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Modeling the heat transfer characteristics of flow melting of phase change material slurries in the circular tubes

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ABSTRACT

The heat transfer characteristics of phase change material slurries, e.g. tetra-*n*-butyl ammonium bromide (TBAB) clathrate hydrate slurry (CHS) and microencapsulated phase change material (MPCM) slurry, flowing through the heated circular tubes under constant heat flux are investigated in the present paper. The continuity equation, momentum and energy equations for the phase change material slurry in tubes are solved to obtain the variation of the temperature of the phase change material slurry with time and along the flow direction. The temperature variation of TBAB CHS can be divided into two regions, while there are three regions for MPCM slurry due to the existence of supercooling state. The comparison between the calculated and measured results reveals that MPCM slurry is possibly not fully melted during the flow melting, leading to a shorter melting region and higher outlet temperature than those of calculated values based on the heat balance equations.

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1. Introduction

The investigations of the solid–liquid phase change material slurries attracted intensive attentions in recent years. The involved latent heat during phase change process and the yet-good fluidity make the phase change material slurry possibly to serve as dual-functional medium for high-density cold energy storage and transport. Ice slurry [1,2] is a conventional phase change material slurry which has been investigated and applied widely over the world. Its excellent cooling and transporting features enable it can be used in many fields, such as the building cooling, supermarket display cabinet, food industry, brewery, mine cooling and so on. Phase change material in microencapsulated phase change material (MPCM) slurry [3,4] is coated by a thin shell, e.g. natural or synthesized polymer, then the agglomeration of PCM particles is avoided, and the shell provides a protective structure element which improves the mechanical stability, hence the core phase change material can change the volume frequently as phase change occurs. Tetra-*n*-butyl ammonium bromide (TBAB) clathrate hydrate slurry (CHS) [3,5,6] is a new phase change material slurry which attracts more and more attentions in recent years and is considered as promising for applications. The adjustable freezing point between 0 and 12 °C based on the initial aqueous solution concentration makes it suitable to the air conditioning utilization, and its cold carrying capacity is high and the fluidity is also good.

The characteristics of the forced convective heat transfer of phase change material slurry are apparently important for its application, and it is commonly believed that the phase change process results in a higher heat transfer coefficient, since the temperature is nearly maintained constant during the phase change. Apparently, the temperature evolution of phase change material slurry either along the heated tube or further inside the heat exchangers is important and valuable, which is a straightforward parameter to evaluate the performance of phase change material slurry. The effect of the latent heat and the corresponding dominant region can be apparently understood from the temperature profile, and then the working conditions of the slurry, e.g. flow rate and slurry fraction, can be adjusted to achieve a better utilization. However, it is difficult to obtain accurate temperature variation of the phase change material slurry, since the thermo-hydraulic phenomena associated with the flow melting of the phase change material slurry is very complicated, for examples, the solid–liquid two-phase, probable non-Newtonian fluidity, phase change, and etc. Up to now, only a few studies [7–14] reported the temperature variation characteristics of the phase change material slurry in flow melting. Choi et al. [7] argued that the temperature variation of phase change material slurry could be divided into three regions, and the so-called three-region model was developed by the authors to calculate the temperature. Yamagishi et al. [8] calculated the temperature variation of MPCM slurry using the three-region model, however, there were discrepancies between the calculated results and the measured results in both the laminar and turbulent flow states. Wang et al. [9] also adopted the three-region model to estimate the temperature of MPCM slurry in

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Nomenclature

A	area (m^2)
c_p	heat capacity ($J\ kg^{-1}\ K^{-1}$)
D	diameter (m)
K	fluid consistency coefficient (–)
h	enthalpy ($J\ kg^{-1}$)
ΔH	latent heat ($J\ kg^{-1}$)
L	length (m)
n	flow behavior index (–)
P	pressure (Pa)
q	heat flux ($W\ m^{-2}$)
q''	volume heat flux ($W\ m^{-3}$)
Q	heating power (W)
Re	Reynolds number (–)
t	time (s)
T	temperature (K)
u	velocity ($m\ s^{-1}$)
x	distance (m)

