Numerical Investigation on Critical Velocity of Ice Slurry Flow

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Abstract. The use of ice slurry as a working fluid in secondary-loop of refrigeration system not only enhances the system performance but also reduces the refrigerant charge and its leakage to environment. It can be transported through pipes; however, flow of ice slurry is a quite complex two phase flow, which significantly differs from conventional fluid flow. Ice slurry flow can be influenced by on several operating parameter viz. initial velocity, ice concentration, freezing point depressant concentration and particle size. Solution of such type of flow through pipe is a difficult task through experiments due to complexities in visualization and measurements. Therefore, a CFD model is developed to simulate the ice slurry flow to predict the safe conditions for the transportation of ice slurry. In the present work, numerical investigation of flow of ice slurry has been analyzed in order to predict the critical velocity and effect of different parameters on critical velocity. Eulerian granular flow model has been used for the simulation, which is also validated with existing experimental results in the literature. Result shows that, the critical velocity is especially influenced by the particle size. Critical velocity at 10 % initial ice concentration increases from 0.4 m/s to 0.16 m/s with increase in particle size from 0.1 mm to 0.4 mm.

1. Introduction
The HVAC&R systems are consuming a huge share of the entire world electricity generation and also damaging the environmental by emission of the synthetic refrigerants [1]. It is reported in the literature that, use of the SLR system enhances performance and reduce the refrigerant charge [2]. The SLR systems consist two loops: primary loop and secondary loop. The primary loop is a conventional vapour compression refrigeration system in which refrigerant flow through the expansion valve, compressor, condenser, and evaporator. The secondary loop is connected with a primary loop through the evaporator. The working fluid in the SLR system can be single phase fluid or a two phase fluid [2-3]. The single phase fluids are the low freezing point solutions which can be classified in aqueous and non-aqueous solutions. The aqueous solutions are more preferred over non-aqueous solutions as they have much lower volume flow rate for the same cooling conditions. The two phase fluids can also use in the SLR system, which has various advantages over the single phase fluids. The two phase fluid can be generated by forming of slurry of PCM. PCM slurry can be defined as the mixture of solid PCM particles with liquid and which can be flow through pipes [4-7]. Ice slurry is a PCM slurry, which is mixture of aqueous solution and ice. However, during transportation its flow is significantly differs from the conventional fluid flow [8]. Ice slurry flow influenced by different parameter i.e. inlet velocity, FPD concentration, ice concentration, pipe and particle size.
During the flow, the ice particles tend to settle (due to density difference) towards the top of the pipe, as a result different concentration lies in the radial direction [9]. Depending on concentration distribution, flow can be classified into homogeneous, heterogeneous, moving bed and stationary bed flow regimes (shown in Fig. 1).

At a very high flow velocity, particles are uniformly suspended and flow regime is known as the homogeneous flow and if the particles are randomly suspended such that concentration gradient is formed in flow is called heterogeneous flow. At low velocity the concentration increases at the top of the pipe and layer with maximum possible concentration forms, the corresponding velocity at this stage known as critical velocity [10]. This layer moves along the top wall and in the bottom of this layer heterogeneous flow exists. In such type of concentration distribution, flow known as moving bed flow. Further reduction in velocity leads to increase in the thickness of layer and at a very low velocity, ice layer become stationary and only liquid flow through bottom side known as stationary bed condition [11]. During the transportation, to avoid chock condition, the velocity should be far away from critical velocity which is challenging task by experiments. Therefore, in this section simulation of the ice slurry flow at a low initial velocity has been carried out to predict the value of critical velocity and the effect of different parameters on critical velocity.

Fig. 1. Different flow regimes during the flow of ice slurry
2. Mathematical Modelling

The mathematical model has been developed on the bases of Eulerian approach.

