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CFD Prediction of Stratification in Isothermal Ice Slurry Pipe Flow

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ABSTRACT

Stratification in isothermal ice slurry pipe flow was investigated. A computational model which includes the shear-induced particle migration and the hindered settling was developed. The model, together with flow equations, was employed to calculate the flow patterns and particle concentration distributions in the ice slurry pipe flow. The effects of ice concentration on local ice concentration and velocity profiles were predicted. The model captures the trends found in experimental investigations.

1. INTRODUCTION

Ice slurries are mixtures of small ice particles (typically 0.1 to 1 mm of diameter) and a carrier liquid (a mixture of water and an additive such as glycol, sodium chloride or calcium carbonate which lowers the freezing temperature). They offer the possibility of enhanced energy transport density and energy storage due to the combined effects of sensible and latent heat. Applications include comfort cooling of buildings, food processing and the replacement of secondary refrigerants in ice rinks or supermarkets. Their thermophysical properties can be derived from linear weighing of the corresponding properties of the ice (which are essentially determined by the temperature) and the carrier liquid (which vary with the temperature and the concentration of the additive).

The behavior of ice slurries in heat transfer installations is complex. Thus, in horizontal pipes separation of the solid ice particles and carrier liquid occurs with any particle size at very low velocities and with large particles at high velocities. Various flow patterns can be encountered in ice slurry pipelines that affect the hydrodynamics of the flow and the mechanism of heat transfer. The different experimentally observed flow patterns are classified as homogeneous, heterogeneous, sliding bed and stationary bed (Kauffeld et al., 2005). Kitanovski and Poredos (2002) calculated the concentration distribution of ice in horizontal pipe flow by integrating the one-dimensional diffusion equation with constant values of the diffusion coefficient and the hindered settling velocity of the ice particles. They then calculated the average ice slurry viscosity by integrating the well-known Thomas equation applied locally with the calculated concentration profile. They concluded that for high average velocities and very low ice concentrations “the ice slurry viscosity is almost independent of velocity as for Newtonian fluids”. On the other hand, ice slurries exhibit a non-Newtonian behavior for ice concentrations exceeding approximately 20% but this threshold value is also influenced by parameters such as the size of the ice particles and the nature of the additive. Several experimental studies have determined values of the effective viscosity of ice slurries and compared them with different rheological models (Kitanovski et al, 2005).

In the present study we consider the isothermal steady laminar flow of ice slurry in the entrance region of a horizontal pipe and solve simultaneously the three-dimensional differential equations of motion for the two-phase mixture as well as the conservation equation for the ice particles which was derived from the Phillips model (Phillips et al., 1992) combined with gravitational settling effects. These equations are coupled since the viscosity of
the two-phase mixture depends on the ice concentration which changes from the assumed uniform distribution at the inlet due to the opposing effects of buoyancy and diffusion. The results show that the ice concentration and the velocity profile reach fully-developed distributions which are not symmetrical with respect to the axis of the pipe.

2. CFD MODEL OF ICE SLURRY FLOW

The present study concerns the pressure-driven flow of ice slurry (based on 14% ethylene glycol and 0.4mm ice particle diameter) in a horizontal pipe. Figure 1 shows a schematic diagram describing the problem. The diameter and length of the pipe are denoted by D (10mm) and L=300D, respectively. The pipe thickness is considered negligible. At the pipe inlet the velocity and the ice particle mass fraction are assumed to be uniform; the outflow condition is applied at the pipe outlet. Specific no-ice particle-flux and no slip boundary conditions have been applied to the pipe wall.

2.1 Governing Equations.

We consider that the ice slurry is a Newtonian fluid. The governing equations are based on the continuum approach. The ice particles migration that includes several mechanisms (Brownian motion, particle settling, shear-induced, and viscosity gradients migration) is described by an additional transport equation. The steady state continuity and momentum conservation equations are given respectively by:

\[
\nabla \cdot (\rho_i \mathbf{u}) = 0
\]

\[
\nabla \cdot (\rho_i \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot \mathbf{\tau}
\]  

The steady state species mass conservation equation, based on the particle diffusive model proposed by Phillips et al. (1992), is given as:

\[
\nabla \cdot (\rho_i \mathbf{u} \varnothing) = -\nabla \cdot \mathbf{N}_t
\]  

This equation represents a balance between the convective and diffusive particle flux. Neglecting Brownian motion, we model the diffusive particle flux as:

\[
\mathbf{N}_t = \mathbf{N}_c + \mathbf{N}_\mu + \mathbf{N}_s
\]  

