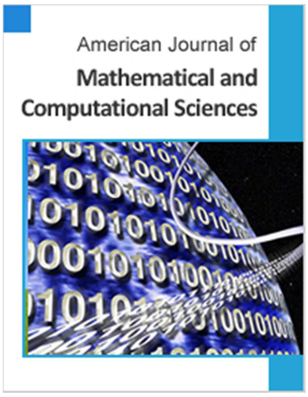
American Journal of Mathematical and Computational Sciences
2018; 3(1): 10-16
http://www.aascit.org/journal/ajmcs

American Association for Science and Technology



Pneumatic Conveying in Horizontal Pipes: Eulerian Modeling and Pressure Drop Characteristics

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Citation
Pandaba Patro. Pneumatic Conveying in Horizontal Pipes: Eulerian Modeling and Pressure Drop Characteristics. *American Journal of Mathematical and Computational Sciences.* Vol. 3, No. 1, 2018, pp. 10-16.

Keywords
Pneumatic Conveying,
Pressure Drop,
Eulerian Modeling,
KTGF,
CFD

Received: July 21, 2017
Accepted: November 23, 2017
Published: January 11, 2018

Abstract
In the present paper, gas–solid flow (i.e. pneumatic conveying) in a horizontal pipe has been investigated numerically using the Eulerian or two-fluid model to predict pressure drop. Consideration of inter-particle collisions give rise to solid phase stresses and are modeled using kinetic theory of granular flow (KTGF). It was observed that consideration of inter-particle collisions, particle-wall collision and lift help in the radial dispersion of the solid particles in a horizontal pipe. The value of the numerical parameter specularity coefficient strongly affects pressure drop and hence, has to be chosen correctly. The effect of flow parameters as well as particle properties on pressure drop was investigated in detail. The conclusions are (a) pressure drop increases with gas velocity (b) pressure drop increases with solids loading (c) pressure drop first increases, reach a peak and then decreases with the increase in particle diameter in the range 35 to 200 micron.

1. Introduction

In pneumatic conveying, solid particles are moving inside a pipe with the help of a high speed gas stream. The most widely used industrial application of gas-solid flows is pneumatic conveying. Pneumatic conveying may occur in a horizontal pipe or along a vertical pipe. Generally, most of the piping layout is horizontal in nature. Because, pumping power requirement in horizontal flow is less compared to vertical flow. However, gravity induced settling on the bottom wall has always been a great challenge in horizontal flows. If the gas velocity in horizontal flows is below the saltation velocity, it is insufficient to maintain the solids in suspension and solids begin to settle out and slide or roll along the bottom of the pipe and hence, gas velocity must be more than the saltation velocity to have the particles in suspended mode. For the design of pneumatic transport systems, knowledge of pressure drop is required. A minimum value of the pressure drop for effective transport without particles settling is preferred. Many researchers [1-4] predicted pressure drop in gas-solid flows under low solid loading conditions (volume fraction in the order of 10^{-3}). But, in industrial practice, solids loading are much more than this. It is very difficult to perform experiments under different operating conditions taking different particle sizes. The availability of high speed computers and CFD packages make it comparatively easy to perform numerical experiments under any flow conditions. There are generally two computational approaches used to investigate gas-particle flows: Eulerian-Eulerian approach and Eulerian-Lagrangian approach. This approach is generally used in very dilute phase gas solid flows. The Euler-Euler method treats the solid phase as a continuum which interacts with the fluid continuum. Basically, this approach has been developed for relatively high solids laoding. This method has been used in the present study. Many researchers [5-10] investigated gas-solid flows using this approach. They had shown that Eulerian model is capable of predicting the flow physics of gas-solid flows qualitatively as well as quantitatively.

In the present investigation, Eulerian-Eulerian approach has been used for the flow of a gas-solid flow in a horizontal pipe accounting for four-way coupling i.e. particle-wall interaction and inter-particle collisions. Lift forces are also considered which is caused by particle rotation due to collisions with the bottom wall and a nonuniform gas velocity field. Numerical prediction for pressure drop and velocity profiles were made with the numerical settings validated against bench mark experimental data by Tsuji et al. [11]. An extensive study was also performed to investigate the effect of important flow parameters like inlet gas velocity, particle properties and solid volume fraction on the pressure drop prediction. Particle concentrations in the range 1% to 10% by solid volume fraction (α) and particle sizes from 35 micron to 200 micron were considered for the pressure drop prediction. The gas used is air with density, ρ_g = 1.225 kg/m^3 and dynamic viscocity, $\mu_g = 1.79\times10^{-5}$ kg/m.s.

