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Experimental investigation on inhomogeneity of ice packing factor in ice slurry flow

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ABSTRACT

We investigated inhomogeneity in ice slurry, which can pose problems such as sudden increase in pressure drop and blockages in flow. Although in many previous studies fully dispersed ice slurry flow is assumed homogeneous, inhomogeneity appears as a variation in physical properties in the actual measurements. From experiments, it was found that the fluctuation in pressure drop is relatively small at the beginning, but becomes larger after long-term periods. Additionally, the ice particle size included in the ice slurry also affects this fluctuation. We supposed the fluctuation is caused by the variation in IPF, because it appears only in laminar flow. This implies ice slurry is not homogeneous after long flow periods. From the present study, the variation of IPF was estimated to be 2.6 wt% at maximum. Although the physical mechanism of the variation in IPF has not been clarified, we suggest that it is a consequence of the accumulation/adhesion of ice particles in the pipe.

Étude expérimentale de l'inhomogénéité du facteur de compacité de glace dans un écoulement de coulis de glace

Mots clés : Coulis de glace ; Écoulement diphasique ; Chute de pression ; Frigorigène secondaire ; Accumulation thermique

1. Introduction

A solid–liquid two-phase mixture, including the many fine ice particles in the liquid, is called ice slurry. As a secondary refrigerant and a thermal storage material, ice slurry has some advantages such as its good fluidity and heat transfer capability (Egolf and Kauffeld, 2005; Kauffeld et al., 2010; Saito, 2002).

In many cases, ice slurry is made from some aqueous solution. In particular, ethanol solution, which is used in this study, is suitable in a wide range of industrial fields, for example medical and food industry, because of its antiseptic properties and non-toxicity.

To clarify the complicated behavior of ice slurry flow, many studies have been performed. Knodel et al. (2000) investigated the flow and heat transfer characteristics of ice-water slurry

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Nomenclature

C	specific heat [kJ kg^{-1} K^{-1}]
c	ice packing factor (IPF) [wt%]
D	inner tube diameter [m]
h	pressure drop [Pa m^{-1}]
h_m	mean pressure drop [Pa m^{-1}]
L	latent heat of fusion of ice [kJ kg^{-1}]
m	mass [kg]
Re	Reynolds number
T	temperature [°C]
u	flow velocity [m s^{-1}]
u_m	mean velocity [m s^{-1}]
Δc	IPF fluctuation range [wt%]
Δh	pressure drop fluctuation range [m s^{-1}]
Δu	velocity fluctuation range [m s^{-1}]
λ	coefficient of pipe friction
ρ	density [kg m^{-3}]
ν	kinematic viscosity [m^2 s^{-1}]

Subscripts

ini	initial condition
e	phase equilibrium
fin	final condition
s	ethanol solution
sl	ice slurry
w	water

in a 24-mm-diameter horizontal tube. They reported that flow relaminarization can be observed with increasing ice packing factor (IPF). Niezgoda-Zelasko and Zalewski (2006) investigated flow characteristics in 10- to 20-mm-diameter horizontal tubes. They reported a critical velocity and mass fraction corresponding to a change in character of ice slurry flow from laminar to turbulent. They have evaluated the pressure drop treating ice slurry as a Bingham fluid. Certain rheological models concerning pressure drop in ice slurry flow have been investigated. Kitanovski and Poredoš (2002) used suspension viscosity to evaluate ice slurry flow. Mellari et al. (2012) used the Ostwald–de Waele model. Other models used in recent research have been summarized by Monteiro and Bansal (2010) and Ayel et al. (2003). Mika (2013) studied the flow resistance in pipe tees and flow dividers with the aim to avoid blockages from ice slurry flows. We have investigated the characteristics of flow and heat transfer of ice slurry (Kumano et al., 2010a, 2010b, 2012, 2013, 2014). The characteristics of ice slurry depend on IPF, the size/shape of ice particles, and the concentration of the aqueous solution. In particular, the pressure drop increases with IPF when Reynolds number Re is small but is independent of IPF when Re is large (Kumano et al., 2010a). From these results, we believe that the rheological characteristics of ice slurry depend on IPF under laminar flow conditions but are independent of IPF under turbulent flow conditions. We have reported that the variation in pressure drop for laminar flow can be expressed as a function of the apparent Reynolds number, with treating ice slurry as a pseudo-plastic fluid.

In most studies, including presented above, the rheological characteristics of ice slurry were evaluated assuming it was homogeneous. As introduced by Doron and Barnea (1996), flow pattern of solid–liquid two-phase flow transitions depending on flow velocity. When flow velocity is low, the flow pattern becomes heterogeneous flow or flow with moving/stationary bed. With increase in flow velocity, it transitions to fully dispersed flow, which is generally assumed as homogeneous flow. However we suppose it is not completely homogeneous in the case of ice slurry, because in actual measurements, fluctuations in measured data, such as pressure drop, were observed that may be a consequence of inhomogeneity in the ice slurry. As is discussed below, we suppose the fluctuations arise from a variation in IPF, because the fluctuation in pressure appears only under laminar conditions, in which pressure drop depends on IPF. Since the variation in IPF should be suppressed in practical applications to prevent accidents caused through sudden increase in pressure drop and blockages in slurry flows, we focused it in the present work. Much more investigations of inhomogeneity have been performed for gas–liquid two-phase flow. Nishikawa et al. (1969) reported that pulsation of static pressure was observed even in the bubbly flow/fully dispersed flow of water–air two-phase mixture. From the results, they supposed there is a series of dense and sparse bubble clouds in the bubbly flow. As they presented, measuring pressure fluctuation is one of the effective methods to investigate homogeneity in dispersed flow. In the present study, we measured the pressure drop of ice slurry flow in 7.5-mm-diameter horizontal tube, and the variation in IPF was estimated. The knowledge will contribute to maintaining fluctuations within acceptable levels to prevent potential problems.

2. Experiment apparatus and procedure

2.1. *Properties of ice slurry*

A description of the apparatus for producing ice slurry is omitted here as it has been given previously (Kumano et al., 2010a). Ice slurry was produced using a supercooling-type method. The size/shape of the ice particles found in the ice slurry varies depending on storage time and ethanol solution concentration. In this study, ice slurry was produced with 5 wt% ethanol solution. The average diameter of ice particles is about 0.15 mm just after production, but increases to about 0.3 mm after 24-hour storage. Details of the variation in particle size were presented in previous work (Kumano et al., 2012).

The Reynolds number for ice slurry flow, Re, is defined as

$$Re = \frac{Du_m}{\nu_s}, \tag{1}$$

where D denotes the inner diameter of the tube, u_m mean velocity of the flow, and ν_s the kinematic viscosity of the ethanol solution. The thermophysical properties, such as kinematic viscosity, can be expressed as a function of the phase-equilibrium temperatures of the ethanol solution, T_e, because the temperature of the ice slurry was kept at the phase equilibrium temperature corresponding to the solution concentration. As kinematic viscosity, we have (Kumano et al., 2010a)