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Determination of Pressure Drop Characteristics of Fly Ash Suspension with Additive for Hydraulic Transportation

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Abstract

Present study was conducted with objective of investigating the fly ash slurry transportation at higher solid concentration. The rheological behaviour of fine-particulate fly ash slurry suspension was studied with the additive. Pressure drop was measured in 50 mm diameter pipe with fly ash slurry at solid concentration (Cw) of 30, 40, 50 and 60% (by weight). Measurements were made for flow velocities in the range of 1 to 3 ms^{-1}. Sodium sulfate was used as an additive in range of 0.2-0.6% (by weight). Addition of sodium sulfate in fly ash slurry suspension tends to improve the pressure drop characteristics. Reduction rate in pressure drop was pronounced more with 0.4% sodium sulfate in fly ash slurry and marginal with 0.2 and 0.6%. Therefore, results revealed that fly ash-water slurry can be transported at high concentration thorough pipelines with lower power consumption.

Keywords: Fly ash; Rheology; Relative viscosity; Pressure drop; Energy consumption.

Nomenclature

A	area of cross section of pipe
C_v	volume percentage of solid
C_w	weight percentage of solid
D	pipe diameter
d_{wm}	weighted mean diameter
f	fanning friction factor
f_L	fanning friction factor, laminar flow
f_t	fanning friction factor, turbulent flow
g	acceleration due to gravity
He_d	Hedstrom number
Δh	head loss in meter of water column
∇H	head loss, meter of water per kilometer
P_B	power required for suspension flow
Q	flow rate
Re_b	reynolds number based on Bingham viscosity
Re_{bc}	Critical Reynolds number
Re_{mod}	Modified Reynolds number
SEC	Specific Energy Consumption
V	velocity flow
V_{av}	average flow velocity
W_B	solids flow rate of fly ash suspension
ρ_m	density of suspension
η_{wr}	viscosity of water
τ	shear stress
τ_{yb}	yield stress
μ_p	bingham plastic viscosity of fly ash slurry
μ_r	relative viscosity of ash
γ	shear stress

1. Introduction

Indian coal based thermal power plants produce about 135 million tons of fly ash annually (Singh *et al.*, 2016). Presently, fly ash is transported through pipelines at lower concentrations to the dyke area. During the transportation of fly ash, a large amount of water and pumping power is required (Chandel *et al.*, 2009; Naik *et al.*, 2011). So, an adequate design of slurry transportation system is required. Rheological behaviour of slurry suspension plays a vital role to design its transportation system. Many researchers have studied the rheological characteristics of coal ash slurry suspensions (Gandhi *et al.*, 2001; Verma *et al.*, 2006; Mosa *et al.*, 2008; Seshadri *et al.*, 2008; Naik *et al.*, 2009; Kumar *et al.*, 2013; Kumar *et al.*, 2014).

Researchers (Verma *et al*., 2006; Mosa *et al*., 2008; Sarnecki and Bartosik, 2014) have also studied that additives improve the rheological behavior of the coal ash slurry. However limited database is available in literature to predict the rheological behaviour of fly ash suspension with additives. In present study, the rheological and pressure drop characteristics of fly ash slurry was studied with additive. Sodium sulfate was used as an additive in the range of 0.2-0.6%.

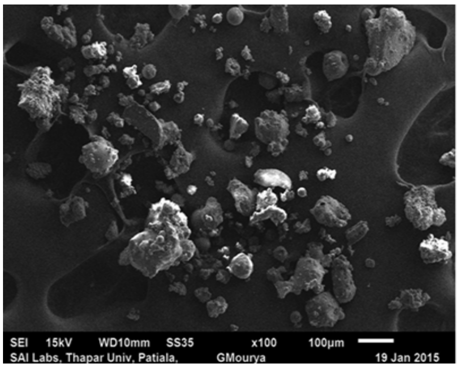

Fig. 1. SEM of fly ash sample.

