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ORGINAL ARTICLE

Transportation of High Concentration Coal Ash Slurries through Pipelines

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ABSTRACT

Present study reports the pressure drop and rheological characteristics of mixture of fly ash (FA) and bottom ash (BA) slurry (4:1) at high concentrations (above C_w 50% by weight). Pressure drops have been measured at various flow velocities using a pilot plant test loop at various concentrations. Such measurements have been made for various concentrations in the range 50-70% by weight. Rheological studies are also carried out for mixture of fly ash (FA) and bottom ash (BA) slurry. The dependence of relative pressure drop on flow velocity at various concentrations has also been analyzed. Further, by using the rheological data, pressure drop has been predicted in a straight pipeline of 42 mm diameter at higher concentrations. Experimental results obtained from a pilot plant test loop were compared with the predicted results. The comparison showed a very good agreement between these data. Specific Energy Consumption for the transportation of coal ash slurry has been calculated at fixed velocities and its dependence in solid concentration has been quantitatively analyzed

Key Words: Coal Ash, Slurry, High concentration, Pressure drop

INTRODUCTION

Thermal power plants generate more than half of the world's electric power by burning millions of tonnes of coal and simultaneously produce large quantity of coal ash. Slurry pipelines are commonly used across the world for the transportation of coal ash (fly ash and bottom ash) from the plant to the ash ponds in thermal power plants. Most of the pipelines operating today in thermal power plants transport ash at low or medium solid concentrations over short as well as medium distances. These systems are very energy intensive and also lead to excessive wear of pipeline and wastage of water. Further, the present enhanced consciousness towards the imbalance in the eco-system and related stringent government policies are forcing the thermal power plants to adopt environment friendly transportation systems. Thus, high concentration slurry disposal (HCSD) system has emerged as preferred option to transport coal ash in thermal power plants as it is economical and environment friendly.

Researchers over the years [1-5] have investigated dense phase conveying of solid liquid mixture in both horizontal and vertical pipelines and have found that dense phase flow is feasible at reasonably low velocities with overall pressure drop being low. Researchers found that at solid concentration above 40% by weight, ash slurries behave like non-settling homogenous slurry and the pipe flow can be maintained in laminar regime at comparatively lower velocities. Thus at low velocities, the pipeline will be subjected to minimal erosion wear. Further, Seshadri et al [6] have elaborated many advantages of high concentrations slurry transportation such as low water and specific energy consumption, absence of contamination of water sources etc. They concluded that the concentration of

50% by weight was the limit of safe pumping of coal ash using a centrifugal pump and positive displacement pumps may become necessary to pump coal ash slurries above this concentration.

The knowledge of slurry rheology is very vital particularly in the High concentration slurry transportation. From the literature [7-10], it is observed that ash slurries at higher concentrations ($C_w \approx$ 50%, by weight) behave like non-Newtonian fluid with rheological equation shows Bingham behavior. They found that the values of yield stress and Bingham plastic viscosity of slurry increase rapidly with increase in concentration. Therefore it is essential to establish the exact rheological nature of coal ash slurries at high concentration.

Review of literature on the dense phase ash slurry disposal system reveals that the basic and the fundamental studies on the subject covering all aspects of ash slurry flow are limited. The pilot plant loop studies offer the most reliable design conclusions for coal ash slurry pipelines especially applied for high concentration solid transportation. In Indian thermal power plants, the production of fly ash (FA) and bottom ash (BA) is approximately in the ratio of 4:1 by weight and there is a need to conduct systematic slurry transport experiments on a pilot plant test loop for mixture of fly ash (FA) and bottom ash (BA) at this ratio at higher concentrations. Thus, the objective of the present study is to conduct a systematic study of coal ash slurry transportation in a pilot plant test loop at higher concentrations. Based on the rheological data, pressure drop has been also predicted at high concentrations. Further, Specific Energy Consumption for the transportation of coal ash slurry has been calculated at fixed velocities and its dependence in solid concentration has been quantitatively analyzed.

