International Journal on Emerging Technologies (Special Issue NCETST-2017) **8**(1): 638-642(2017)
(Published by Research Trend, Website: www.researchtrend.net*)*
ISSN No. (Print) : 0975-8364
ISSN No. (Online) : 2249-3255

Simulation of Isothermal Ice Slurry Flow

Vineeta Adhikari[1], Vinay Sati[2] and Himanshu Khulve[3]
[1]Department of Mechanical Engineering, Amrapali Institute of Technology & Sciences, Haldwani, (U.K.), INDIA
[2]Department of Mechanical Engineering, Amrapali Institute of Technology & Sciences, Haldwani, (U.K.), INDIA
[3]Department of Mechanical Engineering, SRMS, Bareilly

ABSTRACT: Ice slurry gained much attention as a secondary refrigerant due to its high cooling capacity and environment friendly nature, in the last decade. Ice slurry has high cooling capacity, so for the same cooling capacity pumping power, size of the storage tank and pipes are reduced. In the case of retrofitting of ice slurry in secondary loop of cold storage system, mass flow rate is significantly reduced for the given cooling load in comparison to water. Hence, the velocity of the ice slurry is significantly lower than water. In this work simulation of the isothermal ice slurry flow has been carried out at low velocity, in order to develop the basic idea of the ice slurry flow. Prediction of velocity and volume fraction along with flow length has been presented in this work. In the present study CFD simulation has been performed by using software package ANSYS Fluent 12.0. Euler-Euler computational fluid dynamics (CFD) model based on the kinetic theory of granular flow is used to simulate the ice slurry flow without considering the melting of ice

Keywords: Ice slurry, Refrigent, Flow Rate, simulation, ANSYS Analysis.

I. INTRODUCTION

With the growth of world's economy use of refrigeration systems is increasing, which increases emission potential of refrigerants to the environment with its negative effect. Therefore, for the sake of environmental safety, we again concern the natural refrigerants. However the problem with the natural refrigerants is that the most of them are toxic and flammable in nature, so new challenge is to reduce the refrigerant charge in the system for human safety. It is well known that use of the secondary refrigerant in the refrigeration and air conditioning systems can reduce the charging amount of the system, which increases the human and environment safety. Zhang and Ma, (2012) reported that effectiveness of secondary refrigerants can be improved when phase changing media are introduced in place of single-phase media. In recent years ice slurry gain much attention as a secondary refrigerant due to its high cooling capacity and environment friendly nature.

Another issue is the electricity consumption by the refrigeration and air-conditioning systems. Kauffeld *et al.,* (2005) reported that, it uses about 15% of the total electricity produced worldwide and contributes in global warming indirectly. The electricity consumption by the refrigeration and air-conditioning systems accounts for a large proportion of the total energy consumption during summer time, intensifying the energy shortage and environment issues. The secondary-loop refrigeration incorporated with cold storage technology is now considered as one of the most promising solution to the above-mentioned issues. When ice slurries are used instead of cold water as a secondary fluid, a higher cooling capacity can be delivered using the same installed pipes. Under this condition, the installation should be able to work at low ice slurry mass flow rates. If new pipe system designed for the distribution of ice slurry can be nearly 1/3 the diameter of that required for chilled water delivery of the same cooling capacity (Kauffeld *et al.,* 2010).

Ice slurry refers to a homogenous mixture of small ice particles and carrier liquid. The liquid can be either pure freshwater or a binary solution consisting of water and a freezing point depressant. The most commonly used freezing point depressants in industry are Sodium chloride, ethanol, ethylene glycol and propylene glycol. In particular device and applications, the initial concentration of such solution varies. Ice slurry has a high energy storage density because of the latent heat of fusion of its ice crystals. The slurry maintains a constant low temperature level during the cooling process, and provides a higher heat transfer coefficient than water or other single phase liquids. It also has a fast cooling rate due to the large heat transfer surface area created by its numerous particles. Depending on the production method, the size of the ice crystals in the ice slurry may also vary, in industrial applications these typically ranges from 0.1 mm to 1.0 mm.

