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CFD-BASED INVESTIGATION OF POWER PLANT FLY ASH HIGH CONCENTRATION SLURRY FLOW THROUGH HORIZONTAL PIPE CONTRACTION

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ABSTRACT

More than half of the world's electricity is produced by burning large amounts of coal in thermal power plants and at the same time producing huge quantities of coal ash. Hydraulic transportation of coal ash from coal fired thermal power plants to ash ponds, using high concentration slurry disposal systems (HCSD) is safe, reliable, economical and attractive method due to its low maintenance costs, round the year availability and being environmentally friendly. Present study reports simulated pressure drop for the flow of high concentration fly ash slurries (in the range of 50 - 70 % by weight) through sudden and conical pipe contractions at various flow velocities using available experimentally obtained rheological parameters. For calculations the finite volume method is applied, which is the most commonly used and gives very good results in the analysis of problems in fluid mechanics and heat transfer. The method in this paper is adapted for simulation of flow of viscoplastic materials whose behavior is described by viscoplastic (Bingham) model. The simulation results are compared with corresponding analytical solutions and experimental data and good agreement between the results is shown.

Keywords: viscoplastic flow, Bingham plastic, fly ash slurry, rheology

1. INTRODUCTION

Importance of non-Newtonian fluids is continuously increasing as these materials are often encountered in engineering applications. For transportation of coal ash from thermal power plants to the ash ponds slurry pipelines are commonly used. Chandel et al. in his experimental study report [1] the pressure drop and rheological characteristics of coal ash at concentrations above 50% by weight. Verma et al. [2] and Seshadri et al. [3] have studied extensively the rheological behavior of fly ash slurries at high concentrations and they found that above a concentration of 40% by weight slurries are non-Newtonian and the experimental data fits reasonably well with simple Bingham plastic model. This work presents the application of numerical method to solve the problem of high concentration fly ash slurry flow. Use of the method was carried out for calculation of the flow through pipe contraction with the contraction angles in the range of 3° to 180°.

2. MATHEMATICAL MODEL

The mass balance equation and momentum balance equation are obtained by applying the principles of conservation of mass and momentum to an arbitrary volume V bounded by the surface S:

$$\frac{d}{dt}\int_V \rho dV + \int_S \rho \mathbf{v} \cdot d\mathbf{s} = 0 \quad (1)$$

$$\frac{d}{dt}\int_V \rho \mathbf{v} dV + \int_S \rho \mathbf{v} \otimes \mathbf{v} \cdot d\mathbf{s} = \int_S \mathbf{T} \cdot d\mathbf{s} + \int_V \mathbf{f}_b dV \quad (2)$$

where t is the time, ρ is the density, $\mathbf{v}$ is the fluid velocity vector, $\mathbf{T}$ is the stress tensor, $\mathbf{f}_b$ is the body force. Constitutive relationship linking the stress tensor deviator $\mathbf{T}^d$ and the rate of deformation $\dot{\mathbf{D}}$ for Bingham fluid is:

$$\dot{\mathbf{D}} = \begin{cases} \dfrac{1}{2\left(\eta + \dfrac{\tau_0}{2\sqrt{II_D}}\right)}\mathbf{T}^d & \text{for } \dfrac{1}{2}\left(\mathbf{T}^d : \mathbf{T}^d\right) > \tau_0^2 \\ 0 & \text{for } \dfrac{1}{2}\left(\mathbf{T}^d : \mathbf{T}^d\right) > \tau_0^2 \end{cases} \tag{3}$$

where τ_0 is the yield stress, η is the plastic viscosity, $II_{\dot{\mathbf{D}}}$ is the second invariant of $\dot{\mathbf{D}}$.

3. SOLUTION TECHNIQUE

The finite volume method is used to solve system of non-linear equations (1) and (2) with constitutive relationship (3). In this section the finite volume discretization of the transport equations is briefly outlined; a more detailed description is available in Demirdžić and Muzaferija [4]. The solution domain is subdivided into a finite number of contiguous control volumes (CV). Numerical evaluation of integrals in equations (1) and (2) requires that coordinates of the cell and face centers, surface vector and cell volume be known. In order to achieve conservative discretization the convection and diffusion fluxes are unique associated with cell faces. The linear spatial variation of dependent variables is assumed in approximating cell-face values and cell-face gradients, and the mid-point rule for calculating integrals is used. An iterative segregated procedure with decoupling is applied. Equations for dependent variables u, v and p are linearized and temporarily decoupled by assuming that coefficient and source terms are known resulting in systems of linear algebraic equations for each dependent variable. These systems are then solved using conjugate gradient method with preconditioning. After every outer iteration effective viscosity μ_{eff} is calculated for new values of variables. Procedure is repeated until a converged solution is obtained. For Bingham plastic effective viscosity, defined as the ratio of shear stress to average shear rate at the boundary, is given by [6]:

$$\mu_{eff} = \eta\left[1 + \frac{\tau_0}{2\eta\sqrt{II_D}}\right] \tag{4}$$

Reynolds number for Bingham plastics based on effective viscosity is then defined as:

$$\mathrm{Re}_B = \frac{\rho v d}{\mu_{eff}} \tag{5}$$

4. APPLICATION OF THE METHOD

Pipe contractions are one of the most common elements encountered in engineering practice. This work considers contractions with some characteristic contraction angles (Fig. 1). The pipe diameters before and after contraction are 50 and 25 mm respectively. The influence of change in the contraction angle on the change in pressure drop with varying flow velocity for fly ash slurry concentrations in the range of 50 to 70% is shown in Figures 2 and 3. By increasing the contraction angle from 3° to 5° and further to 20°, the decrease in the pressure drop for the same average flow velocity occurs (Fig 2). This can be observed for all slurry concentrations in the range of 50 to 70%. The main reason for these characteristics of the local pressure drop through pipe contraction is that the pressure drop due to friction decreases when increasing the contraction angle from 3° to 5° and further to 20°. Small changes in the contraction angle and high viscosity cannot cause the appearance of vortices and therefore pressure drop caused by changing the contraction angle only slightly increases. With the increase of the contraction angle from 20° to 90° and further to 180 ° there is a significant increase in the pressure drop (Fig. 3). The reason for this is the increase in the contraction of pressure drop from change in contraction angle in the overall pressure drop and its value exceeds the contribution of pressure drop caused by friction. Similar results are obtained in the experimental work by Liu and Duan [7].

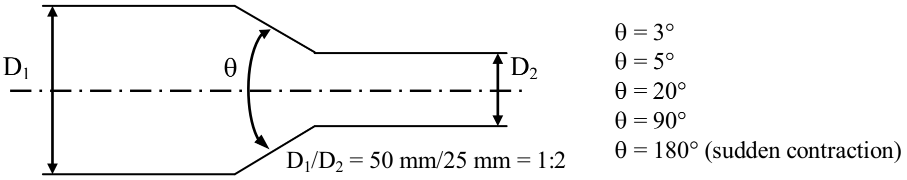

Figure 1. Graphical description of the pipe contraction

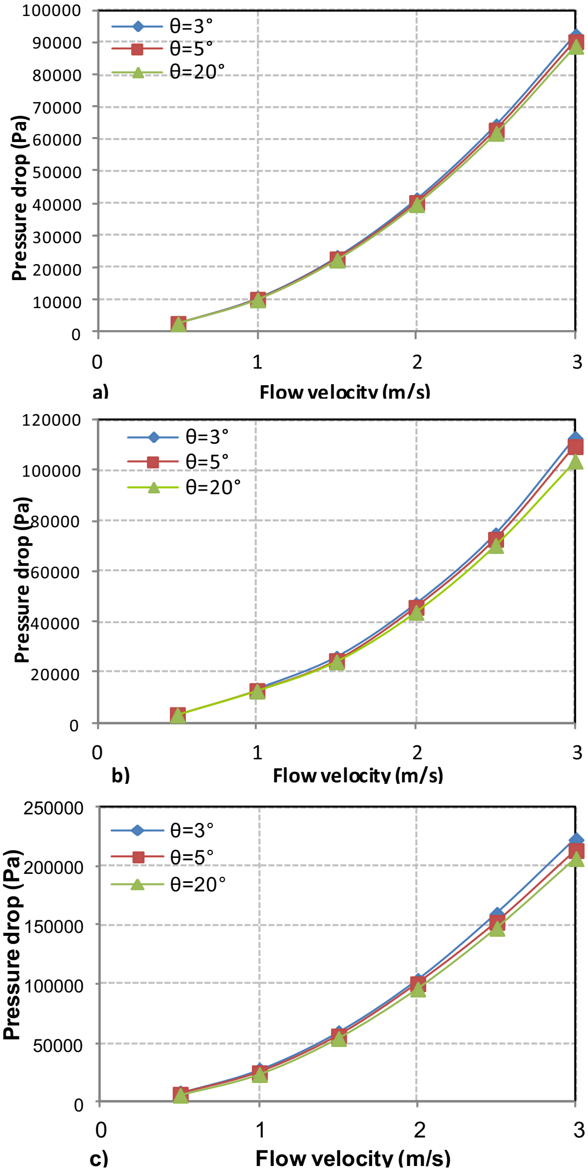

Figure 2. Variation of the pressure drop with the flow velocity for contraction angles of 3°, 5° and 20° and for slurry concentrations of: a) C_w= 50 %, b) C_w= 60 % and c) C_w= 70 %

