Experimental Investigation of Rheological Characteristics of Ice Slurry

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ABSTRACT

Ice slurry which is considered as an environmental friendly refrigerant is a phase-changing fluid consisting of both a liquid and solid-state fraction. It has higher transport properties. It is difficult to measure its characteristics with a desired accuracy due to its structure. Aging, shape and size of the ice particles which change with time are phenomenon that affect thermal and rupture properties.
The objectives of this paper are to determine experimental rheological characteristics and pressure drops of ice slurry with concentration of glycol mono propylene. The results show that pressure drops increase with ice mass fraction, and with the velocity. The critical shear stress is very low, for ice concentration above 15 %. If the initial solute concentration (x_i) < 14 %, the refrigerant behaves as a non Newtonian fluid which can be modeled by the Ostwald law. These results enable to predict the behavior and understand structures of ice slurry.

1. Introduction.

On annual basis 20-35% of refrigerant charge was emitted to the atmosphere in 1995 in developed countries [1]. The Montreal protocol of 1987, which suggested a phase-out of ozone depleting CFCs and HCFCs, was signed by a number of countries around the world. To speed up the phase-out schedule, amendments were made to this protocol. In the Kyoto protocol of 1997, the developed countries committed themselves to reducing their collective emissions of six greenhouse gases, by at least 5% by the period 2008-2012. On the other hand, it has been estimated that refrigeration and air conditioning use approximately 15% of the global production of electricity. The emission level including fugitives emissions, ruptures, emissions during service and at end of life, are generally very high and the larger the charge, the larger the average emission rate, due to very long pipes, large number of fittings and huge emission when ruptures occur.
There are several ways to approach the emission problems from refrigeration; to minimize the charge in the refrigeration system needed to generate a certain refrigerating effect, to design systems that are leak-proof, to use environmentally benign working fluids and to increase the efficiency. There exist two issues which will provide protection to the environment. These are indirect system refrigeration

and secondary fluids refrigerants. Specialists have shown that emissions of refrigerants could be reduced to 2-4% of charge per year if indirect systems are properly used. Today there are also other promising technologies with secondary fluids, like two phase carbon dioxide and ice slurry. Aqueous solutions are the most preferred single-phase secondary fluids; this is due to the fact that water has excellent thermo-physical properties. The most common freezing point depressant additives for water are glycols, alcohols and salts. The choice of additive depends on the applications.
The objectives of this paper are to determine rheological characteristics as well as pressure drops of ice slurry with concentration of glycol mono propylene, using experimental investigations and capillary viscometer principles as well as Rabinowith and Mooney correlations. The experimental investigations carried out have enabled to show the effect of both ice concentration and initial concentration of glycol mono propylene on the shear stress and the pressure drop and describe the rheological behavior of ice slurry.

2. Theory of ice slurry

Ice slurry [2, 3, 4] is a phase-changing secondary fluid consisting of both a liquid state fraction and a solid-state fraction. The solid state fraction is composed of fine ice particles. The main purpose of using ice slurry is to take advantage of the stored cooling energy in the ice particles when they melt. The ice particles are in the range of 0.1 to 1mm in diameter. Due to its high latent heat of melting, ice slurries have higher transport properties than single phase fluids and are referred as an advanced fluid. Ice slurry technology makes it possible to reduce volumetric flow rate for a given cooling capacity, hence decreasing equipment and pipe dimensions. The properties of interest of a single phase secondary fluid are freezing point, density, viscosity, specific heat and thermal conductivity. For ice slurry, ice concentrations and enthalpy changes are of great importance. Since ice slurry consists of a solid and a liquid phase, it is difficult to measure the thermo-physical properties with a desired accuracy. There is often a density difference between the two phases that contributes to the difficulties in measuring the thermo-physical properties. When measurements are performed with two fractions, it is difficult to get the same conditions each time, which implies that it is very difficult to obtain repeatable measurements. Many authors [5, 6, 7]have discussed the behavior of ice slurry, if and when it behaves as Newtonian fluid or non Newtonian fluids. Several experiments show that ice slurry behaves as Newtonian fluid at low ice concentrations, and as a non Newtonian fluid at high ice concentrations. Frei et al [6] and Egolf [8] used Bingham modified model which was initially proposed by Papanastasiou [2] to describe the rheological behaviour of ice slurry. Sasaki [9] has applied Ostwald-de Waele model for this solution fluid, while Benlakdar [10] used Casson model to describe the behaviour of ice slurry with ethanol-water as a carrier fluid for both Newtonian fluid and

non- Newtonian fluid. The same model has been used by Guilpart et al [11] for an initial concentration of ethanol 11 %.
The main relations [12, 13, 14] used to describe the rheological behaviour of ice slurry are;

$$\tau = k(x_g)\dot{\gamma}^{n(x_g)} \tag{1}$$

$$\mu_{app} = \frac{\tau}{\dot{\gamma}} = k(x_g)\dot{\gamma}^{n(x_g)-1} \tag{2}$$