Greeks symbols

ρ	density ($kg\ m^{-3}$)
λ	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
ω	mass fraction (–)
φ	volume fraction (–)
μ	viscosity (Pa s)
τ	shear stress (Pa)
$\dot{\gamma}$	shear rate (s^{-1})

Subscripts

0	inlet
E	next control-volume
L	liquid state
liq	liquid
P	present control-volume
PW	average value of P and W
p	particle
TP	two-phase
S	solid state
W	previous control-volume

heated tube, and the results were used to calculate the local heat transfer coefficient. Sabbah [11] reported the experimental results of the temperature variation of MPCM slurry and also developed the theoretical models to predict the variation of the slurry temperature, but the theoretical results underestimated the measured values. However, unlike MPCM slurry, TBAB CHS showed different heat transfer characteristics, for example, it was reported by Ma et al. [12] that the temperature of TBAB CHS flowing through heated tube clearly showed two-region feature. Moreover, Hu and Zhang [13] and Zeng et al. [14] investigated the heat transfer of MPCM slurry in heated tubes and obtained the dimensionless wall temperature and slurry temperature to understand the heat transfer characteristics.

To achieve better understanding of the temperature evolution of flow melting of phase change material slurries and to further characterize the flow melting heat transfer, the present paper proposed a simple but effective theoretical modeling of the slurries, including MPCM slurry and TBAB CHS flowing through the heated circular tubes in the laminar flow region. The calculated and measured slurry temperatures were compared, and the heat transfer characteristics of the slurries in flowing melting were discussed based on the temperature variation in order to promote the fundamental understanding of phase change material slurries as well as their applications.

2. Theoretical model and numerical method

In order to understand the heat transfer characteristics of flow melting of phase change material slurry in tubes, a numerical model is developed to elucidate the problem. The physical configuration of the concerned heat transfer problem is schematically shown in Fig. 1. As shown in the figure, the outer surface of the circular tube with the inner diameter of D_i is exposed to a constant uniform heat flux, q (=Q/A), within a certain length, L_h. The upstream of the heated tube with a length of L_u is sufficient long to ensure a fully developed flow in the tube, and the length of downstream tube is L_d. Both the upstream and downstream tubes are thermally insulated.

In order to simplify the numerical analysis, the following assumptions are made to the physical model:

(1) The solid–liquid two-phase slurry is homogeneous and is treated as a single-phase fluid with phase change capacity.
(2) The fluid is incompressible, and the flow is steady and laminar.
(3) The flow is horizontal and the effect of gravity is neglected.
(4) Local thermal equilibrium is reached in the flow melting of phase change material slurry.

Based on the above mentioned assumptions, the governing equations, including the continuity equation, the momentum and energy equations, for the concerned problem can be formulated as:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} = 0 \tag{1}$$

$$\frac{\partial \rho u}{\partial t} + \frac{\partial \rho u u}{\partial x} = -\frac{dP}{dx} + \mu \frac{\partial^2 u}{\partial x^2} \tag{2}$$

$$\frac{\partial \rho h}{\partial t} + \frac{\partial \rho u h}{\partial x} = \lambda \frac{\partial^2 T}{\partial x^2} + q'' \tag{3}$$

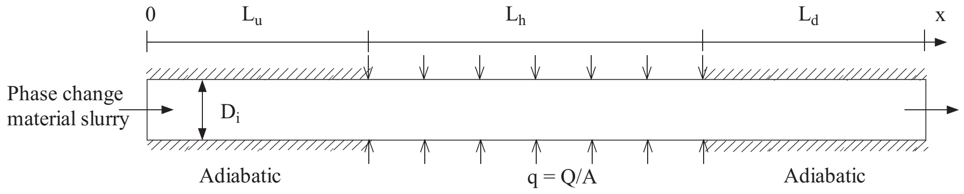

Fig. 1. Schematic diagram of the physical configuration of phase change material slurry flowing through heated tube.

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