Numerical prediction of pressure drop for pneumatic conveying of air-fly ash mixture through pipeline.

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Abstract. Many researchers are working in the field of pneumatic slurry transportation, where the rheological parameters involved in the flow. In the present work is a numerical simulation for the study of pressure drop of 30µm particle size of fly ash air mixture flow through a circular pipe was investigated through ANSYS Fluent. The present paper introduces a simplified 3-D Eulerian model along with RNG k-ε turbulent model. It was observed that the pressure drop was maximum for minimum mass flow rate of air and as the mass flow rate increases the pressure drop decreases and it becomes constant at a threshold mass flow rate for this particle size, which qualitatively matches with the experimental results observed by Bansal et al. (2013).

1. Introduction
Pneumatic conveying is an integral part of many industries like ash, cement, plastic etc. In the current scenario pipe conveyor is playing a vital role in transportation. But because of the complex technology involved in pipeline transportation, its development so far is not satisfactory. The long distance of conveying solids with optimum friction losses and minimum erosion is a great challenge in pneumatic conveying system. The pneumatic suspensions during flow in pipeline could form annulus, snug, churn, column, homogeneous, heterogeneous, fixed bed or moving bed and shows their behaviour like Newtonian or Non-Newtonian suspension. A characteristic of particulate matter plays a vital role in pneumatic transport and they are characterized as size, distribution, shape, density, hardness, friability, etc. In the present study pneumatic conveying of fly-ash mixture has been carried out to evaluate the effect of particle size distribution on the flow behaviour of air-solid suspension. The comparison of the results has been done with available literature and it is well validated. The physical and chemical properties of the aforesaid mixture has been taken from the real time data of Chhattisgarh State Power Generation Company Limited, Korba Chhattisgarh India, in order to simulate the mixture with the real time conditions for the benefit of the industries.

The objective of the paper is to analyse the flow behaviour of the air-fly ash mixture in the pipeline with four different mass flow rate of air i.e. 0.04, 0.07, 0.09 and 0.11 kilogram per second and to analyse the pressure and velocity relationship of air-fly ash mixture so that the initial findings of the flow behaviour of the aforesaid mixture, it’s particle concentration, wear analysis can be done.

A systematic survey of the published literature dealt in the area of research on gas-solid transportation through pipelines reveals that a significant amount of work has been done towards developing theoretical, empirical correlations as well as numerical simulations for the prediction of pressure drop in the flow. Moreover, numerous studies have also been reported on the identification and prediction of the different flow regimes, the transition velocity, and the critical deposition velocity.
Molerus [1] has done experimental study and developed a prediction procedure for pressure drop and state of flow for horizontal glass conveying duct of 0.04m diameter particle taken is polystyrene of 2.3mm diameter. The author found that under constant solid mass flow rate the pressure drop increases with decreasing velocity for horizontal transport. For vertical transport under constant solid mass flow rate the pressure drop also increases with decreasing velocity but when a low solid mass flow rate is conveyed to below a critical value the pressure drop increases sharply which results sudden change in flow pattern.

Manzar and Shah [2] state that because of scarcity of the experimental literature they have modelled the CFD analysis of various straight and curved tubing sections for different flow conditions. The authors observed that the larger particle size results in a conical profile of concentration with a steep rise in concentration towards the middle of the flow. These particles move at the velocities higher than the average flow velocity. The authors also observed that an increase in the particle volume concentration also results in a conical profile of concentration. The authors concluded that generally there is a good agreement between near wall particle concentration and particle shear stress.

Bansal et al. [3] have investigated straight pipe pneumatic conveying characteristics for fluidized dense phase pneumatic conveying of powders. The authors considered two fine powders- fly ash and white powder, having mean particle diameter of 30µm and 55µm and particle density of 2300 and 1600 kg/m$^3$ respectively. They have installed pressure tapping at two different locations for the pneumatic conveying characteristics (PCC). They found that for the straight pipes, shape of PCC curves to be significantly influenced by pipeline layout like diameter or length and location of pressure tapping points. They also derived a model for solid friction factor for fly ash from different straight pipe sections for the three different pipes were found to be all different, which indicates that the highly product dependent and pipeline dependent characteristics of fluidized dense phase conveying of fine powders.