With $n(x_g)=0{,}263+(0{,}737/1+\left(\frac{x_g}{0.112}\right)^{8.34}$ $\quad 0\leq x_g \leq 0{,}28$

And $k(x_g)=\exp(-5{,}441 + 832{,}4.\ x_g^{2{,}5})$ $\quad 0\leq x_g \leq 0{,}13$

$k(x_g)=\exp(-6{,}227 + 16{,}487.\ x_g^{0{,}5})$ $\quad 0{,}13\leq x_g \leq 0{,}28$

Even though the behavior changes with ice content and distributions, it is interesting to make comparisons between aqueous fluids by means of correlations recommended for Newtonian fluids. Another phenomenon that affects how well estimations will agree with reality is the aging of the ice particles. The shape and size of the ice particles change with time and this change affects the thermo-physical properties [14,15].

As surface strains, the shear stress τ and the pressure P appear in the motion equation of the fluid. In the case of a horizontal cylindrical pipe, the shell momentum balance equation enables to obtain an equation relating the shear stress with pressure drop, as follows [16];

$$\tau_w = \frac{R\Delta P}{2L} = \frac{D\Delta P}{4L} \tag{3}$$

Rheograms for particular suspension can be constructed if the shear rate at the wall is known. In the case of a laminar flow in a horizontal cylindrical pipe, the shear rate can be determined by using experimental data (flow rate and pressure drop), as well as Rabinowitch and Mooney's correlations [14], as follows;

$$\dot{\gamma}_w = \frac{(3n+1)}{4n}\frac{8V}{D} \qquad (4),$$

with
$$n = \frac{d\ln\left(\frac{D\Delta p}{4L}\right)}{d\ln\left(\frac{8V}{D}\right)} \tag{5}$$

The n parameter which characterises the flow index as well as the type of the fluid, represents the slope of the curve of $\ln\left(\frac{D\Delta P}{4L}\right)$ versus $\ln\left(\frac{8V}{D}\right)$.

3 Experimental procedures

The experimental rig which is shown in figure 1 is composed of two closed and independent cycles. The link between the two parties is an open 270 litres storage tank made of stainless steel, well insulated and equipped with an agitator type having a power of 150 W. This agitator operates continuously, therefore ensuring good mixing of the brine solution, and producing a homogeneous mixture throughout the experiment. The equipment used in the production part consists of a 16 KW condensing unit and a compressor while the used refrigerant fluid is the R404A of 10 kg charge. The inlet and outlet temperatures of the distribution loop section are measured by two T type thermocouples calibrated with thermostatic alcohol bath. The test section is well insulated to prevent the heat loss and heat transfer across the walls.

Five experimental tests were performed on each aqueous solution of Mono Propylen Glycol (MPG). The ice mass concentration varied between 5 and 25 %, to characterise the rheological behaviour of ice slurries. At given initial MPG concentration and temperature (ice fraction), the rotation speed of the pump motor is varied in order to have five mass flow rate measurements, (400 to 2000 kg/h) for every ice fraction. Temperature, mass flow rate and differential pressure drop are continuously recorded. The same procedure is repeated for different initial MPG mass concentration.

