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Conjugated heat and mass transfer during flow melting of a phase change material slurry in pipes

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ABSTRACT

PCS (phase change materials slurries) are very useful for thermal energy storage. TBAB (tetra-n-butyl ammonium bromide) CHS (clathrate hydrate slurry) is a promising PCS, which is composed of TBAB hydrate crystal and TBAB aqueous solution. In the present study, the flow melting characteristics of TBAB CHS through pipes were numerically investigated. The solid–liquid two-phase nature of TBAB CHS was numerically investigated using the Eulerian–Eulerian multiphase model. And the interphase heat and mass exchange between TBAB hydrate crystals and TBAB aqueous solution was numerically modeled by considering the phase change phenomenon. Moreover, the diffusion of TBAB salt (solute) in TBAB aqueous solution was also numerically investigated. The numerical results showed that the liquid temperature increased more quickly than the solid temperature because of the latent heat involved. Moreover, the local heat transfer coefficient decreased in the thermally fully-developed region because of the increasing temperature difference between the wall and fluid. When the solid particles were almost fully melted, the fluid temperature increased more quickly than the wall temperature due to the absence of phase change, resulting in the increase of the local heat transfer coefficient.

1. Introduction

In recent years, the energy and environment issues attract intensive attention. In total energy consumption, the electricity consumed by the refrigeration and air-conditioning system accounts for a large proportion, in particular during summer time. Meanwhile, the emission of the conventional refrigerants like CFCs and HCFCs induces many environment issues, such as ozone layer depletion. In order to alleviate the aforementioned issues, the secondary-loop refrigeration and air-conditioning system incorporated with cold storage is considered as a promising solution [1]. In the secondary-loop refrigeration and air-conditioning system, the charging amount of environmentally harmful refrigerant can be reduced significantly because the cold energy can be carried by the secondary refrigerant. In addition, in order to adjust the time-discrepancy between the power supply and demand, the cold storage technology can shift the peak electricity load to off-peak time, resulting in more effective energy utilization [2].

The cold storage in a secondary-loop air-conditioning system is commonly implemented through sensible heat storage and latent heat storage. In the first method, water is commonly used as the cold storage medium due to its easy implementation and low cost. In the second method, the cold storage is commonly implemented by using the PCS (phase change materials slurries), whose cold storage capacity is much larger than that of the water due to the phase change involved. The most commonly used PCS is ice slurry, which is composed of ice particles and water. However, the generation of ice slurry requires subzero temperature due to the existence of supercooling phenomenon. Therefore, the cold charging process of cold storage air-conditioning system using ice slurry is energy-intensive because of the subzero freezing temperature, which limits its practical application [3].

In recent years, a promising PCS, TBAB (tetra-n-butyl ammonium bromide) CHS (clathrate hydrate slurry), has been subjected to intensive investigation. Oyama et al. [4] investigated the fundamental thermo-physical properties of TBAB CHS and they found that the phase-change temperature of TBAB hydrate crystal was in the range of 0–12 °C, which was more suitable for the cold storage air-conditioning system than that of ice slurry. And the cold storage capacity of TBAB CHS was about 2–4 times of that of chilled

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Nomenclature

A	thermal conductivity ratio of liquid phase to solid phase
B	modified volume fraction ratio of solid phase to liquid phase
c_p	specific heat, J kg^{-1} K^{-1}
C	mass concentration of TBAB aqueous solution, wt%
C_D	drag force coefficient
C_L	lift force coefficient
C_{TD}	turbulent dispersion force coefficient
d_s	solid particle diameter, m
D_{pipe}	pipe diameter, m
e_{ss}	particle–particle restitution coefficient
e_{sw}	particle-wall restitution coefficient
$\boldsymbol{F}$	force, N
g	gravity acceleration, m s^{-2}
g_0	radial distribution function
h	heat transfer coefficient, W m^{-2} K^{-1}
H	enthalpy, J kg^{-1}
ΔH	latent heat, J kg^{-1}
$\boldsymbol{I}$	unit vector
k_{θ_s}	diffusion coefficient
K	auxiliary parameter
L	distance from the pipe wall, m
$\dot{m}$	mass transfer rate, kg m^{-3} s^{-1}
M	molar mass, g mol^{-1}
n	hydration number
P	pressure, Pa
Pr	Prandtl number
$\dot{q}$	heat flux, W m^{-2}
Re	Reynolds number
s	ratio of distance to radius
U	mean velocity, m s^{-1}
v	velocity, m s^{-1}
T	temperature, K
Z	auxiliary parameter

