Dimensional analysis and experimental study of pressure drop and heat transfer for Na-Cl ice slurry in pipes.

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ABSTRACT.

Over the last few years, many works have been developed to study the influence of some factors like the mass flow, pipe diameter or ice contents on the pressure drop characteristics and heat transfer process when using ice slurry as liquid secondary refrigerant. Nevertheless, most of these works present results of great scientific interest, but hardly applicable to different situations to those of test conditions and therefore they have a limited interest when approaching the design of practical ice slurry installations.

Based on the dimensional analysis, the work reported in this paper try to determine which are the variables that explain the thermal and hydraulic behaviour of ice slurry, to fix the influence of these variables and to present the results so that they can be used as a tool of design for ice slurry applications. Experimental studies were performed to clarify the thermal and hydraulic characteristics of ice slurry with a 3% sodium chloride-water solution flowing in circular pipes. A number of experiments have been carried out to investigate the characteristics of flowing ice slurry for various pipes diameter, ice mass fraction, flow velocity and ice crystal size, and the non-dimensional values have been obtained from the pressure drop (via Fanning factor) and the heat transfer (via Nusselt number).

Experimental data on friction factor are plotted on a Moody diagram. Experimental values of Nusselt number are plotted also versus Reynolds number and others parameters. Both data collection has been compared with other researcher's results, showing the most cases a good level of agreement.

KEYWORDS.

Ice slurry, industrial application, pressure drop, heat transfer, dimensional analysis.

1. - INTRODUCTION.

Ice slurry has shown important competitive advantages against other secondary refrigerants, but its industrial application in any type of process has found for its potential user the difficulty of the lack of knowledge on the properties of the fluid.

In all ice slurry industrial applications is necessary to transport fluid from the generation point to the consumption point, therefore it is necessary to make circulate the fluid through distribution pipeworks and heat exchangers. In this transport, heat transfer and pressure drop process will take place, and it is necessary to estimate this for the correct pipelines and isolation design and also for the optimum design of heat exchangers.

From the designer point of view, the evaluation of the pressure drop is relatively simple when the value of the friction factor is known, and in a similar way, the heat transfer process can be evaluated via de Nusselt number. The problem for the designer is the lack of practical engineering information available for fluid flow and heat transfer characteristics when using ice slurry as a liquid secondary refrigerant. The heat transfer and pressure drop results obtained by different researchers shows that the behaviour of ice slurries is a function of several factors like ice fraction, Reynolds number, mixture viscosity, etc. The influence of these parameters, however, is not fully characterised and there is not yet widely accepted correlations for the calculation of heat transfer coefficients and pressure drop, which can be used for the designer in his work.

Over the last few years, many works have been developed to study the influence of most important parameters on the pressure drop characteristics and heat transfer process. Nevertheless, most of these works present results of great scientific interest, but hardly applicable to different situations to those of test conditions and therefore they have a limited interest when approaching the design of practical ice slurry installations. Thus, the work of Ayel *et al.* [1] presents an extensive review of the state of the art in Rheology, flow behaviour and heat transfer of ice slurries, but in no of the reviewed works a general expression for pressure drop or heat transfer calculations appear. More recent is the review present by Kitanovski *et al.* [10]. In this case numerous research works are discussed affecting the fact that very large differences in the results are observed despite, in many cases, that the suspension was produced in identical types of ice slurry generators. Doetsch [7] present a model for pressure drop calculation based on the Casson model, which allows to calculate the drag coefficient for laminar and turbulent flow. Recently Egolf *et al.* [8] review the thermodynamics and heat transfer of ice slurries and discuss the existing measurements and calculations of heat transfer coefficient, but according with this work the question of time dependency still remains as an unresolved issue for ice slurry research.

According to Kitanovski *et al.* [10], results obtained with a general empirical determination of the friction factor based on a dimensionless analysis agree much better with experimental data than those extracted from semi-empirical models. Based on the dimensional analysis, the work reported in the present paper try to determine which are the variables that explain the thermal and hydraulic behaviour of ice slurry, to fix the influence of these variables and to present the results so that they can be used as a tool of design for ice slurry applications. Experimental studies were performed to clarify the thermal and hydraulic characteristics of ice slurry with a 3% sodium chloride-water solution flowing in circular pipes. A number of experiments have been carried out to investigate the characteristics of flowing ice slurry for various pipes diameter, ice mass fraction, flow velocity and ice crystal size, and the non-dimensional values have been obtained from the pressure drop (via Fanning factor) and the heat transfer (via Nusselt number).

