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Research Article

Numerical Modeling of Dilute Particulate Flows in Horizontal and Vertical pipes

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Abstract

CFD simulation using Eulerian-Eulerian approach is performed for gas-solid flows in horizontal and vertical pipes. The Gidaspow drag model with algebraic granular temperature model were used for the simulation. The algebraic model is the simplified one to model the granular temperature and it speeds up the convergence in two phase flow unsteady simulations. Numerical predictions are compared with experimental data and good agreement was found for vertical flows. The model predicts the gas velocity correctly, but couldn't predict the solid phase velocity in horizontal flows. Vertical flow has symmetrical profiles for velocity, volume fraction and other flow parameters; whereas the asymmetric flow occurs in horizontal flows.

Keywords*: CFD, Gas-solid flow, Euler model, Granular Temperature, Drag model*

1. Introduction

Solids moving with a gas stream in a pipeline can be found in many industrial processes, such as power generation, chemical, pharmaceutical, food and commodity transfer processes. Gas-solid is influenced by several physical phenomena, such as particle sedimentation, inter-particle collisions as well as lift and drag forces, caused by the interaction of particles with the walls. Gas-solid two-phase turbulent flows can be numerically solved by using either the Lagrangian or Eulerian approach. In Lagrangian approach, particles are tracked by solving the Newtonian equations of motion, so it requires a large computational effort in order to describe the two-way coupling between the gas and particle velocity fields. The Eulerian method reduces this problem by considering the fluid phase and the solid phase as separate interpenetrating continua. Both phases are treated as fluids, hence it is also known as two fluid model. Bohnet and Treiesch (2003), Cao and Ahmadi (1995), Zhang and Reese (2001, 2003), Crowe, 2000, Hadinoto *et al*. (2004), Bolio *et al*. (1995) investigated the hydrodynamics of gas solid flows using eulerian approach. They had shown that eulerian model is capable of predicting the flow physics of gas solid flows qualitatively as well as quantitatively.

In our work, we use eulerian approach to simulate 3D, unsteady and turbulent gas –solid flows in horizontal and vertical pipes using the cost effective and convergence accelerating algebraic granular temperature model. We investigated the flow behavior and modeling capabilities in horizontal and vertical gas solid flows. The gas used is air with density, ρ_g= 1.225 kg/m^3 and dynamics viscosity, μ_g= 1.79e-05 kg/m.s.

2 Governing equations

In a two-fluid model, the governing equations for a dispersed solid phase and a carrier gas phase are locally averaged, and both expressions have the same general form. The gas phase momentum equation is closed using k-ε turbulence model. Solid phase stresses are modeled using kinetic theory (Gidaspow, 1994). The conservation equation of the mass of phase i (i=gas or solid) is

$$\frac{\partial}{\partial t}(\alpha_i \rho_i) + \nabla.(\alpha_i \rho_i u_i) = 0 \qquad (1)$$

$$\sum \alpha_i = 1$$

The conservation equation of the momentum of the gas phase is

$$\frac{\partial}{\partial t}(\alpha_g \rho_g u_g) + \nabla.(\alpha_g \rho_g u_g u_g) = -\alpha_g \nabla \overline{p} + \nabla.\tau_g - \nabla.(\alpha_g \rho_g \overline{u_g^{'} u_g^{'}}) + \alpha_g \rho_g g + K_{sg}(u_s - u_g) \qquad (2)$$

The conservation equation of the momentum of the solid phase is

$$\frac{\partial}{\partial t}(\alpha_s \rho_s u_s) + \nabla.(\alpha_s \rho_s u_s u_s) = -\alpha_s \nabla \overline{p} - \nabla \overline{p_s} + \nabla.\tau_s - \nabla.(\alpha_s \rho_s \overline{u_s^{'} u_s^{'}}) + \alpha_s \rho_s g + K_{gs}(u_g - u_s) \qquad (3)$$

