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## Article

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# Effect of ice mass fraction on ice slurry flow for cold energy storage application

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## Abstract

The characteristics of ice slurry flows in a pipe are critical due to the potential consequence of pressure drops. This work attempted to conduct an experimental study on ice slurry flow in a horizontally posited circular pipe. This study was conducted on glycol-added (20%) ice slurry with varied ice mass fractions (10%, 15%, 20%, 25%, 30%). During experiments, the flow tests were conducted by covering both laminar and turbulent flows. Results of the investigation discovered ice slurry to behave as a Newtonian fluid at mass fraction below 10%, while it also behaved as a non-Newtonian fluid at mass fraction up to 15%. Then, pressure drop was revealed to increase significantly at low-speed settings and high ice mass fractions. To maximize the use of ice slurry as a cold energy storage, therefore, ice mass fraction must be kept at below 20% in a laminar flow.

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*Keywords:* Ice slurry; Ice mass fraction; Flow; Pressure drop

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## 1. Introduction

Ice slurry has been recognized as a promising crystalline energy carrier for cold energy storage. In fact, it is particularly related to its pumpable feature, high latent heat and high energy density [1,2]. Besides, ice slurry systems offer advantages compared with chilled water, in which ice slurry system requires lower pumping power and flow rate for the same cooling load. Ice slurry can also shift electricity demand when ice slurry is formed and stored during off-peak load (night) periods to be distributed to afternoon time. Kasza et al. [3] have reported potentially reduced numbers of required cold storage tank to one tenth by using ice slurry for the same cooling capacity of chilled water. Besides, piping diameters for ice slurry flow can be reduced to one third for the same cooling capacity [4]. In other words, the application of ice slurry systems opens a possibility to increase cooling capacity with less required replacements or overhauls of existing storage tank and piping systems.

Despite these benefits, functional utilizations of ice slurry have a drawback due to increased pressure drop alongside increased ice mass fraction. Bordet et al. [5] has investigated a transition flow of ice slurry in which

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**Nomenclature**

$C$	Concentration [kg kg <sup>-1</sup> ]
$f$	Friction factor [–]
$K$	Coefficient of consistency [pa s]
$L$	Length [m]
$m$	Mass [kg]
$n$	Power law fluid [–]
$\Delta P$	Pressure drop [pa]
$Q$	Volume flow rate [m <sup>3</sup> s <sup>-1</sup> ]
$Re$	Reynolds number [–]
$T$	Temperature [°C]
$v$	Velocity [m s <sup>-1</sup> ]
$X$	Mass fraction [kg kg <sup>-1</sup> ]

**Greek letter**

$\rho$	Density [kg m <sup>3</sup> ]
$\tau$	Shear stress [pa]
$\dot{\gamma}$	Shear strain [s <sup>-1</sup> ]
$\mu$	Viscosity [pa s]

**Subscripts**

$app$	Apparent
$is$	Ice slurry
$o$	Initial
$s$	Final
$w$	Wall

the pressure drop is in general much higher for higher ice mass fractions. Besides, Mellari [6] has conducted an experiment on ice slurry flow in a horizontal pipe, discovering extremely high shear stress at low ice flow speeds. In the literature, various authors have investigated the pressure drop of ice slurry flows [7–12] and [13]. However, there is less focus on the effect of high ice mass fraction ( $X_i > 25\%$ ) to ice slurry flow that take pressure drop, shear stress, and viscosity into account. Hence, this work focused on the behavior of ice slurry flow in five variations of ice mass fraction (10%, 15%, 20%, 25%, 30%). Besides, this study investigated effects of the ice mass fraction to pressure drop, shear stress and viscosity.

**2. Methodology***2.1. Experimental set up and apparatus*

Fig. 1 exhibits the schematic view of pressure drop test section. The section was comprised of an ice slurry generator, an ice storage tank, a piping system and measuring apparatus. In particular, the piping system consisted of a magnetic pump, an entrance flow pipe, thermocouples, a test section pipe, and a Coriolis F100S flow meter. The entrance section was designed to have 1.5 m in length to fulfill the fully developed flow, while the test section pipe used a circular pipe with 12.7 mm inner diameter and 1.3 m length. To adjust flow rates, the magnetic pump was equipped with a Toshiba VFS 150 inverter. Pressure differences between inlet and outlet flows in the test section were measured by utilizing TPS20 Series pressure transmitter.

Ice slurry was made by mixing 20% of monoethylene glycol in 25 l of solution. The cooling temperature, flow rate of the ice slurry and ice mass fraction were varied as experimental parameters. The ice mass fraction was varied by 10%, 15%, 20%, 25%, and 30%, respectively.

