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Pressure drop of flowing ice slurries in industrial heat exchangers

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Abstract

Experiments were conducted to determine the characteristics of ice flows through industrial heat exchangers (a Tetra Plex® C6-SR and a Tetra Spiraflo® MTC70/W-3). This type of equipment presents many problems with respect to cleaning and is therefore of particular interest when considering a pigging system using ice slurry. Moderately thick ice slurries (in the range 15 % - 60 % solids) were successfully pumped through commercial heat exchangers. Measured pressure drops were greater than those with water, and rose with increasing ice fraction and flow rate. Evidence was seen for an exponential dependence of pressure drop on ice fraction, in addition to a water-like dependence on the square of flow rate. Blocking events were observed at higher ice fractions, or when large crystal masses were thought to be present in the ice slurry. It is likely that the risks of this could be mitigated by better mixing of the bulk ice slurry prior to and during delivery. For some tests the ice crystals may have grown to almost 1 mm in diameter, which is close to the characteristic dimension of the flow

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channels in the PHE (mean width 4 mm), increasing the likelihood of blockages forming.

Keywords: Ice slurry; pressure drop; heat exchanger; slurry flow; ice pigging.

Symbols

D	diameter
D_h	equivalent hydraulic diameter
f	friction factor
L	length
P_{in}	inlet pressure
P_{out}	outlet pressure
Q	flow rate
$\bar{u}$	flow velocity
W	width
ΔP	pressure difference
ϕ	volumetric solid fraction
ϕ_m	maximum volumetric solid fraction
ϕ_{mitial}	initial solid fraction
μ_{slurry}	viscosity of slurry
μ_r	relative viscosity
μ_l	viscosity of liquid phase
ρ	density

1 Introduction

Bristol University has been developing a novel method of cleaning pipelines and separating fluid flows using a pig [1] formed from a water-ice mix. This slurry has rheological properties somewhere between a soft solid and a very thick non-Newtonian fluid. A pig formed from this slurry flows like a solid plug in pipes yet can negotiate complex geometries like a fluid [2]. The ice pig can thus be used in the same way as a conventional solid or foam pig but does not impose the same constraints that other pigs do.

Ice slurries are used extensively for cooling although their use has spread to other application areas, some of which are given by Davies [3] and by Bellas and Tassou [4]. Ice slurries exploit the latent heat of the ice, making them more efficient heat carriers than single-phase fluids. Their large thermal capacity and lower operating temperatures allow larger temperature differences to be maintained, providing desirable heat sink characteristics. Studies into the behaviour of ice slurries have tended to concentrate on the heat transfer characteristics of low ice fraction slurries. Work carried out to measure the pressure drops of flowing ice slurries has investigated the flow behaviour of ice slurries with ice fractions of less than about 45 % where:

$$\text{Ice fraction} = \phi_s = \text{Vol.}_{\text{solids}} / \text{Vol.}_{\text{slurry}} \qquad (1)$$

Kaushal et al [5] have worked on slurries with volumetric solid fractions of up to 50 %. However, this and earlier work [6] have tended to focus on observations of the flow regime and concentration profile of slurries with a significantly denser solid phase. Interesting pressure drop behaviours were observed [5], which were attributable to the

different flow regimes that occur with changing solid fraction, flow velocity and particle diameter. In general, it was found [6] that thicker slurries of smaller particles flowing at higher velocity are more homogeneous. This is also supported by other work [7] done on the particle distribution in flowing ice slurry.

The behaviour of ice slurries with ice fractions over 45 % is less well known and the data and opinions of authors are divergent [8, 9, 10]. Most researchers have shown pressure drop to increase with increasing ice fraction, with the difference reducing at higher flow rates. The most commonly used model for the viscosity of ice slurries was formulated by Thomas [11] but this equation is seen to over-predict the viscosity of slurries with an ice fraction of more than 15 % [12].