K_{sg}=K_{gs} is the gas-solid momentum exchange coefficient. Solids stress, τ_s accounts for the interaction within solid phase, derived from granular kinetic theory.
The gas phase stress is

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$$\tau_g = \alpha_g \mu_g (\nabla u_g + \nabla u_g^T) + \alpha_g (\lambda_g - \frac{2}{3}\mu_g)\nabla . u_g I \quad (4)$$

The Reynolds stresses of phase i (i= gas or solid), $-\rho \overline{u_i' u_i'}$ employ the Boussinesq hypothesis to relate to the Reynolds stresses to the mean velocity gradients. The kinetic turbulent energy and dissipation energy employ the standard k-ε model.

2.1 Drag Force Model

In gas-solid flow, the gas exerts drag on the solids for their transportation. There are different empirical drag force models available in literature. The gas–solid momentum exchange (drag force coefficient) uses the Gidaspow (1994) model.

$$K_{sg} = \frac{3}{4} C_D \frac{\alpha_s \alpha_g \rho_g |u_s - u_g|}{d_p} \alpha_g^{-2.65} \quad (5)$$

$$C_D = \frac{24}{\mathrm{Re}_p}\left[1 + 0.15(\mathrm{Re}_p)^{0.687}\right], \mathrm{Re}_p \le 1000$$
$$= 0.44 \qquad , \mathrm{Re}_p > 1000 \quad (6)$$

The particle Reynolds number is given by:

$$\mathrm{Re}_p = \frac{\alpha_g \rho_g |u_g - u_s| d_p}{\mu_g}$$

2.2 Constitutive equations using KTGF

The two fluid model treats both phases as inter-penetrating continua. It requires the constitutive equations to explain the rheology of the solid phase i.e the viscocity and the pressure of the solid phase. In the gas-solid flow, particle motion is dominated by the collision interactions. So Fluid kinetic theory (Gidaspow, 1994) can be applied to describe the effective stresses in solid phase to close the momentum balance equation. The solid phase stress is

$$\tau_s = \alpha_s \mu_s (\nabla u_s + \nabla u_s^T) + \alpha_s (\lambda_s - \frac{2}{3}\mu_s)\nabla . u_s I \quad (7)$$

Here λ is the bulk viscosity and I is the unit tensor.
Solid Pressure by (Lun et al., 1984) is

$$p_s = \alpha_s \rho_s \theta_s + 2\rho_s (1 + e_{ss})\alpha_s^2 g_{o,ss} \theta_s \quad (8)$$

Where e_{ss} is the restitution coefficient between the solid particles, θ is the granular temperature and g_0 is the radial distribution function for solid phase. Radial distribution (Ogawa et al., 1980)

$$g_{o,ss} = (1 - (\frac{\alpha_s}{\alpha_{s,\max}})^{\frac{1}{3}})^{-1} \quad (9)$$

Bulk Viscosity (Lun et al., 1984)

$$\lambda_s = \frac{4}{3}\alpha_s \rho_s d_p g_{o,ss}(1 + e_{ss})(\frac{\theta_s}{\pi})^{\frac{1}{2}} \quad (10)$$

Granular Shear viscosity due to kinetic motion and collisional interaction between particles

$$\mu_s = \mu_{s,coll} + \mu_{s,kin}$$

By Gidaspow (1994):

$$\mu_{s,kin} = \frac{10 d_p \rho_s (\theta_s \pi)^{\frac{1}{2}}}{96 \alpha_s (1 + e_{ss}) g_{o,ss}} \left[1 + \frac{4}{5} g_{o,ss} \alpha_s (1 + e_{ss})\right]^2 \quad (11)$$

$$\mu_{s,coll} = \frac{4}{5}\alpha_s \rho_s d_p g_{o,ss}(1 + e_{ss})(\frac{\theta_s}{\pi})^{\frac{1}{2}} \quad (12)$$

