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Optimization of Transport Characteristics of Ice Slurry Flows in Horizontal Pipe

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

Keywords: Ice slurry, MPG Solute, Transport capacity, Pumping power.

1.INTRODUCTION

The ice slurry is a fluid consisting of ice particles dispersed in aqueous solutions. The 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 to the latent heat of fusion, zero environmental impact, pump-able, extend 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 standard equipments...).

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. The effect of flow rate, ice concentration and pipe diameter on the transport capacity of ice slurries was addressed by Grozdek,2009 and Kauffeld *et al*.,2005. Finally, this work aims to present the influence of initial MPG concentration and ice fraction on transport characteristics of ice slurries in horizontal tube.

2.TRANSPORT CHARACTERISTIC OF ICE SLURRI

In order to evaluate transport characteristics of ice slurry flow based on MPG as a solute in horizontal tube transport capacity and required pumping power was determined on the basis of experimental results.

2.1. Transport capacity

The transport capacity is calculated as cooling energy that could be provided at "full melt off" to the initial freezing temperature given by the initial MPG concentration:

$$\dot{Q} = \rho_{is} U_d S(h(x_i, T_i) - h(x_i, T)) \qquad \text{Eq. (1)}$$

The enthalpy of ice slurry,h, at a temperature,T, can be written as :

$$h_{is}(T) = (1 - x_g) h_l(x_{i,} T) + x_x(-L_f + h_g(T)) \qquad \text{Eq. (2)}$$

where L_f is the latent heat of fusion of ice at 0 ° C (333.6 kJ kg-1) and h_g is the enthalpy of ice calculated by the expression cited by Bel,1996:

$$h_g = -332.4 + (2.12 + 0.008T)T \qquad \text{Eq. (3)}$$

The specific enthalpy of the liquid phase is obtained from the expression of the heat capacity of the liquid phase:

$$h_l(T) = \int_0^T c_{p_l}(T) dT \qquad \text{Eq. (4)}$$

The specific heat of the liquid phase is determined by the approach of Lugo et *al*., 2002 described earlier by BenLakhdar *et al.* 1998 and Guilpart *et al*., 1999. A simple reasoning of the expressions given by Lugo et *al*., 2002, for a eutectic mass fraction of MPG equal to 0.6, gives us the following correlation:

$$c_{p_l}(T) = (a_1 - a_2 x_i - a_3 x_i^2)(1 + a_4 x_i T) \qquad \text{Eq. (5)}$$

With: a_1=4.2058, a_2=1.29583, a_3=0.49528 and a_4= 2.25 10^{-3}

2.2. Required pumping

While the required pumping power is determined according to pressure drop and fluid volume flow and is expressed per meter of tube length, the overall efficiency of the pump, η, was fixed at 0.65:

$$P = \frac{U_d S.\Delta p}{\eta} \qquad \text{Eq.(6)}$$

3. EXPERIMENTAL SETUP

3.1. Experimental apparatus

Applying the principle of capillary Viscometer measure pressure drop and velocity, one can establish the experimental rheograms ice slurry. The experimental setup (Fig.1) consists of two independent closed loops.The vaporization latent heat of the refrigerant fluid cool the secondary refrigerant fluid and provoke the formation of fine particles of ice on the external surface of two plates evaporator situated in a brushed surface heat exchanger Heatcraf type. In distribution cycle part, we carried out the measurement. The loop components are: Coriolis mass-flow meter ABB/ MC 2000 type (max. mass flow 6000kg.h^{-1}), calibrated from 0 to 4000 kg h^{-1}, density from 950 to 1050 kg.m^{-3}, with ±1% accuracy. The loop is equipped with differential pressure meter

ROSEMOUNT type; Model 3051/3001 ranges of 0 to 40 mbar, with ± 0.1 % accuracy, each with a separating distance of 1 m and a diameter of 2.54 cm.

The inlet and outlet temperatures of the loop of distribution are measured by two T type thermocouples (copper-constantan, with 1.5 mm diameter) calibrated with thermostatic alcohol bath (type KB25-1Calcon) in range of -15 ÷ 0 °C, with 0.5 K accuracy. Test section are well insulated using Armaflex insulating form to prevent the heat loss and heat transfer across the walls to the ambient was neglected.