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

\[
\frac{\partial}{\partial t}(\alpha_l \rho_l) + \nabla \cdot (\alpha_l \rho_l \vec{v}_l) = 0 \\
\frac{\partial}{\partial t}(\alpha_s \rho_s) + \nabla \cdot (\alpha_s \rho_s \vec{v}_s) = 0
\] (1)

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

\[
\tau_l = \alpha_l \mu_l \left( \nabla \vec{v}_l + (\nabla \vec{v}_l)^T \right) + \alpha_l \left( \lambda_l - \frac{2}{3} \mu_l \right) \left( \nabla \vec{v}_l \right) I
\] (4)

\[
\frac{\partial}{\partial t}(\alpha_s \rho_s \vec{v}_s) + \nabla \cdot (\alpha_s \rho_s \vec{v}_s) = -\alpha_s \nabla P + \nabla \tau_s + \alpha_s \rho_s \vec{g} - \nabla P_s + \vec{R}_s
\] (5)

\[
\tau_s = \alpha_s \mu_s \left( \nabla \vec{v}_s + (\nabla \vec{v}_s)^T \right) + \alpha_s \left( \lambda_s - \frac{2}{3} \mu_s \right) \left( \nabla \vec{v}_s \right) I
\] (6)

where \(\mu\), \(R\), \(I\) and \(\lambda_s\) are viscosity, interfacial forces, unit tensor and bulk viscosity respectively. Bulk viscosity defined from Lun et al., 1984 [12].

\[
\lambda_s = \frac{4}{3} \alpha_s \rho_s d_s g_{o,ss} \left( 1 + e_{ss} \right) \left( \frac{\Theta}{\pi} \right)^{0.5}
\] (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 calculated in the present work as

\[
\vec{F}_{lift,sl} = C_L \rho_s \alpha_s \left( \vec{v}_s - \vec{v}_l \right) \times \nabla \vec{v}_l
\] (9)

\[
\vec{F}_{lift,ls} = -\vec{F}_{lift,sl}
\] (10)

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

Solid viscosity is the sum of frictional, kinetic and collisional viscosity however, frictional viscosity contributes when concentration reaches the frictional limit.

\[
\mu_s = \mu_{col} + \mu_{kin} + \mu_{fr}
\] (11)

\[
\mu_{col} = \frac{4}{5} \alpha_s \rho_s d_s g_{o,ss} \left( 1 + e_{ss} \right) \left( \frac{\Theta}{\pi} \right)^{0.5}
\] (12)

\[
\mu_{kin} = \frac{\alpha_s \rho_s d_s \sqrt{\pi \Theta}}{6 (3 - e_{ss})} \left[ 1 + \frac{2}{5} (1 + e_{ss}) (3 e_{ss} - 1) \alpha_s g_{o,ss} \right]
\] (13)
\[ \mu_{yi} = \frac{P \sin \phi}{2\sqrt{2I_{zD}}} \]  

(14)

\[ g_{o,ss} = \left[ 1 - \left( \frac{\alpha_s}{\alpha_{s,\text{max}}} \right)^{\frac{1}{2}} \right]^{-1} \]  

(15)

where \( \alpha_{s,\text{max}} \) is maximum packing limit.

Fig. 2. Variation of solid phase velocity profile with different grid size

Fig. 3. Horizontal meshed pipe for laminar flow

2.1. Discretization

Simulation has been performed in a pipe of 23 mm diameter and 2 m length. The hexahedral mesh by ‘O’ grid and sweep method has been generated using ICEM. At a velocity of 0.1 m/s, 10% concentration with 10 % ethanol and 0.1 mm particles, mesh independent test has been performed. The velocity profile of the solid phase has been drawn (fig. 2) that shows that, the variation for elements 347000 and 429000 is very less and it becomes negligible with further refinement. Therefore, 429000 elements are considered as optimum mesh size (shown in Fig. 3).
2.2. Boundary Conditions

The boundary conditions for each phase are assigned at inlet, outlet and wall. For the inlet, velocities and concentration are assumed to be uniform. For the outlet, pressure outlet condition, at wall, no-slip condition is adopted for liquid phases and for the solid phase Johnson–Jackson condition is adopted.