2. - EXPERIMENTAL APPARATUS.

Fig. 1 shows a schematic diagram of the experimental set-up, consisting mainly of two independents circuits; the ice slurry generation circuit and the ice flow circuit.

The major component of the ice slurry generation circuit is an ordinary single stage refrigeration system (1) with the evaporator (2) being the external passage of a concentric pipe heat exchanger with the inner cylinder surface alternatively scraped. For the test conditions, the refrigeration power of the system is around 12 kW. A hydraulic unit (3) moves the alternative agitator system used to remove the ice crystals from the inside surface of the cylinder. Impelled by a centrifugal pump (4) the aqueous NaCl solution circulates through the inner cylinder and in a closed loop is discharged on the 1 m^3 capacity storage tank (5). On this storage tank there are 10 RTD's probes, which allows to know the temperature in any point and locates possible stratification. In order to avoid stratification process an agitation system (6) was installed on the storage tank. Operation of the refrigeration system is controlled by fluid temperature at evaporator outlet, so when the consign temperature is reached the installation is able to maintain stable the fluid conditions.

It's possible to transport directly the fluid from the evaporator outlet to the ice flow circuit, to study the ice generation process, but under normal conditions of operation the storage tank acts like an interface between ice slurry generation circuit and ice flow circuit. Thus, thanks to the temperature control of the generation process and the presence of a great capacity storage tank, fluid conditions can stay stable throughout the tests duration. Finally the experimental apparatus also allows to control the recrystallization process by means of the time of storage. The mean crystal size can be increased switching off the agitation system and maintaining the generation system on for a long time (from 8 to 24 hours) with a constant temperature control.

When the test conditions are reached, the fluid pass into the fluid flow circuit through a centrifugal pump (7) equipped with a frequency changer that allows to control the fluid mass flow. At an appropriate distance of that pump there is a Coriolis mass flow meter (8). From that point, the ice flow is divided in a total of six pipes, four PVC pipes of 20, 25, 32 and 40 mm diameter, a 20 mm diameter stainless steel pipe and a 20 mm diameter stainless steel corrugated pipe. In each one of these pipes it has been collocated two normalized pressure drop outlets, connected to one of the tree available differential pressure transmitter (9) of different measurement range. The determination of the crystal size is done before and after any test, through the image captured by a CCD camera connected to a stereomicroscope (10), with no need to extract a sample of ice slurry thanks to a transparent rectangular duct placed in the pipe circuit. Finally, there is a 6 kVA power electric transformer (11) which allows to apply a variable heat flow and so to perform the heat transfer tests.