Solids loading ratio (SLR) is defined as the ratio of mass flow rate of solid phase and mass flow rate of gas phase.

$$SLR = \frac{\alpha\rho_s}{(1-\alpha)\rho_g} \tag{1}$$

The gas Reynold's number is defined as

$$\mathrm{Re}_g = \frac{\rho_g UD}{\mu_g} \tag{2}$$

Where D is the pipe diameter, ρ_g and μ_g are the density and dynamics viscosity respectively of gas phase, U is the inlet gas velocity and D is the pipe diameter.

2. Governing Equations in Eulerian Modeling

In Eulerian Modeling, both gas and solid phases are treated as continuum and hence, continuity and momentum equations are written for both the phases. The gas phase momentum equation is closed using k-ε turbulence model. Solid phase stresses are modeled using kinetic theory [12].

The conservation equation of the mass of phase i (i=gas or solid) is

$$\frac{\partial}{\partial t}(\alpha_i\rho_i) + \nabla.(\alpha_i\rho_i u_i) = 0 \tag{3}$$

$$\sum \alpha_i = 1 \tag{4}$$

The conservation equation of the momentum of the gas phase is

$$\begin{aligned}\frac{\partial}{\partial t}(\alpha_g\rho_g u_g) + \nabla.(\alpha_g\rho_g u_g u_g) = -\alpha_g\nabla\overline{p} + \nabla.\tau_g - \nabla.(\alpha_g\rho_g\overline{u_g^{'}u_g^{'}})\\ + \alpha_g\rho_g g + K_{sg}(u_s - u_g)\end{aligned} \tag{5}$$

The conservation equation of the momentum of the solid phase is

$$\begin{aligned}\frac{\partial}{\partial t}(\alpha_s\rho_s u_s) + \nabla.(\alpha_s\rho_s u_s u_s) = -\alpha_s\nabla\overline{p} - \nabla\overline{p_s} + \nabla.\tau_s - \nabla.(\alpha_s\rho_s\overline{u_s^{'}u_s^{'}})\\ + \alpha_s\rho_s g + K_{gs}(u_g - u_s)\end{aligned} \tag{6}$$

$K_{gs} = K_{sg}$ 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

$$\tau_g = \alpha_g\mu_g(\nabla u_g + \nabla u_g^T) + \alpha_g(\lambda_g - \frac{2}{3}\mu_g)\nabla.u_g I \tag{7}$$

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.

For α_g > 0.8:

$$K_{sg} = \frac{3}{4}C_D\frac{\alpha_s\alpha_g\rho_g\left|u_s - u_g\right|}{d_p}\alpha_g^{-2.65} \tag{8}$$

For α_g <0.8:

$$K_{sg} = 150\frac{\alpha_s(1-\alpha_g)\mu_g}{\alpha_g d_p^2} + 1.75\frac{\rho_g\alpha_s\left|u_s - u_g\right|}{d_p} \tag{9}$$

In the gas-solid flow, particle motion is dominated by the collision interactions (inter-particles as well as particle-wall). This gives rise to solids pressure and solid stresses. Kinetic theory of granular flows (KTGF) [12] can be applied to describe the effective stresses in solid phase to close the momentum balance equation. Granular temperature is defined as the kinetic energy associated with the random motion of the particles. The granular temperature (θ_s) equation for the solid phase is

$$\frac{3}{2}\left[\frac{\partial}{\partial t}(\rho_s\alpha_s\theta_s)+\nabla.(\rho_s\alpha_s u_s\theta_s)\right]=(-\overline{p_s}I+\tau_s):\nabla u_s+\nabla.(k_{\theta_s}\nabla\theta_s)-\gamma\theta_s+\phi_{gs} \tag{10}$$

Where

$(-\overline{p_s}I+\tau_s):\nabla u_s$ is the energy generation by the solid stress tensor

$k_{\theta_s}\nabla\theta_s$ is the diffusion of energy (k_{θ_s} is the diffusion coefficient)

$\gamma\theta_s$ is the collisional dissipation of energy

ϕ_{gs} energy exchange between the solid and gas phase

The solid phase stress is

$$\tau_s=\alpha_s\mu_s(\nabla u_s+\nabla u_s^T)+\alpha_s(\lambda_s-\frac{2}{3}\mu_s)\nabla.u_s I \tag{11}$$

Here λ is the bulk viscosity and I is the unit tensor.

