Modeling of Ice Slurry Flow through Bend Pipe

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Abstract. In this work, CFD Eulerian multiphase model with KTGFis used to investigate the flow behaviour of the ice slurry in 90⁰ elbow bend pipe. The present model considered the particle-particle collisions along with particle-wall collisions. In the modeling of ice slurry flow various interfacial forces viz. drag force, lift force and turbulence dispersion force are considered. The solid phase viscosity is calculated as a sum of kinetic and collision viscosity component and the turbulence in the ice slurry flow is modeled by the per phase k- model. Simulation has been performed at velocity of 1 m/s, concentration of 10% and particle size of 0.25 mm for the bend radius ratios (R/r) of 2, 2.98 and 5.6. Apart from that, effect of particle size, velocity and concentration on solid particle distribution has also been investigated. Results show that, secondary flow is generated similar to single phase flow which influences the velocity, particle distribution and pressure drop.

1. Introduction

Humans are always dependent on ice for cooling from the ancient times. In earlier time before the invention of the artificial refrigeration system natural ice was used for the food preservation and cooling. The ice from the colder areas was transported to hotter areas and mixture of ice with salt also used to attain temperatures lower than 0 °C. However, with the subsequent development of artificial refrigeration lead us to harvest ice in the form of cubes, block and flakes for cooling and other applications. The Ice has good value of latent heat during melting, however, it has slow cooling rate due to poor heat transfer characteristics. Therefore, the use of ice has become superseded due low heat transfer characteristics and complications in transportation [1]. Apart from that, melting of ice creates some sharp edges due to which manual handling and transportation of ice is not too easy. Moreover, these sharp edges also responsible for damage of surfaces of product in case of direct contact chilling. The above-mentioned difficulties can be simply controlled by using ice in the form of slurry which has excellent transportation and heat transfer characteristics [2].

Ice slurry can be defined as a mixture of micro sized ice particles with binary solution of water. On the bases of use, configuration of slurry may vary i.e. the particles concentration (10-30 %), size (0.1-1.0 mm) and concentration of depressant in water. Ice slurry has good fluidity and high energy storage capacity. Apart from that it remains at constant temperature during the heat transfer due to phase change process, hence higher heat transfer coefficient in comparison to other conventional fluid. The flow of ice slurry through pipe is a convolute phenomenon in compare to other conventional fluid which affected by configuration of slurry, flow parameters and pipe geometry. For such types of problem, CFD analysis can delivers plenty information about the flow [3].
Most of the studies on ice slurry flow available in the literature are related to the determination of rheological behaviour and pressure drop. The ice slurry behaves as a Newtonian fluid for lower than 10 % initial ice concentration and non-Newtonian fluid for higher initial ice concentration [4]. Several researchers considered the different rheological model (Bingham, Power Law, Herschel–Bulkley and Cassion) for ice slurry. Monteiro and Bansal [5] proposed the empirical or semi-empirical correlations based on the mentioned rheological models to predict the pressure drop. However, these models usually considered uniform distribution of ice particles which is possible only at very high velocity therefore, fail to predict the pressure drop [6]. Vuarnoz et al. [7] and Stamatiou and Kawaji [8] measured the velocity and ice concentration distributions for ice slurry flow in horizontal and vertical pipes, respectively. However, only few experimental data are available on the velocity and concentration distribution due to complexity of the measurements. CFD approach has been widely used by several researchers to simulate the different material’s slurry flow [9-16].

In any pipe line system, bends are compulsory as they provide flexibility. During the flow through the bend pipe, secondary flow occurs as a result of centrifugal force acting on the fluid and cause additional pressure losses [17]. The generated secondary flow does not only affect the pressure drops but, also the solid particles and velocity distribution across the cross section. During the flow through the bend, the flow depends on bend radius and other operating parameters. Therefore, it is essential to investigate the flow of ice slurry through bend to develop better understanding of flow behaviour.

2. Problem Description
In this work, flow has been presented in bend pipe (as shown in Fig. 1) of 23 mm diameter with different bend radius ratios (R/r) of 2, 2.98 and 5.6, where, r is pipe radius and R is the bend radius. Pipe has contains 90° elbow bend section, downstream and upstream pipe. The investigations have been carried out in bend section.

![Fig. 1. Schematic diagram of 90° elbow bend pipe](image-url)
3. Mathematical Modelling

The mathematical model has been developed on the bases of Eulerian model and per phase k-e turbulence model [3].

