Effect of Particle Size on fluid flow and heat transfer in a Pipe with slurry flow

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Abstract. A three-dimensional numerical simulation is carried out in a straight horizontal pipe to predict the impact of particle size on fluid flow and heat transfer of ash water slurry. Steady turbulent equations are solved by using commercial code Fluent. Eulerian Method is incorporated considering ash as granular material. Fly-ash particle diameter is varied with 12, 20, 28 and 34 µm suspended in water for a flow velocity 4m/s and solid concentration of 40%. The temperature of pipe wall is kept at 400K and the granular temp i.e. slurry temp is taken as 300K. Present study finds asymmetric velocity distribution at higher particle size. Pumping power increases with particle size. Granular pressure and heat transfer increases with particle size. Granular pressure is maximum at bottom of the wall.

Keywords: Slurry flow, Eulerian method, Granular pressure, Heat transfer.

Nomenclature

Roman Symbols

| Symbol | Description                  |
|--------|------------------------------|
| C_d    | Drag Co-efficient            |
| C_p    | Specific heat, J/KgK         |
| C_vf   | Solid Volume concentration % |
| D      | Pipe diameter in m           |
| d_p    | Particle diameter            |
| F_lift | Lift Force, N                |
| F_vm   | Virtual mass force, N        |
| f_r    | Roughness Function           |
| F_r    | Froude number                |
| g      | Acceleration due to gravity  |
| g_r    | Radial distribution function |
| h      | Heat exchange coefficient W/mK |

Greek Symbols

| Symbol | Description                      |
|--------|----------------------------------|
| α      | Volume fraction                  |
| β_t    | Thermal expansion Coefficient, K⁻¹ |
| Φ      | Dimensionless temperature        |
| ε      | Dissipation rate for turbulent kinetic energy, m²/s³ |
| φ      | Friction angle                   |
| k      | Thermal conductivity, W/mK       |
| λ_s    | Bulk viscosity of solid Kg/m-s   |

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1 Introduction

Slurry is a mixture of solid and liquid. There are many industries that produce slurry. Maximum flyash is produced in coal based thermal power plant. This ash is transported by mixing with water and making slurry through pipe. This transportation is reliable and safe because it has low maintenance cost rather than bulk material handling. Apart from thermal power plant, slurries transportation through pipe line is common in different industries like oil and gas, food, pharmaceutical, transportation of metal concentrate and tannings, chemicals processing, deep sea mining, mineral processing and others. The presence of ash particles in water changes its viscosity, temperature, turbulence depending on the particle size and concentration. This is essential for designing of slurry pump, heat exchanger, fluidized beds and others.

Numerical and experimental work has been carried out to study the fluid flow and heat transfer phenomenon through pipe with ash slurry flow by various researchers. Among of them, Ku et al. [1] have done experimental investigation in an 8 mm diameter pipe, mass median ranges from 4 to 78 micron with flow velocity 1m/s to study the effect of solid concentration. From the experimental investigation [2, 3, 4, 6], Horiuchi et al. [2] have shown the increase in strength of slurry with density by comparing different samples. In the study of Harada et al. [3], heat transfer coefficient is observed to be high compared to water in case of flow with glass bead particles larger than 0.35 mm diameter. Vlasak et al. [4] have observed asymmetrical velocity distribution in the upper wall of pipe for course grained with water mixture. Numerical study is carried out by various researchers [5-11], the study of Wilson et al. [5] is done to check the energy efficient transport at higher concentration. Numerical and experimental study by Kaushal et al. [6] is conducted to observe the effect of velocity concentration for sand water slurry. In the study of Ozbelge et al. [7], they have revealed that the velocity increases with solid concentrations. In a U tube pipe of Cvetkovski et al. [8], heat transfer is noticed in bend portions. The effect of particle size on flow behaviour is studied by Gopaliya et al. [9]. Kumar et al. [10] have shown that asymmetry decreases with increase in flow velocity. Pipe with 90\(^0\) elbow pipe is taken by Yang et al. [11] to compare the pressure loss with horizontal pipe.

