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CFD modeling for pipeline flow of fine particles at high concentration

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ABSTRACT

Pipeline slurry flow of mono-dispersed fine particles at high concentration is numerically simulated using Mixture and Eulerian two-phase models. Both the models are part of the CFD software package FLUENT. A hexagonal shape and cooper type non-uniform three-dimensional grid is chosen to discretize the entire computational domain, and a control volume finite difference method was used to solve the governing equations. The modeling results are compared with the authors' experimental data collected in 54.9 mm diameter horizontal pipe for concentration profiles at central vertical plane using γ-ray densitometer and pressure drop along the pipeline using differential pressure transducers. Experiments are performed on glass beads with mean diameter of 125 μm for flow velocity up to 5 m/s and four overall concentrations up to 50% (namely, 0%, 30%, 40% and 50%) by volume for each velocity. The modeling results by both the models for pressure drop in the flow of water are found to be in good agreement with experimental data. For flow of slurry, Mixture model fails to predict pressure drops correctly. The amount of error increases rapidly with the slurry concentration. However, Eulerian model gives fairly accurate predictions for both the pressure drop and concentration profiles at all efflux concentrations and flow velocities. Velocity and slip-velocity distributions, that have never been measured experimentally at such higher concentrations, predicted by Eulerian model are presented for the concentration and velocity ranges covered in this study. Slip velocity between fluid and solids dragged most of the particles in the central core of pipeline, resulting point of maximum concentration to occur away from the pipe bottom.

1. Introduction

Conveyance of solids through pipelines on large scale has now come to be accepted as a viable alternative to the conventional modes of transportation. Pipes are very commonly used for long distance transportation and, at present in the world, there are many pipelines transporting different solid materials such as coal, fly ash, lime stone, zinc tailings, rock phosphate gilsonite, copper concentrate and iron concentrate. In difficult terrains, such a system of transportation is found to be techno economically more suitable as compared to conventional modes like railways, roadways and conveyors. A study of existing slurry pipe line systems shows that they broaden the economic reach of mineral deposits which could be utilized, since such a system could be used to transport materials from remotest areas which are otherwise not accessible to conventional modes of transport. In any practical situation, the solids being transported are multisized and their size may span three orders of magnitude.

The flow of slurry is very complex. It has been the endeavour of researchers around the world to develop accurate models for concentration distribution in slurry pipeline. These models may be used to determine the parameters of direct importance (mixture and solid flow rates and pressure drop) and the secondary effects such as wall abrasion and particle degradation.

The advection–diffusion (AD) model has been extensively used to predict the variation with depth of the particle concentration due to its simplicity (Kaushal and Tomita, 2002). However, AD model is unable to predict the concentration profiles with points of maximum concentration away from the pipe bottom (Kaushal and Tomita, 2007). The reasons for such drawbacks in AD model are described later, in the article 5.5 of this paper.

CFD based approach for investigating the variety of multiphase fluid flow problems in closed conduits and open channel are being increasingly used. One advantage with CFD-based approach is that three dimensional solid–liquid two phase flow problems under a wide range of flow conditions and sediment characteristics may be evaluated rapidly, which is almost impossible experimentally. Thinglas and Kaushal (2008a, 2008b) have recently performed three dimensional CFD modeling for optimization of invert trap configuration to be used in sewer solid management. However, the use of such methodology for evaluating flow characteristics in slurry pipelines is limited.

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Ling et al. (2003) proposed a simplified three dimensional algebraic slip mixture (ASM) model to obtain the numerical solution in sand–water slurry flow. In order for the study to obtain the precise numerical solution in fully developed turbulent flow, the RNG k–ε turbulent model was used with the ASM model. An unstructured (block-structured) non-uniform grid was chosen to discretize the entire computational domain, and a control volume finite difference method was used to solve the governing equations. The mean pressure gradients from the numerical solutions were compared with the authors' experimental data and that in the open literature up to an average volumetric concentration of 20%. The solutions were found to be in good agreement when the slurry velocity is higher than the corresponding critical deposition velocity. However, as mentioned in FLUENT manual (2005), Mixture model used by Ling et al. (2003) holds good only for moderate concentrations. For the flow of high concentration slurries, the same manual recommends use of Eulerian multiphase model.

Kaushal and Tomita (2007) repeated experimental study for concentration distributions in slurry pipeline conducted by Kaushal et al. (2005) by using γ-ray densitometer. Their measurements show that, for finer particles, point of maximum concentrations are near the pipe bottom and for coarser particles, maximum points are relatively away from the pipe bottom with decrease in shift as flow velocity increases. Pressure gradient profiles of equivalent fluid for finer particles were found to resemble with water data except for 50% concentration, however, more skewed pressure gradient profiles of equivalent fluid were found for coarser particles. Experimental results indicate absence of near-wall lift for finer particles due to submergence of particles in the lowest layer into the viscous sublayer and presence of considerable near-wall lift for coarser particles due to impact of viscous-turbulent interface on the bottom most layer of particles and increased particle–particle interactions. It is observed that near-wall lift decreases with increase in flow velocity. Kaushal and Tomita (2007) also concluded that the near-wall lift observed in case of coarser particles is not associated with the Magnus effect, the Saffman force or Campbell et al. (2004) lift-like interaction force, and not yet modeled mathematically.

In the present study, three-dimensional concentration distributions, pressure drops and velocity distributions are modeled using Mixture and Eulerian models in 54.9 mm diameter horizontal pipe on glass beads with specific gravity of 2.47, mean diameter (d_{50}) of 125 μm and geometric standard deviation of 1.15, for flow velocity up to 5 m/s and overall concentration up to 50% by volume for each velocity. The computations are done considering particles as mono-dispersed. Three-dimensional modeling results for concentration distribution and pressure drops are compared with the experimental data.