Greek letters

γ_{sl}	momentum exchange coefficient
δ_{sl}	energy exchange coefficient
ζ	bulk viscosity, mPas
Θ_s	granular temperature, K
λ	thermal conductivity, W m^{-1} K^{-1}
μ	viscosity, mPas
ρ	density, kg m^{-3}
σ_{sl}	dispersion Prandtl number
Γ	diffusion coefficient, m^2 s^{-1}
$\boldsymbol{\tau}$	shear stress, Pa
ϕ	volume fraction, vol%
ϑ	specularity coefficient
ψ_{θ_s}	collisional dissipation of energy, kg m^{-1} s^{-3}
ω	mass concentration, wt%

Subscripts

f	fluid
in	inlet
l	liquid
loc	local
m	mean
s	solid
w	wall

water due to large latent heat of TBAB hydrate crystal. Moreover, TBAB CHS had good fluidity because the diameter of TBAB hydrate crystals was only about 0.2–0.5 mm, which was beneficial for the pumping of TBAB CHS as secondary refrigerant.

During the cold release process, TBAB CHS is pumped from the storage tank to the user side and is melted to release cold energy on the user side. Therefore, the pressure drop and flow pattern of PCS are key factors for the application of the secondary refrigerant because the pressure drop determines the pumping power consumption and the flow pattern is closely relevant to the cold release as well as pressure drop. Moreover, the heat transfer coefficient of PCS during the cold release process dominates the performance of the secondary-loop air-conditioning system used in the buildings. Therefore, the knowledge of the flow and heat transfer characteristics of TBAB CHS during the flow melting process is essential for its application in the secondary-loop air-conditioning systems. So far, many investigations have been carried out to understand the flow and heat transfer characteristics of TBAB CHS. Darbouret et al. [5] measured the pressure drops of TBAB CHS and they concluded that TBAB CHS exhibited Bingham fluid behavior in laminar flow region. Kumano et al. [6] reported the flow and heat transfer characteristics of TBAB CHS in horizontal circular pipes under a constant wall heat flux of 5000 W m^{-2}, and the heat transfer coefficient was obtained by measuring the wall temperature and fluid temperature. However, the heat flux was so small that few solid particles were postulated to be melted along the flow direction. Ma et al. [7] investigated the flow and heat transfer characteristics of TBAB CHS in circular tubes with the diameters of 6.0 mm and 14.0 mm under constant heat flux within 29,190–58,500 W m^{-2}. They reported the local heat transfer coefficient along the flow direction by measuring the wall temperature and estimating the fluid temperature numerically. Zhang and Ye [8] also carried out investigation on the forced flow and heat transfer characteristics of TBAB CHS in mini-tubes with the diameters of 2.0 mm and 4.5 mm under constant wall heat flux within 22,121–34,607 W m^{-2}. They reported the local heat transfer coefficient along the flow direction using the energy balance approach, and it was reported that type B TBAB CHS was more beneficial to be used as the cold storage and transport medium because of smaller pressure drop and larger heat transfer coefficient. Due to the two-phase nature of TBAB CHS, the phase distribution and temperature distribution are important to obtain comprehensive knowledge on the interphase heat and mass transfer mechanism. However, to the best knowledge of the authors, the local solid fraction distribution and the local temperature distributions of solid and liquid phases during the flow melting process have not been reported because of the experimental difficulty. Hence, more efforts are need to be devoted to the investigation of the interphase heat and mass transfer mechanism of TBAB CHS.

In view of the aforementioned technical difficulties in experimental investigation, CFD (computational fluid dynamics) is a promising way to obtain comprehensive knowledge on the flow and heat transfer characteristics of TBAB CHS. The solid–liquid two-phase flow is mainly modeled by the Eulerian-Lagrangian and Eulerian–Eulerian approaches. The former approach assumes the liquid phase to be a continuum and track the solid particles through the flow field. However, such approach ignores the collision interaction among solid particles, which has massive influence on the