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Focusing of phase change microparticles for local heat transfer enhancement in laminar flows

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ABSTRACT

Phase change material (PCM) suspensions have received wide spread attention for increased thermal storage in various thermal systems such as heat sinks for electronics and solar thermal applications. To achieve further heat transfer enhancement, this paper investigates the effect of focusing micron-sized phase-change particles (PCMs) to a layer near the heated wall of a parallel plate channel. A numerical model for fully-developed laminar flow with a constant heat flux applied to one wall is developed. Melting of the focused PCMs is incorporated using a temperature-dependent effective heat capacity. The effect of channel height, height of the focused PCM stream, heat flux, and fluid properties on the peak local *Nusselt* number (Nu^*) and the averaged *Nusselt* number over the melting length (Nu_{melt}) are investigated. Compared to the thermally-developed *Nusselt* number for this geometry ($Nu_o = 5.385$), Nu_{melt} and Nu^* enhancements of 8% and 19% were determined, respectively. The local heat transfer performance is optimized when the PCMs are confined to within 30% of the channel height. The present work provides an extended understanding of local heat transfer characteristics during melting of flowing PCM suspensions, and offers a new method for enhancing heat transfer performance in various thermal-fluidic systems.

1. Introduction

When suspended in a heat transfer fluid, PCMs serve to increase the effective heat capacity of a fluid over a relatively small temperature range as the core undergoes melting (i.e., phase change). Since thermal systems are operated with a limited temperature difference between inlet and outlet, the enhancement of effective heat capacity resulting from the latent heat of fusion increases the energy storage density. Consequently, either thermal performance is improved or the pumping power requirement may be reduced.

Previous studies have developed numerical models to understand the hydrodynamic and heat transfer characteristics of PCM suspensions (i.e., slurries). A review by Dutil et al. focuses on numerical studies modeling convective heat transfer in PCM suspensions with summaries of methods, model validation steps and main contributions [1]: while, Zhang et al. summarizes work addressing material properties and applications of PCM suspensions [2]. Most of the numerical studies model the slurry as a bulk fluid using the effective heat capacity model [3–9] originally introduced by Alisetti et al. [3]. Alternative approaches treat the latent heat as an additional source term representing the absorbed heat during the phase change process in the PCM [10,11], or describe the carrier fluid and the PCM phases using separate conservation equations with appropriate interaction terms [12].

Experiments have also been conducted to evaluate the heat transfer characteristics of PCM suspensions [13–23]; results from forced convection, constant heat flux experiments with suspensions of microencapsulated PCM particles show the effects of the following: Stefan number, PCM mass fraction, flow rate, flow regime, inlet temperature subcooling, and particle size. Thermal performance tends to increase as the mass fraction increases, but the optimal mass fraction balances both the heat transfer enhancement and the pumping power increase [15,16,23]. To improve the effective thermal conductivity of slurries, investigators have studied hybrid suspensions of alumina nanoparticles and PCMs [21,22]; however, experiments showed that the viscosity of hybrid suspensions is anomalously high, exceeding enhancements in heat transfer.

Although previous work has focused on enhancing overall thermal performance using PCM suspension fluids, certain studies have also considered the effects of PCM suspensions on the local heat transfer characteristics. Local heat transfer coefficient variations along the axial direction (h_x) have been reported using both

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Nomenclature

c_p	heat capacity [J/kg K]
d_p	particle diameter [m]
D_h	hydraulic diameter (2H for parallel plates) [m]
D_B	Brownian diffusion coefficient [m^2/s]
h_{sf}	latent heat of PCMs [kJ/kg]
H	channel height [m or mm]
k	thermal conductivity [W/m K]
L_{th}	thermal entrance length [m]
$\dot{m}$	mass flow rate [kg/s]
ML	dimensionless initial subcooling: $(T^{-} - T_i)/\Delta T_o$ [-]
Mr	dimensionless melting temperature range: $\Delta T_{melt}/\Delta T_o$ [–]
Nu	*Nusselt* number [–]
P	pressure [Pa]
Pe	*Peclet* number: UD_h/α [–]
q''	heat flux [W/m^2]
Re	*Reynolds* number: $\rho UD_h/\mu$ [–]
Ste	*Stefan* number: $\frac{c_{p,f}}{\omega h_{sf}/\Delta T_o}$ [–]
Ste_m	modified *Stefan* number: $\frac{c_{p,f}}{\omega h_{sf}/\Delta T_{melt}}$ [–]
T	temperature [K]
t	time [s]
u	local velocity [m/s]
U	mean fluid velocity [m/s]
x, y	coordinates [m]
x^*	dimensionless position: x/D_hPe [–]