3. Validation

Present model has also been validated with the Kauffeld et al., 2005 [16]. The value of critical velocity lies between 0.13 to 0.25 m/s in an experiment. Fig.4 shows that critical velocity lies in range of 0.15 to 0.20 m/s for the same condition. Hence, present model has ability to predict the critical velocity.
4. Results and Discussion

Simulation has been carried out to identify the critical velocity. Fig. 5 shows the contours of the concentration for the different velocities of 0.01, 0.05, 0.01 & 0.02 m/s. The results are obtained for 10% concentration with 0.25 mm diameter in the 10% ethanol based ice slurry [17]. It is clear from the contours (a to d) that flow converted from homogeneous to moving bed when velocity reduced from 0.1 to 0.05 m/s. The same results have also been shown in Fig. 6 except at velocity of 0.1 m/s. It can be observed from the figure that, the maximum concentration reaches to 0.52 (maximum packing limit) at velocity of 0.05 m/s.

![Graph](image-url)

**Fig. 6.** Solid particle distribution profile at different initial velocities

![Contours](image-url)

**Fig. 7.** Contours of frictional viscosity at different initial velocities
Fig. 7 shows the contours (a to d) of the frictional viscosity at the different velocities of 0.01, 0.05, 0.01 & 0.02 m/s. In present model the shear viscosity affected with frictional viscosity when concentration crosses the value of friction packing limit which is considered 0.45. It has been shown in the contours that the frictional viscosity reach to the significant value when concentration cross the frictional packing limit.

Fig. 8. Variation of the critical velocity with initial particle concentration and ice particle diameter

Fig. 9. Variation of the critical velocity with initial particle concentration and different concentration of ethanol

Fig. 10. Variation of the critical velocity with different pipe diameters
The effect of particle diameter and concentration on critical velocity has been shown in Fig. 8. The figure shows the concentration on the x-axis and velocity on the y-axis. It is clear from the figure that, the critical velocity increases with increase in concentration as at more concentration rate of moving bed formation increase. However, critical velocity affected most with particle diameter as the fact that bigger particle are subjected to strong buoyancy and the inertia forces in comparison to small particle. The effect of ethanol concentration on critical velocity has been shown in Fig. 9 for particle diameter of 0.25 mm. The figure shows the concentration on the x-axis and velocity on the y-axis. The results are obtained for 0%, 5% and 10% ethanol in the slurry. It can be observed from the figure that, with the decrease in ethanol concentration in the slurry, the value of critical velocity increases as density difference increase between the phases and decrease in viscosity [17].

Fig. 10 shows the value of critical velocity for different diameter of pipes. Three different pipe diameters 23, 50 and 100 mm have been considered. The results are shown for the 10% ethanol based ice slurry with particle diameter of 0.25 mm. It is seen that, the value of critical velocity increases with increase in pipe diameter. The pipe of bigger diameter has bigger cross-section area that increases the rate of moving bed formation due to which value of critical velocity is increased.

5. Conclusions

- Critical velocity increases with increase in initial particle concentration. The value of critical velocity for 0.4 particle diameter increases from 0.16 m/s to 0.30 m/s with the increase in from 10% to 30%.
- Critical velocity also depends on particle diameter and it increases from 0.4 m/s to 0.16 m/s with increase in particle size from 0.1 mm to 0.4 mm at 10% initial particle concentration.
- The value of critical velocity increases with decrease of ethanol concentration. At lower ethanol concentration in ice slurry, the density difference between the phases becomes large and viscosity of liquid phase also decreases due to which critical velocity increases.
- The value of critical velocity increases with pipe diameter. The large diameter has bigger cross-section area that increases the rate of moving bed formation due to which value of critical velocity is increased. Therefore the value of pipe diameter should be small to avoid chances of formation of moving bed. The value of critical velocity for ice slurry at 10% initial particle concentration and 0.25 particle size has been determined in 23, 50 and 100 mm diameters pipe and it is found to be 0.6, 0.12 and 0.19 m/s, respectively.

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