Euler-Granular Approach for Modelling of Dilute Phase Pneumatic Conveying in a Vertical Pipe

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Abstract

In the present study, vertically upward dilute phase pneumatic conveying flow was predicted using Euler-Granular method. Three dimensional computational fluid dynamics simulations were carried out for an 8 m long and 30.5 mm diameter circular pipe. The density of conveyed materials was 1020 kg/m^3. Simulations for different particle diameters; 200 µm and 500 µm were performed. The air velocities ranged from 9 to 17 m/s and solid to air mass flow ratios ranged from 0.0 to 3.8. Pressure drop, air and particle velocity profiles and solid distribution profiles were studied and some of the results were compared with experimental data from existing literature. Predicted pressure drop and air velocity profiles are in good agreement with experimental results.

Keywords: Computational Fluid Dynamics, pneumatic conveying, pressure drop, velocity, solid distribution, experimental data

1 Introduction

Pneumatic conveying method is widely used for granular particles transport in cement, mining, petroleum and other industries. The materials are conveyed along horizontal and vertical distances; therefore the vertical upward flows can be expected in any industrial pneumatic conveying line. Vertical pneumatic flow is generally used in dilute phase pneumatic conveying systems (Haim *et al*, 2003). Particulate material transportation in suspension mode by employing gas which are at high velocities, is usually termed as dilute phase conveying (Ratnayake, 2005). In addition to the experimental studies, Computational Fluid Dynamics (CFD) modelling has been identified as a powerful and versatile tool for understanding the complex gas-solid interactions in a pneumatic conveying system (Ouyang *et al*, 2005). In general, there are two basic modelling approaches in use; Eulerian-Eulerian and Eulerian-Lagrangian. Euler-Granular model is such an Eulerian-Eulerian model approach in where both gas and solid phases are treated as inter-penetrating continua (Ariyaratne *et al*, 2016a).

Several modelling studies have been performed previously for vertical pneumatic conveyors (Manjula *et al*, 2017). Azizi *et al* (2012) studied dense to dilute gas-solid flow behavior in a vertical pneumatic conveyor. The turbulence interaction between gas and solid particles were investigated by using Simonin's and Ahmadi's models. Ahamdi's model predicted lower granular temperature and pressure drop compared to Simonin's model. According to their predictions, the minimum voidage and the maximum particle velocity in dilute phase were found along the centerline of the vertical pipe. It was showed that the solid phase turbulence plays a significant role in numerical predictions of pneumatic conveying of 1.91 mm particles and the capability of those models depends on tuning of the parameters of slip-wall boundary condition. The combined "Computational Fluid Dynamics – Discrete Element Method (CFD-DEM)" developed by Kuang *et al* (2009) gives satisfactory predictions for vertical pneumatic conveying characteristics. The mechanisms underlying the relation between pressure drop and gas velocity were analysed for dilute and dense phases. The forces that govern the flow of particles were investigated and a new phase diagram was established for the particular conveying system. Bilirgen *et al* (1998) used FLOW3D to determine vertical pipe flow characteristics and the pressure drop and velocity profiles were compared with available experimental data. Haim *et al* (2003) carried out a parametric study for dilute gas-particle flow in a vertical pipe using Eulerian-Lagrangian approach. It was concluded that the increase of Reynolds number, solid loading ratio, particle density and particle diameter increases the slip velocity and the acceleration length. Moreover, the pipe diameter has no significant effect on acceleration length and slip velocity as long as the particle mass flow rate and solid loading ratio are constant. The effects of different turbulent modulation models in vertical pipe pneumatic conveying were investigated by El-Behery *et al* (2011) using Eulerian-Lagrangian approach. The effects of solid loading ratio and particle size on boundary layer thickness and pressure drop results were analysed. It was also identified that the concentration distribution is dependent on particle-particle collision, turbulence dispersion and lift force. Li *et al* (2013) carried out CFD-DEM simulations for a vertical pipe flow in order to investigate the effects of friction coefficient on pressure drop, solid concentration, the transition velocity from slug flow regime to dispersed flow regime and any reverse flow in the slug flow regime. In a previous study that was carried out by current authors, the sensitivity of a model parameter (specularity coefficient) on the predictions of pneumatic conveying characteristics in a vertical pipe was investigated (Ariyaratne *et al*, 2017).