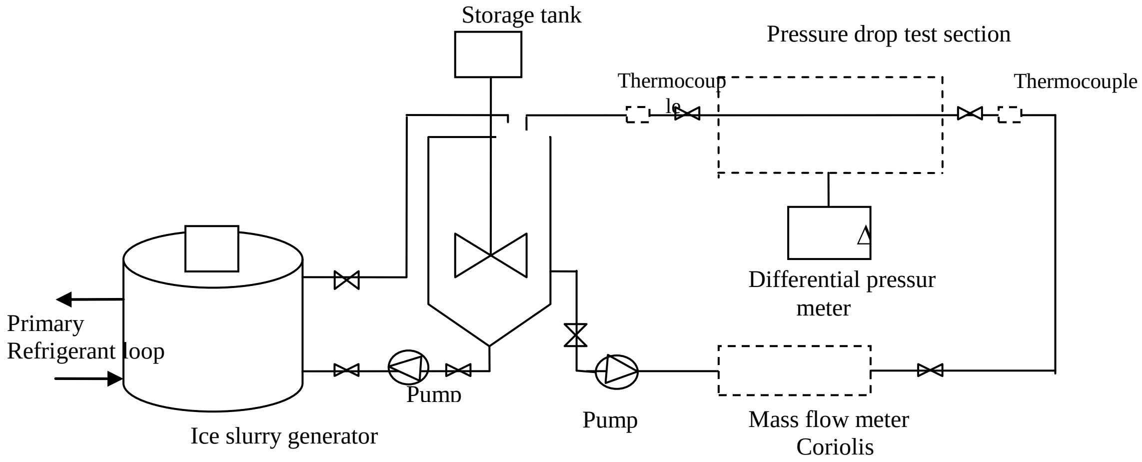

Figure 1: Layout of simplified flow chart of the experimental setup

3.2. Determination of ice fraction

Direct measurements of this parameter are still poorly developed, so a theoretical conversion model for determining ice fractions from the measured variables, temperature and initial MPG solute,were used as part of this work.

$$x_g = \frac{x_f - x_i}{x_f} \qquad \text{Eq. (7)}$$

The volume fraction of ice C_v is calculated easily from the ice mass fraction by:

$$C_v = x_g \frac{\rho_{is}}{\rho_g} \qquad \text{Eq. (8)}$$

Where ρ_{is} is the measured density of ice slurry and ρ_g is the density of ice calculated by the expression of Levy, 1982:

$$\rho_g = 917 + 1.7310^{-4} T \qquad \text{Eq. (9)}$$

4. RESULTS AND DISCUSSION

The Figs. 2 (a-e) show the variation of the transport capacity (in kW of cooling at full melt off) in the pipe for the five fixed initial MPG concentrations versus the velocity in the conduct of characterization (D=2.54 *cm*, L=1*m*) for a fixed initial mass concentration of MPG x_i = 5, 11, 14, 19, 24% and varying fractions of ice 0% < x_g < 25%.

The Fig. 2 shows the linear dependence of the transport capacity with the average velocity. One can observe that the transport capacity increases with increasing ice fraction and the initial MPG concentrations. On the other hand, one can observe clearly that the level of increasing of the transport capacity for a given ice fraction to an another is higher up to an initial MPG concentration of 15%. (Important latent melting heat of ice) and too higher for high ice fractions.