2.3 Fluctuation energy conservation of solid phase

Kinetic energy associated with the random motion of the particles results in the transport equation for the granular temperature. The granular temperature equation for the solid phase is (Syamlal et al, 1993)

$$(-\overline{p_s} I + \tau_s) : \nabla u_s - \gamma \theta_s + \phi_{gs} = 0 \quad (13)$$

Where

$(-\overline{p_s} I + \tau_s) : \nabla u_s$ is the energy generation by the solid stress tensor. $\gamma\theta_s$ is the collisional dissipation of energy. Φ_{gs} is the energy exchange between the solid and gas phase. This is the Algebraic model where convection and diffusion terms are neglected.

3. Numerical procedure and boundary conditions

The AMG solver Fluent6.3 is used to predict complex 3D gas solid flows in horizontal and vertical pipes using two-fluid Eulerian model. Mean momentum and mass conservation equations are solved for each phase using a finite volume scheme with two-way coupling and a standard k–ε turbulence model with standard wall function. The governing equations for both gas and particulate phases are solved sequentially at each iteration to obtain all the dependent variables. At each global iteration each equation is iterated using a strongly implicit procedure. The time step is 0.001 and residuals are 0.001. Fully developed velocity profile (1/7th power law) is used for gas phase and uniform flow for solid phase at inlet. The outlet is outflow where the gradients of all flow parameters except pressure in the flow direction is zero. Coefficient of restitution (0.9) is used for particle-particle collision and particle-wall collision. No slip boundary condition is used for gas phase and partial slip boundary condition for solid phase (specularity coefficient=0.005) is used.

The computational domain is a 3D pipe with diameter 30mm and length 2 m. The geometry is discretized using quadrilateral mesh comprising of around 45000 cells.

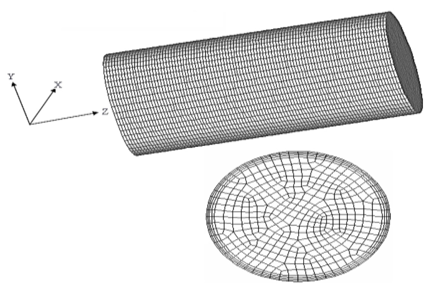


Fig.1 Computational domain with cross-sectional mesh

4 Results and discussions

4.1 Velocity profiles

The study in this section covers the gas – particle flow through a horizontal pipe and vertical pipe. The benchmark experimental data by Tsuji et al. (1982) for horizontal case and Tsuji et al. (1984) for vertical case is used to validate our numerical results. The diameter of the pipe is 30mm. Same computational domain and grid is used for both cases. The particle diameter is 200 micron and density is 1020kg/m^3. The velocity profiles are drawn in the vertical radial direction. The solids loading ratio is defined as the ratio of solid phase mass flow rate and gas phase mass flow rate. The plots are drawn in the vertical radial direction (along y-axis).

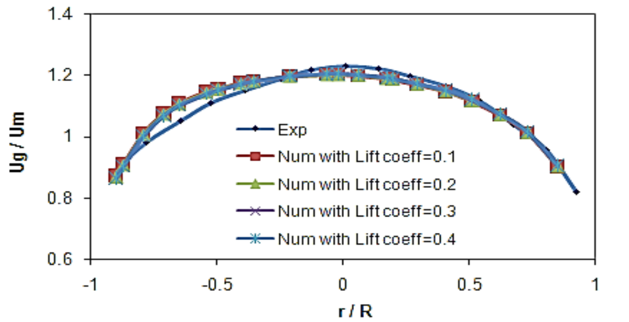


Fig.2 Velocity profiles of gas phase in horizontal flows for Um=15 m/s, SLR=0.4

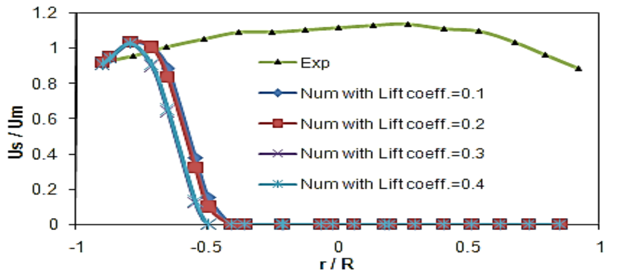


Fig.3 Velocity profiles of solid phase in horizontal flows for Um=15 m/s, SLR=0.4