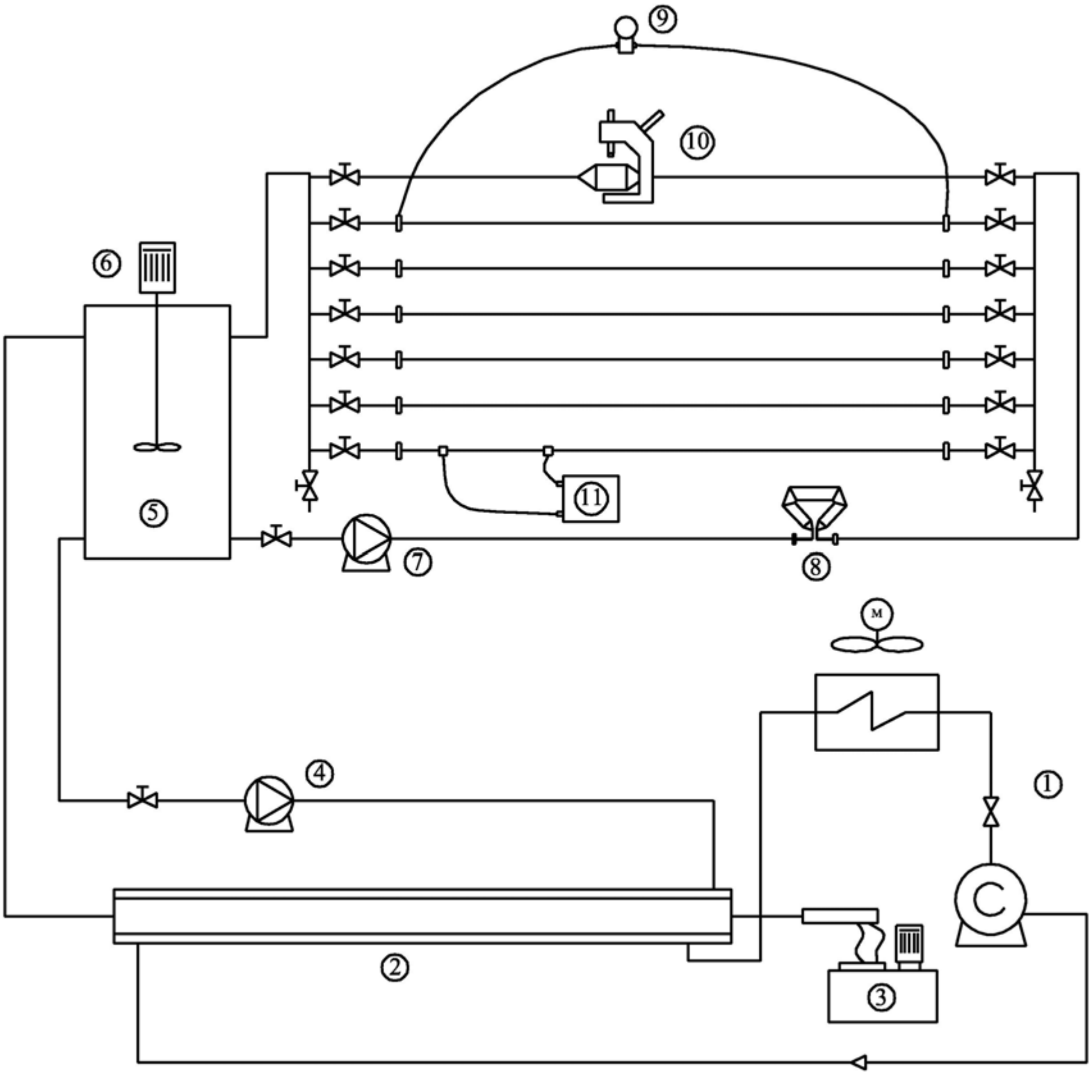


Fig. 1. Schematic diagram of the experimental apparatus.

In addition to all the already cited instruments, the facility has different RTD's probes which allows to know the temperature evolution for the fluid in different points of the circuit, the ambient temperature or the surface pipe temperature.

All the equipments describe previously are connected to a HP-3790A multiplexer that it is connected as well to a personal computer, where all the measures acquired are stored and processed.

3. - DIMENSIONAL ANALYSIS.

The dimensional analysis allows to establish the minimum number of non-dimensional parameters that are present in the problem.

PRESSURE DROP.

To assess the pressure drop in a circular and horizontal pipe with an ice slurry flow made from a solution of NaCl in water, the following parameters and variables are to be considered:

- Solution fluid properties: density ρ_s, viscosity μ_s
- Solution concentration: γ% of NaCl
- Ice variables: density ρ_i, mass fraction ϕ, average size d,
- Flow parameters: pipe diameter D, pipe relative roughness ε, mean velocity U, temperature T
- Gravity: g

At a first view, the pressure drop by length unity of the pipe is a function of all the parameter involved:

$$\Delta p / L = f(\rho_s, \mu_s, \gamma, \rho_i, \phi, d, D, \varepsilon, U, T, g) \tag{1}$$

Some considerations can be made to reduce the number of parameters or to explain better its influence:

- The ice fraction is a function of the temperature and the solution concentration $\phi = f(\gamma, T)$, so one of theses three variables can be omitted.
- The gravity is present due to the possible buoyancy effect on the ice particles. This is due to the density difference, so is more clear to expresses $g \cdot \Delta\rho$, as the parameter in play.

The above equation can be write in the way:

$$\Delta p / L = f(\rho_s, \mu_s, \gamma, \rho_i, \phi, d, D, \varepsilon, U, g\Delta\rho) \tag{2}$$

Applying the Π theorem with U, D and ρ_s as base parameters the following expression can be written:

$$\frac{\Delta p/L}{\frac{1}{2}\rho_s U^2/D} = f\left(\frac{\mu_s}{\rho_s UD},\gamma,\frac{\rho_i}{\rho_s},\phi,\frac{d}{D},\varepsilon,\frac{g\Delta\rho D}{\rho_s U^2}\right) \tag{3}$$

The left term of the expression (3) is the friction factor and the non-dimensional parameters on the right are:

