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Effect of initial aqueous solution concentration on rheological behavior of ice slurry

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ABSTRACT

Ice slurry displays many advantages as a phase-change material because the latent heat of ice particles can be used and their heat exchange area is large. In this study, the effect of initial concentration on the rheological behavior of ice slurry was investigated experimentally. Ice slurry flowed upward and downward to keep it homogeneous in the tube, and pressure drop was measured to explain the rheological behavior of the ice slurry. The ice packing factor, Reynolds number, and initial aqueous solution concentration were varied as parameters. The ice slurry flow characteristics exhibit a pseudo-plastic fluid tendency for 5 and 10 wt% of the initial concentration. Ice slurry generated from 2 wt% ethanol solution behaves as a Newtonian fluid.

Effet de la concentration initiale de solution aqueuse sur le comportement rhéologique de coulis de glace

Mots clés : Coulis de glace ; Écoulement diphasique ; Chute de pression ; Fluide non newtonien

1. Introduction

Thermal energy storage systems using ice as a phase-change material have many advantages in terms of leveling electric power (Saito, 2002). In particular, ice slurry has been recognized as an optimum second refrigerant in these systems. Ice slurry is a mixture of fine ice particles and aqueous solution, and cold thermal energy can be transported directly in this system. Ice slurry has a high heat transfer rate, because the latent heat of fusion of ice particles can be used and their heat exchange area is large. Because ice slurry exhibits good

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Nomenclature

c	ice packing factor [%]
D	inner tube diameter [m]
Fr	Froude number
g	gravitational acceleration [m s^{-2}]
K'	coefficient in Eq. (7)
L	tube length [m]
n'	exponent in Eq. (7)
Re	Reynolds number
T	temperature [°C]
u_m	mean velocity [m s^{-1}]
Δp	pressure drop [Pa]
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

e	phase equilibrium
exp	values obtained from experimental results
i	ice
s	aqueous solution
sl	ice slurry
th	theoretical value

properties as a second refrigerant, its characteristics in fundamental processes, including generation, storage, transportation, and melting, have been investigated by many researchers.

To design thermal energy storage systems using ice slurry, it is important to understand the flow characteristics of the ice slurry. Many researchers have investigated ice slurry flow characteristics over the past decade. Niezgoda-Zelasko and Zalewski (2006) investigated the flow characteristics of ice slurry experimentally in horizontal tubes. The critical velocity and mass fraction that correspond to a change in character of the ice slurry from laminar to turbulent flow were determined. Knodel et al. (2000) reported the flow and heat transfer characteristics of ice slurry in a 24-mm-diameter tube. Kitanovski and Poredos (2002) investigated heterogeneous flow in ice slurry analytically. The flow and melting characteristics of ice slurry have been investigated by many researchers (Bellas et al., 2002; Doetsch, 2001; Guilpart et al., 1999; Kumano et al., 2010a; Lee et al., 2006). Ayel et al. (2003) and Kitanovski et al. (2005) reviewed the flow and heat transfer behavior of ice slurries. In these reviews, it has been reported that some works propose to treat the ice slurry as a non-Newtonian fluid, using the Bingham or Casson models. Kumano et al. (2010b) investigated the flow characteristics of ice slurry in narrow tubes and found that the ice slurry can be treated as a pseudoplastic fluid under laminar flow conditions. However, no unified view exists on the flow characteristics of ice slurries.

In a previous study by the authors, ice slurry was produced from ethanol solution at different concentrations, and the effect of initial aqueous solution concentration on the flow and heat transfer characteristics of ice slurry was examined

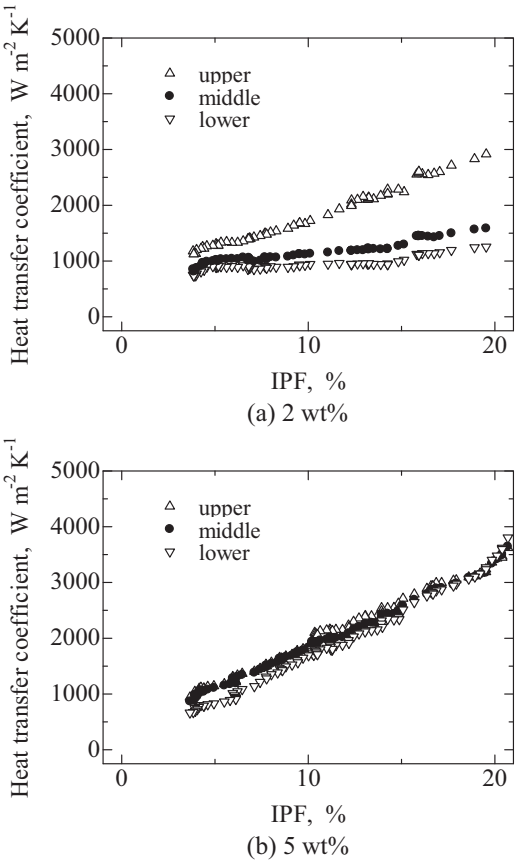

Fig. 1 – Effect of buoyancy force on heat transfer coefficient of ice slurry.

(Kumano et al., 2014). One of the results in Fig. 1 shows the relationship between heat transfer coefficients of a horizontal 7.5-mm-diameter tube and the ice packing factor (IPF) at the upper, middle, and lower positions. The initial ethanol solution concentration was varied at 2 and 5 wt%. The heat transfer coefficient at the upper position increases for a 2 wt% initial concentration. Many ice particles exist in the ice slurry in the upper side of the tube because of buoyancy force effects. Differences resulting from the position were insignificant for the 5 wt% concentration. Therefore, the ice particles exist homogeneously in the ice slurry flow. The results suggest that the initial solution concentration affects the rheological behavior of the ice slurry.

In this study, the effect of initial concentration on the rheological behavior of ice slurry was investigated experimentally. As described above, buoyancy force affects the flow characteristics of the ice slurry at low concentration, and the flow does not become homogeneous because of the buoyancy force. Therefore, the ice slurry flowed upward and downward in a tube to exclude the buoyancy effect, and the pressure drop was measured to estimate the rheological behavior of the ice slurry. The IPF, Reynolds number (Re), and the flow direction were varied as experimental parameters. The effect of flow direction of the flow characteristics of the ice slurry was also considered.