FRICTION LOSSES FOR FLOW OF CONCENTRATED SLURRIES

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ABSTRACT

The aim of this work is to study the hydraulic behaviour of ice slurries. The solid phase is replaced by polypropylene particles with a density close to that of ice to determine the behaviour of ice/water mixture in adiabatic conditions. The experimental tests are carried out using a slurry flow facility, consisting of a flow loop though which the different piping elements are installed. Friction losses in horizontal pipes, bends, contractions, and enlargements have been measured. The pressure drops depend strongly on the flow pattern. For suspended particles regimes, the Blasius law based on Reynolds numbers defined from water viscosity and mixture density, is appropriate. Inversely, for moving bed regimes, pressure losses depend on the concentration of the solid phase.
Two models of pressure losses in pipes have been developed. The fist one is a correlation. The second one uses the Bingham fluid to model the flow of solid-liquid mixture. An extended Reynolds number is introduced. The Blasius law computed by replacing the classical Reynolds number with the extended Reynolds number is found to be applicable to the two-phase flow in its full range.

INTRODUCTION

Ice slurries are characterized by high energy potential. However the process is expensive and requires complex facilities. Therefore, their main application consists at present in climatisation or cooling large construction works that are located far away from the place of the cooling process (mine in South Africa, tunnels…). The configuration of the hydraulic circuits depends on the characteristics of the ice-liquid two phase flows : the size and the shape of the solid phase (grain, flakes…) the physical properties of the liquid phase (water, brine…) and the boundary conditions (adiabatic conditions, heat exchange…). From all the interesting works on that subject, we can mention the work of Takahashi et al. (1993) and Bell (1996).
The aim of this work is to study the flow of ice slurries in industrial hydraulic configurations in adiabatic conditions. The conception of the hydraulic ice-water test loop requires many problems to be solved such as the production and regulation of ice fractions and the visualisation of the two phase flow at 0°C. We choose to replace the solid phase with polypropylene particles with a density close to that of ice ($\rho_{poly.}$= 0.910 kg/m3). The present work is limited to the study of spherical grains of 3 mm in diameter.
The experimental study is based on visualisation and measurement of pressure drop. The results are compared to the one obtained with clear water.
Under isothermal conditions and with no work involved, pressure drop in a piping system can be described by the steady state macroscopic mechanical energy balance given by Equation 1 (subscript 1 and 2 correspond respectively to the upstream and the downstream section ; α is a kinetic energy correction factor) :

$$\Delta H = \frac{P_1}{\rho.g} + Z_1 + \alpha_1 \frac{V_1^2}{2.g} - \frac{P_2}{\rho.g} - Z_2 - \alpha_2 \frac{V_2^2}{2.g} \qquad (1)$$

Pressure drops result from two factors : friction losses ΔH_R (the pressure drop for fully developed flow through a straight pipe), and pressure drop caused by a disturbance ΔH_S . Each fitting disturbs the flow upstream and downstream from its its position. The measurement positions are taken at points where the effects of the fitting are no longer felt, and the flow is reverted to a fully developed condition. The pressure losses due to a fitting are expressed in terms of resistance (Coefficient K) defined by :

$$K = \Delta HS/(V^2/2g) \quad (2)$$

The friction losses are expressed in term of friction factor λ defined by

$$\lambda = \Delta HR \,/\, (V^2/2g)\, D/L \quad (3)$$

1 CONSTITUTIVE EQUATION

Solid-liquid two phase flow though a straight pipe may be classified into different flow patterns which can be determined by visual observations. The transition between flow with stationary bed and moving bed is generally associated with a limit deposit velocity corresponding to a minimum pressure gradient. In this present study, we use the classification of Doron and Barnea (1993) who define 3 main flow patterns :

1. "Fully suspended flow": The whole solid particles are suspended. This pattern includes the homogeneous flow and the heterogeneous flow which are defined by a solid phase concentration gradient in a direction perpendicular to the pipe axis.
2. "Flow with moving bed": solid particles accumulate at the top of the pipe. It is characterised by a solid concentration near the maximal "packing". The rest of the pipe is occupied by heterogeneous mixture.
3. "Flow with stationary bed": A stationary bed develops on the top of the pipe. Deposit particles are transported as a separate moving bed on the bottom of the stationary bed.