As a result of these attractive features, the ice slurry presents a promising substitute for cold energy storage and transport as compared to the traditional single-phase fluid. However, the ice slurry application in engineering practice is not as wide as expected due to many difficulties in the transportation of ice slurry. As ice slurry flow is a complex multiphase flow, which is affected by many parameters i.e. velocity, particle size, concentration, type of flow, heat interaction etc. during the flow. Therefore one should able to predict the velocity and ice particle distribution during the flow.

Ice slurry has high cooling capacity, so in secondary loop of cold storage system mass flow rate is significantly reduced for the same cooling load. If we use same piping system, our velocity of ice slurry is much lower than water. So in the present study simulation of the ice slurry flow between two parallel plates has been carried out at low velocity, in order to predict the behaviour of ice slurry.

In the present study we consider the isothermal laminar flow of ice slurry flow in a horizontal pipe. The pipe is 3 meters long and 0.001 meters diameter. Homogeneous ice slurry is provided at the inlet with uniform velocity of 0.1 m/s for both the phases (water and ice particles). Initial concentration of ice particles is 0.1 with particle diameter of 0.0004 m. In the present study simulation of the isothermal ice slurry flow has been carried out at low speed, in order to predict its velocity and ice concentration during the flow at different positions.

II. REVIEW OF LITERATURE

There have been many analytical and experimental studies done so far on the topic of ice slurry flow. Ice slurry flow is considered as multiphase (liquid-solid) flow. A basic prelude introduction of multiphase flow and then review of ice slurry flow has been presented in this section on various studies done so far on this topic.

Four flow regimes (shown in fig.2.1) have been identified for ice slurries during a flow: homogeneous, heterogeneous, moving bed and stationary bed flows. Homogeneous flow occurs at high flow rate when ice particles distribution is uniform. Heterogeneous flow occurs when ice slurry concentration gradient increases through a horizontal pipe section. With a decreasing flow rate,

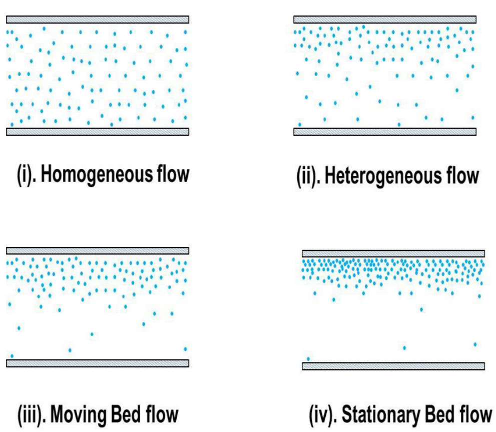


Fig. 1

a moving bed appears when the maximum possible ice fraction occurs at the top of a horizontal pipe. The thickness of the moving bed grows up as long as the velocity decreases. At very low flow rate, stationary bed occurs when the velocity of the ice moving bed decreases down to zero. Only a liquid flow will be seen at the bottom of the pipe.

In the past different rheological models have been used for the ice-slurry. One of first tries was performed by Sasaki *et al.* (1993), where he used a dilatant fluid model to describe a rheological behaviour of ice-slurry. After that, Egolf*et al.* (1996) proposed the Bingham fluid model. All the experimental data on ice-slurry rheological behaviour had shown that at a certain low ice concentration the ice-slurry behaves as a Newtonian fluid and at higher concentrations as a Bingham fluid. To describe both, one of the possibilities is to use the apparent viscosity as it was shown by Guilpart*et al.* (1999). Another proposal was done by Jensen *et al.* (2000), who had actually modified the Bingham model. Later, a model was proposed by Doetsch (2001), where he proposed the Casson model to describe Newtonian and Bingham behavior of ice-slurry. First model that consider the ice-slurry as a heterogeneous flow given by Kitanovski and Poredos (2002) which is based on the Doron's two and three layer model, which is based primarily on the solids concentration distribution.