Solid Pressure:

$$p_s=\alpha_s\rho_s\theta_s+2\rho_s(1+e_{ss})\alpha_s^2 g_{o,ss}\theta_s \tag{12}$$

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:

$$g_{o,ss}=(1-(\frac{\alpha_s}{\alpha_{s,\max}})^{\frac{1}{3}})^{-1} \tag{13}$$

Bulk Viscosity:

$$\lambda_s=\frac{4}{3}\alpha_s\rho_s d_p g_{o,ss}(1+e_{ss})(\frac{\theta_s}{\pi})^{\frac{1}{2}} \tag{14}$$

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

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

$$\mu_{s,kin}=\frac{10 d_p\rho_s(\theta_s\pi)^{\frac{1}{2}}}{96\alpha_s(1+e_{ss})g_{o,ss}}\left[1+\frac{4}{5}g_{o,ss}\alpha_s(1+e_{ss})\right]^2 \tag{15}$$

$$\mu_{s,coll}=\frac{4}{5}\alpha_s\rho_s d_p g_{o,ss}(1+e_{ss})(\frac{\theta_s}{\pi})^{\frac{1}{2}} \tag{16}$$

3. Computational Procedure

Numerical simulations of turbulent and unsteady gas-solid flow are performed on a horizontal 3D pipe of diameter 30 mm and length equal to 100 times the diameter. The standard *k–ε* epsilon turbulent model [13] with standard wall function was used for gas phase and kinetic theory of granular flow (KTGF) was used to close the momentum balance equation in solid phase. The computational domain with the cross sectional mesh is shown in figure 1.

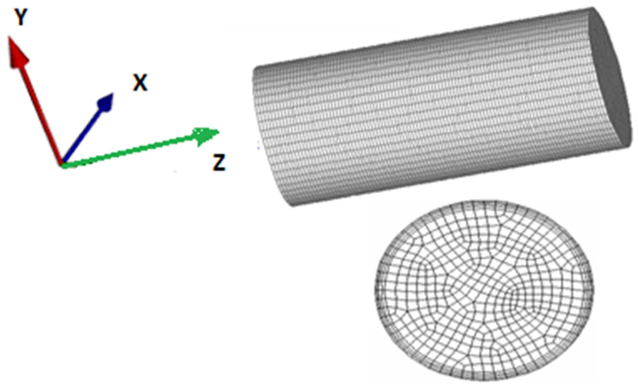

Figure 1. *Computational domain with cross-sectional mesh.*

Grid independence test was carried out using 3 grids of mesh sizes 21800, 32700 and 70600 cells, respectively. It has been that an increase in the number of grid points had a negligible effect on the computed profiles for velocity and pressure. We choose the second grid with 32700 cells for the numerical prediction of pressure drop.

The detailed model parameters and boundary conditions used in our simulation are listed in the Table 1. The numerical parameter values are selected based on the findings of Patro et al. [14, 15].

Table 1. *Simulation model parameters.*

Description	Value
Coefficient of restitution for particle-particle collisions	0.9
Coefficient of restitution for particle-wall collisions	0.95
Inlet boundary condition	Velocity inlet (Fully developed)
Outlet boundary condition	Outflow (Fully developed)
Wall boundary condition	No slip (Gas)
	Partial slip (solid)
Maximum iterations	20
convergence criteria	1×10^{-3}
time step	1×10^{-3} s
gravity	enabled

Gas-solid flow is always unsteady due to the presence of the particles, which modulates the gas flow field and turbulence. So, it is important to monitor the important flow parameters like solid velocity and volume fraction at outlet. After a lot of iterations, degree of unsteadiness reduces and flow variables have a periodic variation with respect to time and finally, the variation becomes negligible.