It is evident from the brief literature review that the works of particle size for describing the heat transfer and fluid flow analyzing in case of slurry flow is less. In this study, effect of particle size on velocity, pressure drop, granular pressure, temperature and molecular viscosity is focused for ash water slurry flow through a horizontal pipe. Particle sizes are considered as 12\(\mu\)m, 20\(\mu\)m, 28\(\mu\)m and 34\(\mu\)m. Mean slurry velocity and solid volume fraction is 4 m/s and 40 % respectively.
2. Mathematical Formulation
2.1 Problem Description
The geometry of physical problem carried in this study is horizontal pipe. The length (L) of the pipe is taken 1.5m and diameter of the pipe is $D=0.008\text{m}$ [1]. The length is taken above 50D to confirm fully developed flow. Water is taken as a primary fluid and fly-ash as a secondary phase material. The temperature of pipe wall is kept at isothermal condition of 400K and the granular temp i.e. slurry temp is taken as 300K. The inlet velocity is kept constant equal to 4m/s. Volume fraction has been kept constant of 40% and the diameter of the particle of the fly-ash is varied as 12, 20, 28 and 34 $\mu\text{m}$. Properties of ash and water are given in Table 1.

Table 1. Physical Properties of fly-ash and water

| Items                                | Test Particle | Test Liquid |
|--------------------------------------|---------------|-------------|
| Material                             | Fly-ash       | Water       |
| Diameter of Granular Particle ($\mu\text{m}$) | 12,20,28,34   |             |
| Density (Kg/m³)                      | 2270          | 997         |
| Specific Heat (J/KgK)                | 745           | 4,179       |
| Thermal Conductivity (W/mK)          | 1.38          | 0.613       |
| Viscosity (Ns/m²)                    | ----          | 855 $\times 10^{-6}$ |

The mesh is formed by using commercial software Fluent, shown in Fig. 1.

![Fig.1 Mesh of computational domain](image)

The details of mesh are given below, in Table 2. Body meshing is adopted with element size $1\times10^{-4}$ m.

Table 2. Mesh details

| Type of mesh | Hexahedral |
|--------------|------------|
| Transition Ratio | 0.27 |
| Maximum Layer(wall) | 5 |
| Growth Rate( Inflation) | 1.2 |
| Nodes | 1386164 |
| No of Elements | 1318350 |
| Min Aspect Ratio | 1.19 |
| Max Aspect Ratio | 4.9 |
| Skewness Factor | 2.33$\times10^{-2}$ |

2.2 Modelling and governing equations
The Eulerian model, the different phase’s present in the system is treated mathematically as interpenetrating continua. Individually each phase satisfied the laws of momentum, energy and conservation of mass. Each phase contained their own physical properties, velocity, and temperature. In this model volume fraction are considered as a continuous function of space and time and their sum is equal to one. Volume fraction is nothing but the amount of volume is taken by each phase in a given
Control volume. In this model the solid phase property like granular viscosity, bulk viscosity, shear etc are solved by kinetic theory. Momentum equation also solved differently for solid and liquid respectively.

In this present study we have made some consideration. The mixture is homogeneous and the flow occurs at no slip condition. The governing equations [12.13] are as

**Continuity Equation**

For solid phase
\[
\frac{\partial}{\partial t}(\alpha_s \rho_s) + \nabla (\alpha_s \rho_s \vec{v}_s) = 0
\]

For solid phase
\[
\frac{\partial}{\partial t}(\alpha_f \rho_f) + \nabla (\alpha_f \rho_f \vec{v}_f) = 0
\]

**Momentum Equations**

For Solid Phase
\[
\nabla (\alpha_s \rho_s \vec{v}_s) = -\alpha_s \nabla p - \nabla \vec{r}_s + \alpha_s \rho_s g + \alpha_s \rho_s \left( \vec{F}_{lift,s} + \vec{F}_{vm,s} \right) + \kappa_f (\vec{v}_f - \vec{v}_s)
\]

For Liquid Phase
\[
\nabla (\alpha_f \rho_f \vec{v}_f) = -\alpha_f \nabla P + \nabla \vec{r}_f + \alpha_f \rho_f g + \alpha_f \rho_f \left( \vec{F}_{lift,f} + \vec{F}_{vm,f} \right)
\]

**Turbulence Model**

Turbulence model is much difficult in multiphase model than the single-phase flow. The number of terms used in momentum equation of multiphase model, make the large and complex. Here RNG \( \kappa - \varepsilon \) model is used to solve the flow of slurry. Fluent provides many types of turbulent model like, mixture turbulence model, dispersed turbulence model and turbulence model for each phase. Mixture model is used when phases separate, for stratified multiphase flows. Dispersed model is used in case of dilute concentration of the second phase. Primary phase influences secondary phase for getting random motion. So dispersed model is the better choice for this study.