Computational Fluid Dynamics (CFD) seems an attractive tool to obtain plentiful information of two-phase flows, especially when the detailed ice slurry flow information is expected to be obtained, as well as an accurate prediction of pressure drop in pipes. An Euler-Euler CFD model based on the kinetic theory of granular flow (Gidaspow, 1994) is likely to fulfil the task. So far, the Euler-Euler CFD model has been successfully used in liquid solid slurry flow (Ekambara et al., 2009). Unfortunately, only a few researchers have utilized the Euler-Euler CFD model to solve ice slurry flow, as Niezgoda-Zelasko and Zalewski (2006), Wang (2013) and Zhang and Shi (2015).

The detailed review of various works on this topic is given below.

Vuarnoz (2002) presented experimental investigation of ice slurry flow to that leads to valuable information. In a horizontal pipe velocity profile is measured by using ultrasonic velocity profiler. The achieved profiles show a cylindrical plug, which is in correspondence with the theory of laminar Bingham flow. The obtained profiles are symmetric to the axis of the pipe.

Kitanovski and Poredos (2002) analyzed the heterogeneous ice-slurry flow in a horizontal pipe based on the Doron's two and three layer model. The investigation was accomplished for the ice-particle size of 1 mm. The carrier liquid is mixture of ethanol-water for various average velocities (ranging from 0.25 to 2 m/s), pipe diameters D (27.2, 100, 200 mm) and ice concentrations (ranging from 0.05 to 0.25).

Niezgoda-Zelasko and Zalewski (2006) presented experimental analysis to explanation the various phenomena which accompany ice slurry flows in straight tubes. The data published in the literature are often divergent and this work determines the rheological properties of ice slurry with the different particles size (0.05 to 0.35 mm) and the ethyl alcohol solution of the initial concentration equal to 10.6%. Experimental results were compared to the analytical results, based on the Hedstrom (laminar flow) and Tomita (turbulent flow) algorithms and the comparison showed a very good agreement between these data.

Niezgoda-Zelasko and Zalewski (2006) analyzed the possibility of the modelling of ice slurry flow based on the CFD procedures (Fluent), for both Bingham and multiphase flow models (the mixture and Eulerian models). The ice slurry flow modelled by making two different assumptions:

1. Ice slurry is a single-phase flow having the properties of Bingham fluid which can be characterized by its density, dynamic coefficient of plastic viscosity and effective viscosity and yield shear stress value.
2. Ice slurry is a multiphase (liquid – solid) flow and it's depending on the physical properties of the carrying fluid (water solution with freezing point depressant) and the solid particles (the particle diameter, their viscosity and density).

The calculations were performed for ethanol at the concentration of 10.6% and the inner diameter of tube 0.016 m. From the CFD analysis, it was shown that single-phase model led to an overestimating the pressure drop as compared to the experimental results however, the difference did not exceed 16%. The multiphase simulation of the ice slurry flow gives good agreement with the experiment. Introducing the size of solid particles as a parameter characteristic of the fluid permits to reach the agreement between the simulations and experiments with the accuracy better than 10%.

Wang et al. (2013) applies an Euler-Euler computational fluid dynamics (CFD) model based on the kinetic theory of granular flow to describe the ice slurry flow without considering ice melting. The Euler-Euler CFD model was firstly validated by four different experiments. Then the validated Euler-Euler CFD model was applied to solve the distributions of ice slurry flow, ice particle concentration and pressure drop in horizontal, vertical and 90o elbow pipes respectively. The relative errors of the numerical computation are within ± 20% with respect to the measurements. And the Euler-Euler CFD model is validated to be a more effective and universal model for describing ice slurry flow and can supply plentiful parametric information in the flow region.

