ICE CONCENTRATION MEASUREMENT AND CONTROL FOR ICE SLURRY PIPE FLOW

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ABSTRACT

Ice concentration must be accurately known for most experimental researches about ice slurry and its selected value must be maintained steady during test time to assure the validity of the results obtained.

The aim of this work is to present the practical solutions adopted in an experimental study to achieve the two above cited requirements in a wide range of operation conditions.

The ice content determination method employed in the experimental analysis presented is based on the density measurement by means of a Coriolis mass flow meter. It will be presented the basis of this method and will be discussed all factors that could influence the accuracy of the ice concentration determination, as well as the solutions adopted to evaluate the influence for each of these factors.

In the same way, it will be analyzed all the factors that could cause differences between the actual concentration for an ice slurry flowing in a pipe and the mean concentration of this ice slurry when it's stored in a stirred tank. It will be expounded the results of these analysis and the measures adopted to prevent wrong data. In this way, experimental test to obtain ice slurry properties could be developed at an equilibrium situation for the ice slurry along its freeze curve, independently of ice content, flow velocity or any other influence factor, and simultaneously ice concentration could be fixed and exactly determined for all test time.

1. INTRODUCTION

Ice slurry properties depend on many different parameters, but ice concentration is the most important of all of them. For this reason, any experimental research about ice slurry has two essential requirements: ice concentration must be accurately known and its value must be maintained steady during test time.

According with Hansen and Kauffeld [1], to determine ice concentration various physical properties of ice slurry directly related with this concentration can be used. Many different measuring principles could be distinguished for ice concentration measurement, depending on the physical property and the technology employed to measure it. The most usual classification of these measuring principles is based on the physical properties observed.

All measuring techniques have their application field and there is not appropriate to affirm that one of them is the most adequate, since its depend on the specific application. Nevertheless, in an experimental research the measure accuracy must be a priority objective and in most of cases it is also necessary to obtain this measure in-line with short time response.

These requirements reduce strongly the number of techniques available. According with Hansen and Kauffeld, there are three physical properties that could be easily measured in-line: temperature, density and, in a lower degree, electrical properties.

The experimental facility employed requires an accurate method to measure the mass flow, and due to practical considerations the equipment chosen to measure it was a Coriolis effect mass flow meter. For this reason, at last only the measurement methods based on temperature and density determination were take into account, and the measure of electrical properties was discarded.

In following paragraphs of this work, the accuracy of the two proposed methods will be analysed. The final conclusion obtained is that, in general terms, the method based on density measurement has a better accuracy than the method based on temperature measurement, although density measurement is much more expensive.

Therefore it seems clear that the ice concentration measurement based on density determination is the most appropriate technique for an experimental research, assuming that economic cost is a secondary factor. The main disadvantage of this method is that the presence of air in the system is believed to influence the measuring uncertainty considerably.

Nonetheless, in many cases the accurate known of the ice concentration flowing through the facility is not sufficient. Many experimental tests require, besides an accurate measurement of ice concentration, to maintain steady the selected value during test time to assure the validity of the results obtained.

This objective could be achieved fitting the experimental facility with a high capacity storage tank. This storage tank acts like a shock absorber, minimizing the influence that start and stop periods of the generation system has on ice concentration.

But even with a system capable of maintaining ice concentration stable into the storage tank, there are a lot of parameters that could separate the concentration of the flowing ice slurry to the concentration of the stored ice slurry. If this case is presented, the ice slurry is flowing in a thermodynamic disequilibrium situation. For this reason is necessary to fit the facility with a regulation method that must be able to compensate for the parameters that are capable to lead to a disequilibrium situation.

In the following paragraphs it will be presented the practical solutions adopted in an experimental facility to obtain an accurate measure of the ice concentration for flowing ice slurry and to maintain this concentration stable into a narrow range of variation.

2. ICE CONCENTRATION DETERMINATION.

The method finally adopted to obtain ice concentration is based on density measurement of the ice slurry flow. The reasons for this election were the higher accuracy obtained with this method compared with a temperature based method and the fact that the facility needs a Coriolis effect mass flow meter to obtain an accurate measure of the ice slurry mass flow.

2.1. Method principles

Assuming that it’s formed by pure ice crystal, the density of ice slurry can be calculated from the density of pure ice, the density of the solution and the ice concentration:

$$\rho_{is} = \frac{1}{\frac{\phi_{ice}}{\rho_{ice}} + \frac{(1-\phi_{ice})}{\rho_s}} \tag{1}$$

From this equation it immediately follows that ice content could be determined if all involved densities are known.