Very little work has been conducted on the flow of slurries through heat exchangers. Bellas et al.[13] studied the pressure drop in ice slurries of up to 25 % ice, when flowing through a plate heat exchanger. An increase in ice fraction from 0 to 20 % was found to cause a 15 % increase in pressure drop to maintain the same flow rate over the entire range of flow rates tested. The work of many researchers has been summarised [9, 12] and demonstrated that the behaviour of ice slurries changes from that of a Newtonian type fluid to that of a Bingham type fluid at between 15 and 20 % solid fraction. Predicting behaviour of slurries is not straightforward and the yield stress of a slurry can be dependent on geometry [14]. The apparent viscosity of the slurry is also dependent upon flow geometry and glide affects can be very important [15]. These glide effects are most significant at high solid fractions [16]. The work presented here was conducted to extend the range of previous work to higher ice fractions; for which viscosity, yield stress and fluid behaviour are significantly different.

Establishing how the ice pig might actually clean something as large and complex as an industrial plate heat exchanger was not feasible in the laboratory. Instead, TetraPak provided two typical heat exchangers (a Tetra Plex® C6-SR and a Tetra Spiraflo® MTC70/W-3) that could be tested to determine whether pumping thick ice slurries through such equipment was a realistic proposition or whether there were practical limitations such as the pressure differentials required to drive the flow. This paper reports the flow and pressure drop data for ice slurries flowing through two types of heat exchanger.

2 Experimental set up

A schematic of the testing loop is shown in Figure 1. The test loop has two 200 litre tanks, one of which feeds a lobe pump from a side outlet at its base, whilst the return flow can be directed to either tank via a pair of manual butterfly valves. Between the first two viewing tubes is the point at which equipment is connected to the rig via a pair of 50 mm diameter braided steel hoses (see Figure 2). The test loop has a total length of approximately 46 m and contains thirty-nine 90° bends, twelve stubs for pressure transducers or thermocouples, three butterfly valves and two pneumatic piston valves. The rig also has various other ancillary piping features such as blanked T-pieces, as well as expansions and reductions. Ice may be continually pumped around the rig, through the equipment being tested. The pressure drop and temperature change of the ice slurry can be measured across the equipment as the flow rate and ice fraction are varied.

2.1 Flow meter

The flow meter was a Siemens SITRANS FM MagFlo MAG1100, designed for the general industry environment. MAG 1100's obstructionless performance is unaffected by suspended solids, viscosity or temperatures between –20 °C and 150 °C. The manufacturer's data gives and error of less than 1 % over the range of flow rates investigated.

The SITRANS^{TM} FM is an electromagnetic flow meter, designed to measure the flow of almost any liquid with an electrical conductivity greater than 1 mS/cm, as well as sludges, pastes and slurries. The temperature, pressure, viscosity and density have little influence on the result. The ice slurry used in the experiments has a conductivity much greater than that of water. Calibration tests were performed to establish that the meter gave accurate measurements of flow rate for both water and ice slurry. The results of these tests showed no difference between the flow meter readings and calibration measurements for either water or ice slurry.

2.2 Pressure transducers

The rig contained 3 Bourdon-Haenni FlexBar pressure transducers. These are a common type of pressure transducer, found in the food (and other) industry. They were calibrated up to 4 bar gauge pressure and the error is lower than 0.2 % over their full range.

2.4 Control

The rig allows control of the flow via pneumatic valves and an inverter is used to control the speed of the product pump or re-circulation pump. The status of the rig was monitored and data was logged using Matlab.

2.5 Equipment

The PHE was a Tetra Plex® C6-SR plate heat exchanger (PHE), of which a section of 12 plates was used. Each plate has external dimensions of 250 by 1000 mm, internal dimensions of approximately 200 by 700 mm and a heat transfer area of 0.18 m^2. Fluid flows between these plates in the channels between the ridges (see Figure 3). The channels in each plate have a depth of 4 mm and a width of 11 mm and are miss-aligned when placed against one another. The resulting flow path has a height of between 0 and 8 mm and has a mean height of 4 mm. The perimeter of the flow channel is increased by a factor of 1.14 owing to the corrugations in the plates. An equivalent hydraulic diameter can be calculated for each set of plates:

$$D_h = \frac{4 \times Area}{Perimeter} \approx 7mm \qquad (2)$$

The tubular heat exchanger to be tested was a Tetra Spiraflo® MTC70/W-3 concentric tubular heat exchanger (see Figure 4) of which four serially connected units of 3 m length were used. The Spiraflo has three flow passages that run along the length of each unit. The inner pipe (core) and outer annulus (jacket) usually carry hot water or another heating fluid; this heats the product flowing through the intermediate annulus, which lies between the core and jacket. For the Spiraflo, ice slurry was pumped through the intermediate annulus, which would usually carry the product. These product channels have a gap size of 12 mm and each tube has a volume of 4.2 l and a heat transfer area of 0.725 m^2. The flow path through the Spiraflo was an annulus with an inner diameter of 26 mm and an outer diameter of 50 mm. The equivalent hydraulic diameter can be calculated as:

$$D_h = \frac{4 \times Area}{Perimeter} \approx 24mm \quad (3)$$

4 Ice slurry production

A Ziegra machine was used to produce ice slurry by feeding brine to the bottom of an auger that pushes freezing water up the inner wall of a cylindrical stainless steel jacket. Embedded in the stainless steel jacket is the evaporator of a vapour compression refrigerator. As water freezes on the walls of the stainless steel jacket and in the super-cooled solution, it is pushed up and out of the top of the freezing section by the rotating auger.

The solid/liquid ratio of the emerging ice slurry can be controlled by changing the speed of rotation of the auger: a slower rotation of the auger results in a longer residence time of the brine in the freezing section and thus a higher solid/liquid ratio in the slurry. The crystals produced are finger-like, having one dimension greater than the other two. Observations of the crystals under a stereomicroscope have shown that typically a crystal may be 20-50 μm wide and perhaps 100-200 μm long. These fine crystals give the slurry ice a paste-like feel and soft texture. However, if the slurry is left for very extended periods of time the crystals grow to become larger and more uniform in shape. This results in a more grainy feeling slurry.

Ice slurry was produced from a 5 % NaCl solution that was pumped out of an insulated delivery bin for recycling until a relatively high ice fraction (ϕ > 60 %) was obtained. Typically the volume of ice slurry required for these tests was 200 litres, corresponding to about 8 hours operation of the Ziegra ice machine to achieve the ice fractions needed. The ice fraction was assessed using the coffee press method described below.

4.1 Ice fraction measurement

The ice fraction was measured using a coffee press. This technique involves sampling the ice slurry and placing the sample into the press. A filter is then placed on top of the slurry and depressed by applying a load. This technique has been found to produce quick and repeatable results (to within 3 %) for this type of ice slurry. The size and shape of the crystals gives them a very high packing factor so little fluid remains in voids between the crystals after they have been "pressed".

Although doing work on the ice and applying pressure will tend to melt the crystals, this technique is still thought to over-estimate the ice fraction slightly. The fine crystals of the slurries used for this work had a large surface area, which made the gravity filtration techniques used by other researchers [13] inappropriate since the fluid takes a very long time drain off the crystals and the technique leads to gross over-estimation of the ice fraction.

What this filtration technique actually gives the user is a measure of ϕ/ϕ_m. The maximum packing factor of the finger-like crystals is likely to be similar to that of cylinders (0.907), which would lead to a corresponding correction factor for ice fraction. However, for other slurries with much lower maximum packing factors, this technique will still give a very useful measure. ϕ/ϕ_m is a useful measure, since, as ϕ tends to ϕ_m, so the viscosity also tends to infinity. Kitanovski and Poredoš [7] recognised this and state that the influence of particle concentration on viscosity is best determined in relation to the maximum packing factor. So, in fact, ϕ/ϕ_m is a better

indication of how concentrated the slurry really is since concentrations above ϕ_m cannot be achieved without the introduction of air.

The importance of the maximum packing factor is apparent when considering Krieger and Dougherty's [17] well-known equation for the relative viscosity of slurries:

$$\mu_r = \frac{\mu_{slurry}}{\mu_l} = \left(1 - \frac{\phi}{\phi_m}\right)^{-2.5\phi_m} \tag{4}$$

The equation may be applied to concentrated suspensions and can be adapted by judicious choice of ϕ_m. The equation has been favoured in the modelling of pastes [18] because of its accuracy and relative insensitivity to variation of parameter choice.

5 Experimental procedure

The heat exchangers were tested using the equipment-testing rig described above, and shown in Figure 1. Figure 2 gives a photograph of the plate heat exchanger in the process of being tested. Repeated experiments were conducted using both the PHE and the Spiraflo.