2. Characterization of Fly Ash

Fly ash sample was collected from Electrostatic Precipitator (ESP) hopper of Rajiv Gandhi thermal power plant Hisar (India). Physical and chemical properties of ash sample were analyzed at laboratory scale apparatus/equipments. Particle size distribution range of fly ash was determined by Mechanical sieve shaker. It was found that about 37.20% particles were coarser than 75 µm and only 17.35% particles were finer than 53µm. Surface morphology of fly ash particles was analyzed by scanning electron microscopy-energy dispersive X-ray spectroscope (JEOL, 6510LV model). SEM micrograph of fly ash is shown in Fig. 1. It was observed that fly ash particles were spherical in shape and having the smooth surfaces. Specific gravity of fly ash sample was measured as 2.10 by using pycnometer method. Static settled concentration of fly ash-water suspension was measured by gravitational method at solid concentration of 30%.

During settling process of slurry suspension at fixed interval of time, the slurry level was recorded. The static settled concentration of fly ash-water slurry suspension was observed as 59.68% (by weight). A Digital electrode pH meter was used for measuring pH of slurry suspension. The pH values of different concentrations (10-60%) of fly ash lie in range of 6.55-6.10. Such pH values indicate the non-reactive nature of slurry suspension.

3. Rheological Experimentation

Rheological experiments were conducted with ISO: certified rheometer (Manufactured by: Rheolab Q-C, APC Ltd. Germany). This is a Searle type rheometer. Initially, the rheometer was calibrated by using tap water for ensuring the reliability of equipment. For rheological tests, a 100 ml fly ash slurry sample was prepared by proper mixing of water and ash with the help of glass rod. The suspension was poured out in the cup of rheometer at level of specified mark after weighing on electronic type pan balance with least count of ±0.001 mg. Experiments were repeated to ensure the precision of measured data and their average value was considered. The rheological properties like shear stress and viscosity were measured at a fixed shear rate for all slurry samples. Rheological tests were conducted at shear rate value varying in range of 50-200 s^{-1} for solid concentration of 30-60% with additive. Sodium sulfate was used as an additive with proportion 0.2, 0.4, 0.6 in all solid concentrations of fly ash slurries.

4. Experimental Procedure for Pressure Drop

The pressure drop experiments for fly ash-water slurry were conducted on pilot plant test loop (50 mm NB and 50m length). Figure 2 represents the schematic diagram of the pilot-plant pressure drop test loop. The test loop consists of the slurry preparation tank, measuring tank, electric motor, measuring devices (namely pressure transducer and flow meter), valves pump and pipelines. The test loop also consists of a closed circuit of pipeline which was of approximately 60 meters in length. A hopper shaped slurry preparation tank was used for preparation of solid–liquid mixture. A magnetic stirrer was provided at top of slurry tank which prevents the settling of slurry inside slurry tank. A high performance pump was used to draw the slurry from hopper shaped tank to the pipelines so that necessary measurements can be taken. The flow meters (i.e. electromagnetic type) and pressure transducers were installed at slurry pipeline for measurement of flow, suction pressure and delivery pressure. The pressure transducers were installed at various locations of pipelines so to measure the pressure drop for flow of solid-liquid slurry. At the initial run, the water was flowed through pipeline and its pressure drop was measured. Subsequently, the slurry was prepared by addition of fly ash into water and pressure drop was measured again at various locations of the pipeline. The pressure drop experiments were conducted for the flow of fly ash slurry at four solid concentrations (C_w) namely 30, 40, 50 and 60% respectively. Measurements were made for flow velocities in the range of 1-3 ms^{-1}. The pressure drop measured from pilot-plant test loop was presented as a function of flow velocity in terms of mWc/km (meter of water column per kilometer) of pipeline.