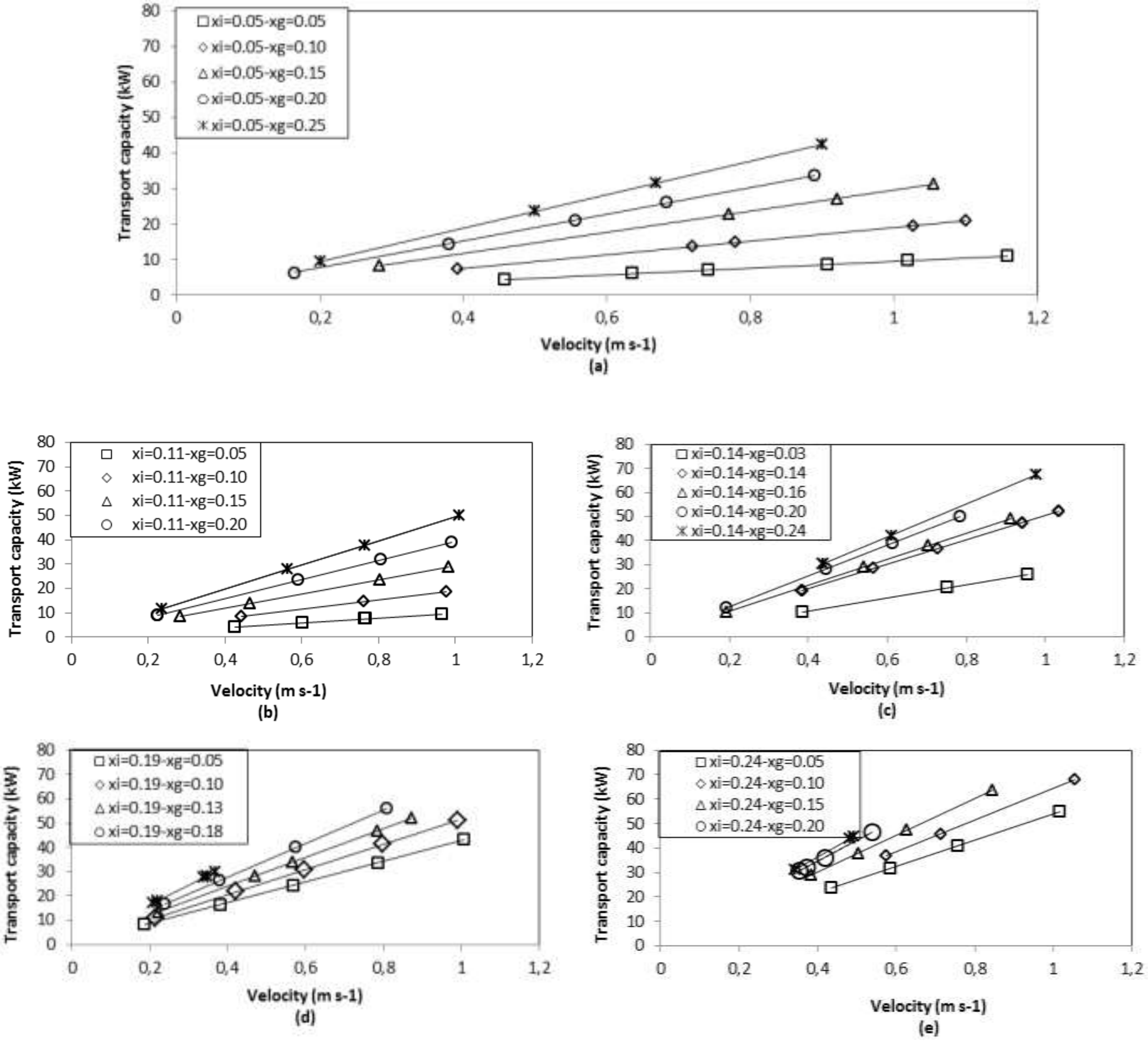

Figure 2: Ice slurry transport capacity for x_i=5% (a), x_i=11%(b), x_i=14%(c), x_i=19% (d) and x_i=24% (e)

