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CFD Analysis of Fly Ash Slurry Flow Across Horizontal Pipe

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ABSTRACT

Fly ash is a significant consequences of coal-fired power stations. Fly ash slurry transportation via long pipelines is a challenge for thermal plants and other industries. In the current investigation, numerical simulation has been performed to analyse the flow pattern of fly ash slurry via horizontal pipe. It has been discovered that pressure loss over horizontal pipe increases with velocity and solid concentration. Study of rheological flow properties of fly ash slurry is crucial for the development of its transportation system. The current work may help develop slurry pneumatic conveying systems for thermal plants.

1. Introduction

Thermal power plants worldwide produce a lot of fly ash as a by-product. The combustion of coal generates it. This ash is carried through a pipe after being mixed with water and formed into a slurry. A slurry is a solid-liquid mixture, as stated by Al-sarkhi *et al.,* [1]. Slurry flow differs significantly from single-phase flow in a pipeline. Fly ash-water slurry is widely encountered in many chemical and mining engineering processes. Ibrahim [2] advocated that slurry transportation via pipelines is cost-effective and environmentally friendly and has several advantages. According to Patnaree *et al.,* [3] it causes minimum pollution. Any pipeline network system would be incomplete without pipe bends.

When compared to straight pipelines, pipeline bends create a higher pressure drop. CFD has been increasingly utilized to explore a wide range of two-phase fluid flow issues through pipelines. Various scholars have conducted a numerical and experimental studies on the behaviour of slurry flow in pipes. Doron *et al.,* [4] studied the frictional loss of slurry through horizontal pipes. The numerical simulation of complex flows in piping systems in the power station was conducted by Sowjanya *et al.,* [5]. They reported that the pressure loss in piping systems is highly dependent on the geometry of the pipelines. Slurry flow across bend pipes was experimentally studied by Verma *et al.,* [6]. Eesa *et al.,* [7] performed a numerical simulation of granular particle suspension in the carrier fluid. Chen *et al.,* [8] modelled coal-water slurry flow via a horizontal piping system. Chandel *et al.,* [9] looked

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into the additive impact on the rheology of FA slurry and pressure loss at significant concentrations. Wang *et al.,* [10] simulated particle flow behaviour inside inverse liquid-solid fluidization by applying a numerical method. Numerical modelling of slurry pipeline flow was performed by many workers [11-13]. Mazumder *et al.,* [14] performed a numerical simulation to analyze the influence of elbow radius on pressure loss. Panda *et al.,* [15] used hydraulic techniques to transport FA slurry and fly ash-bottom ash mixtures via pipeline at increasing concentrations. Messa *et al.,* [16] evaluated the computational estimation of slurry flow along the straight horizontal pipe and bends. Using computational fluid dynamics, Wu *et al.,* [17] assessed the head loss behaviour of solid-liquid slurry flow through the piping system. Gopaliya *et al.,* [18] used CFD to model the sand-water slurry flow via a straight tube. Rashid *et al.,* [19] assessed frictional pressure losses caused by a polymeric additive in crude oil flow in a horizontal pipe experimentally. Kumar *et al.,* [20] studied head loss patterns of bottom ash slurry in the presence and absence of additives. Parkash *et al.,* [21] established CFD modelling of commercial slurry flow via a horizontal pipe. An attempt was made in the present investigation to use CFD to build a slurry flow model and predict pressure loss and profile of solid concentration and velocity profile in a horizontal pipe. The modelling results are evaluated by experimental observations made by Chandel *et al.,* [9] on the horizontal pipe.

2. Mathematical Simulation

Geometry has been created with the ANSYS 19.1 design modeller. The pipe length is 4.5 m, and the diameter is 41 mm, taken in geometry as shown in Figure 1. The length is sufficient for a fully formed flow to occur. The head loss for a wholly developed flow is computed among cross-sections 3m and 4.5m from the entrance