Considering the difference in density between solid and liquid phase and the speed of flow used in industrial configuration (mean velocity is about 1m/s), only Cases 1 and 2 are studied (Case 3 is not met here).

Different methods have been developed to predict friction losses for two-phase solid-liquid flow. Turian and Yuan (1977) have developed a pertinent correlation based on dimensional analysis. It provides a fairly satisfactory prediction of pressure drop :

$$\lambda - \lambda_e = \mathbf{M}\, T^{\alpha} \lambda_e{}^{\beta} C_D^{\chi} \left[\frac{V^2}{D.g.\left(\dfrac{\rho_p}{\rho} - 1 \right)} \right]^{\delta} \quad (4)$$

where T is the mean solid concentration, λ_e is the friction factor for clear water flow and C_D is the drag coefficient for settling of the particle at its terminal velocity in the stagnant unbounded liquid. The dimensionless group $V^2 / [D.g.(\rho_p/\rho - 1)]$ gives a relative measure of inertia to gravitational forces prevailing in the flow. The constants M, α, β, χ and δ are determined for each flow regime by fitting the experimental data for the particular regime.

A second method consists of assimilating the global motion of two-phase flow with a motion of non-Newtonian fluid whose characteristics depend on solid concentration (Ogihara and Miyazawa, 1991). Given the motion law of Bingham fluid, the relationship between the shear stress (τ) and the shear rate (δu/δr) is given by

$$\tau = -\eta \frac{du}{dr} + \tau_c \quad (5)$$

where τ_c is yield stress and η is plastic viscosity

Reynolds number represents the ratio of inertial forces to viscosity forces. Extended Reynolds number Re_1 based on Bingham fluid may be defined by

$$Re_1 = \frac{-\rho\, u\, du/dr}{\tau / l} = \frac{\rho\, ul/\eta}{1 - \dfrac{\tau_c}{\eta\, du/dr}} \tag{4}$$

Friction losses obtained for heterogeneous suspension flow with high Reynolds number are quite similar to the ones obtained with clear water. Therefore the plastic viscosity η is fixed to the dynamic viscosity μ_e of clear water. Considering the Reynolds number Re based on dynamic viscosity μ_e of water, D diameter of pipe and ρ relative density of mixture and using the mean velocity U, and the pipe diameter as characteristic dimensions, the relation becomes

$$\mathrm{Re}_1 = \mathrm{Re} \times \frac{1}{1 + c_1 \tau_c \dfrac{D}{\mu_e U}} = \mathrm{Re} \times \frac{1}{1 + c \dfrac{D}{\mu_e U}} \tag{5}$$

The dimensionless coefficient c_1 is determined experimentally for each solid concentration in order to have a single relation between the friction factor and the extended Reynolds number Re_1. This correlation should be similar to the one obtained in the case of Newtonian flow in order to be applicable to the all solid concentration range. Considering the range of Reynolds numbers studied (Re>10 000) and the pipes used (PVC), the correlation correspond to the Blasius law. The last method is a multi-layer model (Doron and Barnea 1993, Roco and Schook 1985). This model was developed especially to predict stationary bed flow and thus it is not used in this present work.