- Ice slurry density could be obtained with high accuracy (±0.5 kg/m^3) by means of a Coriolis effect mass flow meter.
- Pure ice density depends on its temperature, and this temperature dependence is available in many different bibliography references. The variation on ice density with temperature is so slight that in many cases it could be neglected. Nevertheless, an accurate evaluation of ice density requires knowing its temperature. This value could be obtained easy and accurately (±0.08 ºC) by means of a four wire resistance temperature detector (RTD).
- Carrier fluid density measure deserves a more detailed analysis. In first place, is necessary to take into account that the density of a solution depends on its concentration and its temperature. Therefore, to obtain ice concentration from equation (1), it must be accurately known carrier fluid temperature and

concentration, besides ice slurry density and ice temperature. The carrier fluid concentration could be easy and accurately obtained if the adequate equipment is employed. In the presented case, carrier fluid is a water-sodium chloride solution, whose initial concentration was measured by means of a conductivimeter.

However, carrier fluid concentration is not constant in ice slurry, because this value depends on ice concentration, increasing when ice concentration increase. Thus is necessary to take into account the relationship between ice slurry concentration and carrier fluid concentration. The followed reasoning to evaluate this relationship is explained as follows.

Experimental data obtained for the relationship between density and temperature of different water-sodium chloride solutions are plotted on figure 1. Similar results could be obtained in some reference like the Melinder [4] text, but finally it was chosen to work with own data due to slight differences founds with Melinder data.

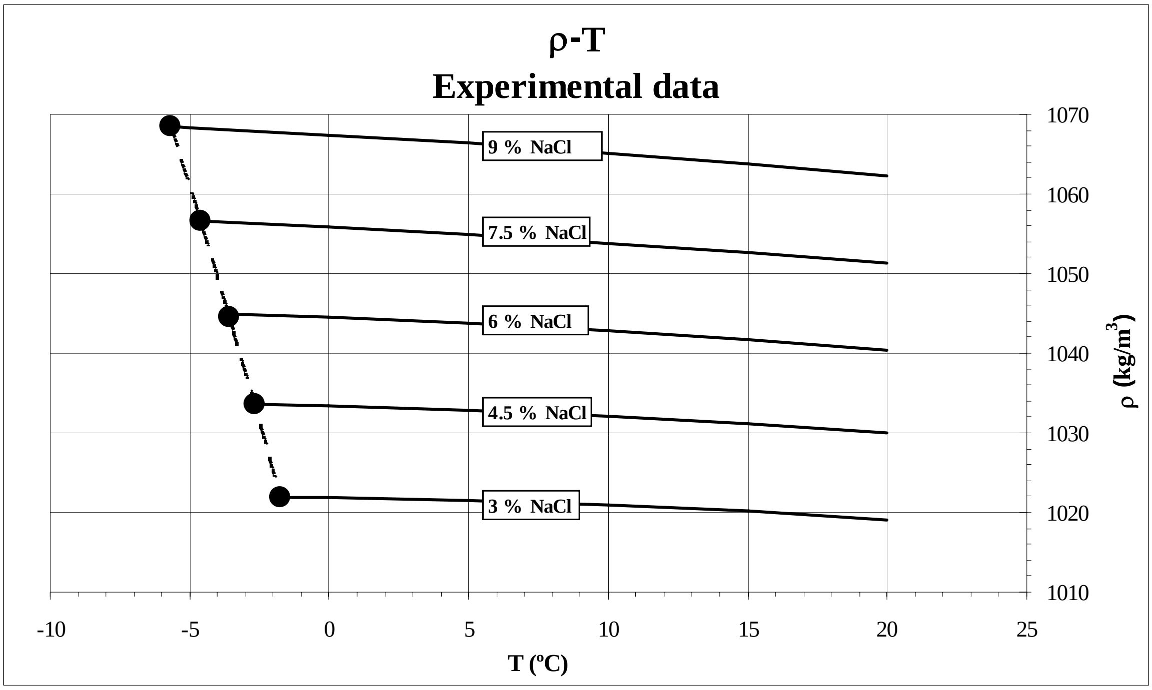

Figure 1. Freezing curve for a sodium chloride-water solution.