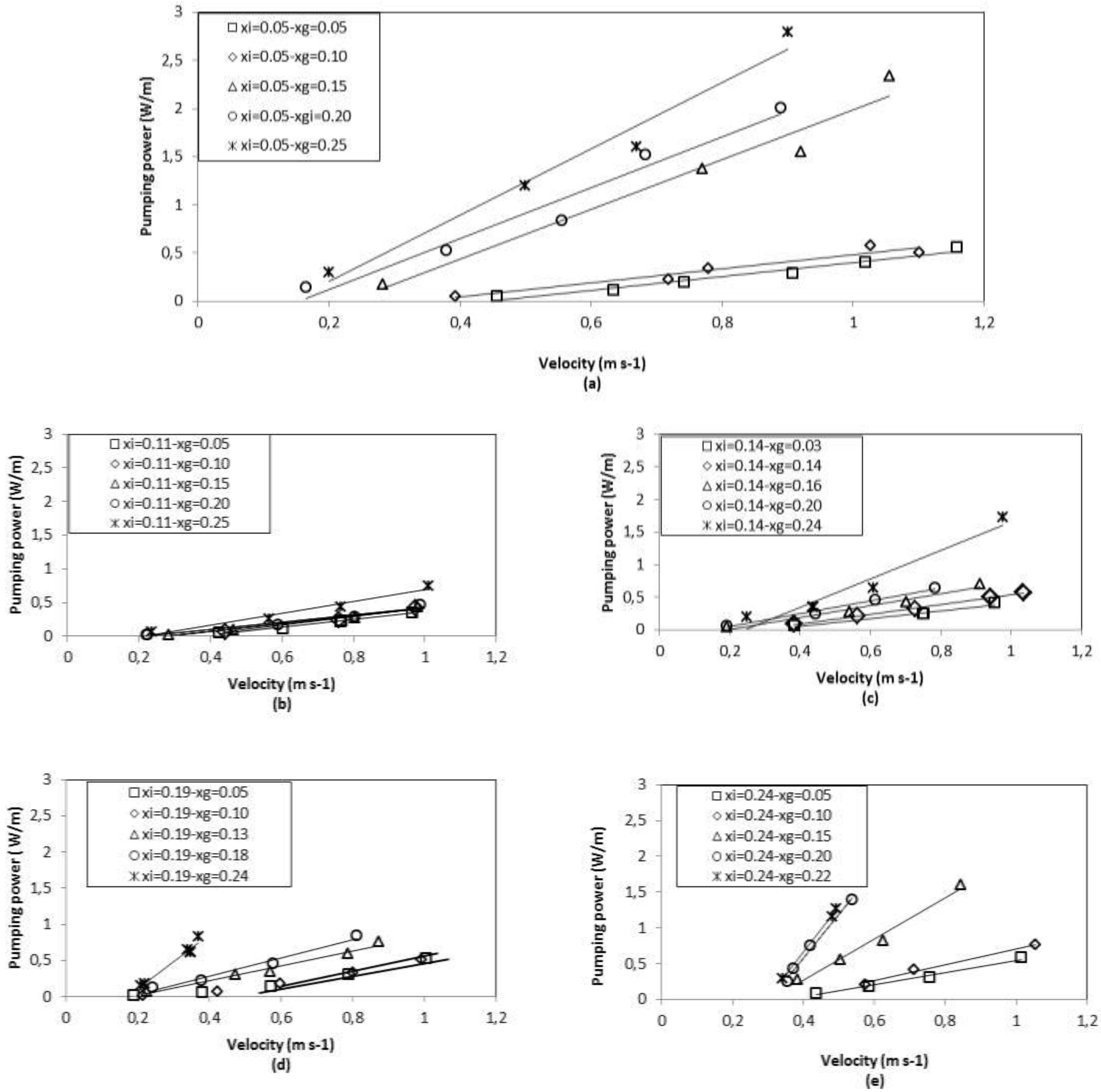

Figure 3: Ice slurry pumping power for x_i=5% (a), x_i=11% (b), x_i=14%(c), x_i=19% (d) and x_i=24% (e)

In Figs. 3 (a-e), the required pumping power of the five fixed initial MPG concentrations is plotted versus the velocity. One can observe the linear dependence of required pumping power with velocity. One can also observe the required pumping power increases with increasing ice fraction and initial MPG concentrations.

However, the rate of increasing of pumping power an ice fraction to an is less up to a certain ice mass fraction it starts to increase rapidly. The values of these ice mass fractions are: x_g=0.10 for x_i=0.05; x_g=0.20 for x_i=0.11; x_g=0.16 and 0.20 for x_i=0.14; x_g=0.10 for x_i=0.19 and x_g=0.05 and

0.10 for x_i=0.24. This suggests the existence of local maximum for transport capacity and pumping ratio at a certain velocity.