4.1 Mathematical Method for Prediction of Pressure Drop

The Friction factor is one of the most important parameter for prediction of pressure drop inside pipeline. The Fanning friction factor value for laminar flow can be obtained analytically. However, the value of Fanning friction factor for transition and turbulent flow is depends on empirical formula. In present study, the fanning friction factor and pressure drop was predicted for flow of high concentrated slurry through straight pipeline. Darby and Melson (1981) empirical

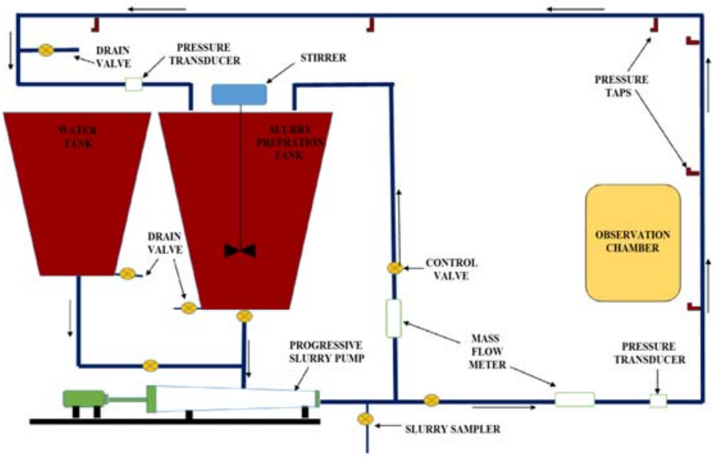

Fig. 2. Schematic diagram of existing pilot plant test loop

approach was used to predict the pressure drop in slurry pipeline. For friction factor, relation between Hedstorm (He_d) and Bingham Reynolds number (Re_b) was given by (Darby and Melson, 1981).

$$\frac{f}{16} - \frac{He_d}{6\,Re_b^2} + \frac{He_d^4}{3f^3\,Re_b^8} = \frac{1}{Re_b} \quad (1)$$

Where

$$He_d = D^2 \tau_{yb} \frac{\rho_s}{\mu_s^2}$$

$$Re_b = DV \frac{\rho_s}{\mu_s}$$

The friction factor can be written in terms of modified Reynolds number as shown below.

$$f = \frac{16}{Re_{mod}}$$

$$Re_{mod} = \frac{6Re_b^2}{6Re_b + He_d} \quad (2)$$

And critical value of Reynolds number is (Re_{bc}) is given by:

$$Re_{bc} = \frac{He_d}{8X_{cs}}\left(1 - \frac{4}{3}X_{CS} + \frac{1}{3}X_{CS}^4\right) \quad (3)$$

The value of X_{cs} can be calculated as

$$\frac{X_{CS}}{(1 - X_{cs})^3} = \frac{He_d}{16800}$$

$$f_t = 10^C (Re_b)^{-0.193} \quad (4)$$

$$C = -1.378(1 + 0.146\exp(-2.9 \times 10^{-5} \times He_d))$$

$$f = \left(f_1^{\,m} + f_t^{\,m}\right)^{\frac{1}{m}} \quad (5)$$

Where, $m = 1.7 + \dfrac{4000}{Re_b}$

5. Results and Discussion

The rheological behavior of fly ash slurry was determined by plotting the shear stress versus shear rate curves. The apparent viscosity of fly ash-water slurry was calculated at a particular value of shear stress and shear rate. The rheological behaviour of fly ash suspension was investigated for solid concentration range of 30-60 %. Figure 3 shows the shear stress vs. shear rate curves for fly ash-water slurry at different solid concentrations. Results represent the non-Newtonian nature of slurry suspension and follows Bingham fluid behavior as written by equation mentioned below:

$$\tau = \tau_y + \eta \frac{du}{dy} \quad (6)$$

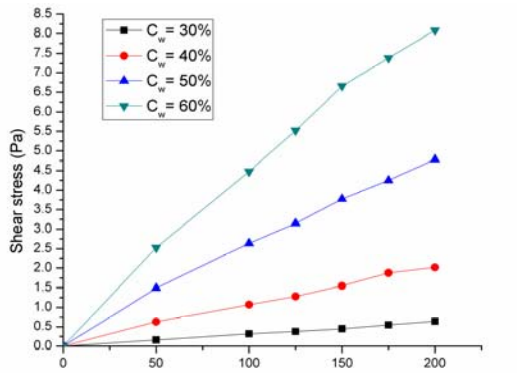

Fig. 3. Shear stress-shear rate of fly ash

Coefficient of rigidity was used in case of Bingham fluid for measuring the relative viscosity. Data follows straight line equation to find viscosity for each slurry suspension sample. The fly ash-water suspension exhibits Newtonian behaviour up to 30% solid suspension beyond this, slurry shows non-Newtonian flow characteristics. The value of shear stress at shear rate of 50 s^{-1} was observed as