For any initial solution concentration there is a temperature value under which ice begins to appear. If the density and temperature values of these points are carefully measured for different initial concentration, the broken line on figure 1 could be obtained. But this broken line could also be interpreted as the evolution on the concentration (and density) of a solution when its temperature decrease under the freezing point. Therefore, knowing the mathematical expression of this curve, it is possible to obtain the density of the carrier fluid only from temperature measurement, obtaining also its NaCl concentration.

With this reasoning, it's not necessary to know initial NaCl concentration to obtain carrier fluid density, and so ice concentration could be obtained only from measurement of ice slurry density and temperature.

Even though, the experimental test developed to obtain data plotted in figure 1 must be performed with a special care, to assure a low uncertain for the mathematical expression of the freezing curve. Since over the freezing curve the solution density only depends on its temperature, the proposed method doesn't require an accurate known of the initial concentration values for the different solution employed to obtain this freezing curve. If these initial values are accurately measured, solution concentration will be obtained as an additional result that allows to employ an alternative method to obtain ice concentration, like will be presented in following parts of this work. For this reason, to obtain the results presented in figure 1, initial solution concentrations were accurately measured by means of a conductivimeter.

2.2. Method accuracy

From equation (1) the following expression to obtain ice concentration could be deduced:

$$\phi_{ice} = \frac{\rho_{ice} \cdot (\rho_s - \rho_{is})}{\rho_{is} \cdot (\rho_s - \rho_{ice})} \tag{2}$$

According with ISO *GUM* [3], uncertainty in the measurement of ice concentration is related with the uncertainty in the measurement of all parameters involved in its determination.

- Ice slurry density is measured by means of a Coriolis effect mass flow meter. The equipment employed has an accuracy of ±0.5 kg/m3, with a repeatability of ±0.2 kg/m3. Therefore, the maximum uncertainty for this equipment is u(ρis)=0.54 kg/m3.
- Ice density determination is based on its temperature measurement, using the equation proposed by Pounder [5]:

$$\rho_{ice} = 917 - 0.1403 \cdot T \tag{3}$$

  Therefore, uncertainty on ice density measurement is related with the uncertainty of the temperature measurement (±0.08ºC with a four wire RTD 1/3 DIN class B) and the uncertainty associate to the equation (3). Assigning an uncertainty of ±0.5 kg/m^3 to this expression and doing the appropriate calculation, the maximum uncertainty corresponding to ice density measurement could be fixed in $u(\rho_{ice})$=0.51 kg/m^3.
- Solution density determination is based on its temperature measurement. In this case, the mathematical equation used was obtained by regression of experimental data. So then, uncertainty on the carrier fluid density evaluation is a function of uncertainty on temperature measurement and the uncertainty associated to the mathematical regression employed.
- Experimental data plotted on figure 1 shows a high adjust (R^2=0.9999) to a second order polynomial.

$$\rho_s = a \cdot T^2 + b \cdot T + c \tag{4}$$

  Uncertainty associated to any regression is a function of uncertainty with which were obtained the experimental data employed on the adjust, in this case density (±0.54 kg/m^3) and temperature (±0.08ºC). Therefore, parameters a, b and c on equation (4) are not exactly values and they have an uncertainty *u*(a), *u* (b) and *u*(c) associated. Those uncertainties could be easily obtained using the rules for determining combined standard uncertainty presented in [3], when the mathematical expressions for the parameters a, b and c are known. The mathematical equations for parameters a, b and c are relatively easy to obtain, since they're correspond to a quadratic regression of the experimental data plotted on figure 1. Doing the corresponding calculation and taking into account the uncertainty in temperature measurement *u*(T), maximum uncertainty obtained for the carrier fluid density determination is $u(\rho_s)$=1.43 kg/m^3.

Finally, uncertainty on ice concentration determination could be obtained using the following expression:

$$u(\phi_{ice}) = \left[\left(\frac{\partial \phi_{ice}}{\partial \rho_{ice}} \right)^2 \cdot u(\rho_{ice}) + \left(\frac{\partial \phi_{ice}}{\partial \rho_{is}} \right)^2 \cdot u(\rho_{is}) + \left(\frac{\partial \phi_{ice}}{\partial \rho_s} \right)^2 \cdot u(\rho_s) \right]^{1/2} \tag{5}$$

Maximum uncertainty on ice concentration obtained with previous equation, for the measuring range of the experimental test developed (γ=0.09, ϕ=0.05÷0.3), is $u(\phi_{ice})$=0.0081.