2 EXPERIMENTAL APPARATUS

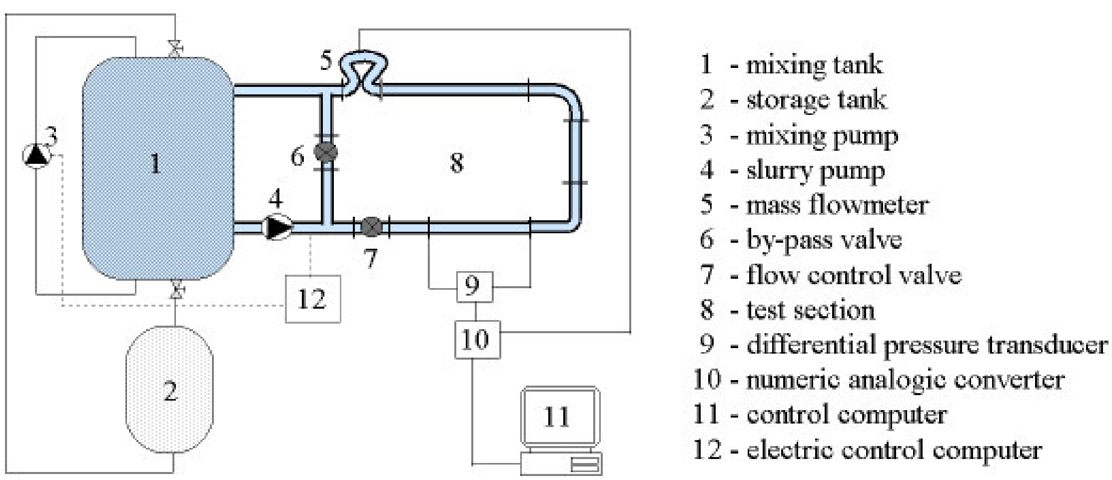

Figure 1 – experimental apparatus

Fig.1 shows a schematic diagram of the experimental apparatus used in this study. A 120 litre storage tank (2) allows changing the particle concentration by introducing or by removing particles. A pump (3) driven by a variable speed motor is connected to the feed tank (1) of 300 littres. It enables an accurate control of the delivered solid concentration. A PCM62I5 screw pump (4) connected to a speed variator sets the flow inside the test section. Two membrane valves (6) and (7) allow an accurate flow regulation. Different piping elements can be tested (8) :

¬ horizontal and vertical straight pipes 22mm, 45mm and 110mm in diameter
¬ 60°, 90° and 180° contractions and enlargements.
¬ 90° bend (C/D=1.8 and C/D=11.3)

A « Rosemound Elite 100 » mass flowmeter (5) measures the mass flow rate Qm, the density of the mixture ρ flowing throughout the test section and the temperature T. The precisions are given by :

$$\Delta Qm = \pm 1 kg/h \qquad \Delta\rho = \pm 0.5 \mathrm{kg/m^3} \qquad \Delta T = \pm 0.5°C$$

The solid concentration T is given by the relation:

$$T = \frac{\rho_e - \rho}{\rho_e - \rho_b} \qquad \text{where :} \quad \begin{array}{l} \rho_e = \text{relative density of water} \\ \rho_b = \text{relative density of polypropylene} \\ \rho = \text{relative density of mixture} \end{array}$$

The maximal uncertainty is less than 1%

Pressure drops are measured using 4 DRUCK differential pressure transducers (9) with a precision of 0.1% on the measure range (0-2bars, 0-200mbars, 0-20mbars, 0-2mbars). Data acquisition is obtained by a Keithley DAS 1700HR card (10) with a resolution of 32 bits i.e. $\Delta V = \pm$ 5mV on the measure range of 0-10V. This card is installed on a CyrixInstead computer (11). It is driven by a software developed with Test-Point. All acquisitions are performed with a sampling frequency of 500 Hertz during 10 seconds.A HI resolution SONY camera with 16x enlargement is linked to a Pentium II Intel MMX computer. It is implemented with an acquisition card AV Master. Video acquisitions are made with "Fast capture" software. The visualisation of the flow is carried out in real time ; 100 pictures per second can be registered.

3 RESULTS AND COMMENTS

Different flow patterns may be observed as a function of the Froude number define as $Fr = V^2 / D.g.(1 - \rho_b / \rho_e)$ (Figure 2)

1. Fr > 15 : Fully suspended flow.
2. 0,2 < Fr < 15 : Flow with moving bed.
3. Fr < 0,2 : Flow with stationary bed.

Considering the flow regime present in industry, only cases 1and 2 will be studied.