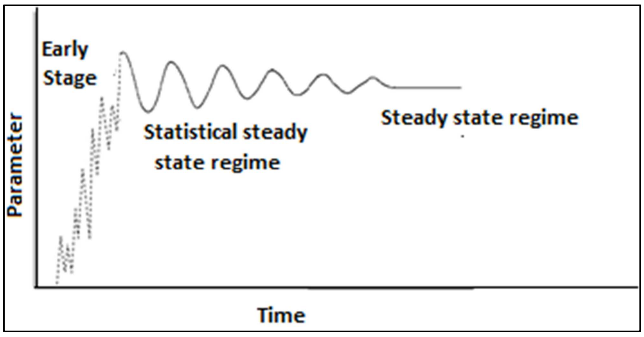

Figure 2. *Behavior of any parameter as predicted from a two-fluid transient simulation.*

Figure 2 illustrates the behavior of any parameter as predicted from a two-fluid transient simulation of the gas–solid flow [16]. From a given initial condition, the simulation goes through an early stage, and finally reaches the so-called statistical steady state regime. When flow parameters start to oscillate around well defined means, statistical steady state regime has been reached. If the behavior of the flow variable becomes a straight line, it is said to be reached steady state regime. In the present study, measurements were taken in the statistical steady state regime, when the variables reach steady state or statistical steady state regime.

4. Results and Discussion

First of all, validation of the numerical model was done by comparing the predicted results for velocity and pressure drop in horizontal gas-solid flows with the benchmark experimental findings of Tsuji et al. [11]. Experiments were conducted in a 30 mm diameter pipe; particle diameter is 200 micron and density 1020 kg/m^3 for different solid loading ratios. The mean velocity of gas was varied from 6 to 20 m/s. As the loading ratio is very low and gas velocity is more than the saltation velocity, particle settling do not happen as predicted in the experiments. First, we used the simplest model neglecting the effect of lift and convection and diffusion terms in the granular temperature equation. The velocity profiles for solid phase are plotted radially at different mean velocity and solid loading ratio (SLR) as shown in figure 3. It is clearly showing the particle settling towards the exit portion of the pipe, which is not expected. Solids are supposed to have suspended throughout the cross section in fully developed conditions as observed in the experiments. So, the simplified model did not yield the required outcome.