Experimental Set-up

The schematic layout of the pilot plant test loop used in the study is shown in Fig. 1. The pilot plant consists of a closed mild steel pipe test loop of 50 m length. The setup comprises of 42 mm diameter pipeline connected to a hopper shaped mixing tank in which the slurry is prepared. The slurry is drawn from the mixing tank into the pipe loop by a "Roto Flow" (Make: Roto Pumps Limited) pump which is of progressive cavity type. The pump is driven by an induction motor of 10 kW capacity (Type: 72P-0132M4, Make: M/s Power Build Limited). The flow rate in the loop can be varied over a wide range by suitably operating the plug valves provided in the pipe loop and the bypass pipeline. The operation of the bypass line also helps in keeping the slurry well mixed in the mixing tank. The pressure drop in the straight pipeline is measured by providing the pressure taps at suitable locations in the pipe loop. Separation chambers were provided at each pressure tap location to provide interface between the flowing fluid and the manometric fluid. For continuous monitoring of the flow rate, a pre-calibrated electro-magnetic flow meter (Make: ABB Limited) is installed in the vertical pipe section of the loop as shown in Fig. 1. Measurement uncertainty for the discharge flow rate was ± 2%. The test loop is provided with an efflux sampler fitted with a plug valve in the vertical pipe section near the discharge end for collection of the slurry sample to monitor the solid concentration. The absolute error in the measurement of solid concentration is less than ± 1%. Deposition velocity is estimated by visual observation of the flow in the transparent observation chamber.

Properties of Coal Ash Used

The coal ash samples from the Electro-Static Precipitators (ESP) and bottom ash hoppers of a thermal power plant have been used for the present study. The various physical properties of mixture of FA and BA in the ratio of 4:1 are given in Table 1. For transportation of solids through slurry pipeline, specific gravity is an important design parameter as it decides the settling characteristics of the slurry. The specific gravity of the solid is determined using Standard Pyknometer Method and is found to be 2.010 for mixture of FA and BA. The measured values of pH at various concentrations in the range of 50 to 70% (by weight) lie in the range of 7.05 to 7.02 for the mixture of FA and BA, which indicate the suspensions to be non-reactive at all concentrations. The static settled concentration is also a very important parameter as it decides the upper limit of solid concentration, which can be achieved by gravitational settling. The maximum static settled concentration for the mixture of FA and BA (4:1) was 60% (by weight).

