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Experimental investigation of forced flow and heat transfer characteristics of phase change material slurries in mini-tubes

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ABSTRACT

Phase change material slurry can be used for thermal and cold storages, where the flow and heat transfer characteristics are very important and necessary for the design and construction of secondary-loop refrigeration and air conditioning so as to realize peak-load shifting and operation cost reduction. In the present study, two types of phase change material slurries: types A and B TBAB CHS (Tetra-n-butyl Ammonium Bromide clathrate hydrate slurry) were generated, and the forced flow and heat transfer characteristics in mini-tubes with 2.0 mm and 4.5 mm in diameters were experimentally investigated with solid fraction of 0–20.0 wt%. Flow behavior index and fluid consistency coefficient were obtained by considering TBAB CHS as a power-law fluid, where the tube diameter and solid fraction affected the fluidity of TBAB CHS. It has been clarified that the pressure drop of type B TBAB CHS was smaller than that of type A TBAB CHS. The main influential factors on the heat transfer characteristic of TBAB CHS were identified, and the heat transfer correlations for flow melting of both types A and B TBAB CHS were developed on the basis of the experimental data. The experimental results showed that the homogeneous model could depict flow melting of TBAB CHS in mini-tube more reasonably than that in large tube. The local heat transfer coefficient of type B TBAB CHS was larger than that of type A TBAB CHS under the similar thermal conditions, which implied that type B TBAB CHS was more favorable to be used as the secondary refrigerant.

1. Introduction

In recent years, environment protection and energy conservation have become two global issues with the development of the economy and human society. In total energy consumption, the percentage of energy consumed by air conditioning increases drastically, and meanwhile, the wide use of the traditional refrigerants like HCFCs and CFCs causes environmental concerns, such as ozone layer depletion [1]. It is a common problem that the difference between the peak-load and off-peak load of the electricity is very large, for example, the difference of the peak-valley electricity load was about 12.0 MkW in the summer of the year of 2013 in Shanghai, which accounted for about more than 40.0% of the peak load. Such tremendous variation of the electricity load over one day will apparently cause big threat to the safety of the electric grid as well as the reduction of the energy efficiency. Therefore, to reduce such large difference of peak-valley electricity load is very important, which promotes the development of the thermal energy storage for refrigeration and air-conditioning. Thermal energy storage is one of the effective methods to reduce the peak demand for electricity [2] because it can convert the electricity into thermal energy and balance the mismatch between the supply and demand [3]. The shaving of the peak electricity load can be realized by air conditioning systems incorporated with thermal energy storage facilities, which can reduce the energy consumption and bring the remarkable economic benefits as well. Apparently, the energy storage medium plays an important role in such systems. Taking the cold storage as an example, ice storage can be used to store the cold energy at the off-peak time and the secondary refrigerants are used to transport cold energy to the individual terminal users at peak time. However, the traditionally-used secondary refrigerants such as water and glycol aqueous solution are hampered by their small cold-carrying capacities because of their single-phase features, which results in very large pumping power consumption.

There are many kinds of two-phase phase change material slurries which can be used as the energy storage and transportation media, such as ice slurry, micro-phase change emulsion, microencapsulated phase change material slurry (MPCS) and clathrate hydrate slurry (CHS). In recent years, MPCS and CHS have been subjected to intensive investigation. Because of the presence of

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Nomenclature

c_p	specific heat (kJ kg^{-1} K^{-1})
D	diameter (m)
f_F	Fanning friction factor (–)
G	mass flow rate (kg s^{-1})
h	heat transfer coefficient (W m^{-2} K^{-1})
ΔH	enthalpy change (kJ kg^{-1})
K, K'	fluid consistency coefficient (–)
L, l	length (m)
n	flow behavior index (–)
Nu	Nusselt number (–)
ΔP	pressure drop (Pa)
Pr	Prandtl number (–)
q	heat flux (W m^{-2})
Q	heating power (W)
Re	Reynolds number (–)
$\mathrm{Re}_{\mathrm{MR}}$	modified Reynolds number (–)
S	area (m^2)
Ste	Stefan number (–)
t	time (s)
T	temperature (K)
u	flow velocity (m s^{-1})
$\dot{V}$	volume flow rate (m^3 s^{-1})
x	distance from the entrance (m)