On the other hand, the rate increases too more for 5% initial MPG concentration and for the three pair of xi and x_g :(x_i=0.19 and x_g=0.24) and (x_i=0.24, x_g=0.20 and 0.22). in effect, it is observed that for the solute concentration of 5% there is a considerable increase in pressure drop with the increase of the concentration of ice, since it is estimated that with low concentrations of solute the particle diameters are larger which says that the interparticle interactions are important, while for (x_i= 0,19 and x_g= 0,24) and (x_i= 0,24, x_g= 0,20 and 0,22) the pressure drop are very high at low speed ($0.2 \leq V \leq 0.5$ m.s^{-1}), This can be interpreted by the ice slurry structure, in fact, the average particle diameter decreases with increasing solute concentration at this stage, the particles are finer and their sizes are smaller than50 μm given by the work of Stamatiou,2005, so because of the small size, these particles can interact remotely from each other by different forces such as colloidal forces of London-Vander Waals cited by Hunter,1993, which has the effect at high concentrations of ice, the particles tend to stick together and form an agglomeration in the upper part of tube($\rho_g \prec \rho_l$).

This also explains that the usual operating speeds are too low to avoid separation and that they are below the critical deposition velocity which is of the order of 0.3 m.s^{-1}. Snoek, 1993 located in the vicinity of this speed 0.25 m.s^{-1} for an ice content of 25%.Under these conditions the pumping energy must be increased. In Fig.4 the transport capacity to the pumping power ratio is displayed versus velocity for different ice fraction at five fixed initial MPG concentration. Up to a velocity of 1.0 m.s^{-1}, 11% initial MPG concentration yields the best result. 19 and 24% initial MPG concentration and for a lower ice fraction offer the acceptable results. The lowest ratio in the almost entire velocity range is given for 5% initial MPG concentration. One can read directly in Figure 19 that the maximum values of this ratio are: 0.392 m.s^{-1}for (x_i=0.05-x_g=0.10); 0,223 m.s^{-1}for (x_i=0.11-x_g=0.20); 0,192 m.s^{-1}for (x_i=0.14-x_g=0.16) ; 0,213 m.s^{-1}for (x_i=0.19-x_g=0.10) and 0.436 m.s^{-1}for (x_i=0.24-x_g=0.05). Although lower flow velocities offer a high ratio of transport capacity and pumping power. Two lower flows of the velocities is not desired from an operational point of view, the flow can lead to system blockage.On the other hand, in order to avoid phase separation in horizontal pipe, the minimum velocity can be calculated from Eq. (10) of Guilpart cited by Kauffeld *et al*., 2005. For additional safety, it is recommended to dimension the piping so as to avoid velocities lower than twice the minimum velocity, u_{min}.

$$u_{\min} = 1.4\sqrt{g.D.\left(1-\frac{\rho_g}{\rho_l}\right)} \qquad \text{Eq.(10)}$$

Which means 0.215 ms^{-1}for (x_i=0.05-x_g=0.10); 0.221 ms^{-1}for (x_i=0.11and x_g=0.20); 0.224 ms^{-1}for (x~~i~~=0.14 and x_g=0.16); 0.229 ms^{-1}for (x_i=0.19 and x_g=0.10) and 0.236 ms^{-1} for (x_i=0.24 and x_g=0.05).