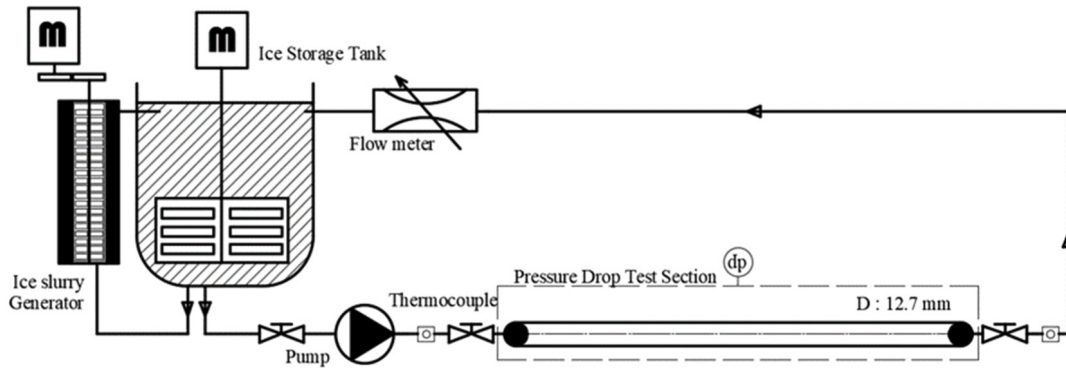


Fig. 1. Experimental set up for the pressure drop test of ice slurry.

## 2.2. Theoretical background

This study attempted to examine ice mass fraction based on its concentration as observed parameter. The ice mass fraction of ice slurry was determined by applying seesaw principle proposed by Melinder [14]. Mathematically, the ice mass fraction is expressed as:

$$X_{IS} = \frac{C_S(T) - C_0}{C_S(T)} \quad (1)$$

Considering time-independent solid–fluid properties of ice slurry, the classical rheology expression for a non-Newtonian fluid is stated as follows:

$$\tau_w = \frac{1}{4} \left( \frac{D}{L} \right) \Delta P = K \left( \frac{8v}{D} \right)^n \quad (2)$$

Besides, power-law fluid ( $n$ ) is determined by the tangent arc curved of logarithmic scale for shear stress and shear rate, which refers to the following equation:

$$n = \frac{d \log(\tau_w)}{d \log(\dot{\gamma})} \quad (3)$$

Then, the apparent viscosity of a non-Newtonian fluid refers to a mathematical relationship between the coefficient of consistency, shear rate, and power-law fluid, which is expressed in the following equation:

$$\mu_{app}(\dot{\gamma}) = K (\dot{\gamma})^{n-1} \quad (4)$$

## 3. Results and discussion

Fig. 2(a) exhibits the flow curve of varying pressure drops as a function of ice slurry fluid velocity in the horizontal pipe. Looking at the figure, pressure drop increased in parallel with velocity and, in a more significant behavior, with ice mass fraction. These findings are in fact consistent with a previous investigation by Grozdek et al. [7]. Meanwhile, Fig. 2(b) exhibits the experimental rheology of ice slurry as a function of shear stress, which is in fact dependent to shear rate. Practically, ice slurry behaves as a Newtonian fluid at low ice mass fractions ( $X_{is} \leq 10\%$ ). Alongside the increases of ice mass fraction, the behavior of ice slurry changes into a non-Newtonian fluid, shifting from a pseudoplastic ( $n > 1$ ) fluid to a dilatant ( $n < 1$ ) one. When ice slurry behaves as a dilatant fluid, however, its pressure drop significantly rises and tends to agglomerate due to the effects of power-law fluid (Fig. 2(c)).

Fig. 2(c) exhibits the correlation of power-law fluid as a function of ice mass fraction, while viscosities as a function of shear rates are plotted in Fig. 2(d). In fact, power-law fluid is positively correlated to ice mass fraction. Besides, the viscosity of ice slurry exhibits a typical pseudoplastic and dilatant fluid that depends on the ice mass fraction. In between 10%–20% of ice mass fraction, the viscosity of ice slurry decreases, which is affected by power-law fluid. In between 20%–30% of ice mass fraction, on the contrary, the viscosity of ice slurry increases

