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Heat transfer analysis of PCM slurry flow between parallel plates

Hamidreza Shabgard, Han Hu, Philipp A. Boettcher, Matthew McCarthy, Ying Sun *

Department of Mechanical Engineering and Mechanics, Drexel University, Philadelphia, PA 19104, USA

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ABSTRACT

A CFD analysis of melting of solid particles during sedimentation in their own melt is presented. The motion of the solid particles is determined using a Lagrangian approach, while hydrodynamics and heat transfer throughout the fluid are determined using a finite volume scheme. Particle and fluid motions are two-way coupled through moving solid–liquid interfaces, whose morphologies are determined from the local interfacial heat fluxes and tracked using a deforming grid. The accuracy of the model is verified using benchmark solutions of a single particle undergoing simultaneous melting and settling. The results show that the presence of solid-phase particles within the liquid enhances the heat transfer between the bulk fluid and the heating surfaces due to improved mixing, as well as the latent heat associated with phase change. Particle loadings corresponding to solid volume fractions of 3–18% have been considered here, and it is found that the average wall Nusselt number increases linearly with volume fraction. An enhancement in the average wall Nusselt number of 100% as compared to a single-phase flow is achieved using a slurry with 18% solid particles by volume. Initial particle arrangement is found to have a minimal effect on the overall heat transfer. Additionally, for a fixed solid volume fraction, it is found that particle diameter does not strongly influence heat transfer enhancement.

1. Introduction

Solid–liquid phase change materials (PCMs) are characterized by large energy densities that enable them to absorb and release large amounts of thermal energy within a small temperature range. For decades, these features have been of interest in short- and long-term thermal energy storage systems. More recently, a new PCM-based technology has been emerged to improve the thermal performance of heat exchangers by developing two-phase heat transfer fluids comprising PCM particles mixed with a base fluid [1,2]. These two-phase slurries benefit from larger apparent specific heats compared to single-phase fluids and are suitable for transferring large amounts of heat without a dramatic temperature rise [3]. In addition to efficient heat transfer, PCM slurry fluids can also serve as thermal storage medium, thereby eliminating the need for separate heat transfer and storage media in thermal energy storage systems [4].

Optimal design of heat exchangers/thermal storage systems utilizing the PCM slurries requires a thorough understanding of interfacial transport phenomena occurring between the solid and liquid phases of the slurry. While experimental measurements of interphase interactions in particulate flows are challenging, numerical models with different levels of complexity have been developed for the analysis of such systems. Traditionally, volume-averaged Euler–Euler methods have been employed for the analysis of PCM slurry flows [5–9]. In these methods, conservation equations are solved on a fixed grid and appropriate source terms, usually based on semi-empirical correlations, are introduced to account for mass, momentum and energy exchange between phases [8,10]. Recently, direct numerical simulation (DNS) of solid–liquid two-phase flows has gained increasing attention. DNS models do not rely on semi-empirical correlations to determine the interfacial forces and fluxes, rather these quantities are obtained by direct integration at the two-phase interface. Several DNS models have been proposed to investigate particulate flows by using either the fixed-mesh methods (e.g., the phase-field [11,12], level set [13], immersed boundary [14,15] and distributed Lagrange multiplier/fictitious domain methods [16]) or body-conformal mesh methods (e.g., the Arbitrary-Lagrangian–Eulerian (ALE) method) [17,18] to directly solve the Navier–Stokes [15,19,20] equations, as well as by solving the lattice Boltzmann equations [21,22]. Compared to the fixed-mesh methods, body-conformal mesh methods provide higher accuracy in interface representation; however, the higher accuracy comes at the expense of greater computational costs associated with mesh movement and re-meshing the computational domain. With the advancements in parallel computations on

* Corresponding author. Tel.: +1 215 895 1373; fax: +1 215 895 1478.
E-mail address: YSun@coe.drexel.edu (Y. Sun).