Greek Symbols

α	thermal diffusivity $(k/\rho c_p)$ [m^2/s]
δ	height of the phase-change stream [m]
δ_B	PCM Brownian diffusion distance [m]
μ	viscosity [Pa s]
ρ	density [kg/m^3]
ϕ	PCM-particle volume fraction [–]
ω	PCM-particle mass fraction: $\rho_p\ \phi\ /\ \rho_{eff}$ [–]

Superscript

$*$	local maximum
min	minimum
-	onset of melting
+	end of melting

Subscripts

b	bulk
δ	pertaining to phase-change stream
eff	effective property of PCM suspension
f	fluid medium
i	inlet
melt	averaged over PCM melt region
o	thermally-developed
p	particle (outside of melt region)
w	heated wall
x	local

numerical models [8,9] and in experiments [17–19]. Sabbah et al. showed that h_x increases when the melting interface is near the heated wall and decreases when the interface moves toward the tube center [9]. Meanwhile, Zeng et al. investigated the effects of the *Stefan* number (*Ste*), the PCM melting range (*Mr*), the flow rate, and the particle diameter on the local heat transfer characteristics; the amplitude of the h_x variation was observed to increase with decreasing *Ste* and decreasing *Mr*, which were the dominant parameters in the study. Furthermore, Wang et al. demonstrated local heat transfer enhancements as high as 60% compared to the basefluid and suggested a heat transfer correlation to predict the average heat transfer coefficient during PCM melting [18,19]. The effects of PCMs on local heat transfer, however, have not been investigated in detail beyond these studies. In particular, understanding the influence of the distribution of PCM particles inside the channel and how it can be used to achieve further heat transfer enhancements was not considered in previous work.

In this paper, we investigated the effect of focusing micron-sized PCMs to a layer near the heated wall on local heat transfer coefficient. Various techniques have been used to focus, separate and sort microparticles demonstrating the feasibility of the proposed concept, including: pinched flows (e.g. [24]), where flow asymmetries are used to separate particles; inertial focusing, where particles migrate away from the channel center and walls generating continuous particle streams due to inertial lift forces (e.g. [25]); magnetophoresis (e.g. [26]), where magnetic particles are manipulated using an externally applied magnetic field; and acoustophoresis (e.g. [27]), where particles are driven towards minima of an acoustic force field acting perpendicular to the flow direction due to density and compressibility contrast compared with the basefluid. The effect of focusing particles on heat transfer, however, has not been investigated. A numerical model is developed which assumes fully-developed laminar flow and a constant heat flux applied to one wall. Melting of the focused phase-change particles is incorporated in the model using a temperature-dependent effective heat capacity. Using near-wall PCM focusing, we report increases in the averaged and peak *Nusselt* numbers.

2. Model Formulation

We developed a two-dimensional model (*x,y*) of laminar flow between parallel plates to investigate the effect of focusing PCMs near a heated wall. Constant heat flux (q'') is applied to the bottom wall, while the top wall is adiabatic. As shown in Fig. 1, PCMs are confined to a layer near the bottom wall (δ) which is a fraction of the total channel height (H). Pure fluid and PCM streams are introduced upstream such that the flow is assumed to be hydrodynamically fully-developed by the time it reaches the heated region. The inlet temperature is uniform and well below the onset of melting (i.e., $ML >> 1$). Melting of the PCMs in the phase-change stream is modeled using a temperature-dependent effective heat capacity.

In modeling this system, we make the following simplifications in order to focus on the effect of the PCMs:

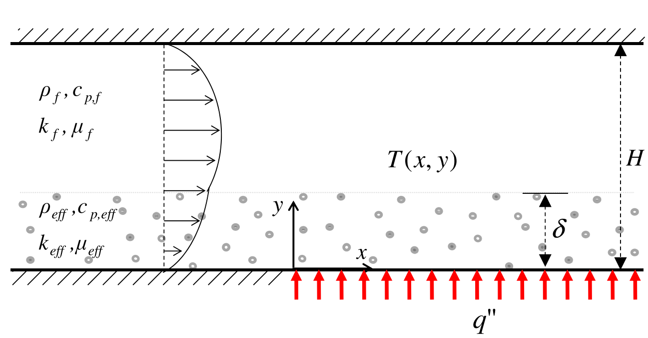

Fig. 1. Schematic for model formulation of a 2-D parallel plate channel with fully-developed flow and PCMs confined to a layer (δ) near the heated bottom wall.