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Rheological and energy transport characteristics of a phase change material slurry

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ABSTRACT

A phase change material slurry – TBAB (tetra-n-butyl ammonium bromide) CHS (clathrate hydrate slurry) has received intensive attractions in recent years due to its dual-function as thermal energy storage and transport media simultaneously in air conditioning and refrigeration applications. In the present study, the rheological characteristics of TBAB CHS were measured using a rheometer at various solid fractions and in a shear rate range of smaller than 1000 s^{-1}. The results indicated that TBAB CHS was a pseudo-plastic non-Newtonian fluid which showed shear-thinning characteristics. The flow behaviour indices and fluid consistencies of type A and type B TBAB CHS were determined based on the power-law fluid model, which showed good consistency with the previous results obtained from the pressure drop measurements in straight tubes. The apparent viscosity of type A TBAB CHS was larger than that of type B TBAB CHS. The obtained apparent viscosities were compared to the calculated results by using the empirical equations, and the reason for the discrepancies was discussed. Based on the obtained rheological characteristics, the pumping power consumption of TBAB CHS as a secondary refrigerant was estimated and compared to that of chilled water at the same cooling capacity. The result showed a drastic reduction of pumping power when using TBAB CHS in lieu of chilled water.

1. Introduction

Due to the rapid development of the human society and economy in recent years, the energy consumption increases drastically, which triggers the energy issue and environment issue becoming two major concerns in the community. For example, more than 10.0% of the world's total energy is believed to have been consumed to create a pleasant space condition [1], among which refrigeration and air conditioning systems contribute significantly. Due to very fast growth of energy consumed by these systems, a big difference of the electricity loads between the peak time and off-peak time emerges, which apparently imposes negative influence on the operation safety of the electricity grid and reduces the total energy efficiency. In addition, the wide usage of traditional refrigerants, such as CFCs and HCFCs results in ozone layer depletion problem and leads to global warming, which arouses gradual phase-out of such environment-negative refrigerants according to the Montreal and Kyoto Protocols.

Thermal energy storage in the refrigeration and air conditioning systems is an effective solution to alleviate the above-mentioned mismatch between the energy supply and demand. The surplus electricity during off-peak time can be converted to and stored as thermal energy, which is then released by using a secondary refrigerant directly during peak time to alleviate the burden on the electricity supply. As a result, the peak-valley load difference can be effectively reduced and the energy is utilized in a more efficient way. An additional merit of incorporating thermal energy storage and secondary refrigerant is that the charging amount of the traditional environment-negative refrigerants is largely reduced, reducing the emission of the refrigerant.

The transport and distribution of thermal energy in a thermal energy-storage refrigeration and air conditioning system is fulfilled by the secondary refrigerant. Single-phase secondary refrigerant such as water, ethanol-glycol, brine, etc., is commonly used due to its easy availability and implementation. However, it has been generally accepted that the performance of the single-phase secondary refrigerant is not competitive to that of solid–liquid two-phase secondary refrigerant. The involved latent heat in the phase change process endows the two-phase secondary refrigerant

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Nomenclature

A, B, C, D	Parameters in the Vogel–Tamman–Fulche model (–)
c_p	Specific heat (J/(kg K))
d	Diameter (m)
f_F	Fanning flow friction (–)
G	Volume flow rate (m^3/s)
ΔH	Latent heat (J/kg)
K, K'	Fluid consistency coefficient (–)
n	Flow behaviour index (–)
N	Parameter in Senapati model (–)
P_P	Pumping power (W)
ΔP	Pressure drop (Pa)
q	Aspect ratio (–)
Q	Cooling capacity (W)
Re	Reynolds number $\rho vD/\mu$ (–)
Re_{MR}	modified Reynolds number (–)
S	Parameter in Senapati model (–)
T	Temperature (°C)
v	Velocity (m/s)
w	Solution concentration (–)
Greeks	
μ	Viscosity (Pa s)
$[\mu]$	Intrinsic viscosity (–)
ρ	Density (kg/m^3)
ϕ	Volume fraction (–)
ω	Mass fraction (–)
τ	Shear stress (Pa)
$\dot{\gamma}$	Shear rate (s^{-1})
η	Efficiency of the pump (–)
Subscripts	
a	Apparent
hyd	Hydrate
liq	Liquid
max	Maximum
slurry	Slurry
water	Water
0	Initial

a larger thermal storage and carrying capacity. Thus, the flow rate of such secondary refrigerant can be largely reduced, leading to a significant reduction of pumping power and improvement of energy efficiency.