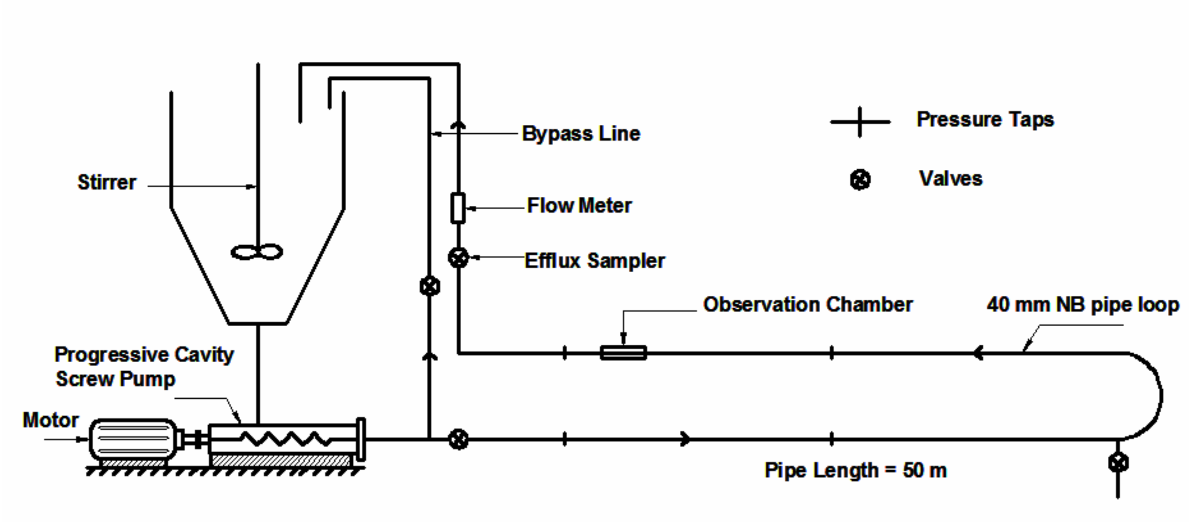

Fig. 1 Schematic Diagram of the Pilot Plant Test Loop

The particle size distribution is determined using sieve analysis and hydrometer analysis. For coarser particle size distribution, i.e. above 75 µm, sieve analysis is used whereas hydrometer analysis is used for finer particles i.e. below 75 µm. For FA and BA mixture (4:1), the top particle size was 850 µm. The median diameter (d_{50}) of the sample was 75 µm and mass weighted mean size (d_{wm}) was 85 µm.
A Weissenberg Rheogoniometer with concentric cylindrical platens (Model: R 18, M/s. Sangmo Control Ltd. U. K.) has been used for obtaining the rheological characteristics of the coal ash slurries at various concentrations. The experimental data of shear stress (τ) and shear rate ($\dot{\gamma}$), in the range of 20 to 120 sec^{-1}, for FA and BA slurries having concentration in the range of 50 to 70% (by weight) are analyzed for identifying the rheological model. The variation of the shear stress with shear rate for all concentrations showed that all the data points have a linear dependence of the form

$$\tau = \tau_y + \eta_p \dot{\gamma} \quad (3.1)$$

The straight-line equation is fitted for each set of data using the method of least squares. It was observed that the values of τ_y are non-zero for all sets of data. This implies that FA and BA slurry over the range investigated, shows a non-Newtonian behaviour and is more representative of a Bingham Plastic fluid. The rheological properties of slurries of FA and BA slurries are tabulated in Table 2 at different concentrations. It was found that as solid concentration increases, the rheological properties namely yield stress and Bingham viscosity of slurry increases. Further, relative Bingham viscosity (η_r) of the slurry is obtained by dividing the Bingham viscosity (η_p) by the viscosity of the water (η_w) at test temperature i.e.

$$\eta_r = \frac{\eta_p}{\eta_w} \quad (3.2)$$

Analytical Method for Prediction of Pressure Drop

Most important parameter for prediction of pressure drop is the friction factor which is dependent on the pipe Reynolds number. For slurries having high concentrations, it is possible that all three forms of flow exist namely laminar flow, transition and turbulent flow depending on the value of Reynolds number. For laminar flow, the Fanning friction factor expression is obtained by theoretical analysis. However for transition as well as for turbulent flow regimes, the evaluation of friction factor is based on some empirical correlations. The present analysis is based on the semi-empirical approach of Darby and Melson [11].

Relationship for the Fanning friction in terms of the Hedstorm number (H_e), and the Bingham Reynolds number (Re_B) in laminar regime are given by,

$$\frac{1}{\mathrm{Re}_B} = \frac{f}{16} - \frac{H_e}{6\,\mathrm{Re}_B^2} + \frac{H_e^4}{3 f^3\,\mathrm{Re}_B^8} \quad (4.1)$$

Where, $H_e = \dfrac{D^2 \tau_{yB} \rho_m}{\eta_p^2}$ (4.2) and

$$\mathrm{Re}_B = \frac{DV\rho_m}{\eta_p} \quad (4.3)$$

It is also possible to express the friction factor in terms of modified Reynolds number, (Re_{mod}) as

$$f = \frac{16}{\mathrm{Re}_{mod}} \quad (4.4)$$

where, $\mathrm{Re}_{mod} = \dfrac{6\,\mathrm{Re}_B^2}{6\,\mathrm{Re}_B + H_e}$ (4.5)

Though the exact formula for Fanning friction factor is expressed by equation (4.1), the friction factor can also be obtained approximately from equation (4.4).