0.15, 0.41, 0.86 and 1.4 Pa whereas at shear rate of 200s^{-1}, shear stress was found to be 0.68, 1.91, 3.78 and 6.09 Pa for solid concentration of 30, 40, 50 and 60% respectively. The value of shear stress was increased by 9.33 and 8.95 times as C_w was increased from 30-60% at shear rate of 50 and 200 s^{-1} respectively. Similar observations for different slurry suspensions were also reported by researchers (Lorenzi and Bevilacqa 2002; Yuchi *et al*., 2005; Kumar *et al*., 2014; Singh *et al*., 2016).

5.1 Influence of Additive on Relative Viscosity

Experimentation was carried out to investigate the influence of additive on relative viscosity of fly ash slurry-suspension at solid concentration (C_w) ranging from 30 to 60%. Sodium sulfate was used as an additive with fraction of 0.2, 0.4 and 0.6. Variation of relative viscosity for fly ash suspension with additives is shown in Fig. 4. Experimental results reveal that apparent viscosity of fly ash suspensions was dependent on solid concentration. It also seems that relative viscosity was increased monotonically with slight increase in solid concentration. In other words, relative viscosity of fly ash slurry suspension was increased more rapidly at higher solid concentration. At higher solid concentration, the increase in relative viscosity was observed due to increase in number solid particles per unit volume of slurry. Hence, for the flow of such slurry suspensions, initially high shear strain in required which results in high shear stress (Verma *et al*., 2006; Seshadri *et al*., 2008; Singh *et al*., 2016) with fly ash slurry. However, reduction in relative viscosity was observed by adding high proportion of additive in fly ash slurry at fixed value of shear rate. The addition of sodium sulfate changes molecular structure of fly ash suspension (He and Laskowski 2000). This also reduces the drag friction for the flow of solid particles in liquid phase. The addition of small quantity of additive tends to decrease the forces of interaction between particle-particle and the fluid-particle in slurry suspension. Relative viscosity of fly ash was reduced by 11.14, 17.31 and 12.30% at solid concentration 30% (by weight) whereas it decreases about 13.34, 24.71 and 16.36% at solid concentration of 60% (by weight) with blending of 0.2, 0.4 and 0.6% additive respectively. It was also observed that the reduction in relative viscosity is more pronounced with addition of 0.4% additive as compared to 0.2 and 0.6% dosage of additive.

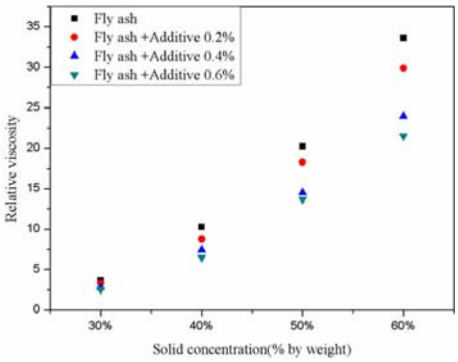

Fig. 4. Variation in relative viscosity of fly ash suspension with additive.

5.2 Effect of Solid Concentration and Flow Velocity on Pressure Drop Characteristics of Fly Ash

Pressure drop was measured in 50 mm diameter pipe with fly ash slurry at solid concentration (C_w) of 30, 40, 50 and 60%. At each solid concentration, the pressure drop was measured in meter of water column per km pipeline (mWc/km) within the specified range of velocities. Figure 5 represents the influence of solid concentration and flow velocity on pressure drop for the fly ash suspension. It was observed that pressure drop increases with the increase in solid concentration at a specified velocity. This is due to the fact that increase in solid concentration results in steep increase in density and viscosity of the slurry suspension. Similar type of phenomenon was observed by investigators (Verma *et al*. 2006; Seshadri *et al*. 2008; Chandel *et al*. 2009; Kumar *et al*. 2017).