Fig 2 and 3 show that the model predicts the gas velocity correctly for horizontal flow. Effects of lift force are also investigated. The lift has not much influence on velocity profiles. Unfortunately the model is not able to predict the solid phase velocity reasonably. Due to gravity, the particles try to settle down and most of the upper region is particle free.

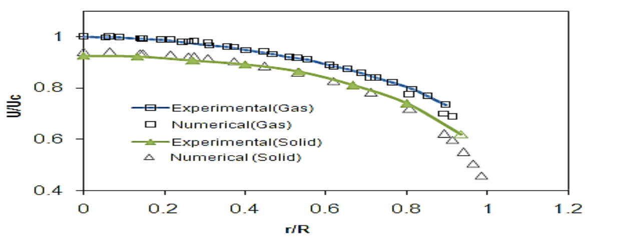
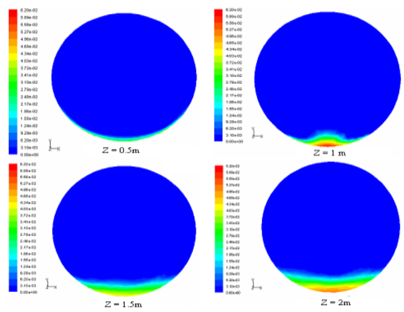


Fig.4 Velocity comparison with experimental data in vertical flow for Um=11 m/s, SLR=1.3

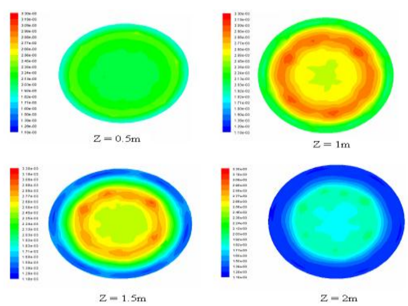
In case of vertical flow, gravity acts in the opposite direction of the drag. The lift force is very small compared to the drag force. Hence in the model, we neglected the lift force. Our simulation results are in reasonable agreement with the experimental data for the velocity profiles of both phases. The velocity profiles are symmetric in vertical flow.

4.2 Volume fraction

In this section, we investigate some of the hydro-dynamic characteristics of gas-solid flow in a horizontal pipe and a vertical pipe under same flow conditions. Glass particles of density of 1020 kg/m^3 and diameter 200 micron are used. Loading ratio is kept constant at 1.3. It is a case of dilute phase gas-solid flow. The mean bulk velocity of the gas (Um) is 11 m/s.



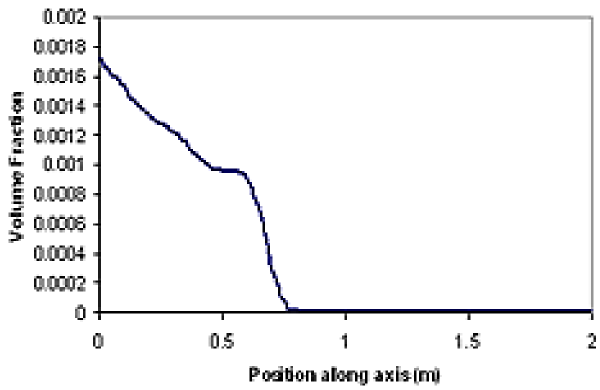
(a)