2. Mathematical model

The use of a specific multiphase model (the discrete phase, mixture, Eulerian model) to characterize momentum transfer depends on the volume fraction of solid particles and on the fulfillment of the requirements which enable the selection of a given model. In practice, slurry flow through pipeline is not a dilute system, therefore the discrete phase model cannot be used to simulate its flow, but both the Mixture model and the Eulerian model are appropriate in this case. Further, out of two versions of Eulerian model, granular version will be appropriate in the present case. The reason for choosing the granular in favour of the simpler non-granular multi-fluid model is that the non-granular model does not include models for taking friction and collisions between particles into account which is believed to be of importance in the slurry flow. The non-granular model also lack possibilities to set a maximum packing limit which makes it less suitable for modeling flows with particulate secondary phase in the present case. Lun et al. (1984) and Gidaspow et al. (1992) proposed such a model for gas–solid flows. Slurry flow may be considered as gas–solid (pneumatic) flow by replacing the gas phase by water and maximum packing concentration by static settled concentration. Furthermore, few forces acting on solid phase may be prominent in case of slurry flow, which may be neglected in case of pneumatic flow and vice versa. In the present study slurry pipeline is modeled using granular-Eulerian and Mixture models as described below:

2.1. Eulerian model

Eulerian model assumes that the slurry flow consists of solid "s" and fluid "f" phases, which are separate, yet they form interpenetrating continua, so that $\alpha_f + \alpha_s = 1.0$, where α_f and α_s are the volumetric concentrations of fluid and solid phase, respectively. The laws for the conservation of mass and momentum are satisfied by each phase individually. Coupling is achieved by pressure and interphasial exchange coefficients.

The forces acting on a single particle in the fluid:

1. Static pressure gradient, ∇P.
2. Solid pressure gradient or the inertial force due to particle interactions, ∇P_s.
3. Drag force caused by the velocity differences between two phases, $K_{sf}(\vec{v}_s - \vec{v}_f)$, where, K_{sf} is the inter-phase drag coefficient, $\vec{v}_s$ and $\vec{v}_f$ are velocity of solid and fluid phase, respectively.
4. Viscous forces, $\nabla \cdot \bar{\bar{\tau}}_f$, where, $\bar{\bar{\tau}}_f$ is the stress tensor for fluid.
5. Body forces, $\rho\vec{g}$, where, ρ is the density and g is acceleration due to gravity.
6. Virtual mass force, $C_{vm}\alpha_s\rho_f(\vec{v}_f \cdot \nabla\vec{v}_f - \vec{v}_s \cdot \nabla\vec{v}_s)$, where, C_{vm} is the coefficient of virtual mass force and is taken as 0.5 in the present study.
7. Lift force, $C_L\alpha_s\rho_f(\vec{v}_f - \vec{v}_s) \times (\nabla \times \vec{v}_f)$ where, C_L is the lift coefficient taken as 0.5 in the present study as such a value is suggested in literature for glass beads.

2.1.1. Governing equations

2.1.1.1. Continuity equation.

$$\nabla \cdot (\alpha_t \rho_t \vec{v}_t) = 0 \tag{1}$$

where, t is either s or f.

2.1.1.2. Momentum equations.

For fluid phase:

$$\begin{aligned}\nabla \cdot (\alpha_f \rho_f \vec{v}_f \vec{v}_f) = &-\alpha_f \nabla P + \nabla \cdot \bar{\bar{\tau}}_f + \alpha_f \rho_f \vec{g} + K_{sf}(\vec{v}_s - \vec{v}_f) \\ &+ C_{vm}\alpha_f\rho_f(\vec{v}_s \cdot \nabla\vec{v}_s - \vec{v}_f \cdot \nabla\vec{v}_f) \\ &+ C_L\alpha_s\rho_f(\vec{v}_f - \vec{v}_s) \times (\nabla \times \vec{v}_f)\end{aligned} \tag{2}$$

For solid phase:

$$\begin{aligned}\nabla \cdot (\alpha_s \rho_s \vec{v}_s \vec{v}_s) = &-\alpha_s \nabla P - \nabla P_s + \nabla \cdot \bar{\bar{\tau}}_s + \alpha_s \rho_f \vec{g} + K_{fs}(\vec{v}_f - \vec{v}_s) \\ &+ C_{vm}\alpha_s\rho_f(\vec{v}_f \cdot \nabla\vec{v}_f - \vec{v}_s \cdot \nabla\vec{v}_s) \\ &+ C_L\alpha_s\rho_f(\vec{v}_s - \vec{v}_f) \times (\nabla \times \vec{v}_f)\end{aligned} \tag{3}$$

where $\bar{\bar{\tau}}_s$ and $\bar{\bar{\tau}}_f$ are the stress tensors for solid and fluid, respectively, which are expressed as

$$\bar{\bar{\tau}}_s = \alpha_s \mu_s (\nabla \vec{v}_s + \nabla \vec{v}_s^{tr}) + \alpha_s\left(\lambda_s - \frac{2}{3}\mu_s\right)\nabla \cdot \vec{v}_s \bar{\bar{I}} \tag{4}$$

and

$$\bar{\bar{\tau}}_f = \alpha_f \mu_f (\nabla \vec{v}_f + \nabla \vec{v}_f^{tr}) \tag{5}$$