- Inverse of the Reynolds number.
- Solution concentration γ and ice mass fraction ϕ.
- Ice-solution density ratio ρ_i/ρ_s
- Ice particle - pipe diameter ratio *d/D* and pipe relative roughness ε
- Square of the ratio between buoyancy related velocity, $\sqrt{g\Delta\rho D/\rho}$, and mean velocity *U.*

This last parameter is the one responsible for the stratification of the ice in the horizontal pipe flow when the mean velocity is low. According to Kitanovski and Poredoš [9], the concentration profile of ice slurry flow can be determined using the diffusion equation of the turbulent flow. The transition from heterogeneous flow to that with a moving or stationary bed depends on this concentration profile, that can be determined knowing the local diffusion coefficient and the local hindered terminal velocity of the ice particle. These parameters are function of pipe diameter, ice particle size, ice-solution density ratio, average concentration and velocity, but depending on ice concentration, in general terms transition occurs for a buoyancy parameter value near 0.075.

For a fixed solution concentration, ice density constant and assuming that the pipe is smooth, the relationship is reduced to:

$$\lambda = f\left(\mathrm{Re},\phi,\frac{d}{D},\frac{g\Delta\rho D}{\rho_s U^2}\right) \tag{4}$$

Not all these parameters have been varied in the performance test. Assuming that in our experimental test flow velocity is fitted to obtain a buoyancy parameter lower than 0.075, only ice fraction, diameter ratio and Reynolds number are considered in the results presented. So the results will be given in the way $\lambda = f\left(Re,\phi,\frac{d}{D}\right)$

HEAT TRANSFER.

To study the heat transfer when the flow is exposed to a hotter pipe wall temperature, some additional parameters have to be added to the previous study:

- Solution thermal properties: specific heat c_s, heat conductivity k_s, expansion coefficient $\beta = -\frac{1}{\rho}\frac{\partial \rho}{\partial T}$
- Ice thermal properties: specific heat c_i, heat conductivity k_i, melting latent heat h_{sl}
- Pipe wall temperature T_p

So the heat transfer to the flow, by surface unit, is a function of:

$$\dot{q} = f\left(\rho_s, \mu_s, c_s, k_s, \beta, \gamma, \rho_i, c_i, k_i, h_{sl}, \phi, d, D, \varepsilon, U, T_o, T_p, g\right) \tag{5}$$

Using some of the above simplifications introduced and expressing the buoyancy effect due to the thermal expansion associated to gravity, this relation can be expressed as.

$$\dot{q} = f\left(\rho_s, \mu_s, c_s, k_s, g\beta\Delta T, \gamma, \rho_i, c_i, k_i, h_{sl}, \phi, d, D, \varepsilon, U, \Delta T, g\Delta\rho\right) \tag{6}$$

Now it is clear that two buoyancy effects are present: the one due to the ice lower density and the other due to the liquid thermal expansion.

Taking $\rho_s, D, U, \Delta T$ as the basic parameters for the Π theorem, it can be written

$$\frac{\dot{q} \cdot D}{k_s \Delta T} = f\left(\frac{\mu_s}{\rho_s U D}, \frac{c_w \Delta T}{U^2}, \frac{k_s}{\mu_s c_s}, \frac{D^3 \rho_s^2 g \beta \Delta T}{\mu_s^2}, \gamma, \frac{\rho_i}{\rho_s}, \frac{c_i}{c_s}, \frac{k_i}{k_s}, \frac{h_{sl}}{c_s \Delta T}, \phi, \frac{d}{D}, \varepsilon, \frac{g \Delta \rho D}{\rho_s U^2}\right) \tag{7}$$

The non-dimensional number on the left term is the Nusselt number. The first three parameters within the function are the inverse of the Reynolds, Eckert and Prandtl numbers. The fourth is the Grashof number of the natural convection in the liquid phase. After the solution concentration γ, four non dimensional ratio of the ice physical properties follow and the rest are already commented parameters.

Some of these parameters are not significant if the objective is to obtain a practical correlation for design purposes. Eckert number is only important in gases, but not for liquids and the thermal properties of the ice must be important for the evolution of the flow parameters (ice fraction, temperature, etc…) but for the temperature range at the experimental test were carried out, the ratio between ice thermal properties and solution thermal properties is practically constant. Anyway these parameters would be the same for any ice-water solution slurry.