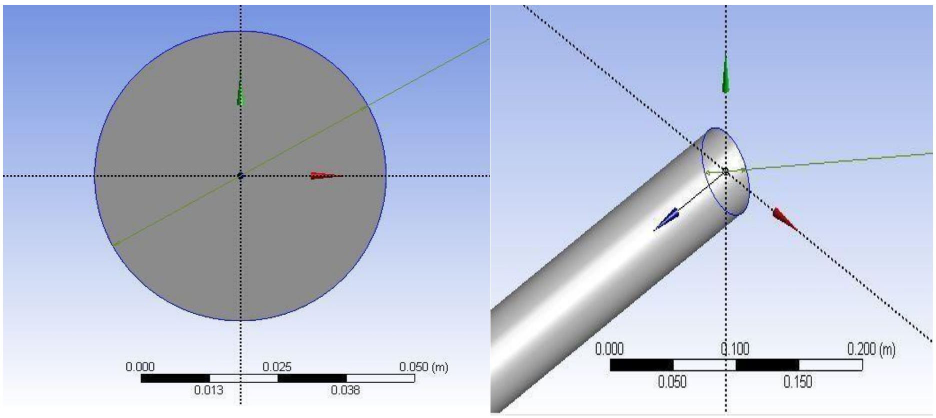
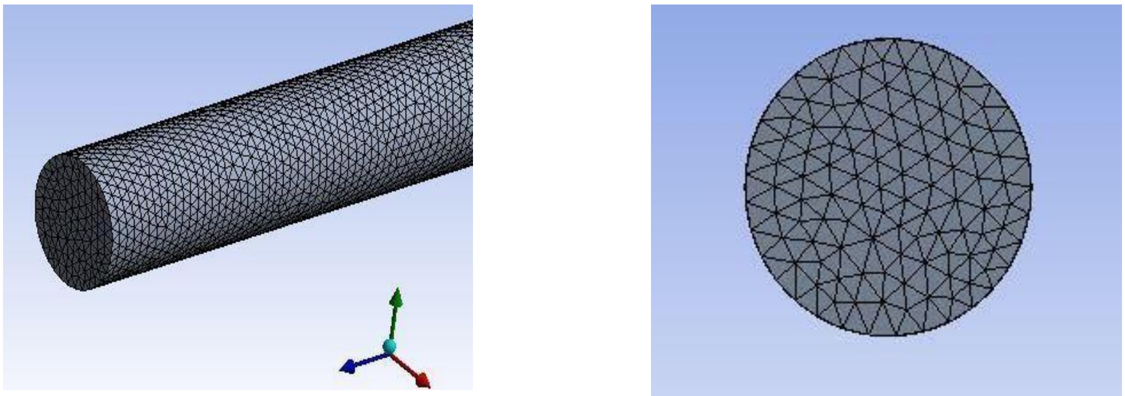


Fig. 1. Horizontal pipe geometry

The 41mm internal diameter pipe meshing generated in the ANSYS 19.1 with the different number of element size ranges 7mm-3mm. In order to achieve optimum mesh element, a grid independence test is being conducted on this geometry of tetrahedral volume mesh elements. The mesh sizes of 3, 4, 5, 6, and 7 mm had 149287, 186441, 298789, 541461 and 1111719 elements, respectively. After selecting the mesh size, the standard k-epsilon turbulence models were performed on 5 mm mesh with fly ash mixture. The velocity of the fluid (1m/s) is kept constant for all models. Figure 2 represents mesh elements and a cross-sectional view along the horizontal pipe used for further study. The change in pressure head is a consequence of the number of elements in the discretized horizontal pipe (Figure 3). So, mesh element 3 mm, and 7 mm is used for the further study pressure loss calculation of solid-liquid mixture flow via the pipe. The mesh structure remains the same thorough out the length of the pipe.



(a) (b)

Fig. 2. (a) Mesh elements along horizontal pipe (b) C.S. view of horizontal pipe

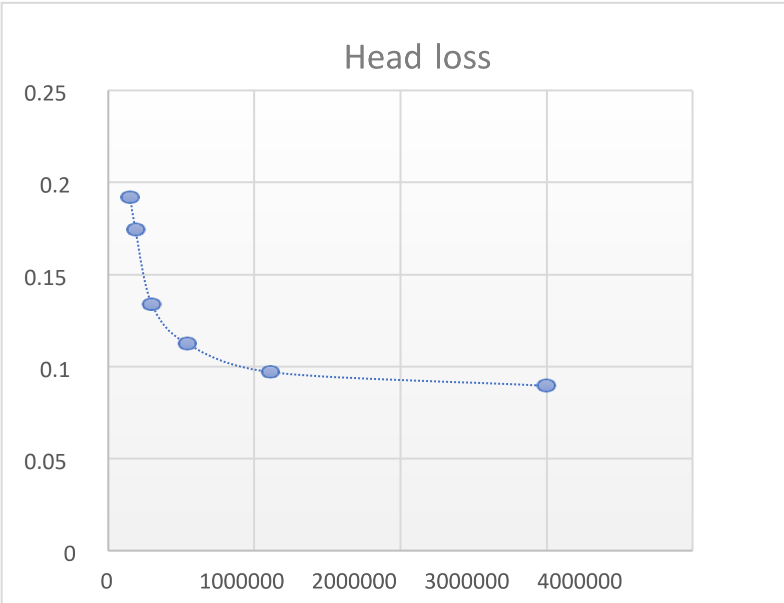


Fig. 3. Head loss variations with no. of elements in Horizontal pipe

i. **Governing Equations:** They constitute the base of all computational hydrodynamic investigations. Such are numerical expressions of conservation law fundamentals. The following are governing equations of computational fluid dynamics