In the current work, the characteristics of dilute upward vertical pneumatic conveying flow are investigated. The pressure drop, mean air and solid velocity profiles, solid distribution over the pipe cross section are studied for conveying of 200 μm and 500 μm diameter particles. Some of the simulation results are validated by experimental data from existing literature (Tsuji *et al*, 1984). The commercial CFD software ANSYS Fluent, version 16.2, was used for modelling and simulation. Steady state three-dimensional simulations were carried out using Euler-Euler approach for granular flows (Euler-Granular model).

2 Numerical Model

Both gas and solid phases are considered as continuous phases in Euler-Granular approach. Since the volume of a phase cannot be occupied by the other phases, the sum of volume fractions is equal to one. The steady state mass and momentum equations are solved for both gas and solid phases. To model the turbulent viscosity in the gas phase, the standard k-epsilon model is used. The Gidaspow model is used for the calculation of gas-solid exchange coefficient. The aerodynamic lift and vorticity induced lift force are calculated using Saffman-Mei model. The solid-phase stresses are derived by making an analogy between the random particle motion arising from particle-particle collisions and the thermal motion of molecules in a gas (kinetic theory of granular flow). Constitutive model from Lun et al. is used to calculate the solids pressure. The collisional and kinetic contributions are taken into account when modelling the solids shear viscosity. The bulk viscosity of solids is modeled through Lun et al. The equations of the models are not presented here and more details can be found elsewhere (Ariyaratne et al, 2016b).

3 Computational Domain, Boundary Conditions and Material Properties

ANSYS DesignModeler 16.2 and ANSYS Meshing 16.2 were used for the geometry drawing and mesh generation, respectively. The diameter of the vertical pipe is 30.5 mm which was selected based on the experimental setup used by Tsuji *et al* (1984). The simulated pipe length is 8 m which is a good enough length to achieve a fully developed flow situation. The gas-solid mixture enters from bottom of the pipe and leaves from top of the pipe. Figure 1 shows the mesh. The total number of elements in the mesh is 46080 and the maximum skewness is less than 0.39. The computational time is around 4 hrs for a run when 2.4 GHz Intel ® Xeon ® processor and 32 GB installed memory are used.

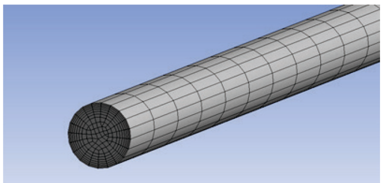

Figure 1. The mesh.

There are two types of boundary conditions, particularly for the gas phase and for the solid phase. Air and the solid particles enter to the pipe with similar and uniform velocities. The real velocities of air and particles and the solid volume fraction at the inlet defined for each case are shown in Table 1. The turbulence intensity of the air at the inlet is assumed as 10%. Solid phase granular temperature at the inlet is calculated according to the formula mentioned by Patro and Dash (2014) and it is in the range of values between 0.44-0.49 for all the cases. The outlet is treated as a pressure outlet. The pipe wall is considered as hydrodynamically smooth and no-slip for the gas phase. Johnson and Jackson (1987) wall boundary condition is used for the solid phase. According to the recommendation from a previous study, the specularity coefficients 0.0001 and 0.0004 were selected for 200 μm and 500 μm diameter particles, respectively (Ariyaratne *et al*, 2017). Coefficient of restitution for particle-wall collisions used in the simulations is 0.95 for all particle sizes.

The conveying medium is air which is having 1.225 kg/m^3 density and 1.7894×10^{-5} kg/m/s viscosity. The particles are polystyrene particles which are having spherical shape and 200 μm and 500 μm diameters. The particle density is 1020 kg/m^3.