3. CONTROL FOR ICE SLURRY PIPE FLOW

Assuming that there is no air in the ice slurry flow, the presented method allows to obtain ice concentration with an uncertainty $u(\phi_{ice})$=0.0081. Nevertheless, this uncertainty value is not constant since it depends on test conditions. Maximum uncertainty is obtained for minimum ice concentration conditions, decreasing slightly when ice concentration increase. In most of cases obtained uncertainty is sufficient, although for low ice concentration, the error associated to the measurement uncertainty represents an important part of the obtained value. So the measurement error fluctuate from minus than 2% for ice concentration of 30% (ϕ=0.3±0.005) to near of 16% for ice concentration of 5% (ϕ=0.05±0.008).

Nonetheless, an accurate knowing of ice concentration is a necessary but not sufficient condition to assure the success of the experimental tests. In most of cases is also necessary to assure that the ice concentration selected value is maintained steady into a narrow range of variation during test time to assure the validity of the results obtained.

Nevertheless, experience in last years shows this requirement is difficult to achieve. Along the experimental tests developed on these years, some different factors capable to destabilize the system could be identified. This unstable working is easy to cause and identify: in many cases, only modifying ice slurry mass flow, an important variation in measured flow density could be perceived.

Different densities between stored and flowing ice slurry implies a disequilibrium situation. Ice concentration in flowing ice slurry is not in equilibrium with antifreeze concentration in its carrier fluid. Therefore experimental tests are developed under a thermodynamic disequilibrium condition, distorting the validity of these tests.

3.1. Influence factors on ice slurry pipe flow concentration

The presence of air in the flow is believed to decrease the measured density considerably, influencing on ice concentration determination based on the measure of ice slurry density. This is a problem associated to a malfunction in any equipment of the experimental facility, so in normal conditions this problem must not be presented. Therefore, if this problem exist, not always is easy to detect, especially if is presented united with another problem that is capable to affect to ice concentration measurement.

For example, a presence of only a 1% on volume of air, in a ice slurry flow with a 25% in mass of ice, produce such decreasing in the measured density that the ice concentration measure obtained by means of a Coriolis effect mass flow meter will be 30.5%, that is, a 5,5% of absolute error.

The mentioned example is really difficult to detect by visual observation of the flow. So then, if a malfunction of the system brings about the presence of air in the flow, and ice concentration is measured by means of a Coriolis effect mass flow meter, two important errors are committed: estimated concentration is greater than real concentration and there is a third phase in the flow (air) that there is not taking into account and could modify considerably ice slurry properties.

Another aspect to asses is the functioning of the stirring system employed. An efficient stirring system must be able to maintain a homogeneous ice concentration into the storage tank. Nevertheless in many cases, in spite of an efficient stirring equipment is been used, important differences exist in ice concentration between the top and the bottom layers of the storage tank.

When these differences exist, the relative position of the suction pipe inside the storage tank has an important influence on the properties of the ice slurry flow. An aspiration pipe placed in the bottom of the tank will be produce the suction of an ice slurry with an ice concentration lower than the average concentration inside the tank; on the other hand, an aspiration pipe placed in the top of the tank will be produce the suction of an ice slurry with an ice concentration upper than the average concentration inside the tank. Moreover, in any case, the flowing ice slurry will be in a thermodynamic disequilibrium situation.

Ice slurry’s characteristics make difficult to detect these differences when they are present. In fact, is difficult to find a technique that allows detecting them. Nonetheless, experimental test developed in our facility suggest that often these differences are presents in spite a high efficiency stirring system is employed.

Stirring system can also influence in the air intake into the stored ice slurry. When a high velocity stirring system is employed, the turbulence into the storage tank is high, so the mixed is improved and there is high homogeneity in the stored ice slurry, but in the other hand increase the air intake. Figure 2 shows a microscope image taken to ice slurry stored in a tank equipped with a high velocity stirring system. It can seen the presence of air bubbles, very difficult to appreciate without the aid of a microscope, and that will affect strongly to the ice concentration obtained by means of density measurement.

Mass flow value is the third parameter which influence on ice concentration measure has been detected in developed experimental tests. In general terms, a decreasing in ice concentration measure is detected for a mass flow decrease. It seems that the velocity at which the ice slurry is sucked from the storage tank can influence on phase separation in the fluid into the tank just before it is sucked. Therefore for high mass flow values, the ice slurry which is been sucked has such a high velocity than the phases have not time to separate and the suction is homogeneous. On the other hand, for low mass flow values, the suction velocity is low and the ratio of carrier fluid sucked increase, so the suction is not homogeneous and the flowing ice slurry is not in thermodynamic equilibrium situation.