5.1 Water tests

The bulk tank (see Figure 1) was filled with water. The frequency inverter for the pump was then used to set the flow rate, Q, for around 10 values in the range 0 to 2.5 l/s. Each flow rate was maintained for 50 s to allow the flow to stabilise.

5.2 Ice slurry tests

Approximately 200 l of ice slurry was loaded into the bulk tank and homogenised, initially using an electric drill with a plaster mixer attachment, and then by re-circulating through the rotary lobe pump. To compensate for the gradual buoyancy-driven stratification of the ice solids and the brine, the contents of the tank were stirred continuously for the duration of each experiment. This agitation is also necessary to 'fluidise' the ice such that both phases flow easily and brine is not drawn off from the tank preferentially, allowing the ice to bridge over the outlet of the tank.

Ice slurry was pumped through the rig at a flow rate, Q = 1.5 l/s, with the returning flow directed initially to the purge tank (see Figure 1). Once the slurry flowing through the rig into the purge tank had developed from brine, through low ice fraction slurry, to visibly thicker slurry, the manual valves were switched to divert the flow back to the bulk tank. The purpose of this procedure was to use an initial quantity of sacrificial slurry to cool the test rig, without allowing the resulting 'warm' brine to dilute the bulk slurry.

At this point the data acquisition stage of the experiment could begin. The frequency inverter for the pump was then used to alter the flow rate, Q, from 2.5 l/s to 0.5 l/s in 0.5 l/s increments. As with the water test, each flow rate was maintained for 50 s to allow pseudo steady-state flow to develop. The lowest flow rate was maintained for a further 50 s to allow a sample of ice slurry to be taken in order that the ice fraction, ϕ, could be determined using the coffee press method. This series of operations and readings was repeated continuously until ϕ dropped to 15 %, below which it was too low to measure.

6 Results

Data logged on the PC during each experiment were analysed to determine the flow rate and pressure drop for each pump setting. The data from the first ten and last five seconds of each pump setting were disregarded and the remaining 70 points averaged to determine the values of flow rate and pressure drop. The signal from the flow metre exhibited significant noise, which was uniform across the range of flow rates investigated and gave a standard error in the calculated flow rate of 0.040 l/s. The signals from the pressure transducers showed less noise and the standard error in the calculated pressure drop was found to be 0.010 bar. The errors in instrument measurement were small compared to the uncertainty introduced by the noise in the system.

6.1 Plate heat exchanger (PHE)

Test data for water flow through the PHE are depicted by the blue dots in Figure 5. The data produced from this pressure drop calibration gave a reasonable match to data supplied by the manufacturers (dashed line) for water flow through this section of the PHE. However a significantly better fit was obtained by extrapolating data from the later ice slurry tests to find the ΔP at $\phi = 0$ %, depicted by the green circles in Figure 5. This validated the experimental and analysis methods used for acquiring and interpreting the data for ice fraction, flow rate and pressure drop.

It was found that the pressure drop, ΔP, matched well with a line of the form:

$$\Delta P = \alpha Q^2 + \beta Q + \gamma \qquad (5)$$

where α, β, γ are fitting parameters.

The Q^2 term in Equation (5) was significantly larger than the other terms, which implies that ΔP is primarily a function of Q^2. Clearly flow rate Q is directly proportional to velocity $\bar{u}$, which leads to a comparison with Darcy's results, which suggested the following formula for pressure drop in a straight pipe:

$$\Delta P = \left(P_{in} - P_{out}\right) = f\,\frac{4L}{D}\,\frac{\rho\bar{u}^2}{2} \tag{6}$$

where f is the dimensionless friction factor, L is the length, D is the diameter, ρ is the density and $\bar{u}$ is the mean flow velocity. Friction factor f is a function of Reynolds number Re, which is in turn a function of viscosity μ, a quantity that is difficult to define for ice slurry [9].

Experiments in which ice slurry was pumped through the PHE produced somewhat variable results. Whilst Figure 6 shows the most complete set of data, results obtained from different experiments did not share exactly the same traits, making authoritative analysis difficult. In fact the evidence suggested that a slightly different PHE was tested on each occasion. This may in fact have some validity if, for example, on each test the flow through one or more of the parallel plates was blocked. However, the obvious trend in each experiment was that ΔP increases with increasing ϕ. The fitted curves shown in Figure 6 take the form of a simple exponential function. Although similar to the analysis of the Spiraflo (see below), this was a less convincing match and the lines could also be considered to be approximately linear.