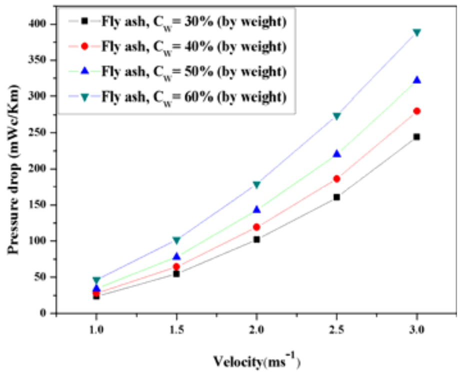

Fig. 5. Effect of solid concentration on pressure drop characteristics for fly ash suspension

It can be observed that pressure drop increases about 18.22 and 23.65% with increase in solid concentration (C_w) from 30-40 and 40-50% respectively at a flow velocity of 1.0 ms^{-1} whereas increases about 35.07% for 50-60%. The pressure drop at a particular solid concentration increases with the increase in flow velocity. Moreover, the pressure drop was found to be more pronounced at higher velocity but increase in rate of pressure drop was marginal at higher velocities. Reynolds number at 1 and 1.5 ms^{-1} velocity was calculated as 2759 and 4138. It may be attributed that flow is laminar mainly at lower velocities (1.0 to 1.5 ms^{-1}) and beyond this range, it showed turbulent flow characteristics. The turbulent motion is a dominating effect on pressure drop thus slurry velocity will also have dominant effect on pressure drop characteristics (Verma *et al*. 2006; Chandel *et al*. 2009; Nahhas *et al*., 2009). At C_w = 60%, the pressure drop was increased by 118.85, 76.40, 61.19 and 54.82% with increase in velocity within the range of 1.0-1.5, 1.5-2.0, 2.0-2.5 and 2.5-3.0 ms^{-1} respectively.

5.3 Pressure drop characteristics of coal ash with additives

A series of experiments were carried out in order to determine pressure drop for fly ash suspension with additive. Sodium sulfate was used as an additive with proportion of 0.2, 0.4 and 0.6%. The effect of additive was investigated by comparing pressure drop results for slurry suspensions with additive. Results revealed that addition of additive significantly changed the pressure drop phenomenon at higher concentrations. Experimental results of pressure drop for fly ash suspension with additive at solid concentrations (60%) are shown in Fig. 6. It was observed that the pressure drop increases with increase in flow velocity and solid concentration for fly ash slurry suspension. However, a remarkable reduction in pressure drop was observed with additive. In other words, the pressure drop reduces with addition of additive in slurry suspension. This may be attributed that additive reduces the inter-particulate frictions and surface tension among the particles of ash in slurry suspension which further lead to decrease in pressure drop (Kosswig 2002). Similar observations were also drawn by investigators (Chandel *et al*. 2009; Seshadri *et al*. 2008 and Kumar *et al*. 2017) for other additives. The reduction in pressure drop for fly ash slurries was observed as 9.14, 20.97 and 6.19% with increase in dosage of additive from 0-0.2, 0.2-0.4 and 0.4-0.6% respectively. So, at a given flow velocity, maximum reduction in pressure drop was observed by increasing the additive percentage in weightage of 0.2-0.4%. On the other hand, the reduction in pressure drop was less as blending of additive increased from 0.0-0.2 and 0.4-0.6% for fly ash slurry suspension. The optimum percentage of sodium sulfate for maximum reduction in pressure drop was found as 0.4%.

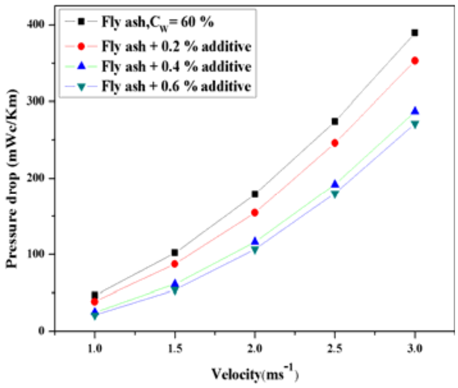

Fig. 6. Effect of additive on pressure drop characteristics of fly ash suspension.