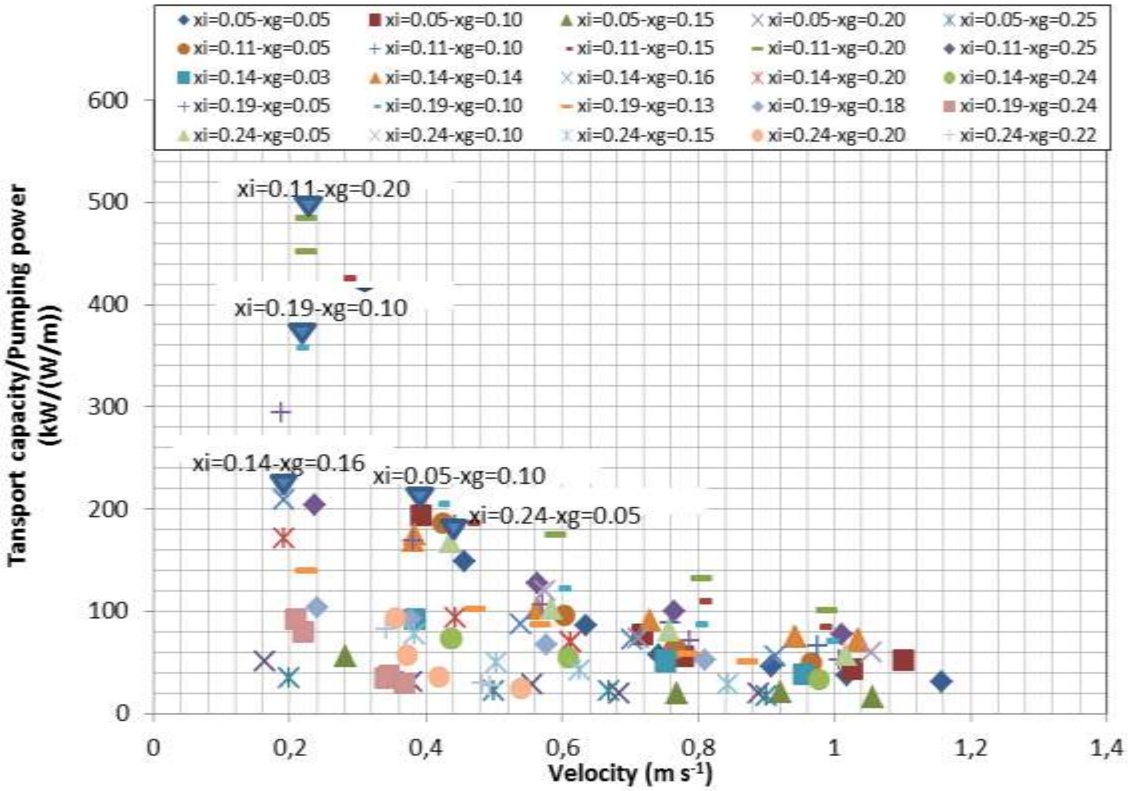

Figure 4: Ratio of ice slurry transport capacity and pumping power versus average velocity for 2, 54 cm tube.

3. CONCLUSIONS

With thes results we could highlight: the influence of the ice concentration and the influence of solute concentration on ice slurry transport characteristic.

From a transport point of view in order to exploit the advantages of ice slurries over conventional fluids it is recommended to keep the ice fraction at (x_g=0.10 - x_i=0.05); (x_g=0.20 - x_i=0.11); (x_g=0.14 - x_i=0.16); (x_g=0.10 - x_i=0.19) and (x_g=0.05 - x_i=0.24). While for velocity it is concluded that:

For D=2.54 cm the velocity should be kept as high as possible but still in laminar regime; which means a velocity up to 1.0 ms^{-1}.If minimum pumping power is desired, the flow velocity should be kept as low as possible, but still enough to meet cooling requirements and more than minimum velocity to prevent system blockage. Generally, regarding ice slurry transport characteristic, one can recommend that for ice slurry based on MPG as the solute, the initial concentration of 11% gives the best results because it has the lowest pressure drop at the velocity between 0.2 and 1.0 ms^{-1} whatever ice mass fraction.

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NOMENCLATURE

C	vomum fraction (m^3 × m^{-3})
cp	specific heat (kJ × Kg × K^{-1})
D	diameter (m)
g	gravity constant (ms^{-2})
h	enthalpy (kJ × kg^{-1})
L	pipe length (m)
L_f	latent heat (kJ × kg^{-1})
p	pressure (Pa)
P	required pump power (W)
$\dot{Q}$	transport capacity (kW)
S	section (m^2)
T	temperature (°C)
U_d	average flow velocity (m×s^{-1})
u_{min}	minimum velocity (m×s^{-1})
x	mass fraction (kg ×kg^{-1})

Greek Symbols

η	overall efficiency
ρ	density, kg m^{-3}

Subscripts

l	carrier fluid
f	final mass MPG
g	ice
i	initial mass MPG
is	ice slurry

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