hard-sphere colloidal suspensions. They obtained the relation for the melting temperature and diffusion coefficient of the suspension that was nonlinear function of the particle volume fraction. The research work was further extended to include a linear stability analysis in order to investigate the parameters that affected







the deformation of the solid–liquid interface [18]. It was found that increasing the volume fraction of the particles and decreasing the particle radius destabilized the interface. Elloitt and Peppin [19] further developed a mathematical model and studied the effect of particle size on segregation coefficient. More recently, El Hasadi [20] numerically investigated the effect of the size of suspensions on the solidification process of the nanoparticle-enhanced phase change materials. It was demonstrated that the particle size largely affected particle segregation. From the above research works, it is found that the particle physical parameters had large effect on the particle segregation. However, the effect of the physical parameters on the particle segregation in the PCM energy storage system has been seldom studied in literature. In particular, the relationship among the segregation mechanism, particle size and energy storage system configuration has never been studied in literature. In this paper, a simplified geometrical model and a deviation from the well-known solution of the Stephan problem are proposed and applied to study the effect of the particle size on the particle segregation at different PCM energy storage system configurations. It provides researchers better understanding on segregation mechanism in colloidal suspensions with different system configurations and useful information in system optimization and simulation.

2. Segregation mechanism

2.1. Behavior of particles at the solidification front

The behavior of a particle at the solidification front has been well-studied [21]. If the solidification front moves with a rate lower than a critical velocity, V_c , the particle is rejected by the solidification front; otherwise, the particle is engulfed by the solidification front as shown in Fig. 1. Based on a large number of experimental data, Li et al. [21] found that the critical velocity for particle engulfing, V_c could be determined by the following expressions:

$$Re_{\rm c} = 1.29 \times 10^{-3} \left[\frac{\overline{F}}{\overline{D}} \right]^{-0.52} Q^{1.70}$$
 (1)

for $D < 100 \ \mu m$; and

$$Re_{\rm c} = 3.98 \times 10^{-29} \left[\frac{\overline{F}}{\overline{D}} \right]^{-3.15 - 1.10 \log Re_{\rm c}} Q^{-11.12}$$
(2)



Fig. 1. Schematic of the behavior of a particle at a solidification front moving from the periphery towards the center of the body. (A) The solidification front approached the particle. (B) If $V < V_c$ the particle is rejected by the solidification front. (C) If $V \approx V_c$ the particle is pushed for a short distance before to be engulfed by the solidification front. (D) If $V > V_c$ the particle is promptly engulfed by the solidification front.

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