For transition from laminar to turbulent flow, Hanks and Pratt [12] proposed the following critical Reynolds number criteria. It occurs at a critical value of 'Re_B' given by

$$(\mathrm{Re}_B)_c = \frac{H_e}{8x_c}\left(1 - \frac{4}{3}x_c + \frac{1}{3}x_c^4\right) \quad (4.6)$$

Where x_c is evaluated from the relation

$$\frac{x_c}{(1-x_c)^3} = \frac{H_e}{16800} \quad (4.7)$$

In the turbulent flow regime, the expression for 'f_T' is based on the empirical formulae developed by Darby and Melson [11]. The following expression is used for evaluating the Fanning friction factor in the present study.

$f_T = 10^c\, \mathrm{Re}_B^{-0.193}$ (4.8) Where, $c = -1.378(1+0.146 \exp(-2.9\times10^{-5}\, He))$ (4.9)

To arrive at a single friction factor expression valid for all flow regimes, modified friction factor is evolved by Darby and Melson [11] as

$f = [f_L^m + f_T^m]^{1/m}$ (4.10)

Where, $m = 1.7 + 40000/\mathrm{Re}_B$ (4.11)

On the basis of the above formulation, a simple computer program was developed for the evaluation of the pressure drop. The program covers the whole range of fluid flow i.e. laminar, transition and the turbulent regimes of flow.

Results and Discussion

In the present work, an effort has been made to generate pressure drop and flow velocity data in the 42 mm NB pipe loop for slurries of mixture of FA and BA in 4:1 proportion (by weight). The relative pressure drop is also calculated for all the solid concentrations. During the pilot plant loop tests the settling of the slurry was not observed even at the minimum value of the flow velocity (0.5 m/s) at all the concentrations tested.

Pressure Drop Characteristics of Mixture of FA and BA (4:1) Slurry

The pressure drop measurement for mixture of FA and BA (4:1) slurry in 42 mm NB pipe loop for solid concentration of 50.3%, 60.2%, 65.3%, 68.0% and 70.2% by weight are graphically shown in Fig. 2. From the figure it is observed that the pressure drop at any given flow velocity increases with increase in solid concentration. From the experiments, it is observed that for mixture of FA and BA slurry at a flow velocity of 2.0 m/s, approximately the increase in the solid concentration (by weight) from 60.2 to 65.3%, increases the pressure drop by 16%.

It is well known that the pressure drop for slurries is always higher compared to water. The additional pressure drop is generally represented as relative pressure drop. So the relative pressure drop represents the additional head required to transport the slurry as compared to water. It is calculated as the ratio of pressure drop in the slurry to the pressure drop in water at the same velocity over the same length. Fig. 3 shows the variation of relative pressure drop with velocity for mixture of FA and BA

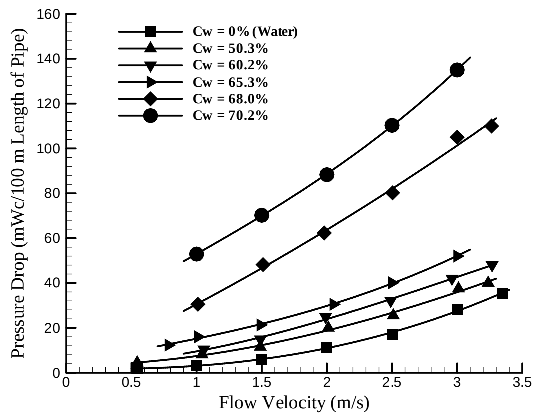

Fig. 2 Pressure Drop Variation in 42 mm NB Diameter Pipeline for Mixture of FA and BA (4:1) Slurry with Flow Velocity at Different Concentrations (by weight)