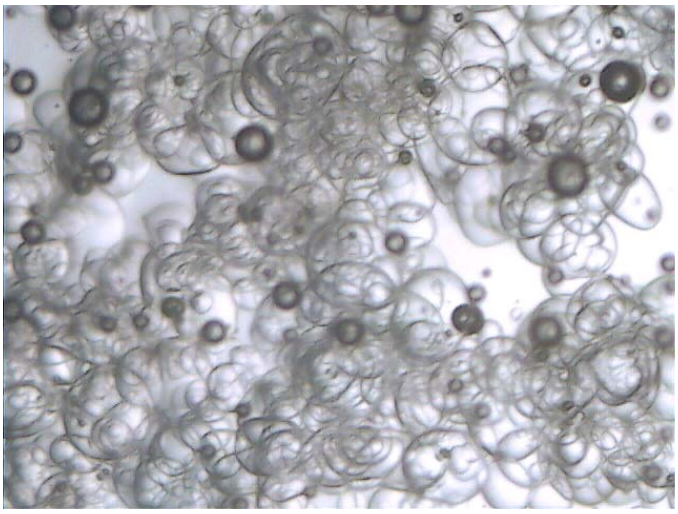

Figure 2. Air bubbles for a high velocity stirring system.

3.2. Adopted measures to control ice slurry flow

Stratification in the storage tank has a high influence in flowing ice slurry properties, so it must be avoided. Nevertheless, in many cases is clear that this stratification exits, in spite that all habitual measures to prevent it have been adopted. In those cases, the best choice is to try of minimize the influence that this stratification has on the properties of the ice slurry sucked from the tank.

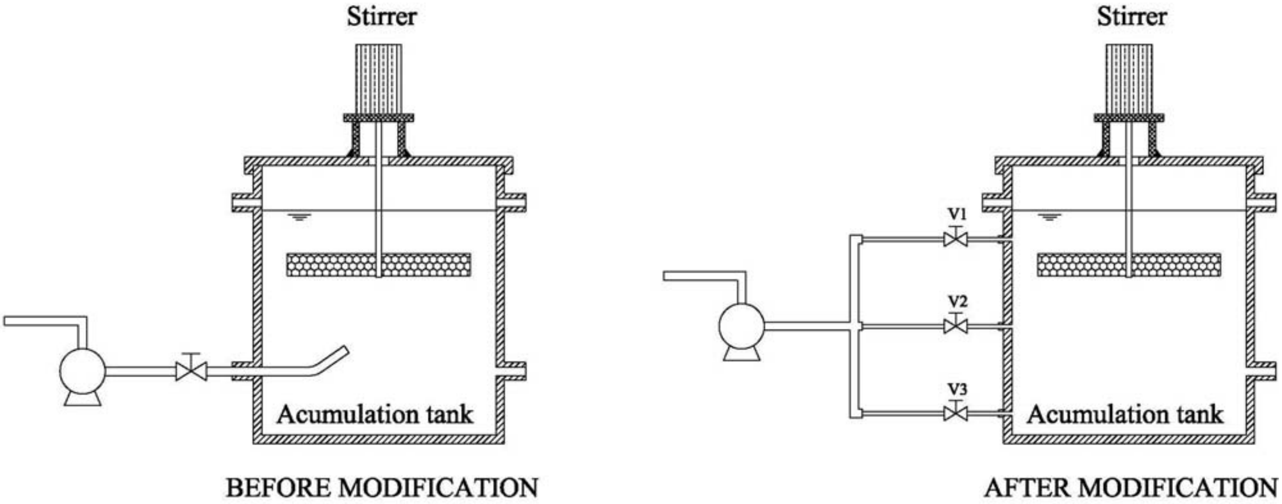

Figure 3. Adopted solution for the suction system.

The first measure adopted in our case was to place diverse suction points distributed at different highs into the storage tank. Thus, a single suction point is replaced by a suction supply system. Figure 3 shows a schematic representation of the suction system before and after its modification.