On a number of occasions the flow through the PHE halted altogether, with the consequence that the ice slurry was diverted to drain via a pneumatic valve acting as a pressure-relief set at ~4 bar. Once a blockage had been initiated, the experiment almost always had to be abandoned. This was either because too much ice or brine had been lost from the pressure relief valve or simply because the blockage could not be cleared quickly, resulting in the slurry melting.

Factors that seemed likely to be relevant to the initiation of such blockages forming were the size, structure and concentration of ice crystals in the slurry. The ice crystals may have been large since they will 'ripen' over the course of several hours, increasing in size. Larger particles may also have been created from accumulations of secondary ice formed from water in the atmosphere that could have contaminated the ice slurry. The slurry may have contained stiffer lumps of ice formed from agglomerations of ice crystals, which could have survived the initial homogenisation. An excessively high ice fraction could have occurred due to the starting ϕ of the ice slurry, or brine may have been drawn-off from the slurry in the bulk tank as a result of insufficient agitation, or the slurry may have changed in composition whilst flowing through the rig.

It is worth noting that it was not easy to produce a graph similar to Figure 5 for a particular ice slurry owing to the continuous drop of ϕ with time. Figure 7 attempts to reproduce the data from the ice slurry test in a plot of ΔP against Q for slurries of different ice fraction, as was done for water. Each set of data in Figure 7 represents one cycle through the five flow rates. Each cycle took 5 minutes to complete, during which time the ice fraction reduced as the slurry melted. Only five of the eleven cycles completed during the experiment are shown to make the plot clearer.

The curves fitted to the data are least squares fits using a quadratic, as was done for water with equation (5). These gave a better fit to the data than the exponential function that was used to model pressure drop as a function of ice fraction. It can be seen from Figure 7 that the slurries with higher ice fraction require a higher ΔP to maintain a given flow rate. Also, each ice slurry appears to exhibit a yield or slip pressure difference below which the ice slurry will not flow. However these yield points cannot be calculated accurately from the data obtained.

6.2 Concentric tubular heat exchanger (Spiraflo)

Manufacturer's data for pressure drops across the Spiraflo with water was not available for comparison with the experimental data. However the form of Figure 8 was very similar to that of the equivalent graph for the PHE (see Equation (5)), which can be simplified by neglecting the insignificant lower order terms to:

$$\Delta P = \alpha Q^2 \qquad (7)$$

where α is a fitting parameter with dimensions of pressure/(flow rate)^2, with a best fit value of 0.132 bar.s^2/l^2.

The data for water flow through the Spiraflo appear to be more systematic than for the PHE. The trendline can be fitted with more confidence since the data show little variance from this relationship. Extrapolation from ice slurry test data also affirmed the accuracy of the tests using water.

The experiments using ice slurry also proved more self-consistent with the Spiraflo than the PHE. This finding is likely to be a consequence of the Spiraflo having a flow path of much greater typical width than the PHE, thus reducing the probability of blockages forming. As was demonstrated previously, the Spiraflo had an annular flow channel with an equivalent hydraulic diameter of 24 mm whilst the PHE had corrugated flow channels with an equivalent hydraulic diameter of 7 mm. On a single occasion blockage did occur in the Spiraflo, but this was probably due to a starting ice fraction that was too high ($\phi_{initial} \approx 70$ %), coupled with insufficient stirring of the slurry during pumping.

Figure 9 shows ΔP against ϕ, with this data being typical of all tests. The curve fitted to the data, which also includes points taken from water tests for $\phi = 0$ %, has the form:

$$\Delta P = ae^{b\phi} + c \tag{8}$$

where a, b, c are fitting parameters.

Further analysis, incorporating Equation (7), produced a more sophisticated equation:

$$\Delta P = a\left(e^{b\phi} - 1\right) + \alpha Q^2 \tag{9}$$

where αQ^2 is the pressure drop for water.