**Governing Equation**

For kinetic energy
\[
\nabla (\rho_m \vec{v}_m) = \nabla (\alpha_k \mu_m \nabla \vec{v}_k) + \mu_m S^2 + \beta_k \Gamma_k \frac{\mu_m \phi}{\phi} \frac{\partial T_m}{\partial \phi} - \rho_m \varepsilon
\]

For dissipation rate
\[
\frac{\partial}{\partial \phi} (\rho_m \vec{v}_m \varepsilon) = \nabla (\alpha_k \mu_m \nabla \varepsilon) + C_{1e} \frac{\varepsilon}{k} \mu_m S^2 + C_{2e} \rho_m \frac{\varepsilon^2}{k} - \Phi
\]

**Energy equation on the basis of heat transfer**

Eulerian model require an extra equation to solve enthalpy, so it has written in the followings for each phase.

For Solid Phase
\[
\nabla (\alpha_s \rho_s \vec{v}_s \bar{T}_s) = \nabla \vec{v}_s \cdot \nabla \bar{T}_s - \nabla \bar{q}_s + Q_{sf}
\]

For fluid phase
\[
\nabla (\alpha_f \rho_f \vec{v}_f \bar{T}_f) = \nabla \vec{v}_f \cdot \nabla \bar{T}_f - \nabla \bar{q}_f + Q_{fs}
\]
2.3 Method of solution

Present numerical study is carried out by commercial code Fluent [13]. The partial differential equations are solved control volume technique, finite volume method. Details of solution method are given in Table.3.

Table.3 Details of solution method

| Solver                 | Pressure based, Algebraic Multigrid (AMG) solver |
|------------------------|--------------------------------------------------|
| Multiphase model       | Eulerian                                         |
| Volume fractions       | Implicit                                         |
| Turbulence model       | k-epsilon method                                 |
| k-epsilon method       | RNG                                              |
| Turbulence multiphase model | Dispersed                                     |
| Iterative algorithm    | PCSIMPLE                                         |
| Discretization of momentum equations | Second order upwind scheme                  |
| Discretization of kinetic energy, dissipation rate and volume fraction | First order upwind                           |
| Convergence criterion  | \(10^{-4}\)                                      |
| Under relaxation factors | 0.5–0.7(momentum)  |
|                         | 0.2–0.3(pressure)                                |
|                         | 0.6–0.8(turbulent kinetic energy)                |

3. Results and Discussion

This present study describes the effect of particle size on velocity, pressure drop, granular pressure, temperature and molecular viscosity for ash water slurry flow through a horizontal pipe. Particle sizes are considered as 12µm, 20µm, 28µm and 34µm. Mean slurry velocity and solid volume fraction is 4 m/s and 40 % respectively.

3.1 Distribution velocity contour, pressure drop and molecular viscosity

Figure 2 presents the velocity contour along axial direction of pipe. It is observed that velocity magnitude at middle section of pipe is more and magnitude increases with the increase in particle size. The velocity distribution of slurry flow in pipe is also important and it is noted that the velocity distribution is symmetrical in nature at 12µm and 20µm, whereas it becomes asymmetrical for the cases of 28µm and 34µm. In comparison with the velocity contour of 28µm and 34µm, contour of higher particle size shows more asymmetric in nature. The reason may be due to intensified turbulence at high particle size.