Wang et al. (2013) applies a Mixture computational fluid dynamics (CFD) model based on different rheological behavior to characterize the heterogeneous ice slurry flow. The Mixture CFD model was firstly validated by three different experiments. Then the validated Mixture CFD model was applied to solve the ice slurry isothermal flow by considering the rheological behavior piecewise. Finally, the numerical solutions have displayed the coupled flow information, such as slurry velocity, ice particle concentration and pressure drop distribution. The results show that, the ice slurry flow distribution will appear varying degree of asymmetry under different operating conditions. As compared with experimental pressure drop results, the relative errors of numerical computation are almost within ±15%. The Mixture CFD model is validated to be an effective model for describing heterogeneous ice slurry flow and could supply plentiful flow information.

Mathematical Modelling

Continuity Equation. For both liquid and solid phases, the total volume fraction relationship between liquid and solid phases is as follows

$\alpha_l + \alpha_s = 1$ (1)

where α is the local phase volume fraction for liquid & solid respectively.

Momentum Equation. The momentum balance for each phase is expressed along with interphase momentum transfer due to different forces acting on that phase.

Interfacial Forces. The interfacial forces (R) for multiphase flow mainly contain drag force, lift force, virtual mass force and turbulent dispersion force. However, the virtual force is significant only when the density difference between the solid and liquid phases are very large, which is obviously not appropriate for ice slurry within 10 % density difference between two phases (Zhang & Shi, 2015). For multiphase flow, the effect of lift forces on the secondary phase particles due to velocity gradients in the primary phase flow fluid. The lift forces will be more significant for larger particles. Thus, the inclusion of lift force is not appropriate for closely packed particle or very small size particles.

The interfacial forces in the present work include drag only, which plays a dominate role in solid–liquid two-phase flow and described by with the help of Gidaspow, 1994.

$R_{sl} = K_{sl}(v_s - v_l)$ *(2)*

$R_{ls} = K_{ls}(v_l - v_s)$ *(3)*

Where (R) interfacial forcesfor multiphase flow mainly contain drag force, lift force, virtual mass force and turbulent dispersion force &(K_{sl}, K_{ls}) are the interphase momentum exchange coefficients

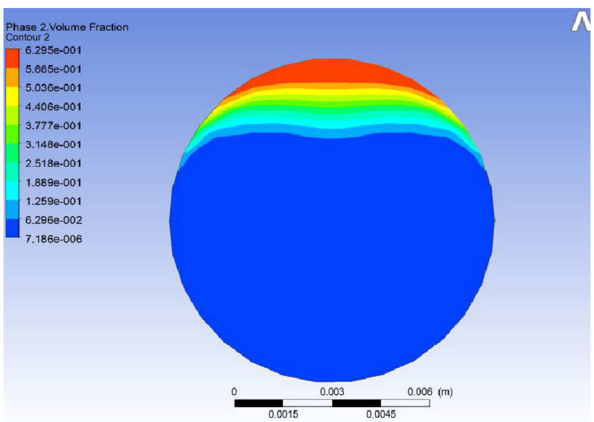
When, α_l> .8 ,the follows of (Gidaspow, 1994).

Bulk Viscosity and Shear Viscosity. Bulk viscosity denoted by λ, accounting for the resistance of the solid particles to compression and expansion Lun *et al,* 1984.

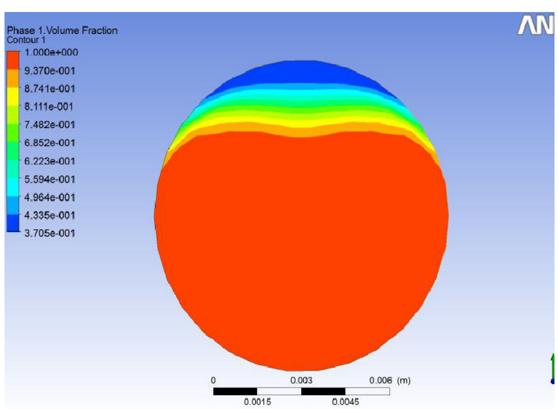
Kinetic Theory of Granular Flow. The solid particle motion arising from particle–particle collision is assumed as the thermal motion of molecules in a gas, taking the inelasticity of the granular phase into account. In such model, the fluctuating solid particles motion is described by the granular temperature defined as to be proportional to the mean square particle fluctuating velocity.