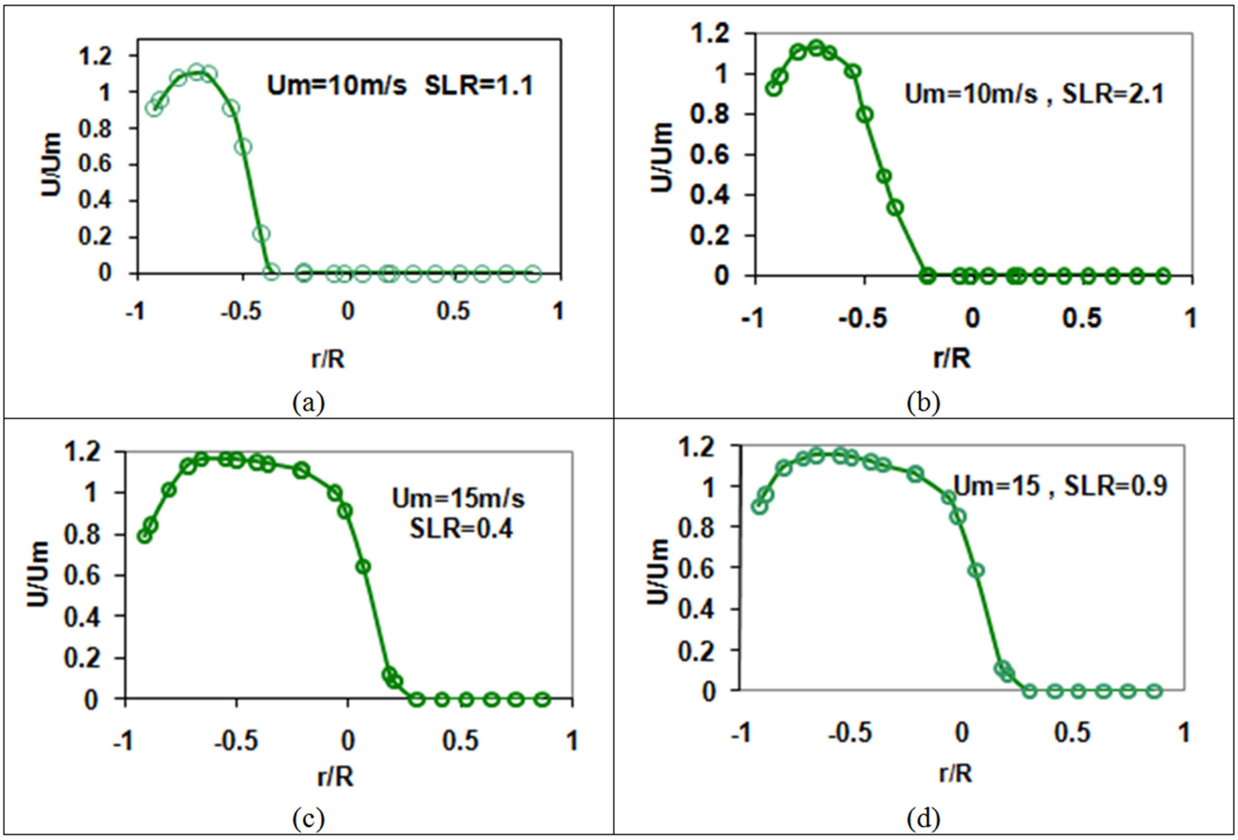

Figure 3. *Velocity profiles of solid phase at the pipe exit (radial variation).*

In confined gas-solid flows, particles experience lift force (a phenomena called Magnus lift effect) that arises due to the rotation of the particle [17]. Inter-particle collisions as well as particle-wall collisions are responsible for the rotation of the particles. Lift force as well as collisions help in the radial dispersion of the particles preventing particle settling. Hence, we considered the effect of lift (lift coefficient=0.2) and particle-wall collision (restitution coefficient= 0.95). Also, the convection and diffusion terms are considered in granular temperature equation.

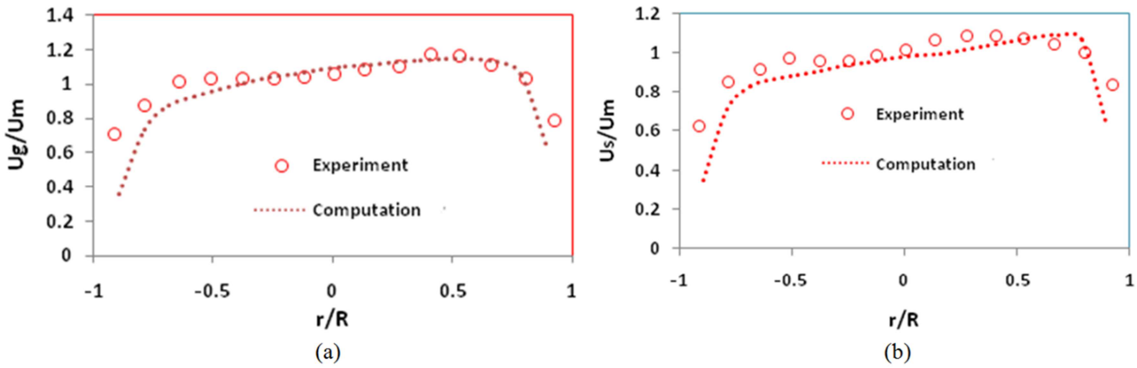

Figure 4. *Comparison of normalized velocity curves at SLR = 2.1 and Um = 10 m/s for (a) gas phase and (b) solid phase.*

Now, the numerical results for velocity profiles are in good agreement with the experimental results as shown in figure 4. The profiles are not symmetric as the particles have the tendency to settle down due to gravity. The gravitational force makes the flow more complicated in the horizontal pipe than in the vertical one, as was mentioned by Owen [18].