In general terms, the mass flow sucked from each suction point is different so then the system is not in equilibrium. Three factors cause this disequilibrium in the sucked ice slurry: i) the lengths of each section of the suction supply system are different, ii) the rheologic properties of the ice slurry varying with ice content (and therefore with the high into the tank) and iii) the total mass flow (and therefore suction velocity) depends on test conditions. Therefore, the ice slurry mass flowing through each suction point depends on specifics functioning conditions, varying ice concentration for the blend obtained.

Valves V1, V2 and V3 on figure 3 might be the solution for the first two problems mentioned above. A correct regulation for these valves allows to maintain in equilibrium the mass flowing through the three suction points, independently of the total mass flow. The trouble in this case is to find an adequate control system to operate these valves. This control system must be able to establish the opening rate for each valve as a function of the length of each section of the suction supply system and the characteristics of the stored ice slurry.

Nevertheless even if the suction is completely equilibrated, the third problem cited above continues existing. The mean concentration of flowing ice slurry constituted by equal mass flow of different concentration will be not constant, because it depends on the total mass flow, decreasing concentration as total mass flow decrease.

Therefore there are two different problems that, in certain mode are complementary. Final solution adopted consists in finding a regulation law different for the valves. The objective isn’t to achieve an equilibrium situation with equal mass flow through each suction point. The goal in this case is to achieve, for each suction point, the adequate mass flow to obtain a mean ice content that coincides with the ice content into the storage tank.

The proposed method consist in determine the theoretical ice concentration for the flowing ice slurry in equilibrium conditions and to compare this value with the ice content measured by means of the method described in previous parts of this work, based on density measurement. If the system is in equilibrium, these two values must be the same, in other case valves V1 to V3 must be regulated until this situation will be achieved.

Theoretical ice concentration corresponding to an equilibrium situation could be obtained from fluid temperature and carrier fluid concentration measurement.

Using the freezing curve plotted on figure 1, carrier fluid density and concentration values could be obtained from temperature measurement. Knowing this value, ice concentration is directly obtained by means of expression (6).

$$\phi_{ice} = 1 - {}^{\gamma_i}\!/\!_{\gamma_a} \tag{6}$$

Uncertainty for ice concentration obtained using this expression is strongly influenced by the uncertainty measurement for initial carrier fluid concentration and by the uncertainty associated to the regression curve obtained for the carrier fluid freezing conditions.

Uncertainty analysis shows that for the accuracy of the RTDs employed in fluid temperature measurement (±0.08ºC) and the characteristics of the conductivimeter used in solution concentration measurement (error $\leq$ 0.5% maximum value, repeatability of 0.2%, maximum uncertainty in concentration measurement $u(\gamma)=0.15$), error in ice concentration measurement fluctuate from ±0.027 for an ice concentration of 5% ($\phi=0.05\pm0.027$) to ±0.0165 for an ice concentration of 30% ($\phi=0.3\pm0.0165$).

In this point in necessary to emphasize that this method for the ice concentration measurement in only valid in equilibrium situation, leading to important errors in concentration measure if this condition is not reached. Furthermore, this method is insensitive to certain problems like air presence; this could be and advantage but also an inconvenient since in case of air presence, ice concentration will be the same, but not ice slurry properties so the validity of the results obtained is compromised.

The proposed method consists on obtain ice concentration measure by means of equations (1) and (6) and to act on regulation valves until the two obtained values will be the same. In this moment, the system will be working under equilibrium conditions and so the facility will be ready to develop experimental tests.

The main trouble is that in case of low ice concentration, the uncertainty associated to expressions (1) and (6) is high. In these cases, is possible that the system work under a disequilibrium situation without the proposed method will be able to detect it.

4. RESULTS AND DISCUSSION

To date, a great number of experimental test were carried out using the proposed method to control ice concentration for the flowing ice slurry.

The proposed method has been revealed as a very effective control method, allows to maintain ice concentration inside of a narrow variation range during all test time.