a) The volume fraction of the solid phase

$$U_f = \int b_f dv \tag{1}$$

Where $\sum_{f=1}^{2} b_f = 1$

$$\hat{\rho} = b_f \rho_f$$

b) Continuity equations for solid phase

$$\frac{d}{dt}\left(b_f \rho_f\right) + \nabla\left(b_f \rho_f u_f\right) = \sum_{p=1}^{n} \left(m_{pf} - m_{fp}\right) + S_f \tag{2}$$

c) Momentum equation for liquid phase

$$\frac{d}{dt}\left(b_1\rho_1\overrightarrow{u1}\right)+\nabla(b_1\rho_1\rightarrow\rightarrow_{u1u1})=-b_1\nabla p+\nabla\bar{\bar{\tau}}_1+b_1\rho_{1\rightarrow}+C_{s1}(\overrightarrow{u_s}-\overrightarrow{u_1}) \tag{3}$$

d) Momentum equations for solid phase

$$\left(\frac{d}{dt}(b_s\rho_s\rightarrow_s)+\nabla(b_s\rho_s\rightarrow\overrightarrow{u_s}\overrightarrow{u_s})=-b_s\nabla-b\nabla p_c+\nabla\bar{\bar{\tau}}_s+b_s\rho_{s\vec{g}+c_{sl}}\left(\overset{\longrightarrow s}{u_1}-\overrightarrow{u_s}\right)\right. \tag{4}$$

e) Phase stress tensor for solid

$$\bar{\bar{\tau}}_s=b_s\mu_s(\nabla\overrightarrow{u_s}+\nabla\vec{u}_s^{tr})+a_s\left(\beta_s-\frac{2}{3}\mu_q\right)\nabla\overrightarrow{u_s} \tag{5}$$

f) Phase stress tensor for liquid

$$\bar{\tau}_1=b_1\mu_1\left(\nabla\overrightarrow{u_1}+\nabla\overline{u_s^{tr})}\right. \tag{6}$$

g) Bulk viscosity of solid

$$\lambda_s=\frac{4}{3}b_s\rho_s d_s f_{0.ss}(1+e_{ss})\left(\frac{\phi_s}{\pi}\right)^{0.5} \tag{7}$$

h) Shear viscosity of solid

$$\mu_s=\mu_{s,col}+\mu_{s,skin}+\mu_{s,fr} \tag{8}$$

i) Collisional viscosity

$$\mu_s=\frac{4}{5}b_s\rho_s d_s f_{0,ss}(1+e_{ss})\left(\frac{\phi_s}{\pi}\right)^{0.5} \tag{9}$$

j) Kinetic viscosity

$$\mu_{s,kin}=\frac{10\rho_s d_s\sqrt{\tau\varphi_s\pi}}{96b_s(1+e_{ss})f_{o,ss}}+\left(1+\frac{4}{5}b_s\rho_s d_s f_{o,ss}(1+e_{ss})\right)^2 b_s \tag{10}$$