Continuity equations: Equation (1) is for liquid, (2) for solid phase where subscripts l & s denotes the liquid & solid respectively.

\[
\frac{\partial}{\partial t} (\alpha_l \rho_l) + \nabla \cdot (\alpha_l \rho_l \vec{v}_l) = 0
\]

(1)

\[
\frac{\partial}{\partial t} (\alpha_s \rho_s) + \nabla \cdot (\alpha_s \rho_s \vec{v}_s) = 0
\]

(2)

\[\alpha_l + \alpha_s = 1\]

(3)

where \(\rho\), \(\alpha\), and \(v\) are density, volume fraction and velocity respectively.

Momentum Equations: Equations (4 & 5) is for liquid, (6 & 7) for solid phase

\[
\frac{\partial}{\partial t} (\alpha_l \rho_l \vec{v}_l) + \nabla \cdot (\alpha_l \rho_l \vec{v}_l \vec{v}_l) = -\alpha_l \nabla P + \nabla \tau_l + \alpha_l \rho_l \vec{g} + \vec{R}_l
\]

(4)

\[
\tau_l = \alpha_l \mu_l \left( \nabla \vec{v}_l + \nabla \vec{v}_l^T \right) + \alpha_l \left( \lambda_l - \frac{2}{3} \mu_l \right) (\nabla \vec{v}_l) \vec{I}
\]

(5)

\[
\frac{\partial}{\partial t} (\alpha_s \rho_s \vec{v}_s) + \nabla \cdot (\alpha_s \rho_s \vec{v}_s \vec{v}_s) = -\alpha_s \nabla P + \nabla \tau_s + \alpha_s \rho_s \vec{g} - \nabla P_s + \vec{R}_s
\]

(6)

\[
\tau_s = \alpha_s \mu_s \left( \nabla \vec{v}_s + \nabla \vec{v}_s^T \right) + \alpha_s \left( \lambda_s - \frac{2}{3} \mu_s \right) (\nabla \vec{v}_s) \vec{I}
\]

(7)

where \(\mu\), \(R\), \(\vec{I}\) and \(\lambda\) are viscosity, interfacial forces, unit tensor and bulk viscosity respectively.

Bulk viscosity defined from Lun et al., 1984 [12].

\[
\lambda_s = \frac{4}{3} \alpha_s \rho_s d_s g_{s,v} \left( 1 + e_v \right) \left( \Theta \frac{\Theta}{\pi} \right)^{0.5}
\]

(8)

The interfacial forces \(\vec{R}\) includes lift and drag forces [13]. Drag force is described by Gidaspow, 1994 [14]. The lift force on the solid phase is calculate in the present work as

\[
\vec{F}_{lift,s} = C_L \rho_l \alpha_s (\vec{v}_l - \vec{v}_s) \times \nabla \vec{v}_l
\]

(9)

\[
\vec{F}_{lift,sl} = -\vec{F}_{lift,ls}
\]

(10)

Lift force coefficient \(C_L\) is assigned to be 0.2.

Solid viscosity is the sum of kinetic and collisional viscosity. Component of frictional viscosity is zero.

\[
\mu_s = \mu_{col} + \mu_{kin} + \mu_{fr}
\]

(11)

\[
\mu_{col} = \frac{4}{5} \alpha_s \rho_s d_s g_{s,v} \left( 1 + e_v \right) \left( \Theta \frac{\Theta}{\pi} \right)^{0.5}
\]

(12)

\[
\mu_{kin} = \frac{\alpha_s \rho_s d_s \sqrt{\pi} \Theta \left[ 1 + \frac{2}{5} (1 + e_v) (3e_v - 1) \alpha_s g_{s,v} \right]}{6 (3 - e_v)}
\]

(13)
where $a_{\gamma_{\text{max}}}$ is maximum packing limit.

\[
g_{\alpha_{\gamma}} = \left[ 1 - \left( \frac{\alpha}{a_{\gamma_{\text{max}}}} \right)^{\frac{1}{\kappa}} \right]^{-1}
\]  

(14)

3.1 Numerical Procedure

The boundary conditions and properties of ice slurry have been given in Table 1 and 2 respectively. The geometry is divided into the hexahedral grids and grid is also optimized. In the present work three different bend radius ratios of 2, 2.98 and 5.6 for which optimum number of elements are 347384, 353160 and 366633 respectively.

3.2 Validation

Model has been validated with the experimental result of Kaushal et al. [17]. The variation in the experimental and simulation values is within 10%.

| FPD   | Ice Concentration (\%) | Density (kg/m³) | Viscosity (m-Pa) |
|-------|------------------------|-----------------|------------------|
| Ethanol | 10                     | 983.9           | 0.00458          |
| Ethanol | 50                     | 981.3           | 0.00809          |
4. Results and Discussion

The simulation is performed for at the velocity of 1 m/s and concentration of 10 %. Fig. 3 shows the variation in the pressure, in plane which contained 20D length of upstream pipe from $\beta=0^\circ$, elbow bend section and 20D length of downstream pipe from $\beta=90^\circ$. It is shown in figure that pressure varies only in longitude direction in both upstream and downstream part and in the bend its variation is in both directions (longitudinal and radial direction) because of the centrifugal force. It can also be observed that pressure is considerably reduced in the inner side of the bend. As a result secondary flow is generated (as shown in Fig. 4).