4 Case Definition

Table 1 shows the cases simulated in the present study. The cases are in accordance with experimental cases carried out by Tsuji *et al* (1984). The real air and particle velocities at the inlet ranged from 9 to 17 m/s and the corresponding Reynolds numbers are $1.8 \times 10^4 – 3.6 \times 10^4$. The solid loading ratios are in the range of 0.0-3.8 and the corresponding solid volume fractions at the inlet vary in between 0.0000 and 0.0045. Coefficient of restitution for particle collisions used in all simulation cases is 0.9.

Table 1. Details of Simulated Cases.

Case	Particle diameter (mm)	Real air velocity at the inlet (m/s)	Real particle velocity at the inlet (m/s)	Solid loading ratio (kg solids/kg air)	Solid volume fraction at the inlet (-)	Reynolds number of the flow (-)
Case -1.1	0.5	10.5795	10.5795	3.4	0.00407	2.2×10^4
Case -1.2	0.5	10.5731	10.5731	2.9	0.00347	2.2×10^4
Case -1.3	0.5	10.5630	10.5630	1.3	0.00156	2.2×10^4
Case -1.4	0.5	10.5529	10.5529	0.0	0.00000	2.2×10^4
Case -2.1	0.5	8.9200 - 17.1800	8.9200 - 17.1800	2.0 - 3.8	0.00230 - 0.00450	1.8×10^4 – 3.6×10^4
Case -3.1	0.2	11.0577	11.0577	3.2	0.00383	2.3×10^4
Case -3.2	0.2	11.0405	11.0405	1.9	0.00228	2.3×10^4
Case -3.3	0.2	11.0220	11.0220	0.5	0.00060	2.3×10^4
Case -3.4	0.2	11.0154	11.0154	0.0	0.00000	2.3×10^4

5 Results and Discussion

The predicted pressure drop profiles, particle and air velocity profiles and solid distribution profiles for two different particle sizes and for different solid loading ratios are presented for the vertical upward pneumatic conveying system. The pressure drop profiles do not include the hydrostatic pressure. The mean air and particle velocity profiles and the solid volume fraction profiles (Figure 4, Figure 5, Figure 6 (a) and Figure 7) are taken along a diameter of pipe cross section at 7.5 m height from the bottom of the pipe which ensures the fully developed profiles. Some of the profiles are compared with experimental results from Tsuji *et al* (1984).

Figure 2 shows the simulated pressure profiles along the pipe axis for 500 μm diameter particles for a certain superficial air velocity but for different solid loading ratios. The pressure drop has been increased from 457 Pa to 786 Pa in the entire pipe when the solid loading ratio is increased from 0.0 to 3.4. The total pressure drop can be considered as the summation of gas phase pressure drop and solid phase pressure drop (Ratnayake *et al*, 2007). When the solid loading ratio is increased by increasing the solid mass flow rate, the work that should be done by unit mass of air on particles is increased. In the same time, the higher solid mass flow rate increases the particle number density in the system which in turn increases the collisions between particle-particle and particle-wall hence the pressure drop.

Figure 3 shows the pressure drop dependence of 500 μm diameter particles on inlet air velocity for the solid mass flow rate of 0.03 kg/s. In contrast to the Figure 2, the pressure drop increases when solid loading ratio is decreased (the solid loading ratio is decreased when increasing air velocity by keeping the solid mass flow rate constant). Similar to the explanation for Figure 2, the work that should be done by unit mass of air in order to move the particles ahead is decreased when the air velocity is increased; hence the pressure drop is decreased. Nevertheless, the pressure drop increases with increased air velocity due to increase of gas phase shear similar to a single phase flow (Azizi *et al*, 2012). The latter is dominant compared to former; hence the result is increase of pressure drop with increase of air velocity.