With these arguments, and others already used the expression can be simplified to the following:

$$Nu = f\left(Re, Pr, Gr, \gamma, \phi, \frac{d}{D}\right) \tag{8}$$

If all the test are made for a constant solution concentration and the Prandtl number is a known constant, the relation is reduce to:

$$Nu = f\left(Re, Gr, \phi, \frac{d}{D} \right) \tag{9}$$

In single phase flow, Rayleigh number $\left(Ra = Gr{\cdot}Pr\right)$ is important in laminar and transition flow, but in turbulent flow Nusselt number is only dependent of Reynolds and Prandtl numbers and so Rayleigh number (and Grashof number) influence could be neglected. Turbulence fluctuation overlaps the effect of the natural convection due to thermal buoyancy. In our case the effect of turbulence will be the same and therefore the results of the experimental test will be given in the way $Nu = f\left(Re, \phi, \frac{d}{D} \right)$.

This expression show how must be processed the results of the tests to be performed when the flow velocity, temperature gap, ice fraction and pipe diameter are changed.

4. - EXPERIMENTAL PROCEDURE AND RESULTS.

The previous dimensional analysis show that ice content is one of the most important factors on the fluid behaviour. Determination of ice content in our case has been obtained from density and temperature registered values, using the NaCl brine properties published by Melinder [12].

Due to the high salts concentration of the water in Cartagena (in the order of 450 ppm), the water used in our test was treated with a reverse osmosis equipment, that provides high pure water (salts concentration in the order of 15 ppm), thus the presence of other chemical components different to NaCl, which can change the behaviour of the solution is avoided.

Experimental test are oriented to determine which are the variables than explain the pressure drop and heat transfer process, and to determine its influence. All the test carried out follow the same initial procedure. In the first place, the refrigeration system is switch on and the consign temperature is fixed to obtain the desired ice concentration. Centrifugal pump (7) is also switch on and so the fluid flows through the ice flow circuit. When the desired ice concentration is reached and the fluid temperature remains stable for a sufficiently long time period, the facility is prepared to begin the test.

PRESSURE DROP TEST.

Our experimental facility allows to vary the major influence parameters on the pressure drop process, although by limitations of time only a part of the programmed test has been carried out.

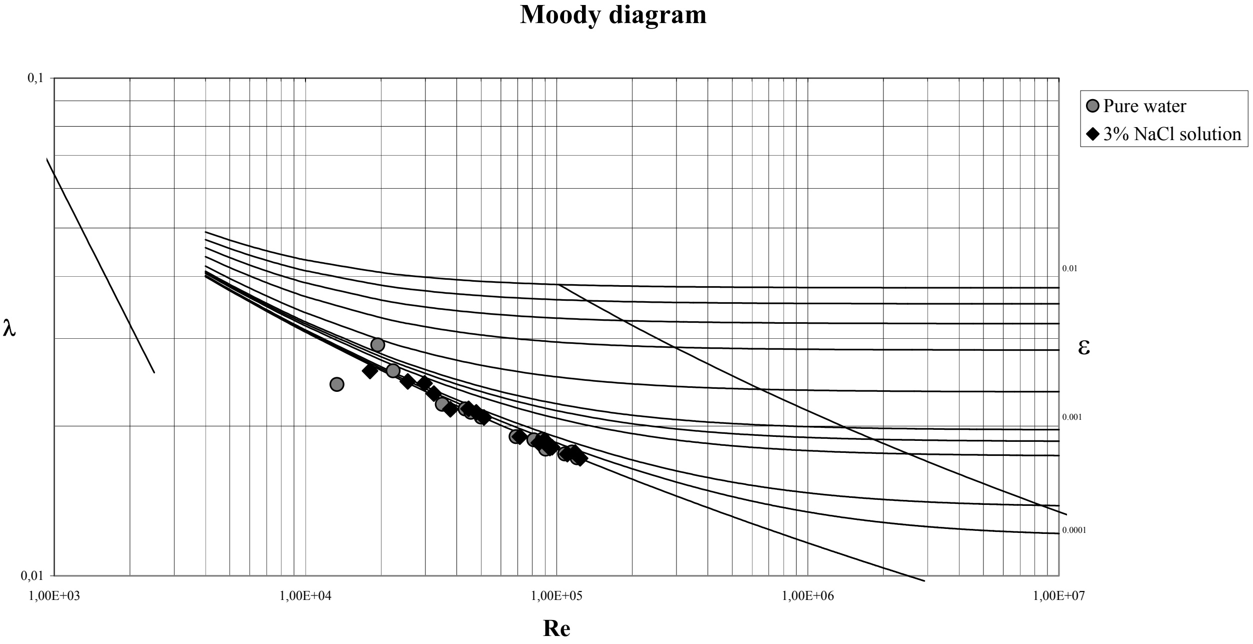
To asses the influence of the ice concentration, same test conditions have been reproduced for ice concentrations of 6, 10, 13 and 22%. Latest test make on the experimental facility when problems of stability were solved, show that is possible to arrive at concentrations near 30% in future test.

