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Thermal conductivity measurements of a phase change material slurry under the influence of phase change

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ABSTRACT

Phase change material slurry is widely used in such applications as thermal energy storage and thermal management. Thermal conductivity of phase change material slurry is one of the most important thermo-physical properties that are necessary for system design and performance evaluation. In the present study, thermal conductivity of a phase change material slurry, tetra-*n*-butylammonium bromide (TBAB) clathrate hydrate slurry (CHS), is experimentally measured by using transient hot-wire method. The theoretical model of thermal conductivity measurement of phase change material slurry under the influence of phase change is proposed and numerically analyzed to obtain real thermal conductivity. It is found that phase change significantly affects the measurement of thermal conductivity in that the real thermal conductivity is smaller than that obtained directly from the experiments because phase change enhances heat transfer during the measurement. The smaller the solid fraction of TBAB CHS, the larger the influence of phase change on thermal conductivity is. Such effect is apparently ubiquitous, which should also be taken into consideration in thermal conductivity measurement of other phase change material slurries.

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1. Introduction

Space cooling and heating by air-conditioner consume a huge amount of energy which accounts for about 30%–40% of the electricity load during the peak-time in summer and causes a significant difference between peak and valley electricity loads, resulting in safety concern to electric grid and low energy efficiency. Meanwhile, conventional refrigeration and air-conditioning may cause serious environment-negative-impact refrigerant emission because the charging amount of refrigerant in such systems is very large, which might in turn result in significant threat to the environment, e.g., ozone layer depletion. Therefore, the consequent energy and environmental issues aroused by the conventional refrigeration and air-conditioning urge further research and development to alleviate their negative impacts.

The above-mentioned drawbacks of conventional refrigeration and air-conditioning can be partially overcome by the suitable alternatives, e.g., secondary loop refrigeration in which secondary refrigerant is responsible for distributing cooling or heating to the individual terminal users. In such system configuration, cooling or heating is centrally produced, and is then transported by the secondary refrigerant. The main merits of such system are that the quantity of the primary refrigerants, such as CFCs and HCFCs usually used in conventional systems, can be drastically reduced, and thermal storage can also be easily implemented so that peak-load can be partially shifted to off-peak time. Taking the cold storage as an example, the widely-used secondary refrigerant is water or ice slurry in current applications. However, the drawbacks of water or ice slurry as the secondary refrigerant are also apparent as follows: (1) the cold storage tank is very large in the case of water used as the secondary refrigerant because cold is stored only in the form of sensible heat; (2) the cold storage temperature below 0 °C in the case of cold storage by ice slurry makes the refrigerating efficiency for ice generation very low because the evaporation temperature must be below 0 °C due to the fact of supercooling for ice slurry generation. Furthermore, the temperature range of cold storage around 0 °C by ice slurry does not match the temperature demand for the air-conditioning which generally ranges around 5–12 °C. The pumping power consumption for transporting secondary refrigerant can be largely reduced if the latent heat associated with phase change is involved, because the flow rate is drastically decreased. Although some other techniques, such as, cold storage by micro-encapsulated phase change material slurry, can also be applicable, the intrinsic drawbacks impede its widespread

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Nomenclature

c_p	specific heat capacity [J kg^{-1} K^{-1}]
I	electric current [mA]
L	length of the hot-wire [m]
q	heating power per unit length [W m^{-1}]
r	radius [m]
R	electric resistance [Ω]
S	internal heat source [W m^{-3}]
t	time [s]
T	temperature [°C]
U	electric voltage [mV]
V	volume [m^3]
w	mass concentration [-]

Greek symbols

α	temperature coefficient [K^{-1}]
ΔH	latent heat [J kg^{-1}]
ϕ	volume fraction of clathrate hydrate [–]
λ	thermal conductivity [W m^{-1} K^{-1}]
ρ	density [kg m^{-3}]
ω	solid fraction of clathrate hydrate [–]

Subscripts

0	initial or radius of the hot-wire
∞	infinite
CHS	TBAB CHS
h	hot-wire
H	hydrate
i	insulation layer
liq	liquid
P	particle
real	truth-value
s	sample
slu	slurry
simple	measurement by the simple method without considering phase change

application. It is very necessary to develop novel technology to promote efficient cold storage for air-conditioning application. Recently, tetra-*n*-butylammonium bromide (TBAB) clathrate hydrate slurry (CHS) was proposed to be used as a phase change material slurry for both cold storage and transport [1,2], which has been proven to demonstrate merits over water and ice slurry for its reduced flow rate and suitable temperature range.