The predicted results are compared with experimental data from Tsuji *et al* (1984) and it shows a good agreement. The difference between experimental and predicted results is in the range of 9-19%. It should be noted that the simulations are carried out with

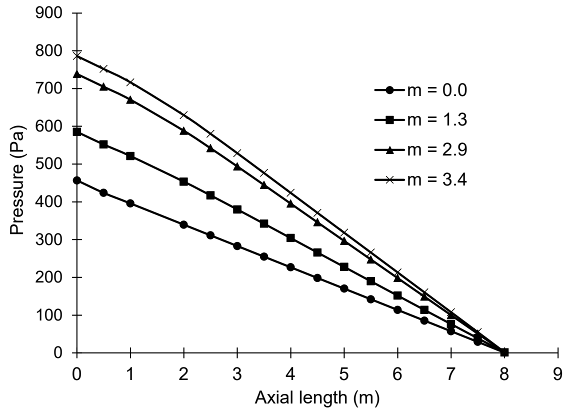

Figure 2. Axial static pressure variation for particle diameter 500 μm and Re = 2.2×10^4 (from Case-1.1 to Case-1.4).

specularity coefficient 0.0004 and the pressure drop prediction is significantly sensitive to this parameter (Ariyaratne *et al*, 2017).

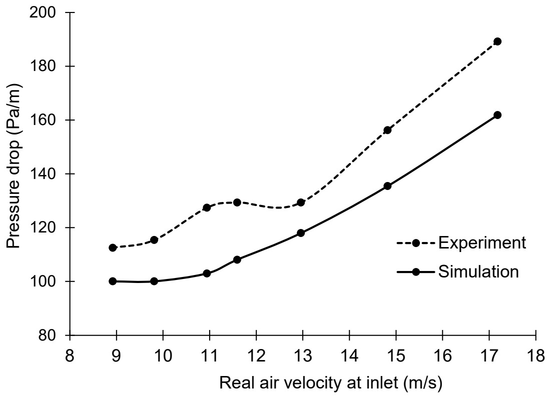

Figure 3. Comparison of simulated pressure drops with experimental data for particle diameter 500 μm and solid mass flow rate 0.03 kg/s (Case-2.1).

In general, Patro and Dash (2014) who used Euler-Granular method to predict vertical pipe pneumatic conveying have shown that the pressure drop depends on gas phase Reynolds number, solid loading ratio, particle diameter and density and on model collision coefficients such as specularity coefficient.

The predicted real mean air velocity profiles along a diameter in a pipe cross section at fully developed region are shown in Figure 4 and Figure 5 for 200 μm and 500 μm diameter particles and for different solid loading ratios. The profiles are also compared with the experimental data (Tsuji *et al*, 1984).

Since the Reynolds number of the flow is around 22000, the single phase velocity profiles should show a turbulence behavior ((a) in both figures). Inclusion of solids into the system changes the air velocity profile remarkably for both particle sizes. In general, the air velocity gets reduced with increase of solid loading ratio because of the increased drag. Moreover, the air velocity profiles become more flattened with increased solid loading ratios (e.g. m=1.9 and m=3.2) for 200 μm diameter particles (Figure 4). Tsuji *et al* (1984) also have observed increase of turbulence intensity in core region of the pipe when the loading is increased from 1.3 to 3.2 for 200 μm diameter particles. The effect of particles on air velocity profiles is more significant for larger particles (500 μm diameter), in where the profile becomes concave when increasing the solid loading ratio (Figure 5). This is reasonable as the larger particles restrict the air flow more than that of the smaller particles.

The agreement between experiments and predictions are significantly good for single phase flows. The deviation between experiments and predictions becomes larger when increasing the solid loading ratio for 200