Where \( \mathbf{N}_c \) is the flux induced by the gradients of shear rate, \( \mathbf{N}_\mu \) is the flux due to spatial variation in viscosity, and \( \mathbf{N}_s \) is the flux due to particle settling. Based on the scaling arguments of Leighton and Acrivos (1987b), Phillips et al. (1992) proposed:

\[
\mathbf{N}_c = -\rho_i \kappa_c a^2 (\varnothing\nabla \dot{\varnothing} + \dot{\varnothing} \nabla \varnothing)
\]  

\[
\mathbf{N}_\mu = -\rho_i \kappa_\mu a^2 \dot{\varnothing} \varnothing \frac{1}{\mu_i} \frac{d\mu_i}{d\varnothing} \nabla \varnothing
\]  

For the settling particle flux we adopt the form proposed by Richardson and Zaki (1954):

\[
\mathbf{N}_s = \rho_i \omega_0 f(\varnothing) \varnothing \mathbf{Q}
\]  

Where \( \omega_0 \) is the terminal settling velocity of a single particle in the aqueous solution and \( f(\varnothing) \) is the hindrance function. In this work, we adopt the form suggested by Revay and Higdon (1992):

\[
f(\varnothing) = (1 - \varnothing)^{6.55} (1 + 3.458\varnothing^2 + 8.990\varnothing^3)
\]  

In this coordinate system, the gravity vector \( \mathbf{Q} \) is giving by:

\[
\mathbf{Q} = [0 \ 1 \ 0]
\]
The final form of Eq. (3) corresponding to the phenomenological model developed by Phillips et al. (1992) leads to the following equation:

$$\nabla \cdot (\rho_s \{ \mathbf{u} + \omega \delta (\varnothing) \mathbf{Q} \}) = \nabla \cdot (\Gamma \nabla \varnothing) + S$$

(11)

The diffusive coefficient $\Gamma$ and the source term $S$ can be written as:

$$\Gamma = \rho_s a^2 \partial (K_c + K_{l_s} \partial (\frac{\partial \mu_s}{\partial \partial \varnothing}))$$

and

$$S = \nabla \cdot (\rho_s a^2 \partial \nabla \varnothing)$$

(12)

Where the coefficients $K_c = 0.41$ and $K_{l_s} = 0.62$.

### 2.2 Ice Slurry Properties

Relations for the calculation of ice and ice slurry properties are given in the Handbook on Ice Slurries (Kauffeld et al., 2005):

$$\rho_s = \rho_{l_{ice}} + (1-\varnothing) \rho_l$$

(13)

$$\mu_{l_{is}} = \mu_\mu (1 + 2.5 \varnothing + 10.05 \varnothing^2 + 0.00273 e^{16.6 \varnothing})$$

(14)

$$\rho_{l_{ice}} = 917 - 0.13T$$

(15)

Properties for different carrier liquids are calculated with the following formulas obtained by polynomial curve-fitting of tabulated data published in ASHRAE Handbook: Fundamentals (2005):

$$\rho_i (\varnothing_i, T) = \sum_{i=0}^{M} T^i \sum_{j=0}^{N} b_{i,j} \varnothing_i$$

(16)

$$\mu_i (\varnothing_i, T) = \sum_{i=0}^{M} T^i \sum_{j=0}^{N} b_{i,j} \varnothing_i$$

(17)

The coefficients $b_{i,j}$ were calculated by Renaud-Boivin et al. (2011) and are given in Tables 1 and 2. The saturation concentration of additive by volume $\varnothing_a$ is given by the following expression:

$$\varnothing_a = \frac{\varnothing_0}{(1-\varnothing_a)} \rho_l$$

(18)

Where $\varnothing_0$ is the initial concentration of additive by volume in the carrier liquid and $\rho_0$ the initial density of the carrier fluid.

### Table 1: Coefficients for density of aqueous solutions of ethylene glycol.

<table>
<thead>
<tr>
<th>b[i,j]</th>
<th>j=4</th>
<th>j=3</th>
<th>j=2</th>
<th>j=1</th>
<th>j=0</th>
</tr>
</thead>
<tbody>
<tr>
<td>i=2</td>
<td>-1,50864E-01</td>
<td>1,843124E-01</td>
<td>-7,800110E-02</td>
<td>1,321932E-02</td>
<td>-3,154897E-03</td>
</tr>
<tr>
<td>i=1</td>
<td>1,784602E+01</td>
<td>-2,179487E+01</td>
<td>9,174996E+00</td>
<td>-1,827717E+00</td>
<td>-1,085019E-01</td>
</tr>
<tr>
<td>i=0</td>
<td>9,375000E+01</td>
<td>-1,026204E+02</td>
<td>-8,634722E+00</td>
<td>1,782307E+02</td>
<td>1,001088E+03</td>
</tr>
</tbody>
</table>
3. CFD SIMULATIONS