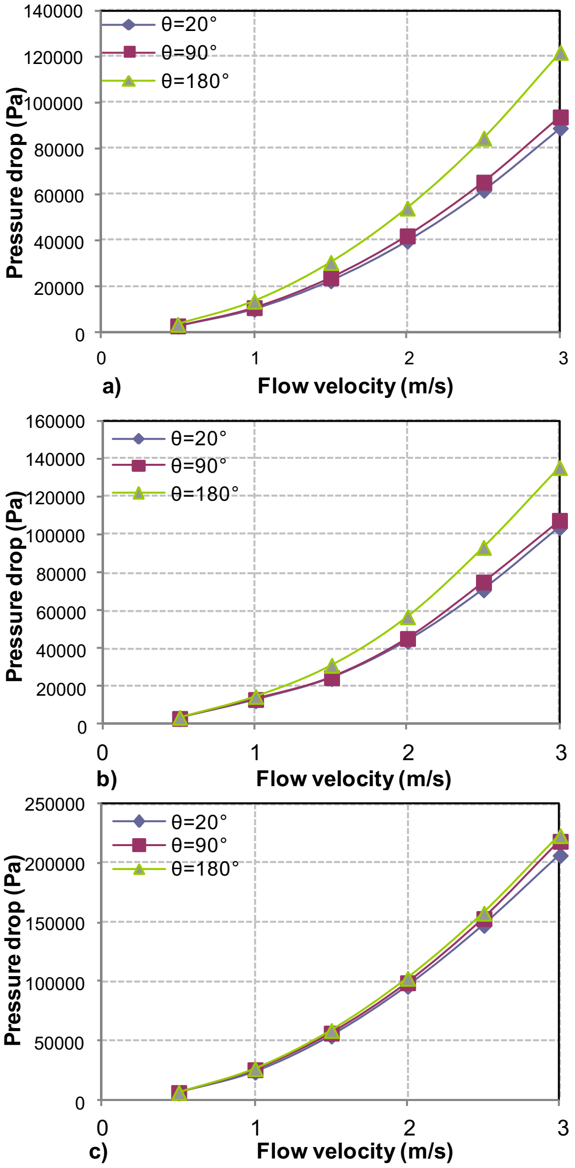

Figure 3. Variation of the pressure drop with the flow velocity for contraction angles of 20°, 90° and 180° and for slurry concentration of: a) C_w= 50 %, b) C_w= 60 % and c) C_w= 70 %

Rheological properties of fly ash and bottom ash slurries with the concentrations analyzed in this work (in the range of 50 to 70 % by weight) are taken from the experimental work by Chandel et al. [1] and are given in the Table 1. Figure 4 shows one of five meshes used in CFD calculations of slurry flow through pipe contraction.

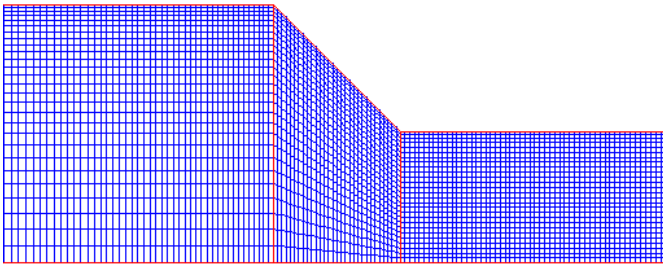

Figure 4. The mesh (θ = 90°) used in simulation of slurry flow through pipe contraction

Table 1. Rheological properties of the material

Slurry concentration C_w [%]	Yield stress τ_0 [Pa]	Slurry viscosity η_p [10^{-3} Pa·s]
50	0.043	3.2
60	0.254	11.3
65	1.1	44.9
70	1.45	201.0

5. CONCLUSIONS

Numerical procedure presented can be successfully applied to simulate flows of high concentration fly ash slurries. In this work the impact of the change in the contraction angle on the change in the pressure drop, depending on the fly ash slurry flow velocities for concentrations ranging from 50% to 70% is analyzed. By increasing the contraction angle from 3° to 5° and further to 20°, there is a reduction in the pressure drop for the same average flow velocity for all observed slurry concentrations. The main reason for the local pressure drop through pipe contraction is that the pressure drop on the basis of friction decreases when increasing the contraction angle from 3° to 5° and further to 20°. Small changes in contraction angle and high viscosity cannot cause the appearance of vortices and therefore pressure drop caused by changing the contraction angle only slightly increases. With further increase of the contraction angle from 20° to 90° and up to 180° there is a significant increase in pressure drop due to contribution from change in contraction angle to the overall pressure drop and its value exceeds the contribution of pressure drop caused by friction.

6. REFERENCES

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