The boundary layer separation has also been observed at the velocity of 1 m/s and concentration of 10 % for $R/r = 2$. It can be observed from the fig. 5 that boundary layer separation occurs and then reattached.

![Fig. 3. Contour of pressure in a plane of bend](image)
Fig. 4. Vector Plot of velocity in a plane of bend

Fig. 5. Vector Plot of velocity in a plane of bend
Fig. 6. Contour of velocity in a plane of bend

Fig. 6 shows the velocity contour and from the figure it can be observed that flow is fully developed earlier elbow section and it get disturbed in bend section then again reattributed. The velocity contour shows that the velocity varies dramatically in the bend. The velocity first increase near the inner side of the bend and after 45° velocity decrease and increase at the outer bend side. It is clearly shown in the figure that, flow is redistribution in the downstream section and flow becomes steady.

Fig. 7. Contours (a) to (c) and vector plots (d) to (f) of solid phase velocity
The contours of velocity (a to c) and vector plots (d to f) are shown in Fig. 7 for \( V = 1 \) m/s, IPC = 10% and \( ds = 0.25 \) mm. The results are shown for the plane at different bend angles (\( \beta = 0^\circ, 45^\circ \) & \( 90^\circ \)). At the inlet of the bend section the velocity increase near the bend section due to small path (shown in contour (a) and vector plot (d)). The contour (b) and vector plot (e) shows that velocity at bend angle of \( 45^\circ \). It can be observed that velocity is still maximum near to inner side however, particles are moving towards outer side. Due to the secondary flow velocity increases at the outer side and decreases near the inner side of the bend at the \( 90^\circ \) bend angle.

![Fig. 8. Contours of particle concentration at different bend angles](image-url)

\[ V = 3 \text{ m/s, IPC = 10\%, ds = 0.25 mm} \]
Fig. 8. The contours of concentration have been shown at different bend angle (a to e) and outlet for elbow pipe with bend radius ratio of 2. Figure shows that at the $\beta = 0^\circ$ flow is heterogeneous. The concentration of particles increase toward the inner side upto $\beta = 45^\circ$ and after that decrease. At the outlet of pipe, flow is more uniform due to redistribution. The effect of particle wall collision can also be observed from the figure.

Fig. 9 shows the concentration contour at $\beta = 0^\circ$, $45^\circ$ and $90^\circ$ for different conditions for bend radius ratio 2. The contours (a) to (c) shows the concentration contours for velocity 3 m/s, concentration 10% and particle 0.25 mm of size. Contour shows that at higher velocity flow is more uniform and effect of particle wall collision is more significant. The contours (d) to (f) shows the concentration contours for velocity 1 m/s, concentration 30% and particle 0.25 mm of size. Contour shows that at higher concentration flow is more homogeneous due to more collisions. The contours g) to (i) shows the concentration contours for velocity 1 m/s, concentration 10% and particle 0.40 mm of size. Contour shows that with bigger particles flow is more heterogeneous due to more buoyancy force.
Fig. 10. Contours of particle concentration at different bend angle

Fig. 5 shows the boundary layer separation for R/r = 2. However, for the higher R/r (2.98 & 5.6) boundary layer separation does not occur. Fig. 10 shows the comparison of concentration contour at velocity 1 m/s, concentration 10% and 0.25 mm size for two different R/r. The contours (a) to (c) and contours (d) to (f) are showing the solid concentration contour at $\beta = 0^\circ$, $45^\circ$ & $90^\circ$ for R/r of 2.98 and 5.6, respectively. It is clear from contour that effect of secondary flow become inferior for R/r = 5.6. Apart from that, pressure losses also decrease to 4% and 14% with increase in the bend pipe radius ratio from 2 to 2.98 and 5.60.

5. Conclusions

From the simulations it is concluded that, during the flow through bend, a centrifugal force acts on the fluid which results in secondary flow at the bend section. Due to the centrifugal force acting on the fluid in the bend section, a secondary flow is generated which may also lead to boundary layer separation. For the ice slurry flow at 1 m/s and ice concentration of 10% in the $90^\circ$ elbow bend pipe with bend radius (R/r) ratio of 2, the boundary layer separation occurs (shown in Fig. 5), however, for the higher (R/r) ratios of 2.98 and 5.60 boundary layer separation does not occur. The effect of secondary flow becomes inferior at higher bend radius ratios. As a result pressure losses across the pipe decrease to 4% and 14% with increase in the bend radius ratio from 2 to 2.98 and 5.60, respectively.
The secondary flow also affects the velocity and particle distribution. The velocity of the particle first increased near the inner wall of the bend at the inlet of the bend (0° bend angle) and beyond the 45° bend angle the velocity of the particle decreases rapidly near the inner wall and increases towards the outer wall of the bend. However, the velocity distribution again becomes steady in the downstream pipe due to redistribution of particles and fluid. At the higher initial velocity, the effect of secondary flow is more significant therefore, particle distribution is more influenced by secondary flow at bend section. However, particle distribution is more homogeneous at higher velocity and higher concentration at the outlet of the pipe.