To date, crystal size in all test carried out was approximately the same, near 500 μm. Crystal growth process in our facility is obtained through de storage of the ice slurry for long time period. This process need a lot of time and for that reason it has been left for later tests.

Pipe diameter influence was evaluated flowing ice slurry, for all ice concentration generated, through four different diameters PVC commercial pipes (20, 25, 32 and 40 mm external diameter).

Finally to asses the influence of fluid velocity, the frequency of the pump has been modified to change mass flow through every pipe and so fluid velocity. For each tested pipe four different values for mass flow were tested.

With the objective of determine the correct operation of the experimental apparatus, before making the tests that have been previously described, a number of similar test were carried out without ice. Thus, pressure drop for different fluid velocity and pipe diameter was obtained in the case of pure water and 3% NaCl solution. Friction factor was calculated and plotted versus Reynolds number in the Moody diagram of Fig. 2. The results show a very good agreement with theoretical values, and only light deviations for pure water and low Reynolds values were appreciated, when differential pressure values were too low to be read it by the differential pressure sensor available in that moment.



Fig, 2. Moody diagram without ice.

Once verified the correct operation of experimental apparatus, experimental test for ice slurry were carried out, and calculated values for friction factor were plotted versus Reynolds number in the Moody diagram shown in Fig. 3. In this case, Re and λ were calculated using density and viscosity values for a 3% NaCl solution in a reference temperature of 0ºC. This is a practical form to present friction values which allows for an ice slurry installation designer to calculate the pressure drop in a pipe knowing only, apart from the density and viscosity values for the selected solution at 0ºC, the values for the mass flow and pipe diameter.

To date, crystal size in all test carried out was approximately the same, near 500 μm. For this constant crystal size, and the pipe inner diameters available in our experimental apparatus (from 16 to 36 mm approximately, corresponding to PVC commercial pipes from 20 to 40 nominal diameters) the diameter ratio varies from 0.014 to 0.03. For this range of diameter ratio, the test carried out have not shown the influence of this parameter on the measured pressure drop, and so results are given in the way $\lambda = f(Re,\phi)$. Further test with different crystal size are necessary to evaluate the influence of diameter ratio on pressure drop, and perhaps an experimental apparatus enlargement, with different piper diameters, could be also necessary.

For the moment it has not been possible to make all the programmed tests. The results plotted in Fig. 3 show a good agreement with others researcher's data. According to most of the previous works, a general tendency to an increase in friction factor with respect to that measured without ice crystal is observed. In our experiments with ice concentration lower than 15%, there is no clear relationship between friction factor and ice concentration for any Reynolds number. In the line of other researchers like Bell & Lallemand [4] or Bedecarrats *et al.* [3], for low Reynolds number it seems to be an increase in Fanning factor simultaneous to ice concentration increase. For high ice concentration, differences in friction factor for different ice concentrations tends to disappear when the Reynolds number is increased.