k) Frictional viscosity

$$\mu_{s,fr}=\frac{p_s\sin\varphi}{2\sqrt{I_{2D}}} \tag{11}$$

l) Liquid solid exchange coefficient

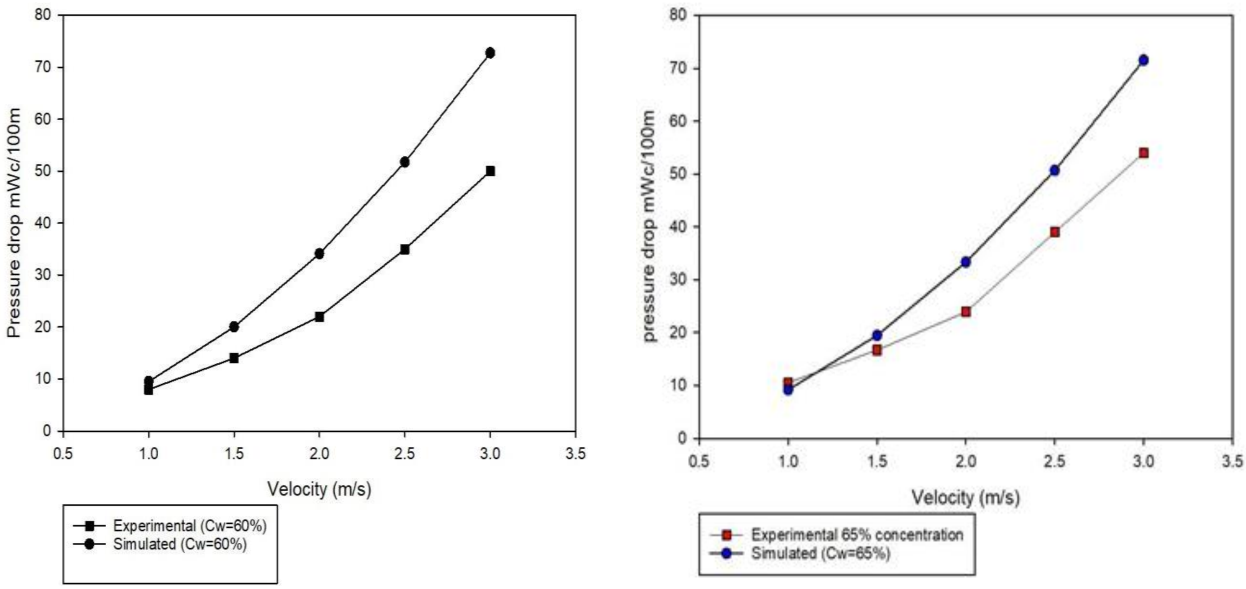
$$C_{ls}=150\frac{b_s 9(1+b_1)\mu_1}{b_1 d_s^2}+1.75\frac{\rho_1 b_s|\overline{u_s}\rightarrow\overrightarrow{u_1}|}{d_s} \tag{12}$$

ii. **Boundary conditions:** In computational, the geometry has three boundaries: outlet, inlet and wall of the pipe. The fluid enters at uniform velocity from the inlet face and is given as a pressure outlet. There has been no slip consequence at the wall, and the roughness constant is set to 0.5. In the current work, the inlet velocity of both phases is the same in the limit of 1 – 3 m/s. A SIMPLE scheme is preferred for pressure-velocity coupling.

This scheme has a higher level of accuracy and convergence. Solution controls contain some relaxation factors for density, pressure, momentum, forces, and slip velocity and remain by default. However, their value can be changed from 0.8 to 0.5 in case of deviation in the results. The convergence criterion in the present work is taken as 10^{-4}.

3. Results and Discussions
3.1 Pressure Drop

In current work, computational modelling has been performed to investigate pressure loss behaviour for fly ash slurry via a horizontal straight pipe. Pressure loss of FA slurry has been observed at different solid concentrations range (Cw) of 60% and 65 % by weight.Within the required range of velocities (1 to 3 m/s), the pressure drop was calculated in metres of water column per kilometre of the pipeline (mWc/km). For any solid concentration, pressure loss increased as the velocity, with the enrichment rate becoming much more observable at more incredible speeds, as depicted in Figure 4. This is due to increasing the solid content that causes a significant rise in the viscosity and density of the slurry suspension. The simulated result agrees with Chandel *et al.,* [9].



(a) (b)

Fig. 4. Pressure drop Vs velocity at a solid concentration (a) 60% and (b) 65% by weight in horizontal pipe

Experiments cannot predict the velocity profile of the solid state in a flow. The vertical velocity profiles generated by computational fluid dynamics agree with theoretical ideas. The velocity of mean flow and solid concentrations determine the symmetrical character of the vertical velocity profile. At low velocities, the velocity profile of the solid state is usually asymmetric about the longitudinal axis due to settling particles due to differences in densities. This asymmetry is reduced with increasing velocities, but most of the particles stay in the pipe's lower half.

3.2 Solid concentration distribution

The findings anticipated by mathematical modelling of solid volume fraction contours at 60% and 65% by weight concentration of FA slurry at velocity 1m/s and 3 m/s for the horizontal pipe. The contact of particles with the wall increased as fluid flow increased from 1 m/s to 3 m/s. The Findings are displayed for the vertical plane at the pipeline's output portion in Figure 5 and 6. Due to gravitational forces, the greater FA concentration area is shown at the pipe bottom. According to the findings, fly ash particles have a nature to settle towards the pipeline bottom at low velocities.