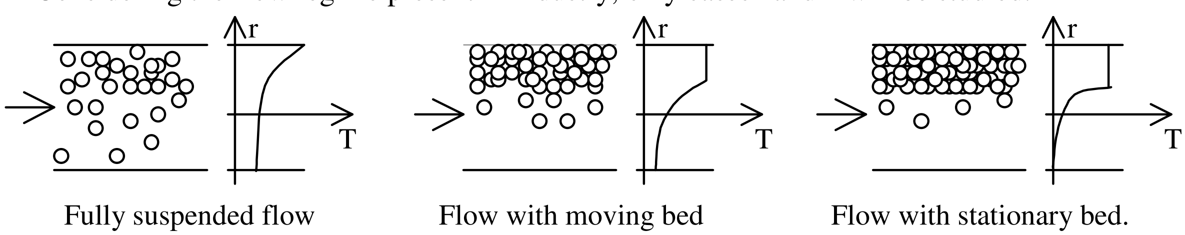

Figure 2 : Flow pattern

3.1 Friction losses through straight pipes

The distribution of the friction factor as a function of the Reynolds number is shown in Figure 3

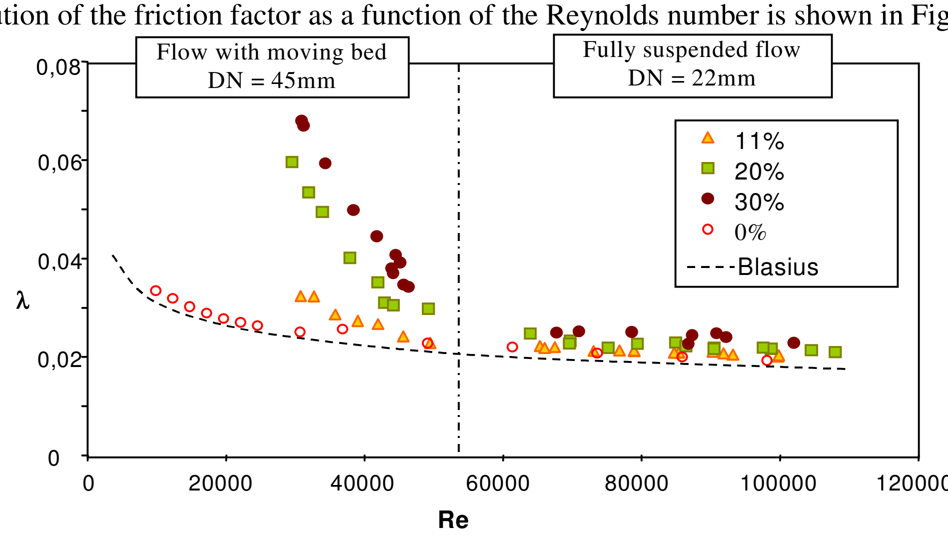

Figure 3 : Distribution of the friction factor as a function of the Reynolds number

The constants M, α, β and χ of the empirical correlation given by Turian et Yuan (équ.1) are determined for each flow regime by fitting the experimental data for the particular regime. The particle size is 3mm for all the experiments. Therefore, the drag coefficient for the free falling sphere is kept constant and is included in the constant M. The comparison between the experimental results and their correlation is shown in Figure 4. The calculated results coincide with the experimental data. The empirical form given by equation 2 can be used to provide satisfactory correlation of polypropylene – water slurry flows.