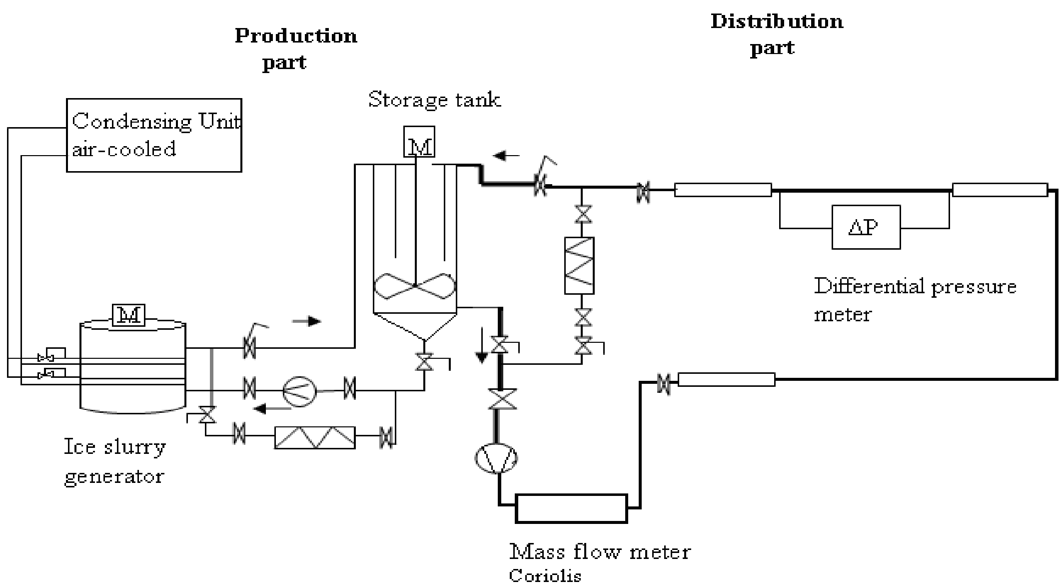

Figure 1 Experimental Rig

4. Results and discussions

(Fig. 1) shows the effect of the flow velocity, five ice mass fractions (Xg) and three MPG mass concentrations (Xi) on the pressure drop of the ice slurry, across a horizontal pipe. It can be seen that the pressure drop varies proportionally with the velocity, the ice mass fraction as well as the initial mass concentration of MPG.

When the initial MPG (Xi) concentration is < 14 %, the ice slurry has a non Newtonian behaviour, showing shear thinning or shear thickening, and becomes Newtonian when Xi is ≥ 14 %, for lower ice fraction (Xg≤ 15 %) and non Newtonian for higher ice fraction. However, as Xi and Xg increase, the pressure drop becomes more important even at lower velocities. The reason for this could be that there is stratification between the liquid and the ice at low velocity. Because there is more ice in the upper wall of the pipe which could increase the pressure drop as a result of friction between the ice particles and the wall of the pipe.

These results enable to assume that ice slurries behave like Newtonian and non-Newtonian fluids. In the latter case, their behaviour is best described by Ostwald - Waele's power law model.

The assumption of non- Newtonian behaviour can be validated by the flow index parameter, n, derived from (Eq.4), as well as the variation of the shear stress with the shear rate. (Fig. 3) represents the variation of the flow index parameter, n, with respect to Xg and Xi, while (Fig. 4) shows the effect of the shear rate ($\dot{\gamma}$) on the shear stress (τ). It can be seen from both figures that when Xi is < 14 %, two cases appear: (n >1 and n< 1), suggesting non Newtonian flow behaviour, while for Xi = 24%, n is very close to 1 when Xg < 15 %, corresponding to a Newtonian flow. .

Conclusions

The present study has presented a rheological characterization of ice slurry of aqueous solution of Mono propylene glycol (MPG) using capillary viscometer principles in order to determine the pressure drop and mass- flow rate. The analysis has enabled to show that the ice slurry behaves as non- Newtonian for low initial MPG concentration 14 %, and high ice mass fraction. It was also observed that for higher initial MPG mass concentrations and, the pressure drop increases with low velocities especially for high ice mass fraction.

It is recommended to carry out further investigations related other solutes and including heat transfer measurements in order to confirm the present rheological characterisation of ice slurry.