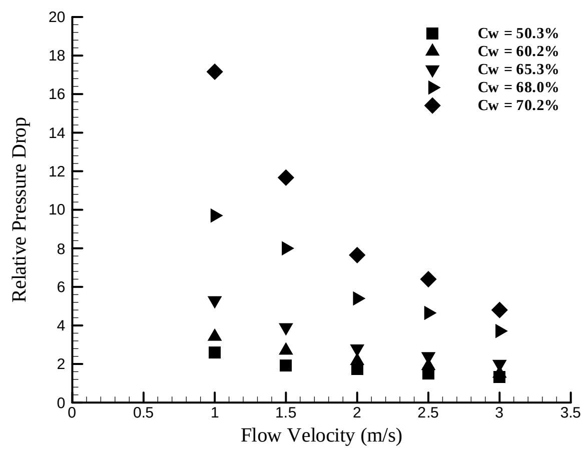

Fig. 3 Variation of Relative Pressure Drop in Straight Pipeline of 42 mm NB Diameter with Flow Velocity for Mixture of FA and BA (4:1) Slurry at Different Concentrations

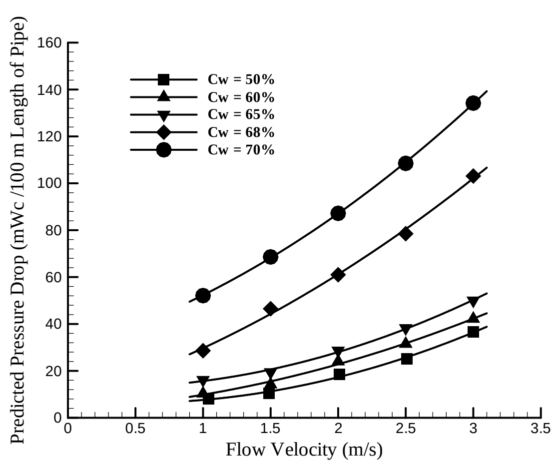

Fig. 4 Predicted Pressure Drop Variation in 42 mm NB Diameter Pipeline for Coal Ash Slurry at Selected Flow Velocities for Different Solid Concentrations (by weight)

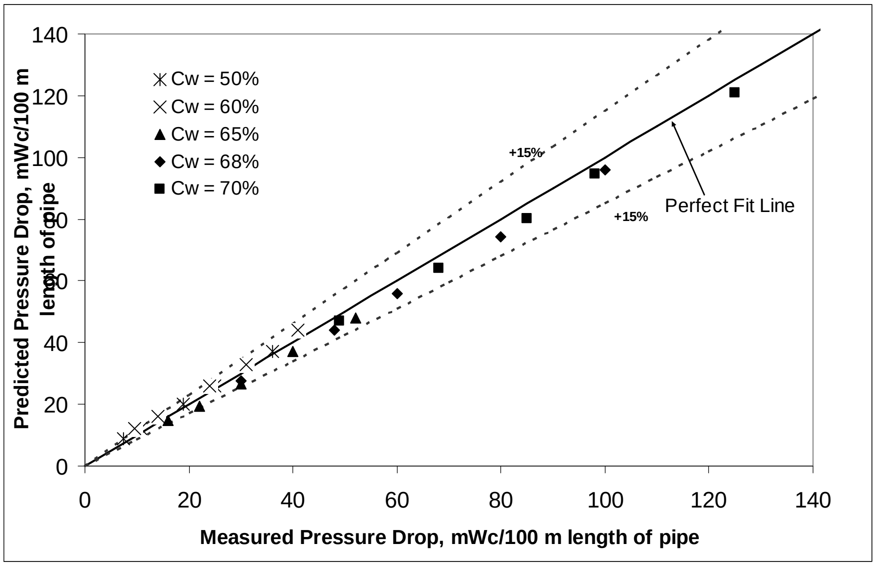

Fig. 5 Comparison between Measured and Predicted Pressure Drop at Various Concentrations and Flow Velocities for Coal Ash Slurry