The coupled equations (1), (2) and (11) were solved using the commercial software package Fluent which is based on the finite volume technique. The particle transport equation (11) was introduced using the user-defined scalar (UDS) functionality. The SIMPLE algorithm was employed to resolve the pressure-velocity coupling in the momentum equation. The QUICK scheme was used to approximate the convection term. The validation of the model was obtained by simulating the steady laminar forced convection of water in a horizontal tube. The mesh independence was examined with different mesh sizes obtained by refining a coarser size until results were unchanged. The results were compared with those obtained by Nascimento et al. (2006) and Liu (1974), as shown in Table 3.

Table 3: Mesh independence tests and Validation (Re=500, Water Flow).

<table>
<thead>
<tr>
<th>Mesh Independence and Validation</th>
<th>Non-Dimensional Velocity V* at various Position Z*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present Model with Coarse Mesh (2169000 cells)</td>
<td>Z*=0.0002116</td>
</tr>
<tr>
<td>Present Model with Medium Mesh (3481885 cells)</td>
<td>1.0359</td>
</tr>
<tr>
<td>Present Model with Fine Mesh (7117986 cells)</td>
<td>1.0108</td>
</tr>
<tr>
<td>Liu (1974)</td>
<td>1.100</td>
</tr>
<tr>
<td>Nascimento et al. (2006)</td>
<td>1.113</td>
</tr>
</tbody>
</table>

Where $Z^* = \frac{z}{D} \frac{D}{R_e}$ and $V^* = \frac{V}{V_{in}}$.

![Figure 2: Predicted ice particle concentration profiles (A) and velocity profiles (B) along the vertical diameter at different axial positions for $V_{in} = 0.1$ m/s and $\Phi_{in} = 0.1$.](image)

Table 2: Coefficients for dynamic viscosity of aqueous solutions of ethylene glycol.

<table>
<thead>
<tr>
<th>$b[i,j]$</th>
<th>j=5</th>
<th>j=4</th>
<th>j=3</th>
<th>j=2</th>
<th>j=1</th>
<th>j=0</th>
</tr>
</thead>
<tbody>
<tr>
<td>i=5</td>
<td>-2.526959E-04</td>
<td>3.204206E-04</td>
<td>-1.452982E-04</td>
<td>2.712083E-05</td>
<td>-1.798788E-06</td>
<td>-2.635893E-09</td>
</tr>
<tr>
<td>i=4</td>
<td>1.979292E-02</td>
<td>-2.576583E-02</td>
<td>1.197782E-02</td>
<td>-2.297945E-03</td>
<td>1.586547E-04</td>
<td>4.360368E-07</td>
</tr>
<tr>
<td>i=3</td>
<td>-4.090770E-01</td>
<td>5.668161E-01</td>
<td>-2.796934E-01</td>
<td>5.701305E-02</td>
<td>-4.304966E-03</td>
<td>-3.310267E-05</td>
</tr>
<tr>
<td>i=2</td>
<td>-1.311978E+00</td>
<td>7.452525E-01</td>
<td>1.747934E-01</td>
<td>-1.338755E-01</td>
<td>2.350798E-02</td>
<td>1.632560E-03</td>
</tr>
<tr>
<td>i=1</td>
<td>9.969246E+01</td>
<td>-1.268873E+02</td>
<td>5.555892E+01</td>
<td>-1.064625E+01</td>
<td>5.244562E-01</td>
<td>-6.195165E-02</td>
</tr>
<tr>
<td>i=0</td>
<td>-9.529375E+02</td>
<td>1.307950E+03</td>
<td>-6.219763E+02</td>
<td>1.413809E+02</td>
<td>-6.181913E+00</td>
<td>1.791184E+00</td>
</tr>
</tbody>
</table>
4. RESULTS AND DISCUSSION

The ice slurry behavior in horizontal tube is discussed. The axial evolution of the flow field and the effects of the inlet ice concentration on local ice concentration and velocity profiles are explored. Most simulations were performed with parameters such that the maximum packing concentration at the top of the tube is not reached.