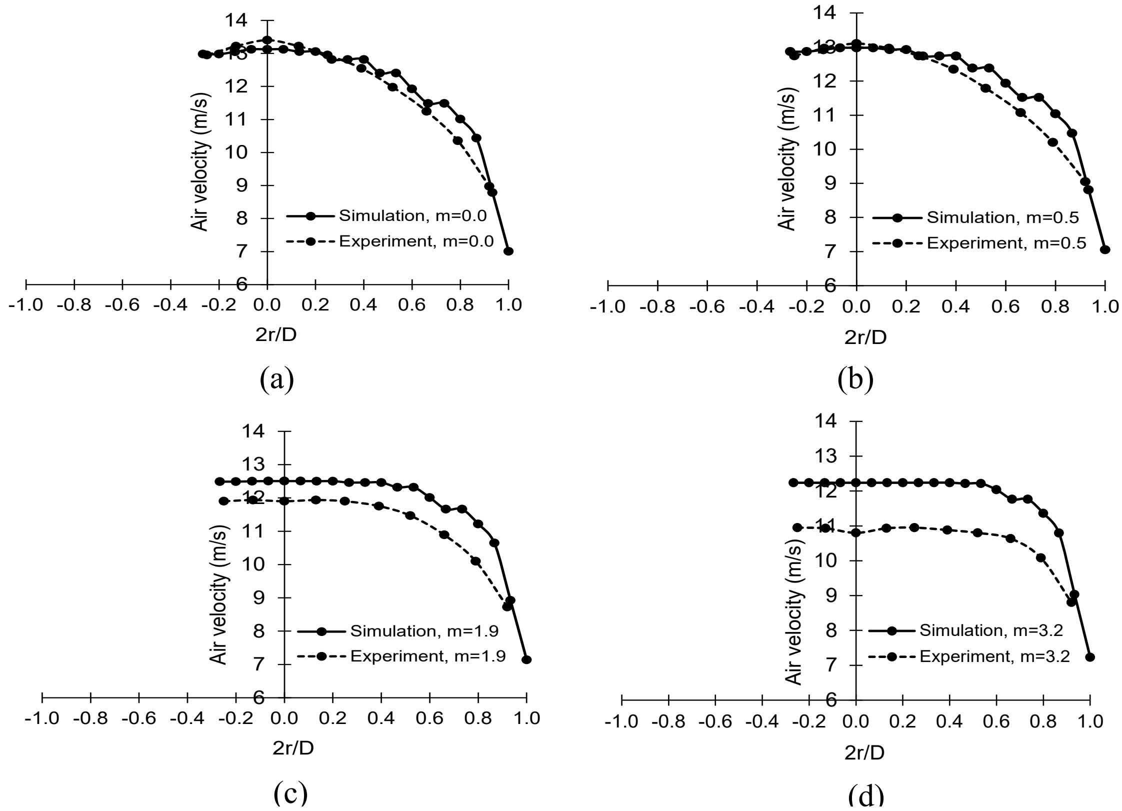

Figure 4. Comparison of predicted and experimental mean real air velocity profiles along a diameter in a pipe cross section at fully developed region for particle diameter 200 μm and Re = 2.3×10^4 (from Case-3.1 to Case-3.4).

