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Experimental investigations of ice slurry flows in horizontal pipe based on monopropylene glycol

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ABSTRACT

In this paper, the pressure drop behavior of ice slurry based on MPG-water in a circular horizontal tube is experimentally investigated. The secondary fluid was prepared by mixing MPG and water to obtain initial MPG concentration varying from 5% to 24%. The pressure drop tests were conducted to cover laminar flow with ice mass fraction varying from 5% to 25% depending on test conditions. Results from test reveal that the ice slurry behaves as non-Newtonian: thickening flow ($n > 1$) or shear thinning flow ($n < 1$) and sometimes as Newtonian flow ($n \approx 1$). The moving bed is observed in particular flow conditions.

The experimental results for viscosities were compared to the analytical results. In addition, experimental results of the Darcy friction factor were compared to Poiseuille model who gives good agreement with experimental results.

Furthermore, for transport purposes, it has been shown that 11% initial MPG concentration gives the best results.

Études expérimentales des écoulements de coulis de glace dans un tube horizontal basées sur le monopropylène glycol

Mots clés : Coulis de glace ; Soluté MPG ; Comportement rhéologique ; Viscosité ; Coefficient de frottement ; Caractéristiques de transport

1. Introduction

The ice slurry is a fluid consisting of ice particles dispersed in aqueous solutions. The latest technological advances in the field of production, transport and cold distribution are to integrate an intermediate circuit between the cooling machine and cold user device through which an ice slurry. This technique allows transporting cooling energy in large quantities in a latent form. It has many advantages (high efficiency thanks

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Nomenclature

C	volume fraction [m^3 m^{-3}]
c_p	specific heat [kJ kg^{-1} K^{-1}]
D	diameter [m]
f	friction factor
g	gravity constant [ms^{-2}]
h	enthalpy [kJ kg^{-1}]
k	consistency coefficient [Pas^n]
L	pipe length [m]
L_f	latent heat [kJ kg^{-1}]
n	flow index
p	pressure [Pa]
P	required pump power [W]
Q	volumetric flow [m^3 s^{-1}]
$\dot{Q}$	transport capacity [kW]
R	radius of the cylinder [m]
Re	Reynolds number
S	section [m^2]
T	temperature [°C]
U_d	average flow velocity [ms^{-1}]
u_{min}	minimum velocity [ms^{-1}]
x	mass fraction [kg kg^{-1}]

Greek symbols

$\dot{\gamma}$	shear rate [s^{-1}]
η	overall coefficient
μ	dynamic viscosity [Pas]
ρ	density [kg m^{-3}]
τ	shear stress [Pa]
τ_p	yield stress [Pa]

Subscripts

l	carrier fluid
f	final mass MPG
g	ice
i	initial mass MPG
is	ice slurry
v	volume
w	tube wall

to the latent heat of fusion, zero environmental impact, pumpable, extends the fresh time of food, human energy saving, has the larger contact surface with the products to be chilled, low energy cost and use of standards equipments. . .).

The ice slurry is defined by their ability to:

- Storing cold energy from a cold source,
- To convey that energy to his or her point of use,
- To transmit direct or indirect contact with the products or environments to cool.

Three major categories of applications using this technology such as industrial applications (Storing ice, indirect cooling method, direct method for cooling, fast cooling and freezing, cold immersion bath), commercial applications (storage of ice, refrigerated display in supermarkets and air conditioning, direct cooling of food like fish, meat, vegetables, indirect cooling of food like milk, oil) and specific applications (marine, mining cooling). This is mainly in Japan, Europe and North America that develops the use of two-phase refrigerants.

During the last twenty years, a lot of research has been done in the field of ice slurry rheology. Regarding the pressure drop of ice slurry, the researchers are basically agreeing that ice pressure drop increases with increasing velocity and more with ice mass fraction. Sasaki et al., 1993 considered ice slurry as a dilatant power law fluid. Then Christensen and Kauffeld, 1997 proposed to apply modified Bingham to the flow of ice slurry, which was originally given by Papanastasiou,1987. This Bingham model was also considered to be useful by other authors (e.g. Egolf et al., 2001; El Boujaddaini et al., 2010; Frei and Egolf, 2000; Jensen et al., 2000). Ben Lakhdar, 1998, Guilpart et al., 1999 and later Mellari et al., 2012 used the Ostwald–de Waele model to describe the behavior of ice slurry. Mika, 2013 has applied the Herschel–Bulkley model to describe the characteristics of slurry flow.

In contrast to other researchers, Doetsch, 2002 had a preference for the Casson model.

Niezgoda-Zelasko and Zalewski, 2007 showed that smaller ice fraction and larger ice crystals favor the segregation of particulate solids. An accumulation of ice in the upper section of the pipe causes the remaining fluid in the bottom of the pipe to flow at a greater velocity.

For viscosity, we know that the dynamic viscosity of a two-phase suspension μ_d is dependent on that of the liquid μ_l, the volume concentration of the particles C_v, the size and shape of the solid particles, the interactions between these particles and the liquid, the distribution of particle sizes, additives chemicals and time. Several models have been used for the suspension viscosity determination as shown in Table 1. The Thomas relation is the most stressed out by several works (e.g. Grozdek et al., 2009; Hansen et al., 2001; Kitanovski et al., 2005; Niezgoda-Zelasko and Zalewski, 2006).

According to Grozdek et al. (2009), Kauffeld et al. (2005) and Kitanovski and Poredos (2002), there are a few semi-empirical or empirical models than can be used to obtain the friction factor for laminar flow, although each parameter of a model has to be determined experimentally. For turbulent flow Doetsch (2002) gives very good results and can be applied to any kind of turbulent ice slurry flow whatever the additive be.

The effect of flow rate, ice concentration and pipe diameter on the transport capacity of ice slurries was addressed by Grozdek et al., 2009 and Kauffeld et al., 2005.

Finally, this work aims to present the influence of initial MPG concentration and ice fraction on pressure drop behavior, viscosity, friction factor and transport characteristic of ice slurries in horizontal tube.

2. Theory analysis

2.1. *Rheological study*

As surface strains, the shear stress and the pressure both appear in the momentum equation of the fluid. In the case of a horizontal cylindrical pipe, the integration of this equation gives