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Research Paper

Numerical evaluation on the flow and heat transfer characteristics of microencapsulated phase change slurry flowing in a circular tube

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HIGHLIGHTS

- The flow and thermal characteristics of microencapsulated phase change slurry is evaluated.
- The factors that influence the heat transfer of microencapsulated phase change slurry are discussed.
- The temperature contour of the actual two phase flow is presented.
- The local heat transfer coefficient reaches 21.7–22.4 kW/m^2 K in the melted region.

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ABSTRACT

In order to alleviate the peak–valley difference of the energy supply load, thermal energy storage techniques have become the promising way. Microencapsulated phase change material slurry (MPCS) is a newly–developed tool to achieve high energy storage efficiency and charge/discharge efficiency due to its large thermal energy density and good heat transfer performance. In the present work, it was numerically investigated that the flow and heat transfer characteristics of MPCS in a horizontal circular pipe under constant heat flux on the pipe wall. It was found that the higher inlet velocity, smaller piping size, higher latent heat capacity, lower fluid viscosity and larger heat flux resulted in higher heat transfer coefficient. For the case under the conditions of $v_{inlet} = 0.5$ m/s, $c_m = 10$ wt%, $q = 200$ kW/m^2, $T_{inlet} = 300$ K, $D = 10$ mm and $d = 20$ μm, the local heat transfer coefficient of the heat collecting pipe reached 25.2 kW/m^2 K in the flow inlet region, remained within the range of 21.7–22.4 kW/m^2 K in the melted region and dropped to 20.15 kW/m^2 K in the outlet region. Finally, temperature field of MPCS was presented to analyze its superiority on heat transfer performance, indicating the reduction of the temperature difference between the wall and the fluid during heat transfer process was about 39% smaller than that of water.

1. Introduction

Latent heat is a major aspect of thermal energy storage due to its large capacity and availability. Based on it, phase change materials (PCM) has long been investigated. However, the leakage, the instability and supercooling problems had become the limitation of its application and working efficiency. Amount of studies had been done to alleviate these limits. The leakage problem can be solved by shape stabilization methods [1]. The functional additives had been explored on their nucleation promotion, thermal conductivity enhancement and some other positive influences [2]. In recent 20 years, microencapsulated phase change materials (MPCM) have been brought out to nearly overcome these defects at one time. A layer of thin polymer/inorganic compact film which can reduce the exposure of PCM and increase the stability of PCM was microencapsulated on the granulated conventional phase change materials, and has been widely put into practical applications [3]. Recently, many studied have been done considering the MPCM working as thermal substance for specific solar energy applications. Zheng et al. [4] used it in a cold storage/transportation system with solar driven cooling cycle. Liu et al. [5] prepared a novel MPCM with CdS/SiO_2 double-layered shell for solar photocatalysis and solar thermal energy storage. Javed et al. [6] applied MPCM in concrete tiles for collection solar energy.

MPCM owns an additional advantage by its dispersion into common carrying fluid to form the microencapsulated phase change slurry (MPCS). MPCS can be used as both the energy storage medium and the heat transfer fluid with good heat transfer performance. As a result, MPCS can find a broad application in energy conservation of

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Nomenclature

A	the surface area per unit volume in Eq. (7)
c	concentration ratio
C	specific heat capacity, kJ/kg·K
d	diameter of the MPCM particles, µm
D	diameter of the pipe, m
f	friction factor
h	convection heat transfer coefficient, W/(m^2·K)
H	enthalpy, kJ
k	thermal conductivity, W/(m·K)
l	the interfacial length scale in Eq. (7)
L	length of the pipe, m
LH	latent heat, kJ/kg
p	pressure, N/m^2
P	pumping power, W
q	heat flux, W/m^2
Re	Reynolds number
T	Temperature, °C
v	velocity of axial direction, m/s
w	pipe wall

Greek letters

$\gamma\alpha$	thermal diffusion coefficient, m^2/s
$\gamma\rho$	density, kg/m^3
$\gamma\mu$	dynamic viscosity, N·s/m^2

Subscripts

1, 2, *l*	phase 1, 2 and *l*
Ste = 1.0b	bulk
Ste = 1.0c	core material
Ste = 1.0f	fluid
m	mass
melt	MPCM melting point
MPCM	microencapsulated phase change material
MPCS	microencapsulated phase change suspension
p	microencapsulated particle
PCS	phase change suspension
s	MPCM shell material
v	volume

refrigerators, heat pump and air–condition, etc. [7].