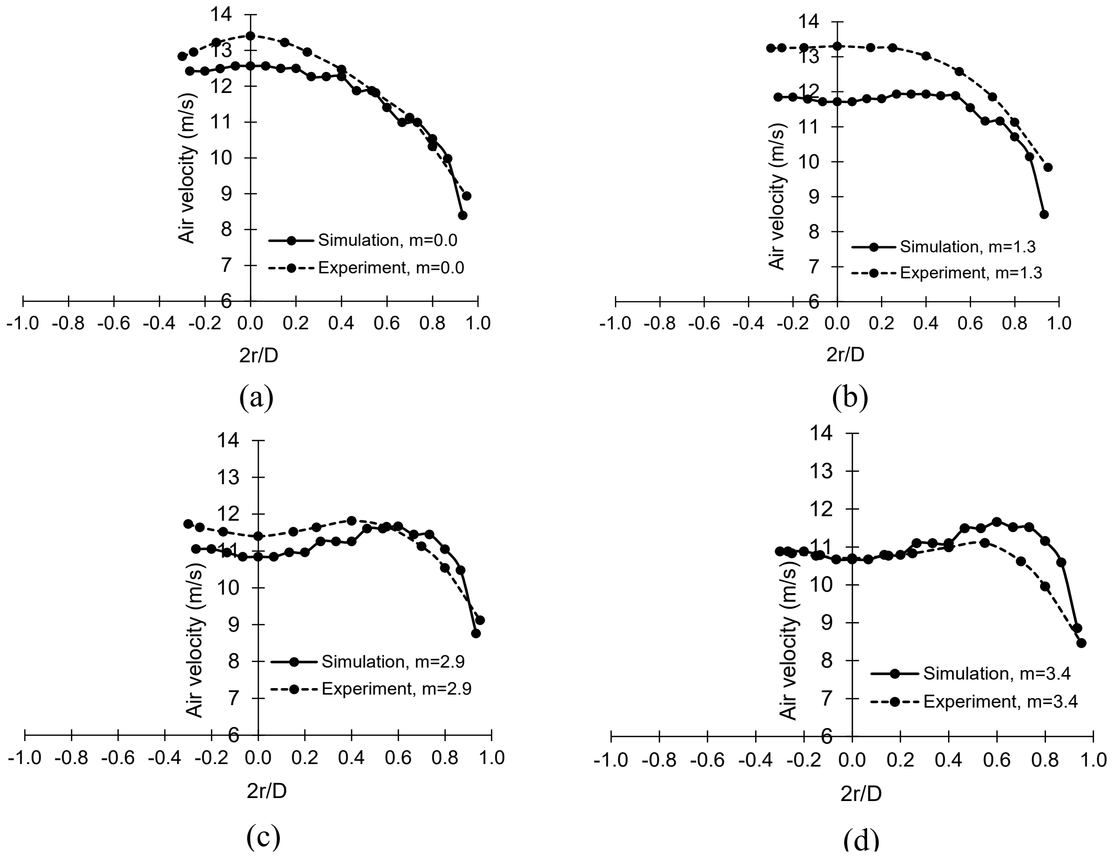

Figure 5. Comparison of predicted and experimental mean real air velocity profiles along a diameter in a pipe cross section at fully developed region for particle diameter 500 μm and Re = 2.2×10^4 (from Case-1.1 to Case-1.4).

μm diameter particles (Figure 4). However, the agreement between experimental and predicted results is good for 500 μm diameter particles for the range of solid loading ratios studied (Figure 5). For the highest solid loading ratio (3.4), the maximum velocity predicted by the model is higher than that of the experiments and the experimental maximum is located at around 2r/D = 0.5 while the predicted maximum is located at around 2r/D = 0.6. In general, having lower velocities in core region compared to annulus region is better explained by solid distribution profiles (Figure 6 (a)).

The predicted solid volume fractions along a diameter in a pipe cross section at fully developed region for 500 μm diameter particles and for different solid loading ratios are shown in Figure 6 (a). It shows that the highest concentration of the solid particles is located in the central part of the pipe cross section. Due to roughness of the wall, the rebound angle of particles increases resulting in particle movement into core region of the pipe. The solid concentration in central region is further increased when increasing the solid mass flow rate (i.e. the solid loading ratio). This is the reason for having lower air velocities in the core region of the pipe (Figure 5). Nevertheless, the extremely low solid concentration nearby walls is peculiar.

Figure 6 (b) shows the solid volume fraction variation along the central axis of the vertical pipe. At steady state, from inlet (z = 0 m) to the outlet (z = 8 m), the solid volume fractions have been increased for all solid loading ratios tested. The particles might tend to move to the core region of the pipe cross section when the particles move along the pipe. However, the reasons for the observation should be further investigated.

Figure 7 shows the predicted particle velocity profiles corresponding to Case 1-1, Case 1-2 and Case 1-3. The air velocities corresponding to these cases are shown in Figure 5. The particle velocities are lower than the air velocities providing drag force to move the particles ahead. When solid loading ratio is increased by increasing solid mass flow rate, the particle velocity is reduced because the work that is done by unit volume of gas on unit mass of particles gets reduced. Moreover, the profiles become concave with increased solid input. The maximum velocities are located in the range of 2r/D = 0.5-0.6 for the solid loading ratios, 2.9 and 3.4. The higher particle concentration in the core region of the pipe might restrict the flow of the particles resulting in lower particle velocity in the core region of the pipe cross section.