TBAB CHS is a solid–liquid two-phase fluid in which small-size particles of TBAB clathrate hydrate crystals present, and it is generally generated by chilling TBAB aqueous solution which is formed by dissolving TBAB in water. TBAB clathrate hydrate crystal will appear when temperature of TBAB aqueous solution decreases to below its phase equilibrium temperature. The cold storage capacity of TBAB CHS depends on the solid fraction in the slurry and the associated latent heat of solid–liquid phase change can make the cold storage capacity up to more than 100 kJ/kg within the temperature range of 5–12 °C. Therefore its cold storage capacity is normally considered to be about 2–4 times of that of the chilled water in the same temperature range [1,3]. TBAB CHS can be directly pumped to the end-user for its good fluidity, and thus the power consumption for pumping is significantly reduced. There are two types of TBAB clathrate hydrate crystals, i.e., type A and type B, where the main difference is that the hydration numbers are different in molecular structures, i.e., hydration number of 26 and 38 for type A and type B hydrate crystals, respectively [4]. Type B TBAB CHS is considered more advantageous for application because the latent heat of type B TBAB hydrate crystal is slightly larger than that of type A TBAB hydrate crystal. Furthermore, the size of type B TBAB hydrate crystal is also smaller, which results in smaller pressure drop in the case of cold transport by TBAB CHS [3].

It is evident that the thermo-physical properties of TBAB CHS and aqueous solution are very important and indispensible for the system design and performance evaluation of a cold storage air-conditioning system using TBAB CHS as secondary refrigerant. Shown in Table 1 are the available thermo-physical properties of TBAB CHS, TBAB aqueous solution and TBAB hydrate crystal, which are summarized from the literature [1–6]. As can be seen from Table 1, the thermo-physical properties of TBAB CHS and TBAB aqueous solution have not yet been systematically studied; therefore, the information about the thermo-physical properties, in particular for the thermal conductivity, is still very rare and is not enough to characterize TBAB CHS and TBAB aqueous solution and for further application.

In general, the thermal conductivity of a slurry, for example, micro-encapsulated phase change material slurry, can be estimated by using the Maxwell's equation formulated as [7]:

Table 1
Thermo-physical properties of TBAB CHS, TBAB aqueous solution and TBAB clathrate hydrate crystal.

	Hydration number	Density (kg m^{-3})	Latent heat (kJ kg^{-1})	Specific heat capacity (kJ kg^{-1} K^{-1})	Thermal conductivity (W m^{-1} K^{-1})
TBAB clathrate hydrate crystal					
Type A	26 [4]/29 [5]/35 [6]	1080.0 [2]	193 [2]/193.18 ± 8.52 [4]/215 [5]/210 [6]	2.22 [2]/1.86–2.61 [4]	0.42 [2]
Type B	38 [4]/36 [1]/44 [5]/47[6]	1030.0 [1]	205 [1]/199.59 ± 5.28 [4]/215 [5]/224 [6]	2.0–2.54 [4]	–
TBAB aqueous solution [3] [a]					
$w_0 = 0.10$		1010.22		4.03	0.521
$w_0 = 0.20$		1019.86			0.472
$w_0 = 0.30$		1030.82			0.418
$w_0 = 0.40$		1040.98			0.351
TBAB CHS [3] [b]					
$\omega = 0.05$		1009.83		3.97	0.502
$\omega = 0.10$		1009.67		3.98	0.507
$\omega = 0.15$		1009.51		3.99	0.523
$\omega = 0.20$		1009.34		3.99	0.577

[a] Density and thermal conductivity were measured at 10 °C, specific heat was determined at 15 °C. The states of TBAB aqueous solutions were above the saturated liquid line of type B TBAB CHS, while the states are on the saturated liquid line in the present study.

[b] Type B TBAB CHS was generated with TBAB aqueous solution of 10.0 wt% initial mass concentration.

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