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Effect of initial aqueous solution concentration and heating conditions on heat transfer characteristics of ice slurry

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ABSTRACT

In this study, parameters affecting the heat transfer characteristics of ice slurry were investigated experimentally. The initial concentration of the ethanol solution from which the ice slurry was produced was varied as experimental parameter. Moreover, the heat flux at the test tube surface was varied as the experimental parameters, and the heat transfer coefficients measured. The effect of initial ethanol solution concentration and heating conditions on the heat transfer characteristics was not significant, and the Nusselt number can be expressed as a function of apparent Reynolds number, ice packing factor and ratio of average ice particle diameter to test tube diameter.

Effet de la concentration initiale de la solution aqueuse et des conditions de chauffage sur les caractéristiques du transfert de chaleur d'un coulis de glace

Mots clés : Coulis de glace ; Ecoulement diphasique ; Coefficient de transfert de chaleur ; Fluide non-Newtonien

1. Introduction

Thermal energy storage systems using ice as phase-change material have many advantages in terms of leveling electric power (Saito, 2002). In particular, cold thermal energy can be transported directly in a dynamic-type ice thermal energy storage system, since fluid ice slurry is used as phase change material. The ice slurry is a mixture of fine ice particles and aqueous solution. It has a high heat transfer rate, because the latent heat of fusion of the ice particles can be used and the heat exchange area is wide. Thus, ice slurries could be used

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Nomenclature

c	ice packing factor, %
d	average diameter of ice particles in ice slurry, m
D	inner tube diameter, m
Fr	Froude number
g	gravitational acceleration, m s^{-2}
k	thermal conductivity, W m^{-1} K^{-1}
K'	coefficient in Eq. (9)
L	tube length, m
n'	exponent in Eq. (13)
Nu	Nusselt number
q	heat flux, W m^{-2}
Re	Reynolds number
Re_M	apparent Reynolds number for pseudo-plastic fluid
T	temperature, °C
u_m	mean velocity, m s^{-1}
Δp	pressure drop, Pa
α	heat transfer coefficient, W m^{-2} K^{-1}
λ	coefficient of pipe friction
ν	kinematic viscosity, m^2 s^{-1}
ρ	density, kg m^{-3}
τ_R	shearing stress at inner surface, Pa

Subscripts

cal	values obtained from Eq. (12)
e	phase equilibrium
exp	values obtained from experimental results
i	ice
lam	laminar flow
s	aqueous solution
sl	ice slurry
w	inner tube surface

advantageously in thermal energy storage. Knowledge of the flow and heat transfer characteristics of the ice slurry is therefore important. Many researchers have investigated ice slurry flow and heat transfer characteristics over the past decade. Niezgoda-Zelasko and Zalewski (2006) investigated these flow characteristics experimentally in horizontal tubes. The critical velocity and mass fraction corresponding to a change in ice slurry character from laminar to turbulent flow were determined. Knodel et al. (2000) reported on the flow and heat transfer characteristics of ice slurry in a 24 mm diameter tube. The ice slurry velocity was varied from 2.8 to 5.0 m s^{-1}, and a reduction in pressure was observed from flow relaminarization for a large ice packing factor (IPF). The flow and melting characteristics of ice slurry have also been investigated by a number of researchers (Guilpart et al., 1999; Lee et al., 2006; Doetsch, 2001; Bellas et al., 2002). Ayel et al. (2003) reviewed the flow and heat transfer behavior of ice slurries, and Egolf and Kauffeld (2005) reviewed their physical properties. In particular, in previous studies, parameters affecting the heat transfer characteristics of the ice slurry were considered by some researchers. Guilpart et al. (1999) showed that the Nusselt number of the ice slurry under laminar flow condition was determined by the Graetz number and the IPF. Horibe et al. (2001) reported that the Nusselt number can be expressed as a function of Reynolds number, Stefan number and IPF. Niezgoda-Zelasko (2006) reported that the Nusselt number can be determined from the Peclet number, Stefan number, IPF and ratio of average ice particle diameter to test tube diameter. However, parameters used to determine the Nusselt number of the ice slurry have not been identified, and there is no unified understanding of the heat transfer characteristics of the ice slurry.

We have established the fundamental characteristics of flow and heat transfer of ice slurry and have found that it can be treated as a pseudo-plastic fluid under laminar flow condition (Kumano et al., 2010a, 2010b, 2013). Then, the heat transfer coefficient can be treated as a function of apparent Reynolds number, IPF and ratio of average ice particle diameter to test tube diameter. In these studies, the ice slurry was generated from a 5 wt% ethanol solution. The apparent enthalpy of the ice slurry varies with initial aqueous solution concentration. Moreover, the effects of heating condition have not been revealed, and it has not been clarified which parameter dominates the heat transfer characteristics. Especially, Stefan number used in the several approximation equations is pointed out in this study, and can be varied by varying the initial aqueous concentration and the heating condition. That is, amount of latent heat of fusion to temperature variation can be varied due to varying the initial concentration. Moreover, temperature difference between the ice slurry and inner surface of the tube can be varied by changing the heat flux given at the tube surface. Therefore, the heat transfer characteristics of ice slurry are investigated experimentally to clarify the parameters affecting heat transfer. The initial ethanol solution concentration and heating condition were varied as experimental parameters, and the heat transfer coefficients were measured. An approximation equation for determination of the Nusselt number was derived from the experimental results.

2. Experimental apparatus and procedure

2.1. Experimental apparatus

Fig. 1(a) shows a schematic diagram of the experimental apparatus. Details of the apparatus have been described previously (Kumano et al., 2010b), and it is only described briefly here. The experimental apparatus consisted of a circulation, storage and measurement unit. The circulation unit consisted of an ice slurry storage tank, gear pump, entrance section, test section and Coriolis-type mass flowmeter. The entrance and test sections were 1 m in length with a 7.5 mm tube diameter. Fig. 1(b) shows the detail of the test section. The test section consisted of a stainless steel tube wrapped with nichrome foil heater. The tube was heated at a constant heat flux, and the heat flux was varied as an experimental parameter. The heating section was inserted 0.8 m into the test section. T-type thermocouples, 0.1 mm in diameter, were inserted inside the stainless steel tube to measure the temperature of the inner surface. The