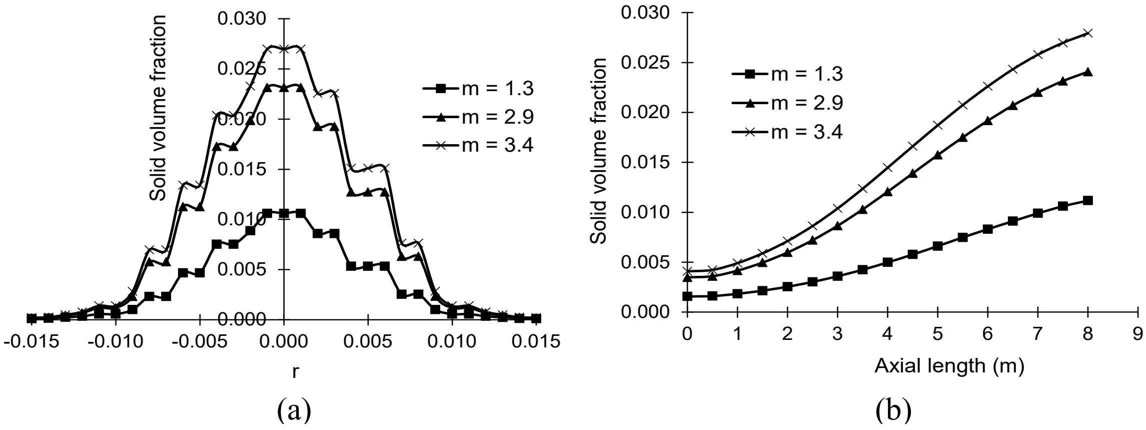

Figure 6. Solid volume fraction along a diameter in a pipe cross section at fully developed region (a) and solid volume fraction along the pipe axis (b) for particle diameter 500 µm and Re = 2.2×10^4 (Case-1.1 to Case-1.3).

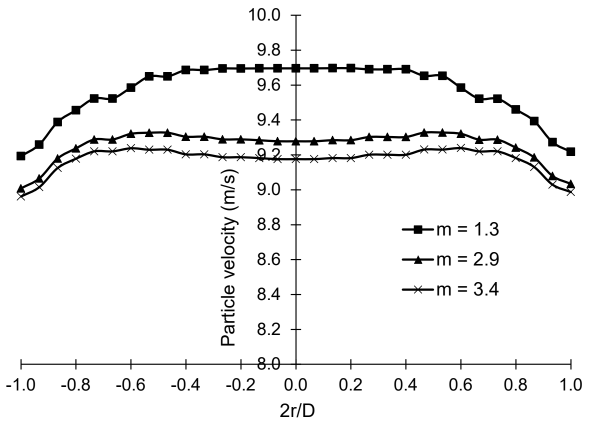

Figure 7. Mean real particle velocity profiles along a diameter in a pipe cross section at fully developed region for particle diameter 500 µm and Re = 2.2×10^4 (Case-1.1 to Case-1.3).

6 Conclusion

Euler-Granular approach is used to study the pneumatic conveying characteristics of dilute phase vertical upward flow. Cases with different operating conditions and particle diameters are simulated and some of the results are compared with experimental data from the existing literature. The pressure drop profiles, air and particle velocity profiles and solid distribution profiles are analysed.

The pressure drop results show good agreement with experimental data for 500 µm diameter particles and the deviation between experimental and predicted pressure drops is in the range of 9-19%. The prediction of air velocity profiles is also good; however the deviation is increased when the solid loading ratio is increased for 200 µm particles. At the higher solid loading ratios tested, the air velocity profiles become concave for 500 µm diameter particles. A higher solid concentration could be observed in the core region of the pipe cross section. However no experimental data is available to validate solid distribution. Finally, it should be noted that the specularity coefficient used in Johnson and Jackson particle-wall boundary conditions in the present model has significant effects on the predictions and the predictions made here is by using certain specularity coefficient values.

Nomenclature

D	Pipe diameter, (m)
m	Solid loading ratio (solid mass flow rate/air mass flow rate), (-)
Re	Reynolds number of the flow, (-)
r	Horizontal distance from pipe vertical axis, (m)
z	Vertical distance from the pipe inlet, (m)

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