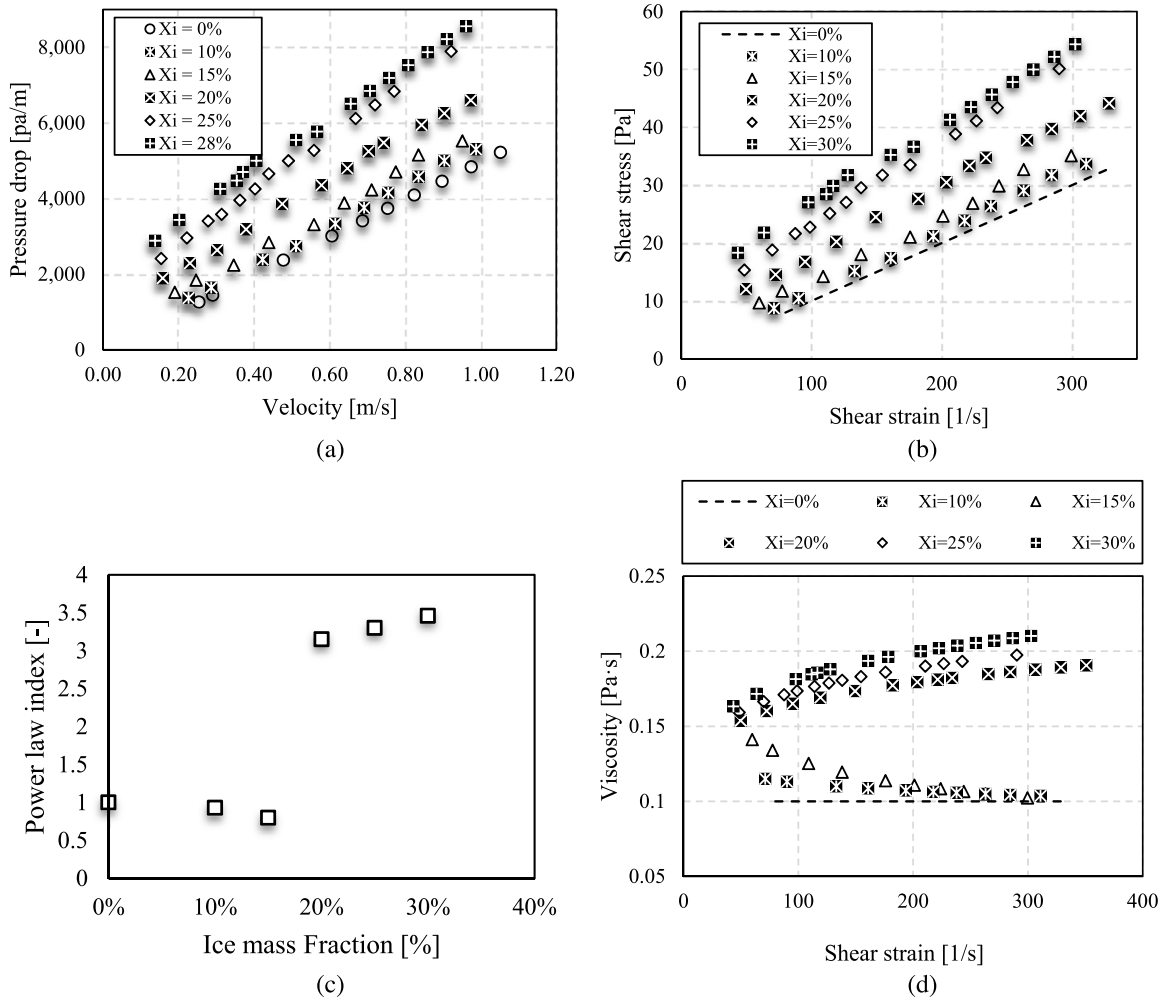


Fig. 2. (a) pressure drop vs. velocity; (b) shear stress vs. shear strain; (c) power law fluid vs. ice mass fraction; (d) viscosity vs. shear strain.

alongside increases in shear rate. The phenomenon shall be fit with increasing power-law fluid, which tends to appear as a dilatant fluid. Prior works on ice slurry flows have also reported increases in viscosity alongside the increases of pressure drop and ice mass fraction [9,15,16]. In fact, the increases of viscosity in the storage tank is considerably more critical than the impact of velocity. Technically, Ostwald ripening process is believed to hardly contribute in the increases of ice mass fraction, yielding the viscosity to increase. Pronk et al. [17] have confirmed Ostwald ripening as a phenomenon in which large crystals of ice slurry tend to bind small crystals, resulting in a larger crystal. Therefore, the storage time of ice slurry causes changes in the grow rate of crystal and, consequently, viscosity.

#### 4. Conclusions

The effects of ice mass fraction on ice slurry flows in a circular pipe have been investigated by utilizing a digital flow meter, thermocouples, and pressure transmitters. Looking at the results of experiments, ice mass fraction is discovered to strongly affect ice slurry flows. Besides, increases in pressure drop and shear stress are revealed to result in a higher ice mass fraction, which consequently increases power-law fluid. The ice slurry behaves as either a Newtonian ( $X_{is} \leq 10\%$ ) or non-Newtonian ( $X_{is} \geq 15\%$ ) fluid, which is largely affected by its mass fraction.

Technically speaking, the use of ice slurry flows for cold energy storage shall consider a 20% (or below) ice mass fraction of ice slurry with monoethylene glycol to expectedly deliver the best results. It is largely affected by its pseudoplastic flows, in which pressure drops and viscosities decrease in parallel with increases in shear strain.

Then, future studies on ice slurry may focus on the formulation of fluid models, which may consider viscosity, friction factor, and shear stress. Hence, those fluid models of ice slurry may predict the flows of ice slurry, which may technically prevent a system blockage in the piping system.

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