4.1 Axial evolution of the flow field

Figure 2 shows the predicted ice particle concentration profiles and velocity profiles along the vertical diameter at different axial positions for $V_{in} = 0.1 \text{ m/s}$ and $\varphi_{in} = 0.1 (\sim 6.12^\circ \text{C})$. Under the effect of buoyancy the lighter ice particles move upwards so that their concentration progressively increases near the top of the tube and decreases near its bottom. The resulting concentration gradient creates a downward diffusive flux which eventually becomes equal to the upward buoyancy induced motion. Thus a fully developed distribution is eventually obtained as indicated by the identity of the concentration profiles at $Z = 1.50 \text{ m}$ and $Z = 2.95 \text{ m}$. The velocity profile also changes along the tube length. Near the inlet ($Z = 0.005 \text{ m}$) we note the overshoot caused by the boundary layer growth. Further downstream the velocity profile is not symmetrical with respect to the tube axis. This is due to the effect of ice concentration on the viscosity of the two phase mixture: thus in the lower part of the tube where the ice concentration is low the viscosity decreases and the velocity increases; on the other hand, near the upper part of the tube where the ice concentration is high the viscosity increases and the velocity decreases. Eventually a fully developed asymmetrical velocity profile is obtained with its maximum value occurring below the tube axis.
Figure 3 shows the corresponding axial evolution of the friction factor at the top, bottom and side of the tube. At the inlet these three values are essentially infinite as the velocity profile adjusts from the imposed uniform value to the no-slip boundary condition. They decrease rapidly as the boundary layer grows with small differences between the three positions. Eventually they reach a minimum value whose magnitude and axial position depends on the circumferential position. Beyond this axial position they increase at different rates (fastest near the top and slowest near the bottom) and reach an asymptotic value which is highest at the top and lowest at the bottom of the tube. These results are consistent with the ice concentration profiles of Figure 2 and the corresponding viscosity distributions of the two phase mixture. Qualitatively similar results have been obtained for other combinations of inlet ice concentrations and inlet velocities. In particular the existence of a fully developed region has been confirmed in all analysed cases.

4.2 Effects of inlet ice concentration

Figure 4 shows the effects of the inlet ice concentration [10% (-6.12°C), 15% (-6.57°C), 20% (-7.09°C)] on the fully developed ice particle concentration profile and on the corresponding velocity profile. For the lowest inlet ice concentration the lowest third of the tube does not contain any ice. The extent of this region decreases as the inlet ice concentration increases. On the other hand, the maximum ice concentration, which occurs at the top of the tube, increases monotonically with the inlet ice concentration. These observations agree qualitatively with experimental observations (Kauffeld et al., 2005; Gillies et al., 1999). The fully developed velocity profiles are also significantly influenced by the inlet ice concentration. As this parameter increases the maximum velocity increases and its position shifts downwards.

5. CONCLUSIONS

CFD simulations of ice slurry flow were performed using diffusive flux modeling in order to assess the capability of CFD Methods to predict the complex behavior of such flows. The model couples a Newtonian stress/shear-rate relationship with a shear-induced migration model of ice particles in which the local effective viscosity is depend on local volume fraction of ice. The shear-induced migration model adopted in this work appears to be quite robust in capturing the main features in three-dimensional pressure-driven ice slurry pipe flow. The validation of CFD would require experimental data which are presently unavailable in the literature. Nonetheless, the study conducted here has shown that; overall, CFD could give reasonable prediction of ice slurry flow patterns and ice concentration distribution and velocity profiles.

NOMENCLATURE

\begin{align*}
\alpha & \quad \text{ice particle radius} \quad (m) \\
\text{conc}=100\phi_{in} & \quad \text{inlet concentration} \quad (\%) \\
p & \quad \text{pressure} \quad (Pa) \\
T & \quad \text{temperature} \quad (^{\circ}\text{C}) \\
u & \quad \text{velocity vector} \quad (m/s) \\
\text{Re} & \quad \text{Reynolds Number} \\
x, y, z & \quad \text{geometrical Coordinates} \quad (m) \\
V & \quad \text{velocity magnitude} \quad (m/s) \\
\dot{\gamma} & \quad \text{magnitude of shear rate} \quad (1/s) \\
\mu & \quad \text{dynamic viscosity} \quad (Pa \cdot s) \\
\rho & \quad \text{density} \quad (kg/m^3) \\
\tau & \quad \text{stress tensor} \quad (Pa) \\
\phi & \quad \text{ice volume fraction} \quad (\text{—}) \\
\text{Subscripts} & \\
\text{ice} & \quad \text{ice} \\
in & \quad \text{inlet} \\
is & \quad \text{ice slurry} \\
l & \quad \text{carrier liquid} \\
x, y, z & \quad \text{coordinate axes}
\end{align*}
REFERENCES


ACKNOWLEDGEMENT

This project is part of the R&D program of the NSERC Chair in Industrial Energy Efficiency established in 2006 at Université de Sherbrooke. The authors acknowledge the support of the Natural Sciences & Engineering Research Council of Canada, Hydro Québec, Alcan International Ltd and Natural Resources Canada.