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NUMERICAL SIMULATION OF POWER PLANT FLY ASH HIGH CONCENTRATION SLURRY FLOW THROUGH CIRCULAR PIPE

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ABSTRACT
High concentration slurry disposal systems are safe, reliable, economical and attractive method for transportation of coal ash from coal fired thermal power plants to ash ponds 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 horizontal circular pipe for two different inner diameters (42 mm and 53 mm) at various flow velocities using available experimentally obtained rheological parameters. Analyzed slurry was assumed to be viscoplastic and Bingham plastic model was applied for viscosity. The simulation results are compared with corresponding experimental data. Good agreement between the results is demonstrated and the method can be successfully used for the analysis of hydraulic transport of viscoplastic slurries with high concentration of solid particles.
Keywords: fly ash slurry, viscoplastic flow, rheology

1. INTRODUCTION
Slurry pipelines are commonly used for transportation of coal ash from thermal power plants to the ash ponds. 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. 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. Primarily, the effects of particulate matter concentration in the slurry on the pressure drop, as one of the most important parameters in the design of the hydraulic transport system is analyzed.

2. MATHEMATICAL MODEL
By applying the principles of conservation of mass and momentum to an arbitrary volume V bounded by the surface *S*, the mass balance equation and momentum balance equation are obtained:

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

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

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 [5]:

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

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

The flow of viscoplastic fluids through a circular pipe is frequently encountered in practice affording a geometry that is simple enough to formulate a numerical scheme in the cylindrical coordinate system. In this work, numerical simulation of power plant fly ash high concentration slurry flow trough a straight circular pipe for two different inner diameters of 42 mm and 53 mm for average flow velocities in the range of 0.5 m/s to 3 m/s is analyzed. The flow at the inlet (x = 0) is assumed to be fully developed, steady, incompressible flow of a Bingham fluid in a pipe and is given in its non-dimensional form. At the exit plane of the computational domain flow is assumed to be fully developed. Two-dimensional solution domain is sub-divided into CV's by a uniform numerical mesh. In Figure 1 the numerical mesh of circular pipe under consideration is shown. Rheological properties for the mixture of fly ash and bottom ash slurries with concentrations in the range of 50% to 70% by weight that are modeled are obtained from the work by Chandel et al. [1] and are given in Table 1.

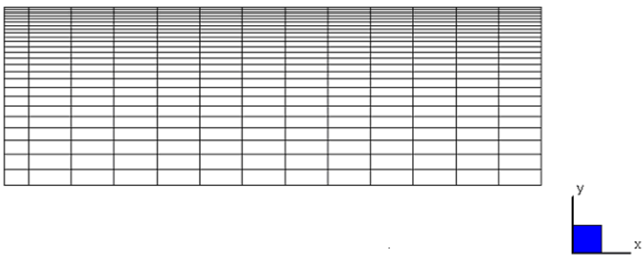

Figure 1. Numerical mesh of the circular pipe

Table 1. Rheological properties of fly ash and bottom ash slurry (4:1)

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
68	1.28	136.5
70	1.45	201.0

Pressure drop through the pipe (two diameters of 42 mm and 53 mm) is first simulated for the flow of water, and then for the fly ash slurry at different concentrations (50% to 70% by weight) for velocities in the range of 1 to 3 m/s (Figure 2, a - b). It can be seen that for all slurry concentrations pressure drop increases with the increase of flow velocity. For the entire velocity range and for all slurry concentration the pressure drop is greater than the pressure drop for the flow of water. For all concentrations, increase in pressure drop is greater at higher velocities. It may be noticed that the increase in pressure drop for a given velocity is more emphasized for higher slurry concentrations. This could be explained with increase in density and viscosity of the slurry with increasing the concentration.