III. RESULTS & DISCUSSIONS

Based on the kinetic theory of granular flow, an Euler-Euler CFD model has been applied to simulate the isothermal ice slurry flow in horizontal pipe. From the simulation, velocity and volume fraction of ice particles along the flow length has been successfully predicted. Contours of volume fraction of ice and water at the outlet of the pipe have been shown in the fig. 1 & 2. Results obtained by the contour satisfied the condition of Fig. 2 shows the maximum value of ice concentration is 0.6295 at the top which is nearly equal to the given maximum packing factor (0.63).



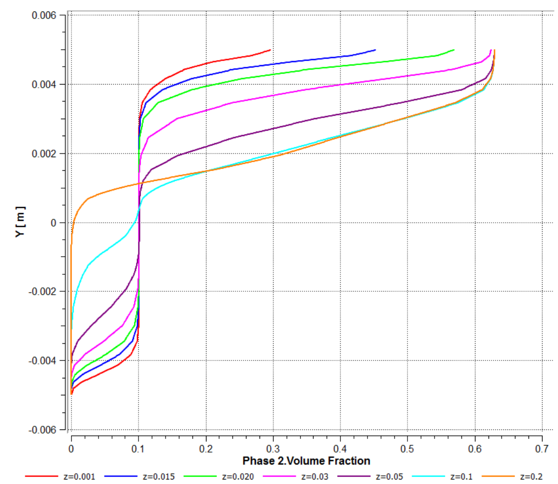
Volume fraction contour of ice at pipe outlet



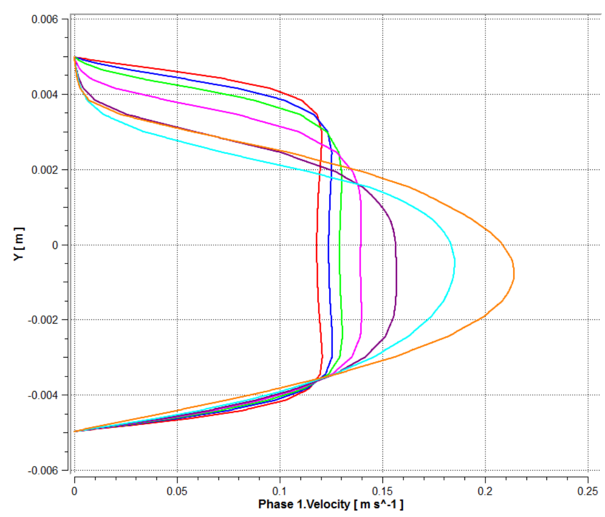
Volume fraction contour of water at pipe outlet

Figure shows the predicted velocities profiles of the water along the pipe length. Figure shows that velocity profiles fully developed at the length of 1.95 meter and after this length velocity profiles are overlapped with the profile at 1.95 meter. The concentration profile symmetry lies below the centre of the pipe.

From the simulation it is clear that at a low velocity of 0.1 m/s, the flow of ice slurry is moving bed type for the given conditions, which is an adverse condition for the transportation of ice slurry. Therefore the design is not recommended at velocity of 0.1 m/s for the given conditions.



Predicted ice particles concentration profiles along the pipe length.



Predicted velocities profiles along the pipe length

Based on the kinetic theory of granular flow, an Euler-Euler CFD model has been applied to simulate the isothermal ice slurry flow in horizontal pipe. From the simulation, velocity and volume fraction of ice particles along the flow length has been successfully predicted which conclude that the procedure use in this present work is correct and fluent has a capability to solve such problem. Now this problem can be extent in three dimensional with heat interaction.

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