The phase change material slurries, such as ice slurry [2,3], MPCS (microencapsulated phase change material slurry) [3,4], micro-phase change material emulsion [3,5] and CHS (clathrate hydrate slurry) [6–8], have been investigated and applied as two-phase secondary refrigerants. Among these slurries, ice slurry has been intensively studied and commonly used for cold storage and transport due to its easy availability and operation. However, there are still several technical obstacles hampering the wide application of ice slurry, e.g., the formation of ice slurry requires low evaporation temperature and extra mechanical energy input. Therefore, MPCS and CHS have been proposed to be the secondary refrigerants to achieve better performance.

As a new phase change material slurry, TBAB (tetra-n-butyl ammonium bromide) CHS (clathrate hydrate slurry) has recently drawn intensive attraction due to its adjustable phase change temperature in the range of 0–12 °C, which fits well the temperature requirement of the chilled water used in the air conditioning system. There are two types of hydrate crystals formed in TBAB aqueous solution, i.e., type A and type B, depending on the temperature and initial mass concentration of TBAB aqueous solution, as can be seen from the phase diagram in Fig. 1. The molecular structures of type A and type B hydrate crystals are different, with the hydration numbers for the two hydrates being 26 and 38, respectively. Therefore, there are big differences on the shapes and morphologies as well as the transparency between these two hydrates.

Apparently, the flow characteristics of PCM slurries are crucial to their applications. As aforementioned, the usage of two-phase slurries as the secondary refrigerant can reduce the pumping power due to their high cold carrying capacity. The knowledge about the flow characteristics, for example, the apparent viscosity, the Newtonian or non-Newtonian feature and the flow resistance and so on, are indispensable to establish the evaluation method of the pressure drop and pumping power for the design of the piping system and the estimation of energy consumption in the refrigeration and air conditioning system. The previous researches suggested that TBAB CHS was a non-Newtonian fluid. However, the flow characteristics of TBAB CHS reported by different authors [9–15] showed big divergence. Darbouret et al. [9] and Song et al. [10] concluded that TBAB CHS was a Bingham fluid, while other studies [11–15] indicated that TBAB CHS was more appropriately described as pseudo-plastic fluid and it showed the shear-thinning feature. It should be noticed that the above results were all based on the pressure drop experiments in which TBAB CHS flowed through horizontal straight tubes. Using such method, as pointed in a recent study [16], the apparent viscosity could only be determined by correlating the shear stress and shear rate at the wall by the slurry flowing at different velocities, and such correlations required some assumptions and the accuracy was not high. Furthermore, the uncertainties in such experimental measurements might be high when the pressure drop was small. The rheological measurement using a rheometer was considered as a more accurate method to determine the rheological characteristics of TBAB CHS [16]. However, to the best of the author's knowledge, only Hashimoto and Kawamura [17] have ever reported the measuring results of type A TBAB CHS using a rheometer.

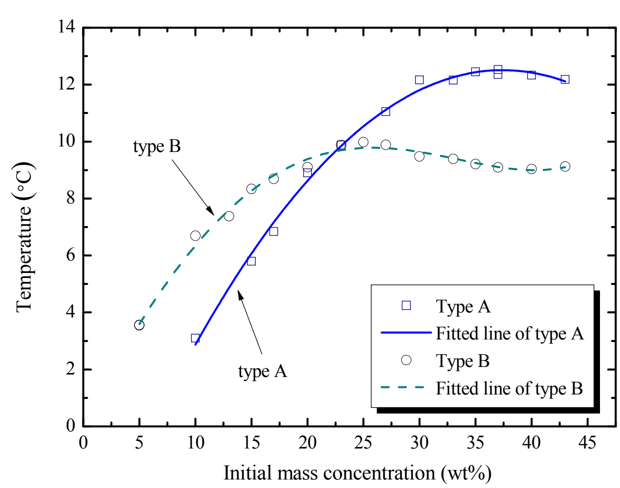

Fig. 1. Phase diagram of TBAB CHS.