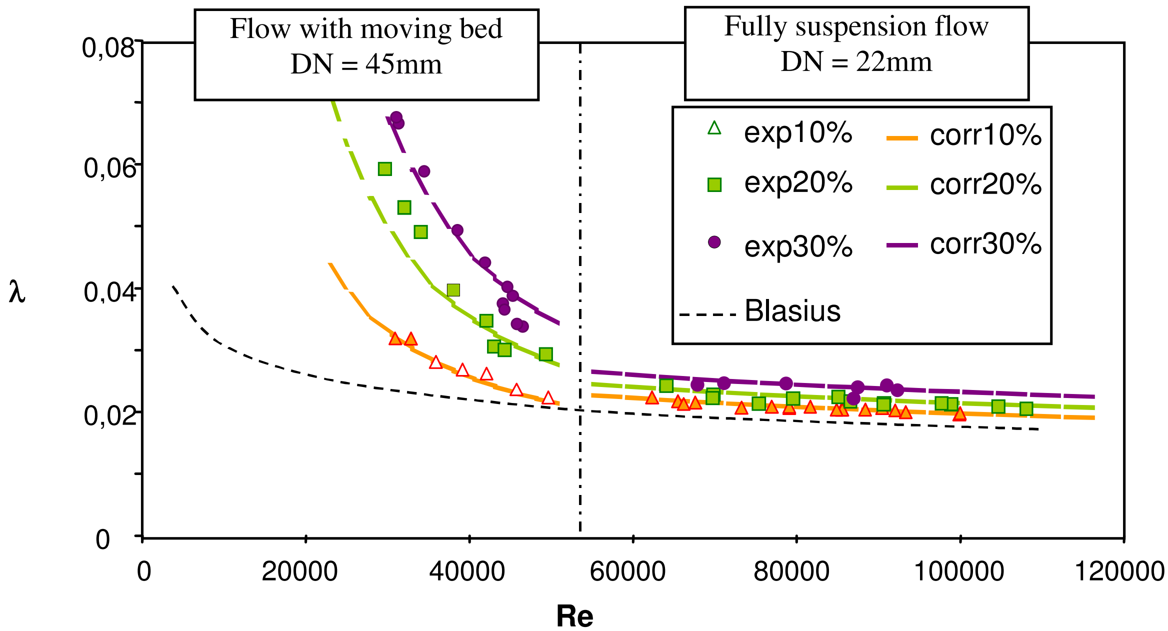

Figure 4 : Distribution of the friction factor as a function of the extended Reynolds number

The adjusted constants in the correlation determined in the present experiment for each flow regime are given in Table 1. The results obtained by Turian and Yuan are quite different, which are based on a large number of data points collected from the literature and also taken from their slurry flow experiment. Contrary to our experiments, the solid density of the entire body of their data points are greater than the water density.
Such empirical form based on power laws can provide a very satisfactory correlation of experimental data. Extrapolations of the results to flow conditions out of the range of the data base used have to be regard with caution. Otherwise, the pressure drop correlation depends on the flow regime and needs to develop an associated quantitative regime delimitation scheme.

Table 1 : adjusted constant in the correlation

		$M'=M.C_D^{\chi}$	α	β	δ
Moving bed	Experiment	440	0.544	2.56	-0.228
	Turian et Yuan	1.346	1.018	1.046	-1.354
Suspension flow	Experiment e	1.027	0.828	0.558	-0.343
	Turian et Yuan	0.756	0.5024	1.428	-0.3531

The value of the c coefficient included in the extended Reynolds number is determined by applying the least square method in order to adjust the Blasius law for a given solid concentration. The relation between the c coefficient and the solid concentration is shown in Figure 5.

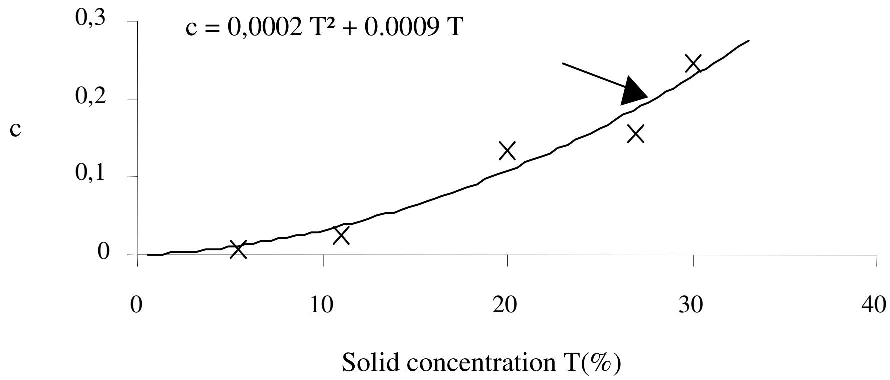

Figure 5 : Relation between the c coefficient and the solid concentration

The distribution of the friction factor as a function of the extended Reynolds number is shown in Figure 6. This method enables an easy computation of the head losses in horizontal pipes, whatever the flow regimes may be.