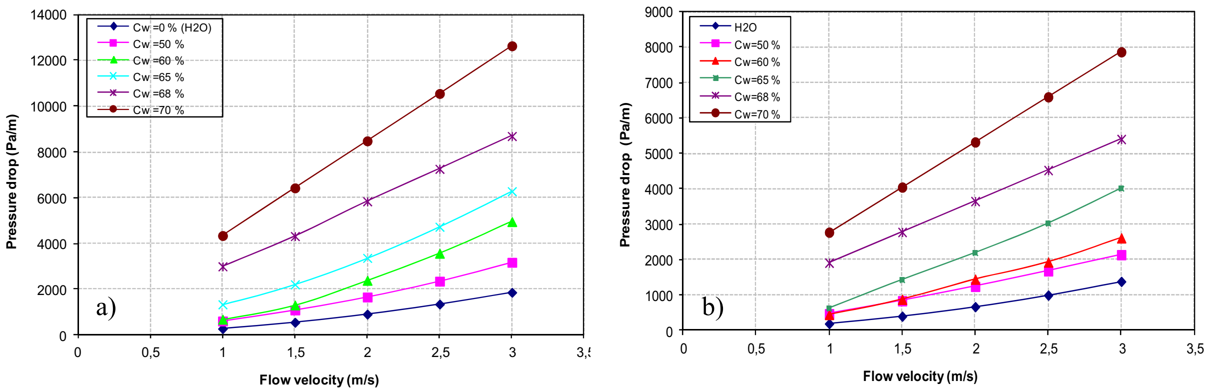

Figure 2. Pressure drop variation for mixture of fly ash and bottom ash (4:1) slurry with flow velocity at different concentrations (by weight) in: a) 42 mm and b) 53 mm, diameter pipeline

It is known that the pressure drop for slurry flows is always higher than for the flow of water. The additional pressure drop is generally presented as relative pressure drop $P_{R,P}$ which is additional energy needed for transport of slurry in comparison to the water and is calculated as the ratio of the pressure drop for the flow of slurry ΔP_{slurry} and water ΔP_{water} for certain speed per unit length:

$$P_{R,P} = \frac{\Delta P_{slurry}}{\Delta P_{water}} \tag{6}$$

In Figure 3 variation of the relative pressure drop in straight pipe of 42 mm diameter with flow velocity for different concentrations of mixture of fly ash and bottom ash (4:1) slurries. It could be seen that with the increase in slurry concentration relative pressure drop is increasing. Relative pressure drop for higher concentrations is quite emphasized at low velocities, and then with the increase of the velocity declines rapidly, which means that the influence of viscous effects with increasing velocity (increasing Reynolds number) decreases, whereas the influence of turbulent effects increases.

Comparison of the results obtained by numerical simulation and experimental results given in the work by Chandel et al. [1] for the high concentration slurry flow (50% to 70%) through the pipe of 42 mm diameter is presented in Figure 4. Good agreement between experimental and numerical results.

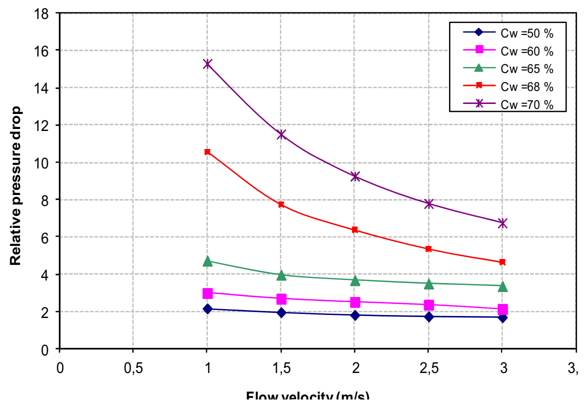

Figure 3. Variation of relative pressure drop in straight pipe of 42 mm diameter with flow velocity for mixture of fly ash and bottom ash (4:1) slurry

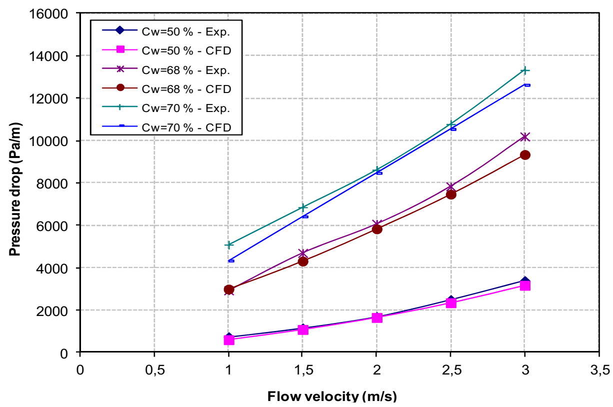

Figure 4. Comparison of numerical and experimental results of pressure drop in straight pipe of 42 mm diameter with flow velocity for mixture of fly ash and bottom ash

5. CONCLUSIONS

Finite volume method is successfully adopted for the solution of highly non-Newtonian flows. Numerically obtained results are comparable with available experimental data. It can be seen that for all slurry concentrations pressure drop increases with the increase of flow velocity. For all slurry concentrations, increase in pressure drop is greater at higher velocities. It may be noticed that the increase in pressure drop for a given velocity is more emphasized for higher slurry concentrations. This could be explained with increase in density and viscosity of the slurry with increasing the concentration. Relative pressure drop for higher concentrations is quite emphasized at low velocities, and then with the increase of the velocity declines rapidly, which means that the influence of viscous effects with increasing velocity decreases, whereas the influence of turbulent effects increases.

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