Greek letters

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

Subscripts

0	initial
cal	calculated
CHS	clathrate hydrate slurry
f	fluid
hyd	hydrate
i	inner
liq	liquid
local	local
mea	measured
N	Newtonian
o	outer
p	particle
s	saturated
sol	solution
ss	stainless steel
tra	transitional
w	wall

solid–liquid phase change in energy storage and release processes, the energy storage densities of MPCS and CHS are much larger than that of single-phase fluid. Thus, the space required for energy storage and flow rate in transportation are both reduced, which can therefore reduce the pumping power consumption. Meanwhile, compared with other slurries, the phase change temperatures of these two kinds of slurries can be modulated to fit the temperature range of air conditioning application better by using different phase change materials or guest materials in different temperature ranges, respectively. It is obvious that the flow and heat transfer characteristics of such phase change material slurries need further investigation in order to provide the fundamental understanding for the design and construction of the energy storage systems.

So far, flow and heat transfer characteristics of MPCS have been widely investigated [4,5], while those of CHS have not been well understood. The typical example of CHS is Tetra-n-butyl Ammonium Bromide (TBAB) clathrate hydrate slurry (CHS). Since the phase change temperature of TBAB CHS can be around 5–12 °C [6], where the cold-carrying capacity of TBAB CHS is about 2–4 times larger than that of the chilled water. Fowler et al. [7] first reported the tetraalkylammonium salts with simple anions, for example, halides, formate and sulfate, could form clathrate hydrate under atmospheric pressure. Lorsch et al. [8] have ever summarized the melting points and latent heats of fusion of the semi-clathrates of several tetrabutylammonium salts in the early 1970s. Fukushima et al. [9] explicitly proposed to apply TBAB CHS to cold storage and cold carrying. Afterwards, the investigation of TBAB CHS gradually attracted intensive attention. However, the investigation of the flow and heat transfer characteristics of TBAB CHS is still very limited so far. The fluidity of TBAB CHS is very different from that of the single-phase fluid because of its solid–liquid two-phase nature. Darbouret et al. [10] reported that TBAB CHS behaved as a Bingham fluid and the corresponding yield stress and apparent viscosity depended on the volume fractions of TBAB CHS. Hayashi et al. [11] measured the flow characteristics of TBAB CHS flowing in tubes with 27.6 mm and 52.9 mm inner diameters, and the power-law fluidity was applied to describe the experimental results. Kumano et al. [12,13] analyzed the flow and forced convective heat transfer of TBAB CHS in straight tubes with different diameters, solid fractions and flow rates. The effects of the hydrate types on the flow and heat transfer characteristics were reported. By analyzing the experimental results, it was reported that TBAB CHS could be treated as pseudo-plastic fluid. Ma et al. [14] reported the forced flow and convective melting heat transfer characteristics of TBAB CHS flowing through straight circular tubes with the diameters of 6.0 mm and 14.0 mm. Song et al. [15] proposed the heat transfer correlations of TBAB CHS for laminar flow, transitional flow and turbulent flow, and the transitional modified Reynolds numbers for type A TBAB CHS and type B TBAB CHS were 2000 and 1800, respectively. In addition, the effect of solid fraction on heat transfer was more evident in turbulent flow than that in laminar flow, which was different from the experimental results of Ma et al. [14]. The summary of the researches on the flow and heat transfer characteristics of TBAB CHS is shown in Table 1.

It can be seen from Table 1 that the previous investigations were performed in tubes with relatively large sizes. However, the small-diameter tube heat exchangers or even micro-channel heat exchangers are gradually applied to save the metal materials and to reduce the charging amount of refrigerants in refrigeration and air conditioning systems, where the flow and heat transfer characteristics of working fluids in small-diameter tube are apparently necessary. For the similar reasons, more investigations are needed to clarify the flow and heat transfer characteristics of TBAB CHS in such small size tubes. In addition, TBAB CHS is a solid–liquid two-phase fluid, and the interaction between the particles and wall becomes more violent in small tubes, which will impose the influence on the flow and heat transfer characteristics, leading to different features from those in large size tubes. Therefore, flow