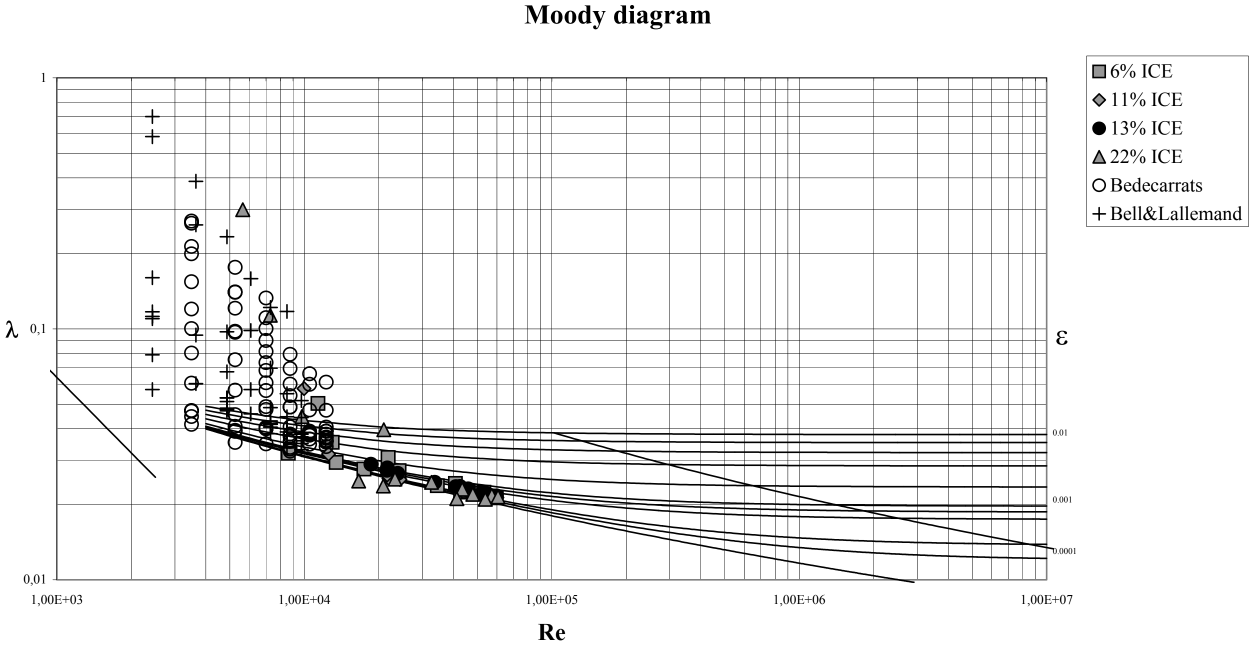


Fig. 3. Moody diagram for ice slurry.

HEAT TRANSFER TEST.

The experimental apparatus for heat transfer test counts with a 20 mm external diameter stainless steel smooth pipe and a 20 mm external diameter stainless steel corrugated pipe. The mass flow through these pipes can be fit to the desired value, and the heat source at the pipe is provided by Joule effect by a 6 kVA electric transformer. The local heat transfer coefficient h can be obtained from the measured heat input, test section wall temperatures and inlet and outlet fluid temperatures.

A 1.1 meter long thermal test section was used for the heat transfer test. Measuring point was situated at a distance of $x = 0.55$ m from the upstream electrode, so test were carried out with a $x/\text{D}\approx 30$ relation. In single-phase turbulent flow, entrance region is relatively short, and from $x/\text{D}=15$, local Nusselt number is asymptotic. So, our test were carried out in the fully developed region, and the calculated local Number Nusselt was the asymptotic value, that for most of practical cases in relatively long pipes, fit in with overall Nusselt number.

Experimental results were plotted in Fig. 4 and compared with Bedecarrats *et al.* [2] data. Nusselt (Nu) and Reynolds (Re) number were calculated evaluating solution physical properties (k, ρ and μ) in a 0ºC reference state. Presents results were calculated for the smooth pipe. Further test for the corrugated pipe must to be developed.

Experimental test were carried out with constant crystal size and pipe diameter, so diameter ratio is also constant and results are given in the way $Nu = f(Re,\phi)$. Further test with different crystal size or pipe diameter are necessary to evaluate the influence of diameter ratio on heat transfer process.