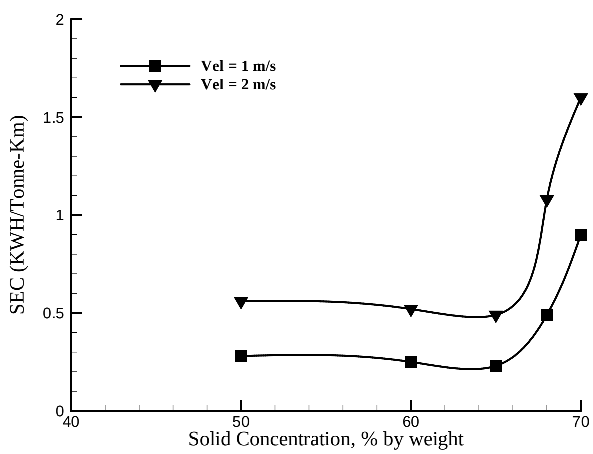

Fig. 6 Variation of Specific Energy Consumption with Solid Concentration (by weight)

(4:1) slurry at different concentrations namely 50.3%, 60.2%, 65.3%, 68.0% and 70.2% by weight. It was found from the investigation that at solid concentrations of 50-65% (by weight), the flow was mainly in turbulent regime and hence, turbulent motion has a dominant effect. For 68% and 70% solid concentration, the flow is in laminar regime at all velocities. Hence, the viscosity has dominant effect on pressure drop characteristics.

Prediction of Pressure Drop for Mixture of FA and BA (4:1) Slurry through Straight Horizontal Pipeline

The prediction of pressure drop in horizontal straight circular pipeline of 42 mm NB diameter have been done [Fig. 4] based on the model discussed in the previous sections for the slurry of mixture of FA and BA (4:1) for the entire range of the efflux concentration namely 50, 60, 65, 68 and 70% (by weight) and at flow velocities of 1.0, 1.5, 2.0, 2.5 and 3.0 m/s for each of the concentration. It is found that the flow is turbulent in nature at solid concentrations from 50 and 60% (by weight) at all velocities. For C_w = 65%, the flow is in laminar regime at lower velocities (1.0 and 1.5 m/s) but above 1.5 m/s, the flow is in turbulent regime. For 68% and 70% solid concentration, the flow is in laminar regime at all velocities due to higher viscosity of the slurry. Hence, at higher concentrations above 65%, the viscosity has dominant effect on pressure drop whereas in turbulent flows ($C_w \leq 65\%$), its effect is relatively less. Comparison between predicted and measured pressure drop against a perfect agreement line for all concentrations are presented in Fig. 5. It is seen that at the lower efflux concentration tested i.e. 50 and 60% (by weight) pressure drop is slightly over predicted. For C_w = 68%, pressure drop is always under predicted but the extent of under prediction reduces. The same trend of under prediction is seen at the highest efflux concentration of 70% (by weight) tested. From the results it is seen that 95% data points lie within an error band of ± 15% which is reasonable for design purposes, considering the various uncertainties involved in the prediction and the measurement procedures.

Effect of Solid Concentration on Specific Energy Consumption (SEC)

Based on the data collected in the present study, it is possible to compute Specific Energy Consumption for transporting mixture of FA and BA (4:1) at higher concentrations. Specific Energy Consumption (SEC) is defined as the energy required to transport one tonne of ash over a distance of one kilometre. Typical results for a 42 mm pipe at two different velocities namely 1 m/s and 2 m/s is shown in Fig. 6. It is observed that at any given velocity Specific Energy Consumption reduces upto 65% solid concentration and increases drastically with further increase in solid concentration. This can be attributed to steep increase in the rheological properties of coal ash slurries at higher concentrations.