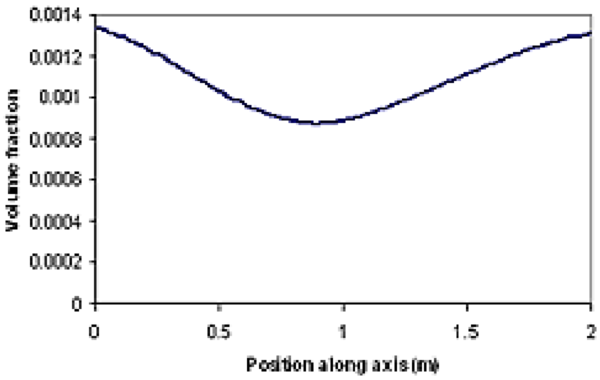
(b)

Fig.5 Volume fraction contours (a) Horizontal flow (b) Vertical flow

In case of horizontal flow, the particles start to settle down due to gravity if the velocity of the carrier gas is not sufficient enough to have fully suspended flow. This phenomenon is clearly observed in fig.5a and fig.6a. The volume fraction profile depends on the bulk velocity of gas in horizontal flow. In vertical flow, the gravity acts opposite to the drag. Hence symmetrical flow occurs. As shown in Fig.5b, the particle concentration is more towards the centre of the pipe. The particles near the wall falls and they are carried away upward by the gas towards the centre. As a result, there is low concentration of the particles near the wall.



(a)



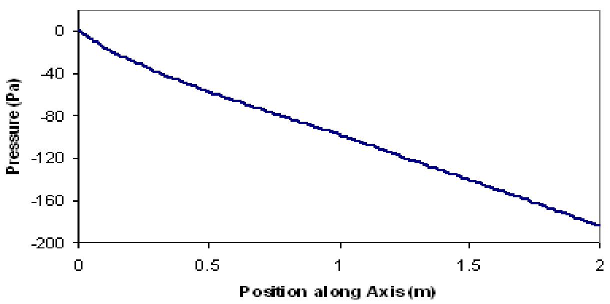
(b)

Fig.6 Volume fraction variation along axis (a) Horizontal flow (b) Vertical flow

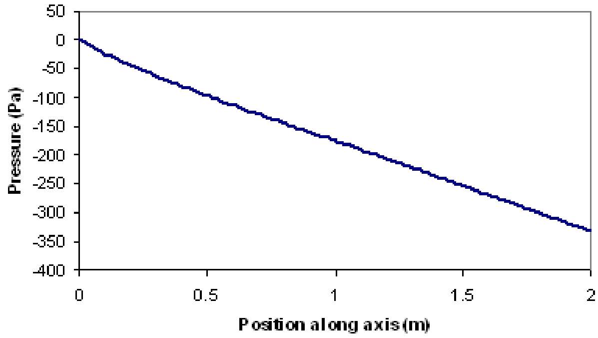
4.3 Axial variation of pressure

Less pressure drop is predicted in horizontal flow (Fig.7). This happens due to the motion of the solid particles and gas against gravity. Eulerian approach should be used in calculating pressure drop in gas-solid flow (Durst et al., 1984). In the Eulerian approach, the shear stress term is multiplied by the fluid volume fraction in order to get consistent momentum equations. This results in a decreasing pressure loss for an increasing void-fraction of the particles, at least in those cases where the shear stress is dominant for the pressure drop.

However, in the Lagrangian approach, the local void-fraction information computed in the program is not transferred to the fluid momentum equation and, because of this, the pressure drop is the same for the single-phase and two-phase pipe flows.