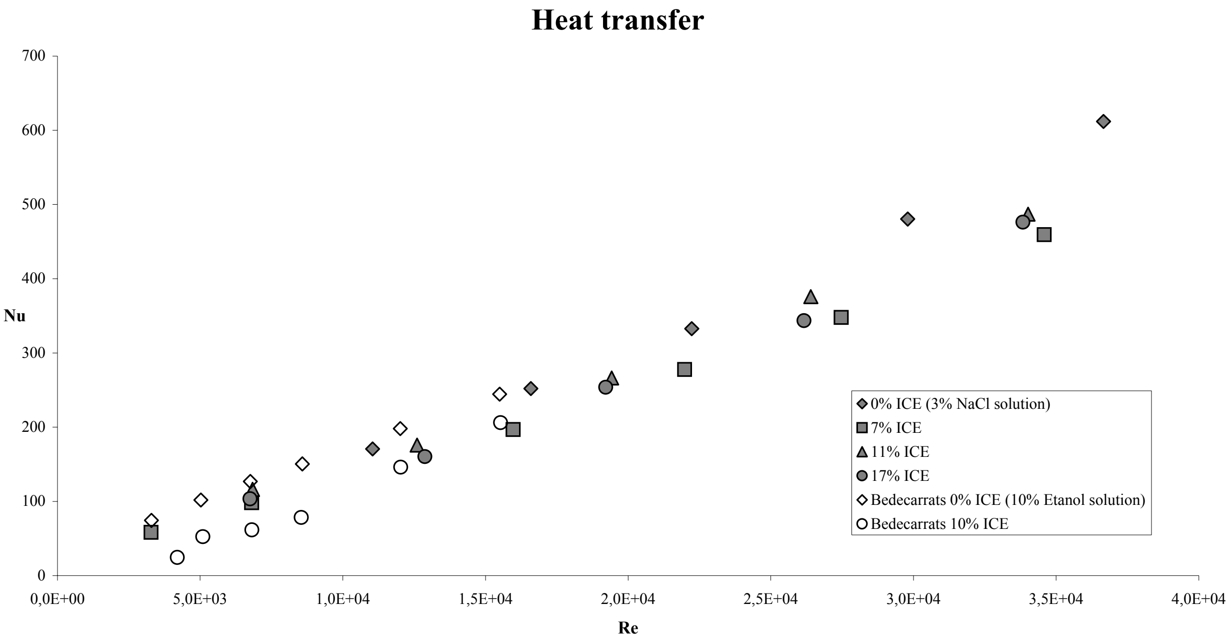


Fig. 4. Experimental Nusselt number versus Reynolds number.

Figure 4 shows the same tendency for both data sets: a light decrease in Nusselt number in presence of ice particles. These results are partially in agreement with Knodel *et al*. [11] data, who found a Nusselt number decrease with increasing the ice fraction, but in our case there is not a clear relationship between ice content and Nusselt number. Also in agreement with ours results is the Bellas *et al*. work [5], that shows an overall heat transfer coefficient that seems to be independent of ice fraction, although those results have been determined for a plate heat exchanger, not for a pipe.

In the other hand, others researchers like Stamatiou and Kawaji [13], found that local ice slurry Nusselt number was higher than the values for single phase brine flow. Even depending on thermal entry length local Nusselt number increases when ice fraction is increased. Others like Ben Lakhdark *et al*. [6] found that for a constant flow rate, the increase in ice concentration implies strong heat coefficient exchange increment.

Despite of the previous differences it is clear that, thanks to the high thermal capacity of ice, the cooling duty obtained using ice slurry is much greater that obtained using chilled mixture.

5. - CONCLUSIONS.

A dimensional analysis of the pressure drop and heat transfer processes was made. This analysis showed that the major parameters of influence in those processes, in our test conditions, are ice concentration and Reynolds number.

The pressure drop and heat transfer of ice slurry made from 3% NaCl-water solution produced by a commercial scraped surface generator were experimentally investigated. Influence of ice concentration and Reynolds number was investigated. The major conclusions that could be obtained are the following:

1. Results shows an increase in pressure drop in the presence of ice particles, specially in the transition zone between laminar and turbulent flow.
2. In turbulent zone ice concentration influence is not clear on the pressure drop. However these results have to be confirmed by new experiments with different ice concentration.
3. There is not a clear relationship between overall heat transfer coefficient and ice content, but it is clear that there is a high increase in the heat transfer capacity compared to single phase flow that can lead to significant reduction in the secondary fluid flow rate for the same load.
4. More experiments are necessary to obtain empirical correlations for heat transfer and pressure drop calculation, especially to evaluate the influence of ice particle - pipe diameter ratio (*d/D*) in those processes.

ACKNOWLEDGEMENTS.

This research has been partially financed by the project DPI2000-0224-P4-02 grant of the "Dirección General de Investigación, Ministerio de Ciencia y Tecnología" in Spain and the HRS Spiratube company from Murcia (Spain). The work described in this paper is a part of that project.

NOMENCLATURE.

Standard

c	specific heat
d	ice particle diameter
D	pipe diameter
g	gravity acceleration
h_{sl}	ice melting latent heat
k	thermal conductivity
L	pipe length
p	pressure
$\dot{q}$	heat transferred
T	temperature
U	mean flow velocity

Greek symbols

β	thermal dilatation coefficient
Δ	difference
ε	pipe relative roughness
ϕ	ice mass fraction
γ	solution initial concentration
λ	Fanning friction factor
μ	dynamic viscosity
ρ	density

Subscripts

i	ice
p	pipe wall
s	solution

Dimensionless number

Gr	Grashof number
Nu	Nusselt number
Pr	Prantl number
Re	Reynolds number

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