As the main objective of the present research is the prediction of pressure drop, validation with experimental data for pressure drop is important. One factor contributing to pressure drop in gas-solid flows is the particle-wall collision momentum loss defined by a numerical parameter known as specularity coeffcient. The correct value for this parameter was chosen by matching the numerical predictions with the experimental data. Figure 5 shows good agreement between the experimental and numerical data occurred at specularity coefficient equal to 0.08 with maximum error of 5%. This value along with other numerical parameter values are used for the subsequent measurement of pressure drop

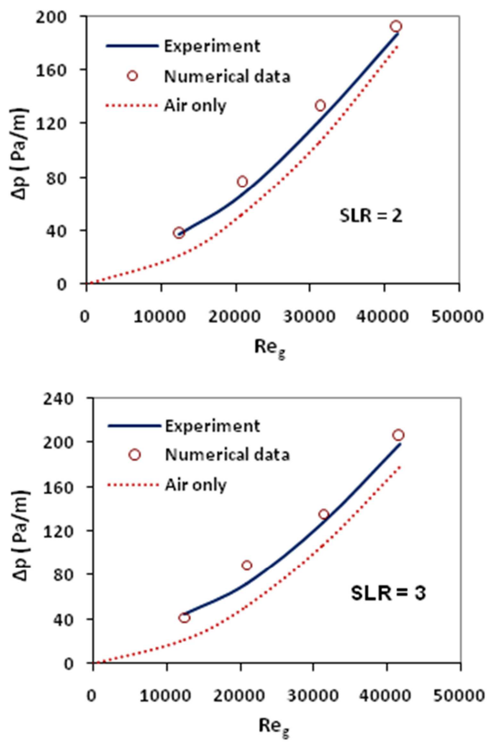

Figure 5. *Comparison of pressure drop prediction.*

5. Pressure Drop Prediction

Under variable solids loading and operating conditions, pressure drop in horizontal gas-solid flows has been computed. The important factors like gas inlet velocity, particle sizes and particle loading are investigated here.

In gas-solid flows, the drag exerted by the gas flow on the solid particles is mainly responsible for the transportation along the pipe. The drag force arises due to the slip velocity and hence, the inlet gas velocity is an important parameter in gas-solid flows. Gas inlet velocity was varied from 10 to 25 m/s and its effect on pressure drop is presented in figure 6. We observed that pressure drop increases with increase in gas velocity.

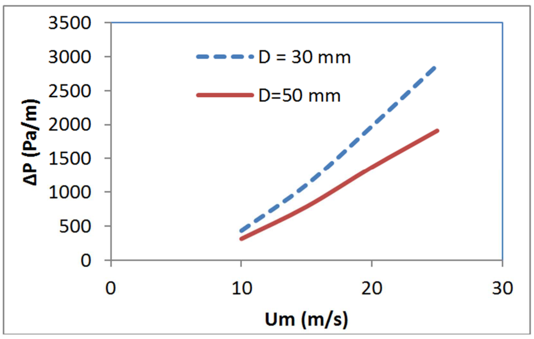

Figure 6. *Pressure drop variation with mean gas velocity for 100 micron particles of density 1500 kg/m^3 at α = 0.04.*

Two pipes of different diameter (30mm and 50mm) were used to study the influence of inlet gas velocity. Pressure drop reduces with increasing the diameter of pipe similar to single phase flows. Most of the pressure loss in gas-solid flow comes out of energy lost due to particle-particle collision and particle-wall collision. A bigger diameter pipe provides more space and hence decreases the number of collisions causing less pressure drop. Solid volume fraction is defined as the ratio of volume of solid phase and total volume of the mixture. It is a measure of solid loading in gas-solid flows. Particle loading, solids loading ratio (SLR) and volume fraction are synonymous terms in pneumatic conveying. Volume fraction in the range 1% to 10% was considered to study its effect on pressure drop.

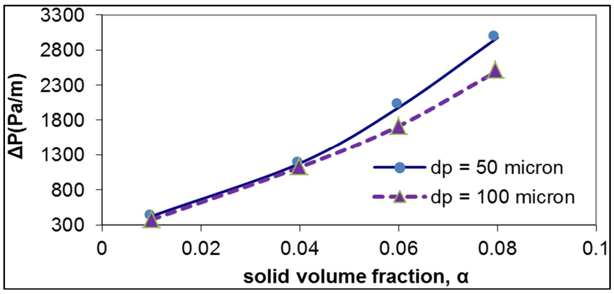

Figure 7. *Effect of solid volume fraction on Pressure drop in a 30mm diameter pipe,* $\rho_s = 1500 kg/m^3$, *Um = 15 m/s.*

As the particle loading or volume fraction increases, the pressure drop along the pipe increases (figure 7). Increasing volume fraction of solids increases the number of inert-particle as well as particle-wall collisions in the pipe and in turn increasing the pressure drop. Singh and Simon [19] performed DEM simulation and had shown that the increase of number of particle-particle collisions is greater than the increase of wall-particle collisions.