(a)



(b)

Fig.7 Axial variation of pressure (a) Horizontal Flow (b) Vertical Flow

4.4 Development of velocity profiles

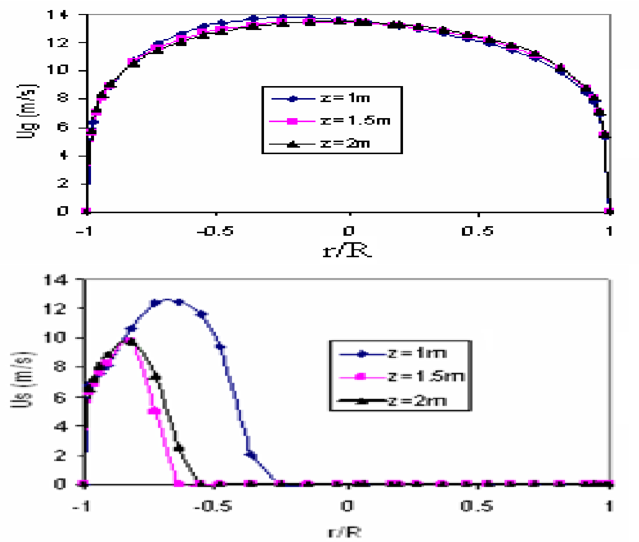
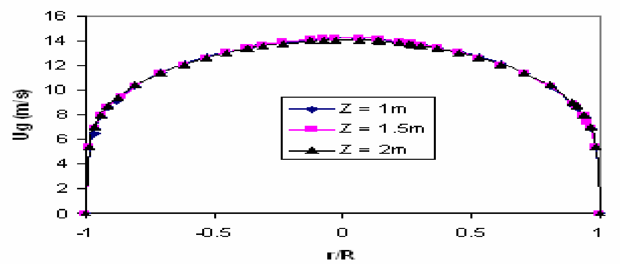
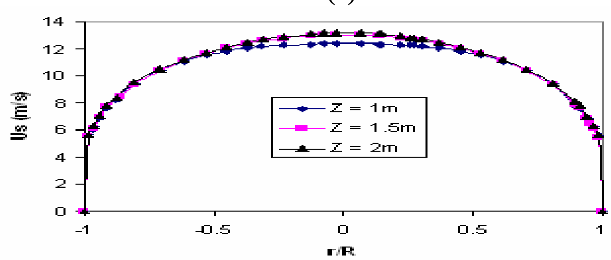


Fig.8 Velocity profiles in Horizontal flow



(a)



(b)

Fig.9 Velocity profiles in vertical flow

Now, we will discuss about the velocity profile development along the length of flow direction. In multiphase flow, all the measurements and calculations are done in the fully developed region. Molodtsof (1989) proposed when a gas-solids mixture flows in the steady-state conditions in a straight pipe, the flow is said to be fully developed when the laws of probability governing the presence and the velocity of each phase become independent of the axial coordinate. According to this definition, volume fraction, void fraction, particle velocity, gas velocity is independent of the longitudinal coordinate, in fully developed flow conditions. In vertical flow (Fig.9), both solid and gas velocity gets fully developed and are axi-symmetric. From Fig.8, we observe that velocity profile of both phases get developed towards exit, but solid velocity profile is not symmetric.

5. Conclusions

The numerical simulation of gas solid flows are performed using algebraic granular temperature model .Our simulation results are generally in reasonable quantitative and good qualitative, agreement with published experimental data for vertical flow. But the model couldn't predict the solid velocity in horizontal flows. We also observe that the velocity and volume fraction profiles are symmetric for vertical flow. The horizontal flow is asymmetry due to the action of gravity which tries to settle the particles downward.

Nomenclature

d_p diameter of solid particles (micron)
e restitution coefficient
g_o radial distribution function
I the tensor unit
K inter-phase momentum exchange coefficient
p Pressure (Pa)
u mean velocity (m/s)
u^1 the fluctuating velocity (m/s)

Greek Symbols

α Volume fraction
φ the energy exchange (kg/ms^3)
γ_θ the collisional energy dissipation (kg/ms^3)
λ the bulk viscosity (kg/ms)
τ the stress-strain tensor (kg/ms^2)
μ the shear viscosity (kg/ms)
θ the granular temperature (m^2/s^2)
ρ density (kg/m^3)

Subscripts

g gas
s solid

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