Rawat et al. [4] have designed and fabricated a modified pot tester for high concentrations ($C_w > 60\%$ by mass) for measurements of fly ash slurries at various concentrations and relative velocities. The erosion wear was found to have a stronger dependence on concentration as compared to relative velocity. Studies are also conducted to investigate the effect of variation of angles of impact on the erosion wear at a solid concentration of 65$\%$ (by mass) and noticed that the erosion rate was maximum at an angle of 45$^\circ$. The researchers concluded that the Erosion wear has comparatively stronger functional dependence on the concentration of solid particles rather than flow velocity of particles for high concentration fly ash slurries for the case of nearly parallel flow.

Mishra. R. [5] have done CFD simulation of coal-water and copper-ore water slurry for predicting the flow behaviour of the slurry, calculated the pressure drop and predicted the erosive behavior inside the horizontal pipeline. The researchers have studied the effect of Reynolds number and Euler’s number for analyzing the effect of flow behaviour and pressure drop. The authors have taken a wide particle size distribution for both the slurries ranging from 70.5µm -275.7 µm and solid density 1980 kg/m$^3$ for coal-water slurry and 40.1 µm-278.5 µm and solid density 2844 kg/m$^3$ for copper ore-water slurry and observed that the erosive wear was maximum somewhere around 700-900mm from the inlet of the pipe for both coal and copper ore water slurry, but the intensity of wear was maximum for copper ore water slurry because of its metallic behaviour.

2. Mathematical modelling and validation
The Eulerian Model is the most complex of the multiphase models. It solves a set of momentum and continuity equations for each phase. Momentum exchange between the phases is also dependent upon the type of mixture being modelled.

Continuity equation for the mixture can be expressed as:

$$\frac{\partial}{\partial t}(\rho_m) + \frac{\partial}{\partial x_i}(\rho_m u_{m,i}) = 0$$

Momentum equation for the mixture can be expressed as:
\[
\frac{\partial}{\partial t} (\rho_m u_{m,j}) + \frac{\partial}{\partial x_i} (\rho_m u_{m,i} u_{m,j}) = - \frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_i} \mu_m \left( \frac{\partial u_{m,i}}{\partial x_j} + \frac{\partial u_{m,j}}{\partial x_i} \right) + \rho_m g_i + F_j + \frac{\partial}{\partial x_i} \sum_{k=1}^{n} \alpha_k \rho_k u_{Dk,i} u_{Dk,j}
\]

(2)

Here \( n \) is the number of phases, \( F \) is the body force, \( \alpha_k \) is the volume fraction of solids, \( \rho_m \) is the mixture density and \( \mu_m \) is the viscosity of the mixture, which can be expressed as

\[
\rho_m = \sum_{k=1}^{n} \alpha_k \rho_k \quad \text{and} \quad \mu_m = \sum_{k=1}^{n} \alpha_k \mu_k
\]

(3)

The 3D Eulerian model with RNG k-\( \varepsilon \) turbulent model has been used to simulate the pressure drop in a horizontal pipeline of 69 mm diameter and 2000 mm length for conveying a pneumatic fly ash – air mixture. The numerical results were compared by the experimental work done by Bansal et al. (2013) and the results were found in a good agreement with a percentage error of 7%. It was observed that as the mass flow rate increases the pressure drop reduces but after the threshold mass flow rate the pressure drop becomes asymptotic. The validation results are mentioned in the Table 1 and Figure 1 in the next section.

| S. No. | Mass flow rate of air (kg/s) | Pressure drop (Pa/m) Present work | Pressure drop Bansal et al. [2013] |
|-------|-----------------------------|----------------------------------|-----------------------------------|
| 1     | 0.04                        | 561                              | 580                               |
| 2     | 0.07                        | 446                              | 476                               |
| 3     | 0.09                        | 410                              | 454                               |
| 4     | 0.11                        | 405                              | 448                               |