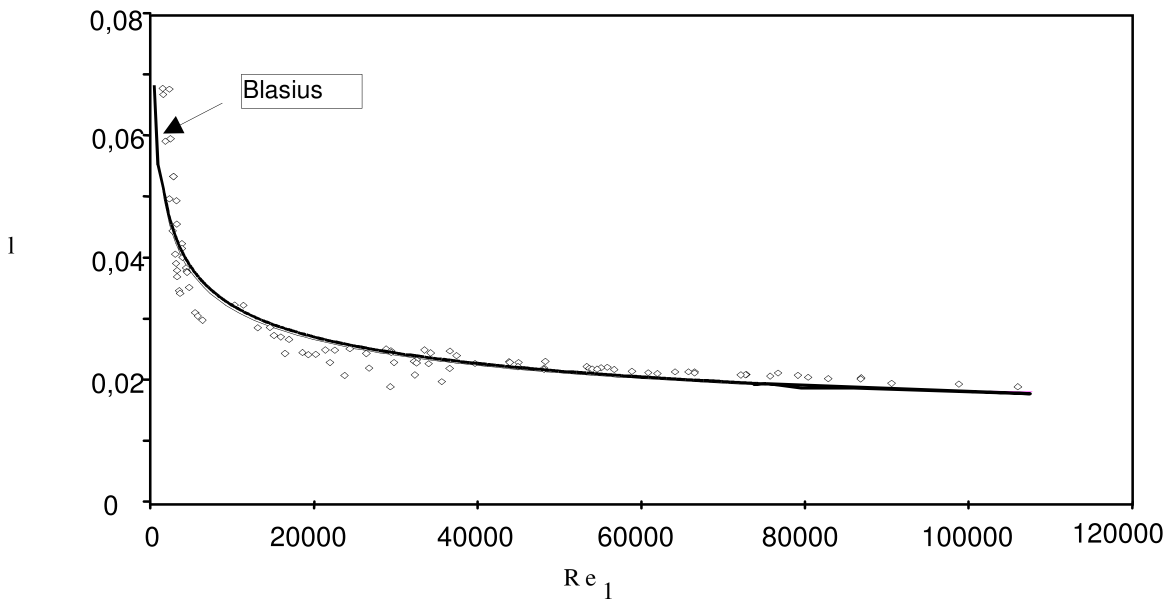

Figure 6 : Distribution of the friction factor as a function of the extended Reynolds number Re_1

3.2 Friction losses in fitting

In this work, the friction losses in the straight pipe upstream and downstream from the fitting for fully developed flow conditions are subtracted from the overall losses to obtain the K coefficient. Friction losses for suspension flows of concentrated slurries of polypropylene particles through fitting are similar to the ones obtained with clear water. Conversely, great differences can appear with moving beds. The presence of a disturbance in the flow may lead to increase turbulence and vortex formation depending on the severity of the disturbance. It may change the two-phase flow pattern, and reduce the head loss coefficient.

Figure 7 shows the distribution of the K coefficient as a function of the Reynolds number for 90°bend. The internal diameter is 45mm and the curvature radius is 40mm. For Reynolds number under 50 000, the moving bed takes place in the upstream section. The disturbance induced by the bend homogenises the flow on a given length downstream of the fitting reducing the friction losses. For higher Reynolds numbers, suspension takes place in the pipes.

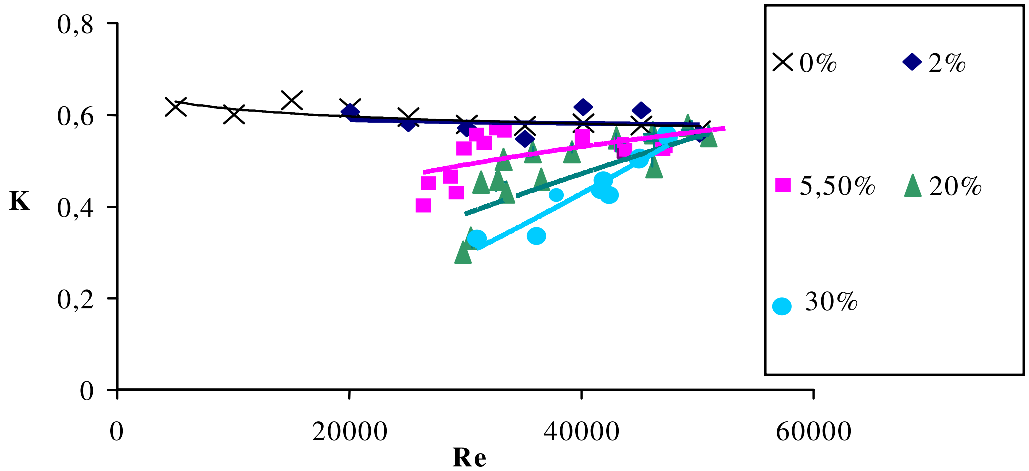

Figure 7 : distribution of the K coefficient as a function of the Reynolds number for 90°bend

Different concentric contraction have been studied. The piping diameter contracts from 45mm to 22mm in diameter or from 110mm to 45 mm. No particle accumulation phenomena have been observed despite any difference in contraction angle of the fitting and in the Reynolds numbers used. The head loss coefficient of such elements are similar to the ones obtained with clear water.