The calculation of pressure drop through slurry pipe is important for determining power required for the pump. The pressure drop in case of slurry flow is the summation of pressure drops of only water and pressure drop due to presence of solid particles. The pumping power of slurry pump is determined by multiplication of pressure drop and mass flow rate. Figure 3 shows the pressure drop in the slurry pipe with the variation of particle size. Pressure drop is observed to increase with increase in particle diameter. The possible reason may be the increase in velocity of slurry and increase in effective viscosity due to increase in particle size. At higher mean diameter of particle size, the rate of increase in pressure drop is high compared to rate of increase in pressure drop for lower size particle as noted in the Fig. 3. As the power required by pump is proportional to the pressure drop, therefore, corresponding power required for pump is more for the larger particle size.

Apart from pressure drop, molecular viscosity plays an important role for determination of pump power. The variation of molecular viscosity with particle size is shown in Fig. 4. It is revealed that the
viscosity of slurry increases with particle size. This may be attributed that increased surface area with particle size enhances solid concentration and thereby it increases the viscosity.

Fig. 2 Distribution of velocity in m/s at 4m/s inlet velocity for 40% volume fraction at different particle sizes

Fig. 3 Effect of particle size on pressure drop at 4m/s inlet velocity for 40% volume fraction
3.2 Variation of granular pressure

Since the ash is considered as granular material, the study of granular pressure may be important for discussing the erosion effect on the wall of pipe. The distribution of granular pressure for our considered particle size along the axial directions of pipe is shown in Fig.5. The granular pressure is the pressure exerted on the wall due to collision of particle. From the contour of granular pressure, it may be said that maximum granular pressure occurs towards the periphery at the bottom for all cases of particle diameter. This may be due to the fact that particles move with reduced velocity near the wall of pipe and higher gravitational effect of granular particles at bottom. The pressure is obviously becomes minimum at the core section of the pipe because of high velocity of slurry at the core. The granular pressure is revealed to be more at higher particle size as depicted in Fig.6. This figure also shows that the rate of increase of granular pressure is larger at higher particle size compared to the lower particle size.

Fig. 4  Effect of particle size on molecular viscosity at 4m/s inlet velocity for 40% volume fraction

Fig.5  Distribution of granular pressure in Pa at 4m/s inlet velocity for 40% volume fraction at different particle sizes
3.3 Variation of temperature and surface heat transfer coefficient

The temperature distribution of slurry flow at the cross section of pipe for the slurry velocity of 4 m/s and 40% volume concentrations is shown in the Fig. 7. Since the wall temperature and the fluid temperature are considered as 400 K and 300 K, therefore, heat exchange should take place from the wall to slurry due to temperature difference. It is obvious to observe maximum temperature at the vicinity to the wall. It can also be said that heat transfer should take place into the slurry mainly because of convective heat transfer. The slurry temperature difference decreases as it moves radially inward towards centre of pipe. Since the slurry velocity is more at the central zone that causes less time for heat interaction, thereby the temperature of the slurry becomes less at the central zone of pipe. The temperature distribution becomes asymmetric with the increases of particle size as observed during velocity distribution. The possible volume concentration towards downward with particle size may support this type of temperature distribution.

Surface heat transfer coefficient depends upon many factors like temperature of wall, mean slurry velocity, distribution of concentrations in the slurry pipe. The variation of surface heat transfer coefficient with particle size is shown in the Fig. 8. From the figure, it is observed that the heat transfer coefficient increases with the increase in particle size. High heat transfer coefficient results high convective heat transfer towards the central zone of pipe, depicted in the temperature contour with particle size. The asymmetric shape of temperature profile due to asymmetric shape nature of velocity, clearly noted in the temperature contour.
Fig. 7 Distribution of temperature in K at 4m/s inlet velocity for 40% volume fraction at different particle sizes

Fig. 8 Effect of particle size on surface heat transfer coefficient at 4m/s inlet velocity for 40% volume fraction

4. Conclusions
From the fluid flow and heat transfer study through a horizontal slurry pipe, the following observations are noted.
(i) Increase in particle size results in asymmetric velocity distribution.
(ii) Pressure drop through slurry pipe increases with particle size. The increment is higher at larger particle size.
(iii) Molecular viscosity increases with particle size.
(iv) More pumping power is required for higher particle size.
(v) Granular pressure is more near wall. It is maximum at bottom.
(vi) Granular pressure increases with particle size.
(vii) Heat transfer from wall increases with particle size.
(viii) Temperature distribution at core becomes asymmetric with particle size.

5. References
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