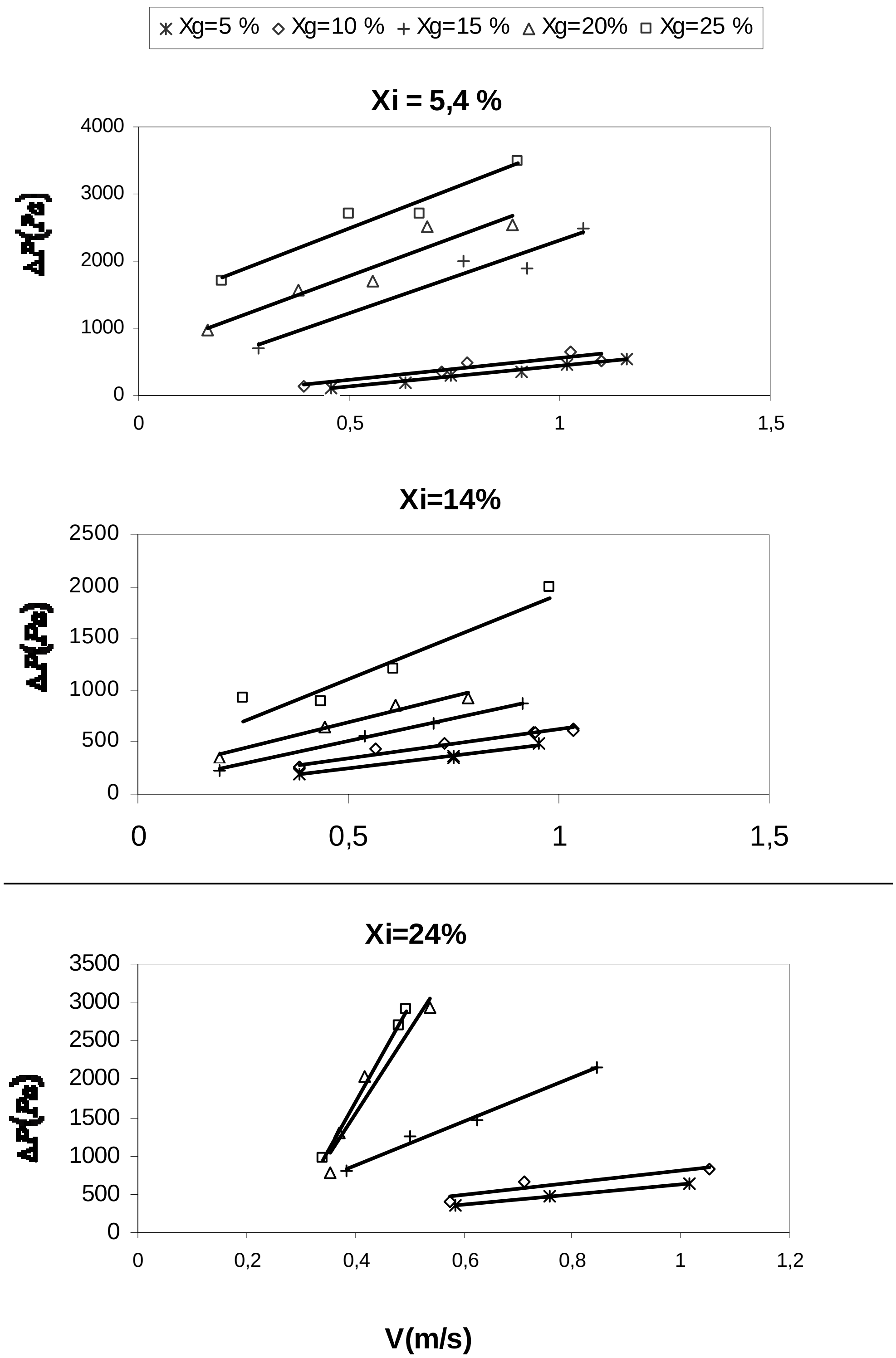

Figure 1: Effect of the flow velocity, ice and solute mass fractions on the pressure drop

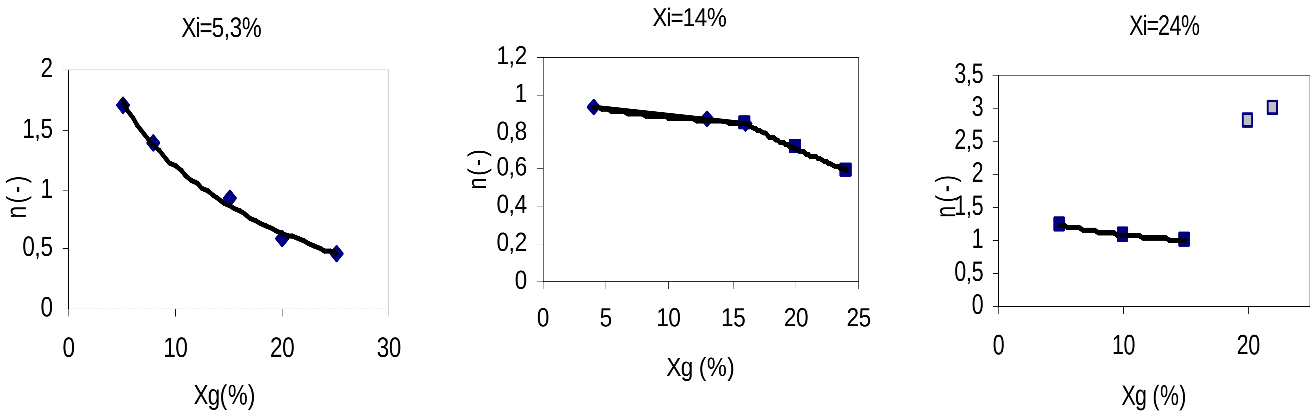

Figure 3: Flow index curves as a function of ice fraction for D_i=2.7 cm.