**Figure 1.** Comparison of pressure drop of the present work with the work of Bansal [2013]

3. Results and Discussions

Many researchers are working on pneumatic flow but maximum work done so far are experimental only and a few literatures have found using simulation software on the pneumatic transportation. The reason behind that are complex calculations of equations and abrupt behaviour of solid-air mixture through CFD analysis. Here a convergence criteria for all variables are considered as 0.003 and solution had converged after 1931 iterations. It is observed that error percentage is nearly 7% to 9% in the validation, which is well within the limit and this slight variation in the result is due to the assumptions made in the simulation. Pneumatic flow of Fly ash-air mixture is simulated in the present work and pressure and velocity contours are shown here at 1500mm pipe length. It is also observed that erosion prone areas can also be predicted on the basis of these results. Here 4 different cases have
been discussed for different mass flow rate of air ranges 0.4 kg/s – 0.11 kg/s and volume fraction has been taken based on the mean values of Froude Number ranges from 7 – 14.

3.1. Contours at Mass flow rate of air 0.4 kg/s

Fig 2(a) Pressure Contour at 1500mm  
Fig 2(b) Velocity Contour at 1500mm

3.2. Contours at Mass flow rate of air 0.7 kg/s

Fig 3(a) Pressure Contour at 1500mm  
Fig 3(b) Velocity Contour at 1500mm

3.3. Contours at Mass flow rate of air 0.9 kg/s

Fig 4(a) Pressure Contour at 1500mm  
Fig 4(b) Velocity Contour at 1500mm

3.4. Contours at Mass flow rate of air 0.11 kg/s

Fig 5(a) Pressure Contour at 1500mm  
Fig 5(b) Velocity Contour at 1500mm

Fig 2(a) shows most of the values of pressure is moderately low at the centre and maximum at the pipe wall, while Fig 2(b) shows that the velocity is highest at the central zone of the pipe and minimum at the pipe wall surface, i.e. the pressure is inversely proportional to the velocity, which shows the efficacy of the similar type of flow. It may be concluded from Fig 2(a) & (b) that for most of the area, pressure increases towards the pipe wall and therefore, at the wall surface the velocity is minimum, as
stated above. It is evident from figure 2(a) that at the centre, the pressure was nearly 3.15x10^2 Pa and at the wall, it is approximately 3.12x10^2 Pa. It has been observed from figure 2(b) that the velocity at centre of the pipe was high nearly about 6.1 m/s whereas near wall surface, it is nearly 0.6 m/s, here it is observed that the velocity is gradually decreasing from centre of the pipe towards the wall of the pipe but at the most of the portions the pressure is gradually increasing from centre of the pipe towards the wall of the pipe.

It is also found that at the left upper side of the wall, pressure is slightly higher than other portions of wall but at the right lower side of the wall the pressure is quite low reason behind that is eddy formation due to pneumatic dense phase flow. It is also observed that three different sections near the wall shows a little high pressure but around these points near the wall, pressure is comparatively low, which shows the phenomenon of eddy formation near the wall, high particle concentration at these sections near the pipe wall results more erosion at these specific regions. Similar types of findings observed for other cases Fig. 3(a) & (b), 4(a) & (b), 5(a) & (b).

4. Conclusions
The present work has attempted to address some characteristics of solid-air two-phase flow for pneumatic conveying system. The following observations been concluded from the present investigation:

- It was observed that the maximum zone of the cross section area, the pressure increases towards the pipe wall and therefore, at the wall surface the velocity is minimum. It is evident that at the centre, the pressure was nearly 3.15x10^2 Pa, at the top portion of the wall surface the pressure was approximately 3.22x10^2 Pa and at the bottom wall surface it was approximately 3.12x10^2 Pa. As a result at the top portion of the wall surface the shear phenomenon is more dominant hence more erosive wear.

- It has been found that for all mass flow rates of air, the erosion prone area would be near the wall surface of the pipe and to be more specific somewhere around the exit length of the pipe along the flow direction.

It was also observed that around 0.09 kg/s mass flow rate of air the pressure drop becomes asymptotic, i.e. the pressure drop reduces from 0.04-0.09 kg/s mass flow rate of air and after that pressure drop becomes constant. Similar finding was observed by Bansal et al. (2013).

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