Clearly when $\phi = 0$ % this reduces to Equation (7). An interesting feature of the data was that it was possible to use the same fitting parameters a, b, α to give a good fit for each flow rate. The best-fit values were $a = 0.008$ bar and $b = 7.7$. Consequently it

appears that for any given ϕ, increasing Q results in the same additive rise in ΔP, e.g. increasing Q from 1.5 l/s to 2.0 l/s raises ΔP by 0.2 bar regardless of ϕ.

It was found that equation (9), which was used to fit curves to the data in Figure 9, could be used to fit the data in a plot of pressure drop against flow rate. These data are plotted in Figure 10 along with the fitted relationship at the median ice fraction for each data set. Each set of data was produced by a single cycle through the five different flow rates, which took 5 minutes to complete. Hence the ice fraction changed during the course of acquisition of this data set. This leads to the trend seen in Figure 10 that the data recorded first (at high flow rates) give high readings of pressure drop compared to the fitted curve since they were actually taken for ice slurry with a higher ice fraction. Conversely, the data for the lowest flow rates actually lie below the fitted curve since they represent the pressure drop for slurry of a lower ice fraction than the curve.

The ice fraction changed more significantly during the first cycle since the experimental rig was still being cooled. The first set of data (for an ice fraction of 62 %) in fact started with the ice fraction at 63.4 % for the highest data point, which dropped to 59.6 % for the lowest point. Also, at higher ice fractions any change in ice fraction has more influence on pressure drop (see Figure 9) so these data lie further away from the fitted curve.

Figure 10 clearly demonstrates that there is a slip pressure difference, below which the ice slurry will not flow. This slip pressure difference is given by the exponential function that makes up the first part of equation (9). This function has the shape of the lines in Figure 9 but passes through the origin. It is interesting to compare this yield

pressure difference with the models for viscosity and critical shear of slurries. The data presented here for the Spiraflo heat exchanger would seem to suggest that the ice slurries have a viscosity similar to that of water but exhibit a yield stress, which is dependent upon the ice fraction. This is the typical behaviour of a Bingham type fluid.

7 Conclusions

This experimental work has shown that moderately thick ice slurries (in the range 15 % - 60 % solids) can be pumped through commercial heat exchangers successfully. As expected from previous research, the pressure drops experienced were greater than those with water, and rose with increasing ice fraction and flow rate. Evidence was seen for an exponential dependence of pressure drop on ice fraction, in addition to a water-like dependence on the square of flow rate. The high slip pressure difference and Bingham characteristics of the thick slurries demonstrate that high wall shear is present even at low flow rates. This high shear stress at the wall is a desirable characteristic and would result in efficient cleaning of process equipment.

Blocking events were observed at higher ice fractions, or when large ice crystals (or agglomerations of smaller crystals) were thought to be present in the ice slurry. It is likely that the risks of this could be mitigated by better mixing of the bulk ice slurry prior to and during delivery. If ice crystals are allowed to 'ripen' over an extended period of time (which may be required to make the ice), their diameter can grow significantly such that it nears the characteristic dimension of the flow channels. The ice crystals may have grown to almost 1mm in diameter for some tests and the flow channels of the PHE have been shown to have an equivalent hydraulic diameter of less than 8 mm. Thus, the larger ice crystals have a diameter similar to the characteristic

dimension of the flow channels, which in fact have a mean width of 4 mm, and increase the likelihood of blockages forming.

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Figure Legends

Figure 1. Simplified diagram of the test rig for pressure drop tests.

Figure 2. Photograph of the test rig showing a plate heat exchanger connected to the equipment-testing loop.

Figure 3. View of one plate showing the corrugations.

Figure 4. Spiraflo® heat exchanger.

Figure 5. PHE with flowing water: plot of ΔP against Q.

Figure 6. PHE with flowing ice slurry: plots of ΔP against ϕ over a range of Q.

Figure 7. PHE with flowing ice slurry: plots of ΔP against Q over a range of ϕ.

Figure 8. Spiraflo® with flowing water: plot of ΔP against Q.

Figure 9. Spiraflo® with flowing ice slurry: plots of ΔP against ϕ over a range of Q.

Figure 10. Spiraflo® with flowing ice slurry: plots of ΔP against Q over a range of ϕ.