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Nomenclature

C_D	drag coefficient
F	force vector
Gr	Grashof number
g	gravitational acceleration vector
H	height of the computational domain
h_{sl}	PCM heat of fusion
i	unit vector in the direction of the gravity
k	thermal conductivity
L	unit length
m	particle mass
Nu	Nusselt Number
n	surface unit normal vector pointing out of the solid particle
p	pressure
Pr	Prandtl number
Re	Reynolds number
r	solid–liquid interface coordinate vector
Ste	Stefan number
T	temperature
T_m	melting temperature of PCM
t	time
u_{ter}	terminal velocity of a settling non-melting particle
V	velocity vector
W	width of the computational domain
x	axis perpendicular to channel wall
y	axis parallel to the channel wall

Greek letters

α	thermal diffusivity of liquid PCM
β	coefficient of thermal expansion
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density

Subscripts

A	Archimedes
ave	average
d	drag
frame	moving frame of the computational domain
i	related to ith particle
l	liquid PCM
p	particle
s	solid PCM
w	wall
0	initial

Superscripts

*	non-dimensional quantity
′	quantity after collision

supercomputers/multi-core processors, this moving-mesh method is expected to become more computationally affordable.

The ALE method was developed to take advantage of the features of both the Lagrangian and Eulerian approaches, while minimizing their limitations [23]. In the ALE method, the mesh motion can be defined in an arbitrary manner with no constraint to follow a fix point of mass or to be fixed in space respectively [20,24]. Such a moving-deforming mesh allows for high-resolution tracking of boundary movements/deformation that is crucial in the analysis of particulate flows. In the ALE method, the movement of the mesh is usually constrained on the boundaries where it has to follow the particles and/or the confining flow boundary. Re-meshing is required to avoid large mesh distortions and data have to be mapped on to the new mesh for consecutive computations [25].

While numerous DNS studies of slurry flows have focused on the hydrodynamic interactions between the solid and fluid phases [26–30], there are only a few studies accounting for heat transfer and phase change effects [31–33]. Gan et al. [31] used a finite element implementation of the ALE method to study melting and sedimentation of one and two cylindrical particles in a vertical channel. Results were presented for instantaneous sedimentation velocity and mass of the particles. It was concluded that sedimentation of melting particles is affected by natural convection of the melt and that while two simultaneously settling particles maintain their circular shape during melting due to rotation, a single particle develops a non-circular surface morphology. Dierich et al. [32] used the implicit fictitious boundary method to simulate the phase change of up to 32 cylindrical ice particles ascending in a closed cavity, where the particles were assumed to remain circular during the phase change process. Three subsequent regimes of particle hydrodynamic were observed: acceleration of particles due to the buoyancy force, followed by a transitional regime and eventually a passive regime, where the solid particles are too small to influence the flow. In addition, a correlation was proposed between the Nusselt number at the surface of a single particle fixed in a hot stream and the Reynolds and Prandtl numbers. In a similar study, Dierich and Nikrityuk [33] analyzed the melting and solidification of 40 circular ice particles during upward motion in hot and subcooled water, respectively. It was found that during melting, the particles tend to move toward the center of the cavity while for solidification no significant displacement from the walls was observed. The effect of particle rotation was also investigated where about 10% increase in melting rate was observed when rotation of particles was accounted for while the solidification rate did not change significantly with and without particle rotation. Deen and Kuipers [34] applied the immersed boundary method to study the heat and mass transfer resulting from exothermal chemical reactions at the surface of stationary particles in a dense fluid-particle system. It was found that the average heat and mass transfer coefficients between the fluid and particles increase with the flow rate through the particle array, and the predictions from the DNS model were found in good agreement with the existing empirical correlations [34].

In addition to the gravity driven particulate flows with direct contact between the fluid and the phase change material (PCM), slurry flows with micro-/nano-encapsulated PCM particles have been investigated extensively [5,9,35–39]. In these studies, the encapsulated PCM slurry flows are often modeled as a homogenous fluid with average thermophysical properties using Eulerian methods on a fixed gird [5–9]. On the other hand, effective specific heat capacity [9] and enthalpy methods [40] have been introduced to account for solid–liquid phase change. In a relevant study, Rao et al. [39] experimentally studied the heat transfer of a micro-encapsulated PCM (MEPCM) slurry flow in minichannels, where *n*-octadecane MEPCM particles of about 5 μm in diameter where suspended in water. Results showed an up to 40% increase in the average Nusselt number at the minichannel wall for 22.3 vol% MEPCM. Kuravi et al. [9] developed a 3D numerical model to study the flow of nano-encapsulated PCM slurry in microchannels. The