Table 1: Physical Properties of Coal Ash

(Source: TPS, Badarpur)

(a) Specific Gravity of FA and BA = 2.010

(b) Settling characteristics of the Suspension (Initial concentration C_w = 30 % by weight)

Time (minutes)	0	¼	1/2	1	1.5	2	5	10	20	40	80	1440
Settled Concentration (FA +BA)	30.0	30.61	31.25	31.58	31.91	32.26	35.30	41.10	51.72	60.0	60.0	60.0

(c) pH values at different concentrations

% C_w, (by weight)	50	60	65	70
pH (FA +BA)	7.05	7.03	7.02	7.02

(d) Particle Size Distribution (% finer by weight) of mixture of FA and BA

Size (μ)	850	600	300	210	150	106	75	53	38	28	18
% finer	100	99.5	93.0	88.5	81.0	71.3	68.0	55.5	43.0	29.0	8.0

Weighted Mean Diameter, d_{wm} = 85 μ, d_{50} = 75 μ

Table 2: Rheological Properties of FA and BA (4:1) Slurry

% C_w (by weight)	Temp. (^{0}C)	Yield Stress τ_y (Pa)	Slurry Viscosity η_p (x 10^{-3}) (Pa-s)	Water Viscosity η_w (x 10^{-3}) (Pa-s)	Relative slurry Viscosity η_r	Remarks
0	25	--	--	0.891	1.0	Newtonian
50	25	0.043	3.20	0.891	3.60	non-Newtonian
60	25	0.254	11.30	0.891	12.70	non-Newtonian
65	25	1.10	44.90	0.891	50.40	non-Newtonian
68	25	1.28	136.50	0.891	153.20	non-Newtonian
70	25	1.45	201.0	0.891	225.60	non-Newtonian

CONCLUDING REMARKS

Flow characteristics of mixture of FA and BA (4:1) have been measured in a 42 mm NB pipe loop in terms of pressure drop and relative pressure drop. Experimental results obtained from the pilot plant test loop have been compared with the predicted results. Based on the experiments and prediction, the following conclusions are drawn.

1. The pressure drop for any given solid concentration increases with increase in velocity and at any given flow velocity, pressure drop increases with increase in solid concentration.
2. Relative pressure drop increases with increase in solid concentration.
3. For a given efflux concentration, relative pressure drop decreases with increase in flow velocity. The increase in pressure drop is much higher in the low velocity range compared to high velocity region for any efflux concentration.
4. Mixture of FA and BA (4:1) slurries can be transported at higher concentrations.
5. The prediction model proposed by Darby and Melson [11] is suitable for the Bingham plastic fluid flow such as mixture of FA and BA (4:1) slurry at concentrations above 50% (by weight).
6. Specific Energy Consumption decreases upto a concentration of 65% by weight and steeply increases beyond this value.

Nomenclature and Symbols

D	Diameter of Pipe, (m)
D	Particle Size, (mm)
d_{wm}	Weighted Mean Diameter, (mm)
C_w	Efflux Concentration, (by weight)
F	Fanning Friction Factor
f_L	Fanning Friction Factor (Laminar Flow)
f_T	Fanning Friction Factor (Turbulent Flow)
G	Acceleration due to Gravity, (m/s^2)
Δh	Head Loss in meter of water column per 100 m length of pipeline, (mWc/m)
H_e	Hedstrom Number
M	Constant
P_R	Relative Pressure Drop w.r.t Water, $\Delta P_{slurry}/\Delta P_{water}$
Q	Flow Rate, (m^3/s)
$(Re_B)_C$	Critical Reynolds number
Re_B	Reynolds Number based on Bingham viscosity
V	Velocity of Flow, (m/s)
V_{av}	Average Velocity, (m/s)

Greek Symbols

γ	Shear rate, (sec^{-1})
η_p	Bingham Plastic Viscosity of Fly ash slurry (Pa-s)
η_{wr}	Viscosity of Water, (Pa-s)
η_r	Relative Viscosity of Fly Ash, η_p/η_{wr}
τ_y	Yield stress, (Pa)

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