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Nomenclature

D : diameter (m)
k : consistency coefficient
L : pipe length (m)
n : flow index
P : pressure (Pa)
R : cylinder radius (m)
V : flow velocity ($m.s^{-1}$)
x :mass concentration (%)
μ : dynamic viscosity (Pa.s)
μ_∞ : Bingham limiting viscosity(Pa.s)
Δ : difference
τ : shear stress (Pa)
τ_y : Herschel-Bulkley yield stress(Pa)
τ_w : shear stress on tube wall(Pa)
τ_o : Bingham yield stress(Pa)
τ_c : Casson yield stress(Pa)
$\dot{\gamma}$: shear rate (s^{-1})

Subscripts

app : apparent
s : solid particle, ice
i : initial concentration of MPG
g: ice

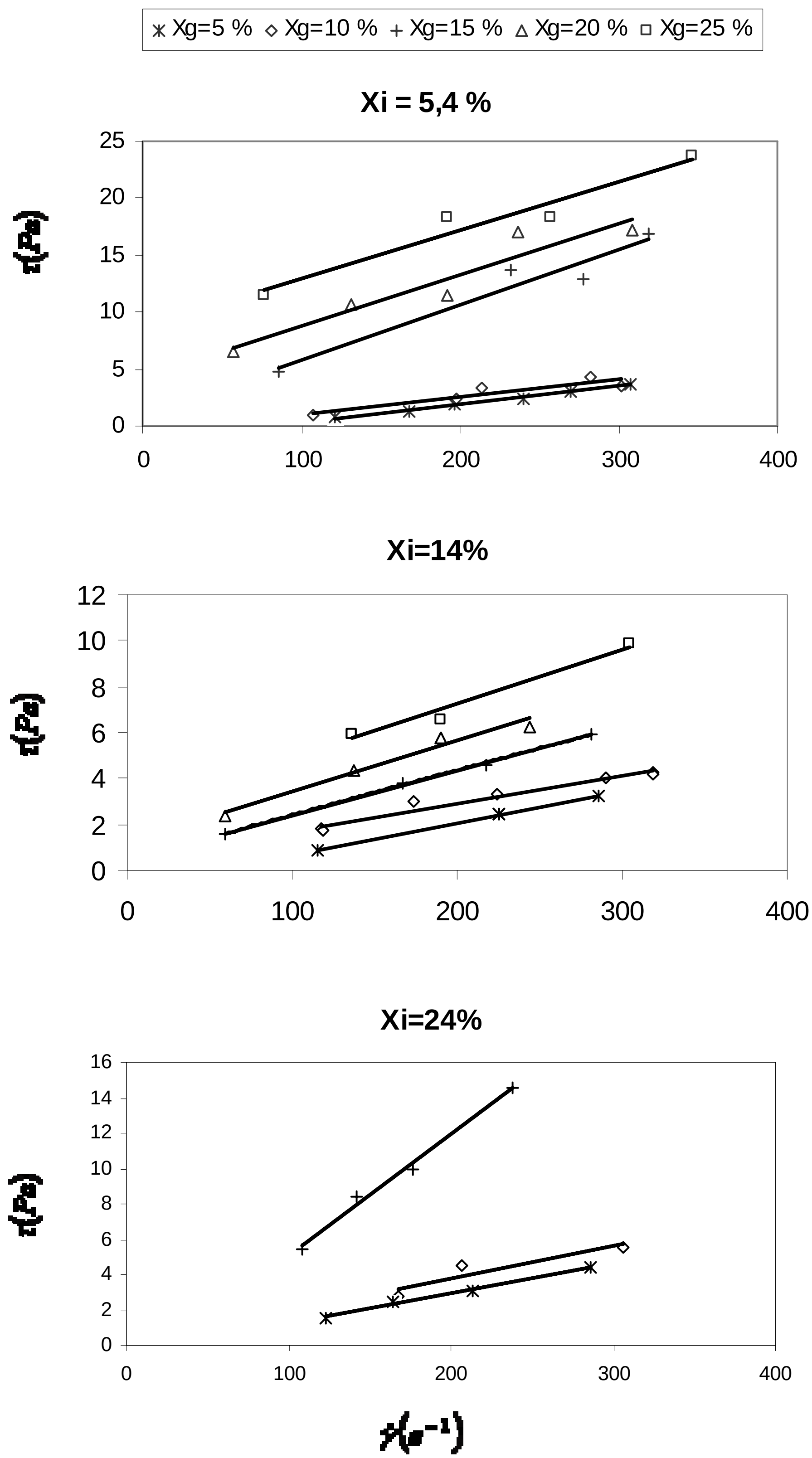

Figure 4: Rheograms of ice slurry (effect of shear rate on shear stress) .

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