References

[1] Kauffeld M, Wang MJ, Goldstein V, Kasza KE. Ice slurry applications. International Journal of Refrigeration. 2010 Dec 31;33(8):1491-505.

[2] Rawat, K.S. and Pratihar, A.K., 2018. Thermo-Physical Properties of Aqueous Solution of Ice Slurry. International Journal of Pure and Applied Mathematics, 119(17), pp.1493-1497.

[3] Rawat, K.S. and Pratihar, A.K., 2018, February. Numerical Investigation of Ice Slurry Flow in a Horizontal Pipe. In IOP Conference Series: Materials Science and Engineering (Vol. 310, No. 1, p. 012095). IOP Publishing.

[4] Grozdek, M., Khodabandeh, R., & Lundqvist, P. (2009). Experimental investigation of ice slurry flow pressure drop in horizontal tubes. Experimental Thermal and Fluid Science, 33(2), 357-370.

[5] Monteiro, A. C., & Bansal, P. K. (2010). Pressure drop characteristics and rheological modelling of ice slurry flow in pipes. International Journal of Refrigeration, 33(8), 1523-1532.

[6] Wang, J., Wang, S., Zhang, T., & Battaglia, F. (2017). Mathematical and experimental investigation on pressure drop of heterogeneous ice slurry flow in horizontal pipes. International Journal of Heat and Mass Transfer, 108, 2381-2392.

[7] Vuarnoz, D., Sari, O., Egolf, P. W., & Liardon, H. (2002, September). Ultrasonic velocity profiler UVP-XW for ice slurry flow characterisation. In Proceedings of the third international symposium on ultrasonic Doppler method for fluid mechanics and fluid engineering, Lausanne, Switzerland.

[8] Stamaoui, E., & Kawaji, M. (2005). Thermal and flow behavior of ice slurries in a vertical rectangular channel. Part I: Local distribution measurements in adiabatic flow. International Journal of Heat and Mass Transfer, 48(17), 3527-3543.

[9] Ekambaram, K., Sanders, R. S., Nandakumar, K., & Masliyah, J. H. (2009). Hydrodynamic simulation of horizontal slurry pipeline flow using ANSYS-CFX. Industrial & Engineering Chemistry Research, 48(17), 8159-8171.

[10] Kaushal, D. R., Thinglas, T., Tomita, Y., Kuchii, S., & Tsukamoto, H. (2012). CFD modeling for pipeline flow of fine particles at high concentration. International Journal of Multiphase Flow, 43, 85-100.

[11] Kumar Gopaliya, M., & Kaushal, D. R. (2016). Modeling of sand-water slurry flow through horizontal pipe using CFD. Journal of Hydrology and Hydromechanics, 64(3), 261-272.

[12] Zhang, P., & Jiang, Y. Y. (2014). Forced convective heat transfer of slush nitrogen in a horizontal pipe. International Journal of Heat and Mass Transfer, 71, 158-171.

[13] Shi, X. J., & Zhang, P. (2016). Conjugated heat and mass transfer during flow melting of a phase change material slurry in pipes. Energy, 99, 58-68.

[14] Jin, T., Li, Y. J., Liang, Z. B., Lan, Y. Q., Lei, G., & Gao, X. (2017). Numerical prediction of flow characteristics of slush hydrogen in a horizontal pipe. International Journal of Hydrogen Energy, 42(6), 3778-3789.

[15] Nayak, B. B., & Chatterjee, D. (2017). Numerical investigation of convective heat transfer in
pipeline flow of multi-sized mono dispersed fly ash-water slurry. International Journal of Heat and Mass Transfer, 108, 1802-1818.

[16] Singh, J. P., Kumar, S., & Mohapatra, S. K. (2017). Modelling of two phase solid-liquid flow in horizontal pipe using computational fluid dynamics technique. International Journal of Hydrogen Energy, 42(31), 20133-20137.

[17] Kaushal, D. R., Kumar, A., Tomita, Y., Kuchii, S., & Tsukamoto, H. (2013). Flow of mono-dispersed particles through horizontal bend. *International Journal of Multiphase Flow*, 52, 71-91