CONCLUSION

Flows of concentrated slurries of polypropylene through different piping configurations have been studied. The diameter of the particles was about 3mm. The use of polypropylene particles with a density close to that of ice aims to determine the behaviour of ice/water mixtures in adiabatic conditions. Different flow patterns can be observed in fully turbulent conditions. The transition between the flow patterns depend on the pipe diameter and the Froude number. Heterogeneous suspension flows are present in the piping elements for Froude number greater than 15. Moving beds take place in the straight pipes for Froude numbers between 0,2 and 15 and stationary beds appear for lower Froude number.

The friction losses depend on the flow pattern : for heterogeneous suspension flows, they are quite similar to the friction losses obtained with clear water. The Blasius law is then appropriate when computing pressure losses. Conversely, for flows with moving beds, the friction losses are greater and depend on the solid concentration.

Two methods have been used to predict pressure losses though straight pipe. The first one is a correlation obtained by dimensional analyses. It gives satisfactory results but depends on the flow configuration. The second one uses the Bingham fluid to model the flow of solid-liquid mixture. An extended Reynolds number is introduced. The Blasius law, computed by replacing the classical Reynolds number with the extended Reynolds number, is found to be applicable to the two-phase flow in its full range.

Friction losses for suspension flows of concentrated slurries of polypropylene particles through fitting are similar to the ones obtained with clear water. Conversely, the presence of a disturbance in the flow may change the flow pattern, and reduce the head loss coefficient.

LIST OF SYMBOLS

C_D	C_D drag coefficient for free falling sphere	
c	parameter (equation 5)	
D	diameter of pipe	(m)
Fr	Froude number	
g	gravitational acceleration	(m/s²)
H	charge totale	(m)
K	resistance coefficient	
L	pipe length	(m)
P	static pressure	(Pa)
Q	volume flow rate	(m^3/s)
S	pipe section	(m²)
Re	Reynolds number	
T	solid concentration	
V	mean velocity V=Q/S	(m/s)
Z	height	(m)
α	kinetic energy correction factor	
λ	friction factor	
μ	dynamic viscosity	(kg/m.s)
η	plastic viscosity	(kg/m.s)
τ	shear stress	(N/m²)
τ_c	yield stress	(N/m²)
ρ	density	(kg/m^3)

Subscripts

1	upstream section
2	downstream section
e	clear water flow
p	solid particles

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RÉSUMÉ

L'objectif de ce travail est d'étudier le comportement hydraulique d'un mélange d'eau et de glace. La phase solide est remplacée par des billes de polypropylène de densité voisine de celle de la glace de façon à simuler des écoulements en condition adiabatique. Les essais sont réalisés sur une boucle hydraulique modulable sur laquelle peuvent être testées différentes configurations géométriques. Les pertes de charge sur des éléments de conduite droite, des coudes, des changements de section ont ainsi pu être étudiées. Ces dernières dépendent fortement des configurations d'écoulement : en présence d'écoulements de billes en suspension, l'utilisation de la corrélation de Blasius, basée sur un nombre de Reynolds défini à partir de la viscosité de l'eau et de la densité du mélange apparaît pleinement justifiée. A l'inverse, en présence d'écoulements stratifiés, les pertes de charges dépendent fortement du taux d'inclusions.

Deux modèles de prédiction des pertes de charge en conduite ont été développés. Le premier consiste en une corrélation semi-empirique. Le deuxième est basé sur un nombre de Reynolds étendu issu du modèle de fluide de Bingham. Il permet de retrouver la corrélation de Blasius sur l'ensemble des régimes d'écoulements.