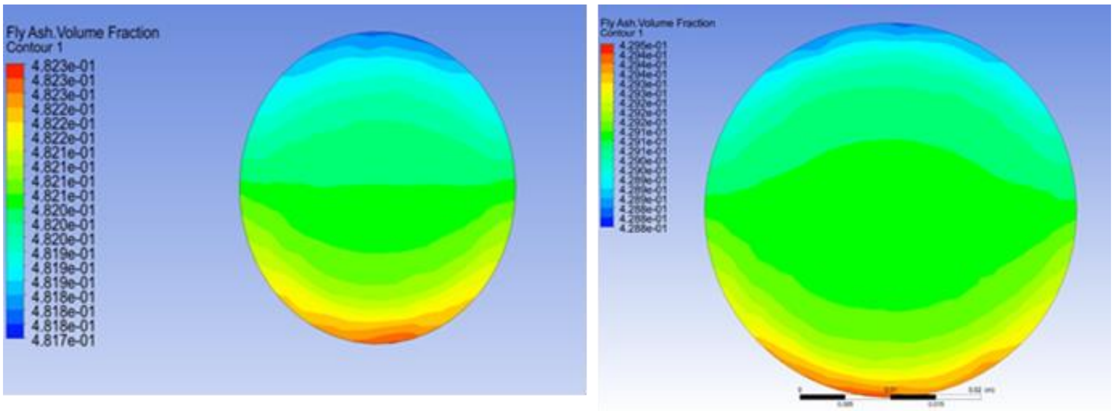


Fig. 5. Solid volume fraction contour of fly ash at 60% concentration at velocity 1m/s and 3m/s in horizontal pipe

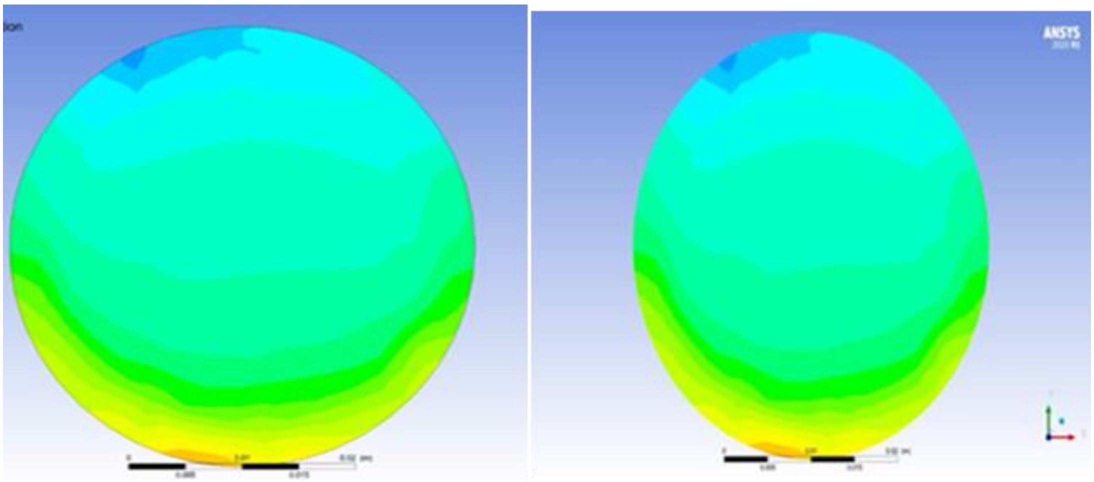


Fig. 6. Solid volume fraction contour of fly ash at 65% concentration at velocity 1m/s and 3m/s in horizontal pipe

4. Conclusions

The commercial CFD Programme could accurately model the fly ash-water slurry flow, and the predicted concentration profiles agree well with the experimental results. As the fluid velocity increases, pressure loss per unit length throughout the horizontal tube also increases. Pressure loss is considerably more significant at high concentrations than at low concentrations. For all solid concentrations investigated, the relative pressure loss over the pipe bend tends to increase with velocity and becomes stable at high velocity. Contour plots indicate that as time passes, more fly ash deposits on the lower pipe section and the impact of the bend are localized in a specific region after the bend. Due to the continuous deposition of fly ash, the maximum flow velocity is moved to the pipe's upper cross-section. The slurry begins to settle as the velocity decreases; gravity causes the higher concentration region to move toward the bottom of the pipe and a decline in turbulent energy that hold the particles in the slurry. Long-distance slurry pipelines are utilized for the conveyance of concentrated slurries around the world today. The slurry's rheological properties are significant for determining essential aspects of hydraulic conveying, like pressure loss in industrial pipelines. Based on the rheological behaviour of fly ash slurry at different solid concentrations and flow velocities, the present study may assist in estimating pressure drop in pipelines. The current research may help develop slurry pneumatic conveying systems for thermal plants.

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