5.4 Experimental and Predicted Pressure Drop

Pressure drop in a straight horizontal circular pipeline of diameter 50 mm have been calculated using the Darby and Melson (1981) model. To achieve better precision, actual experimental results of pressure drop have been compared with predicted values obtained from model. Thus, the variation of pressure drop for experimental and theoretical values was obtained by using 40 data points for the fly ash slurry suspension. Figure 7 shows the experimental and predicted pressure drop data with fly ash slurry at C_w = 60%. Predicted pressure drop values match with experimental values at 45º line. A reasonable agreement has been observed. The pressure drop was observed within the limits of +15% for fly ash slurry suspension.

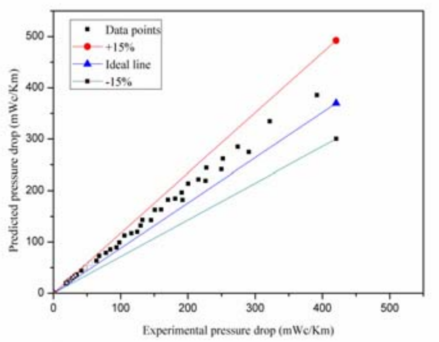

Fig. 7. Variations in experimental and predicted pressure drop.

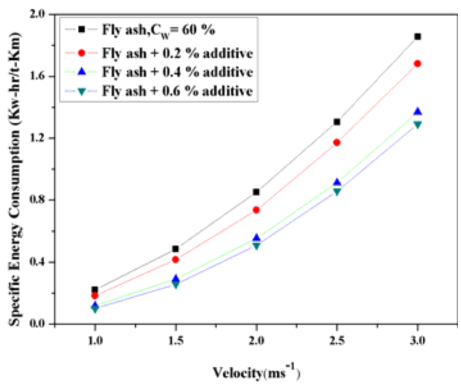

Fig. 8. Specific energy consumption for fly ash with additive.

5.5 Specific Energy Consumption of Fly Ash Slurry with Additive

Based on the results of the present study, specific energy consumption for transporting fly ash slurry suspension by using additive was evaluated. Specific Energy Consumption (SEC) of the suspension can be determined by using following relation:

$$P_B = \frac{Q \times \rho_m \times g \times \nabla H}{3.6 \times 10^6} \tag{7}$$

$$W_B = \frac{Q \times \rho_m \times C_w}{1000} \tag{8}$$

$$SEC = \frac{P_B}{W_B} \tag{9}$$

The experimental data of specific energy consumption for fly ash suspension (C_w = 60%) with additive at different velocities (1 to 3 ms^{-1}) is shown in Fig. 8. It was observed that SEC was very much affected with small dosage of the additive into ash suspension. SEC for fly ash suspension was decreased by 17.38, 35.03 and 15.23% with the addition of 0.2, 0.4 and 0.6% sodium sulfate at flow velocity of 1 ms^{-1} respectively. The results revealed that fly ash slurry with 0.4% sodium sulfate showed maximum reduction in SEC at all respective velocities. The decrease in power consumption leads to reduction in pump power about 35% for fly ash suspension. Thus, the high concentration suspension can be disposed through pipeline system with a lesser principal investment cost and it will be possible to transport the coal ash slurry suspension economically with addition of small dosage of additive (Hashemi *et al*., 2014).

6. Conclusions

Based on present study which deals with pressure characteristics for fly ash-water suspensions with additive, some observations have been made:

- The use of additive improves the rheological behavior of fly ash suspension. The slurry suspension shows Newtonian behaviour up to solid concentration of 30% and at higher concentration i.e. beyond 30% it exhibits non-Newtonian flow characteristics.
- Higher reduction in apparent viscosity of fly ash slurry suspension is noticeable with higher concentration of additive. However, reduction rate is more pronounced with additive in proportion of 0.4%.
- Power required to transport the fly ash slurry get reduced up to 35%. Thus, the high concentration suspension can be disposed through pipeline economically.
- Experimental and predicted pressure drop results showed reasonable agreement for fly ash slurry suspension. Pressure drop was found within the deviation limits of ±15% for fly ash slurry suspension.

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