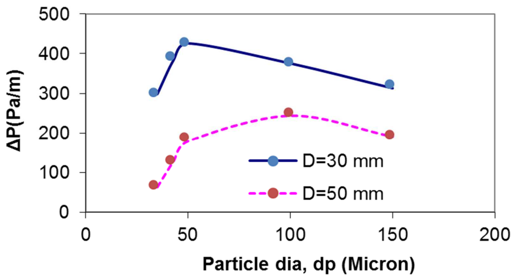

Figure 8. *Effect of particle diameter on pressure drop for 30 mm pipe at* $\alpha = 0.01$, *Um = 15 m/s.*

In industrial pneumatic conveying systems, the same type of material or various materials of different sizes are commonly transported. So, particle size and particle density affects the flow behavior. In the present study, particles of size 35 to 150 micron and density in the range 1500 to 2000 kg/m^3 are investigated in a 30 mm diameter pipe as well as in a 50 mm diameter pipe. It is observed that pressure drop increases rapidly with increase in particle diameter, reach the peak value and then start decreasing for both pipe sizes (figure 8). Peak is different for different pipe sizes. The main contributions to the pressure drop in gas-solid flows in horizontal pipes are:

(a) Energy required to impart drag force on the particles (E_D)

(b) Momentum and energy lost by particle-particle collisions (E_{pp})

(c) Momentum and energy lost by particle-wall collisions (E_{pw})

An increase in particle diameter causes an increase in slip velocity and superficial area of the particle. So energy required (drag force) for the solids transport increases. It is obvious that more energy is required to convey larger particles for the same conveying conditions. At the same time, an increase in particle diameter causes a decrease in the number of particles for a constant solid volume fraction. Hence, the frequency of particle-particle collision and particle-wall collision decreases. So the contributions by E_{pp} and E_{pw} reduce. At the critical value of particle diameter, these three parameters are optimized, and hence maximum pressure drop occurs. However, it is really a difficult task to correlate them with the particle diameter quantitatively.

The variation of pressure drop with particle density is shown in figure 9. The pressure drop increases with particle density at higher solids loading. The rate of increase is more as we go on increasing the solids loading. At lower loadings ($\alpha = 0.01$), the increase in pressure drop is almost negligible.

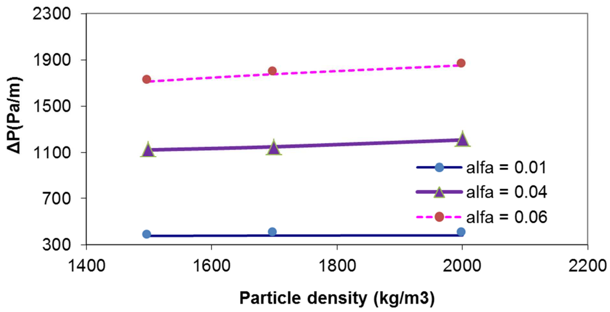

Figure 9. *Pressure profiles with particle density at different volume fractions for 30mm diameter pipe at Um = 15 m/s.*

6. Conclusions

The pneumatic conveying in a horizontal pipe has been numerically solved using Euler -Euler approach. The numerical results for velocity profiles and pressure drop are validated against the experimental data of Tsuji et al. [11]. Excellent agreement was found by the numerical simulation accounting for four-way coupling i.e. particle-wall and inter-particle collisions as well as considering the effect of Magnus lift. The lift force is generally very less in gas-solid flows in comparison to the drag force, but can not be neglected in the numerical simulation. The particle collisions and lift force helps in the radial dispersion of solid particles preventing settling due to gravity. Pressure drop depends on the value of numerical parameter known as specularity coefficient. In the present study, numerical pressure drop was in good agreement with the experimental values for specularity coefficient equal to 0.08. It is also observed that pressure loss increases with inlet gas velocity, and solids loading. However, with respect to particle diameter, pressure drop first increases, reaches a peak and then decreases.

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