To qualify a type of MPCS, there are several aspects for main concern: heat capacity, flow characteristic and heat transfer ability. The PCM core materials used by the former MPCS works were mainly the common paraffin, alkanes, alcohols, acids and their eutectics, owning the latent heat within about 80–260 kJ/kg, the specific heat within about 1.4–2.5 kJ/kg·K and the phase change temperature within about 9–70 °C [8]. Heat capacity is mainly limited by the material itself, to select the PCMS, the high heat capacity and proper working temperature are both supposed to be considered.

The favorable heat transfer ability are attributed by the thermal conductivity of fluid and dispersed material and flow characteristics. For the phase change fluid, the phase change behavior including the supcooling phenomenon and nucleation behavior are also significant. On the other hand, flow characteristics are the major concern in the pumping problem. Therefore, the flow and heat transfer characteristics are mostly investigated at the same time in the researches.

The MPCM is composed by the phase change core material and protective shell. The core material can be organic, inorganic, their composites or eutectic, and the shell material can be organic polymer, mineral crystal or metallic oxide [9]. The process improved the particle smoothness of the primary PCM slurry as proved in Ref. [10]. And the viscoelastic properties of MPCM are inversely proportional to the weight fraction of microencapsulated fillers as proved by Yoo [11]. These factors influence the MPCS fluid flow characteristics, bringing the acceptable fluidity. Serale et al. [12] presented a type of MPCS, whose viscosity is similar to that of water, and as a result, they can be pumped easily. Normally, the microcapsules dispersed in the carrying fluid results in the larger viscosity, stronger heat capacity, and smaller light transmittance. As a result, this MPCS based thermal and power system is superior to the conventional systems in heat transfer [13]. For applications, Zhang and Niu [14] used it in a nocturnal radiative cooling system. The results showed the energy saving potential in Lanzhou and Urumqi can reach 77% and 62% for low–rise buildings, which exhibits strong attractions for building energy conservation and emission reduction.

Numerous experimental investigations have been presented on the heat capacity, heat transfer and flow characteristics of the MPCM suspension. Giro–Paloma et al. [15] did a research on the physicochemical and thermal properties on the MPCM slurries. The results showed this type of fluid is totally capable of being used in the thermal energy storage field, qualified to be a PCM candidate for application in active building applications. Chen et al. [16] experimentally studied the heat transfer characteristics for laminar flow in a circular tube with constant heat flux. The temperature decrease can be up to 30% for the 15.8 wt% MPCM suspension instead of water. Zhang et al. [17] evaluated natural convection heat transfer characteristics of MPCS during phase change process in a rectangular heat storage tank. The experimental results indicate that phase change process of the MPCMS promote natural convection heat transfer. Fu et al. [18] introduced the Tet@PS–SiO$_2$ slurry, which had a high specific heat capacity and obtained an enhancement 8.4% in thermal conductivity by the grafting of SiO$_2$ on the PS shell. In addition, the slurry showed an acceptable viscosity and excellent mechanical stability. Chen et al. [19] built a PEMFC platform to test the cooling capacity of the MPCS. The results showed that the use of MPCS saves the weight and volume of coolant and the power consumption of the pump. Wang et al. [20] experimentally determined the dependence of the specific heat, phase change enthalpy, rheological behavior and thermal conductivity of such fluids on the concentration and temperature. The results showed that the natural convection process can be characterized by three regimes: the pure conduction, the quasi–steady and the decay period.

As for theoretical studies, Charunyakorn et al. [21] developed a temperature transforming model to solve the phase change problem and used the heat source term to characterize the thermal resistance between the microcapsule crust and the working fluid. Their calculation results showed that the bulk Stefan number and volumetric concentration are the two crucial factors on the heat transfer of the MPCM suspension. The Nusselt number for the MPCS was 1.5–3 times higher than that of single phase fluid. Moreover, Goel et al. [22] decided the influence of the particle–duct diameter ratio, Reynolds number and the degree of homogeneity of the suspension on the MPCS thermal behavior. In another studied topic, Bai and Lu [23] combined the finite difference method with the dual reciprocity boundary element method to simulate the heat transfer process of MPCS. Hao and Tao [24] proposed a model that considered the effects including separate and coupled thermal diffusion, convection, inter-particle interaction and phase change effects of liquid–particle two–phase flow on the MPCS thermo–physical behavior. Furthermore, Rao et al. [25] used the molecular dynamics simulation to study the melting mechanism of MPCM. Languri et al. [26] studied the MPCS through a heated helically coiled heat exchanger. Analysis of the numerical and analytical results revealed that the radius of curvature of the helically coiled heat exchanger have a direct effect on velocity profile and heat transfer rate of MPCMs flows.