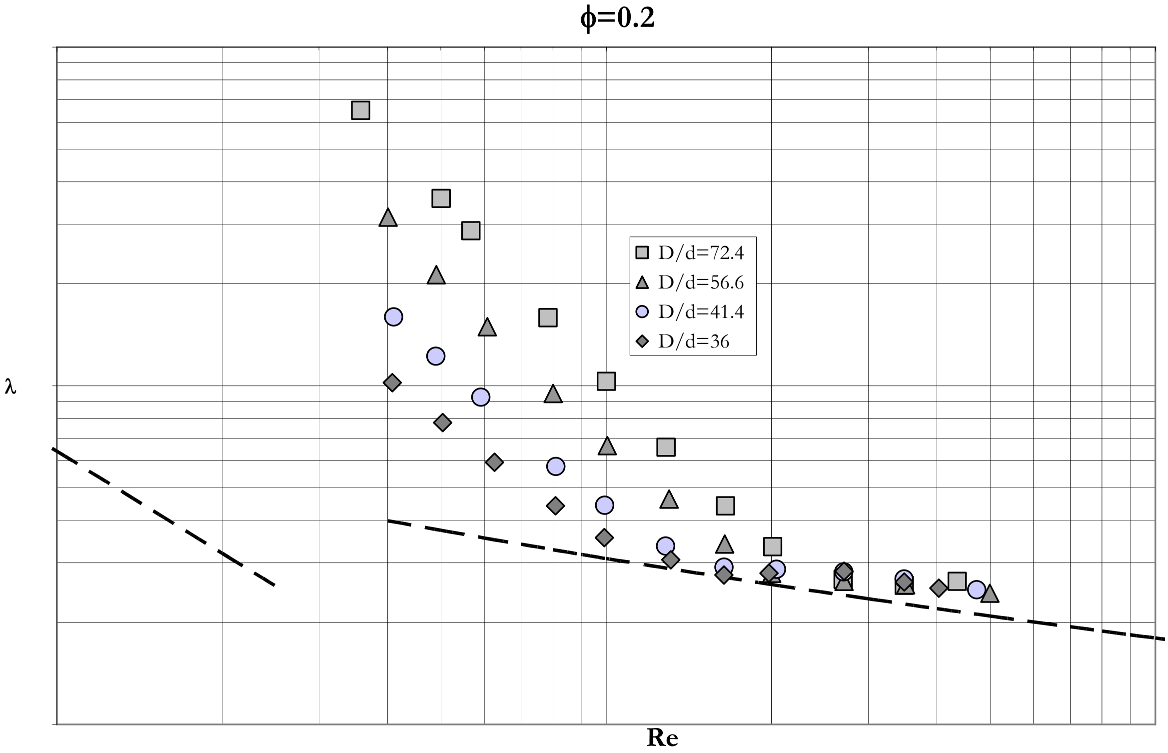

Figure 4. Results obtained employing the proposed control method.

Figure 4 has been included like a sample of the improvement achieved using the proposed control method. This figure shows how friction factor varies when varying Reynolds number, maintaining steady ice concentration. The figure shows a clear influence for the diameter ratio (*D/d*) which couldn't be perceived in previous work by the present authors [2], when the proposed control method had not been developed yet. Similar results were obtained varying ice concentration in the flowing ice slurry, showing a clear relationship between the friction factor obtained and the test condition (Reynolds number, diameter ratio and ice concentration).

The strong increase in the quality of the results obtained employing the proposed control method lead us to affirm that an effective control on ice concentration for the flowing ice slurry has been achieved, with an important improvement in results accuracy.

5. CONCLUSSIONS

A method to measure ice concentration based on density and temperature measurement was presented. Its uncertainty was evaluated.

Main factors that could keep away from thermodynamic equilibrium conditions to flowing ice slurry were analyzed. Measures to avoid this disequilibrium situation were proposed, and they effectively were discussed.

A control method capable to detect and to correct disequilibrium situations when they are present was proposed. This method is based on ice concentration measurement by means of two complementary techniques.

The major conclusions that could be obtained are the following:

- The accuracy of the proposed method to evaluate ice concentration by means of density and temperature measurement is sufficient in most of cases.
- This method is not be able to detect possible thermodynamic disequilibrium situations, therefore the method is not sufficient to assure the validity of the experimental test.
- An optimal design for the experimental facility contributes to minimize the number of disequilibrium situations but is not sufficient to completely avoid them.
- The control method presented, based on the use of two simultaneous techniques to measure ice concentration, allows to avoid in most of cases disequilibrium situations, guarantying the validity of the experimental procedure.

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NOMENCLATURE

d	crystal size	(m)	Subscripts	
D	pipe diameter	(m)	a	actual
Re	Reynolds number	(-)	i	initial
T	temperature	(ºC)	is	ice slurry
ϕ	ice concentration	(-)	s	solution
γ	solution concentration	(-)		
λ	friction factor	(-)		
ρ	density	(kg/m^3)		

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