

Pressure drop for the flow of high concentration solid-liquid mixture across 90° horizontal conventional circular pipe bend

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Pressure drop across a 90° horizontal bend for fly ash slurry at high concentrations is reported in the present study. The pressure drop across the bend has been measured at five concentrations in the range of 50-65% (by weight) and the data has been analyzed to obtain the relative pressure drop, bend loss coefficient and permanent pressure loss. Measurements show that the relative pressure drop across the pipe bends increases with increase in concentration at low velocity. However, at any given concentration relative pressure drop is independent of velocity over the range tested. The bend loss coefficient at any velocity increases with increase in concentration. The permanent pressure loss increases marginally with concentration and velocity. The contribution of disturbed flow conditions downstream of the bend to the total pressure loss is much less in the case of highly concentrated slurries as compared to that in water.

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Pipe bends are an integral part of any pipeline network system. They cause obstruction to the flow resulting in additional pressure losses. The flow characteristics in the bend for single phase fluid (water) have been critically reviewed by Ito^{1,2}, adopting more mechanistic approach for analysis. A few systematic studies on bends commercially available for two-phase flow have also been reported³⁻⁵. The literature on two-phase flow through pipe bends is limited. The limited literature available for flow of solid-liquid mixtures through pipe bends has shown strong dependence of pressure loss across the bend on concentration of solid particles, the pipe diameter, the mean flow velocity, radius of curvature of bend, bend angle, specific gravity of the solids and general configuration of the bend. Semi-empirical models to predict the pressure drop in straight pipeline are available. However no such models are available for pipe bends and as such one has to resort to experimental estimation using pilot plant loops. The flow characteristics in bends are further complicated due to generation of the secondary flows as a result of centrifugal forces created due to the bend curvature. The literature review shows that some studies⁶⁻⁸ in the recent past have been carried out on slurry flow characteristics through pipe bends and a comprehensive methodology is given to estimate the

additional pressure losses, relative pressure drop, bend loss coefficient and permanent pressure loss. However, these studies have been basically carried out at low to medium solid concentrations, and there is hardly any study at high concentrations ($C_w > 50\%$, by weight). In the recent years, for the disposal of the fly ash and other industrial wastes, high concentration slurry disposal system is being increasingly used to reduce the specific energy consumption and avoid wastage of water. In the light of these facts, it is essential to establish pressure loss characteristics for pipe bends at high concentrations ($C_w > 50\%$ by weight). The emphasis in the present study is directed towards this aspect. Effort has been made to generate the basic data on pressure drop across pipe bend at high concentration for fly ash slurry flow using pilot plant test loop.

Pilot Plant Test Loop (50 mm NB)

The schematic layout of the pilot plant test loop is shown in Fig. 1. It consists of a closed circuit mild steel pipe test loop of 30 m length. The set-up comprises of 53 mm diameter (50 mm NB) pipeline, connected to mixing and measuring tank forming the closed re-circulating pipe test loop. The slurry is prepared in the hopper shaped mixing tank having a capacity of 2.73 m³, which is provided with suitable stirring arrangement for keeping the slurry well

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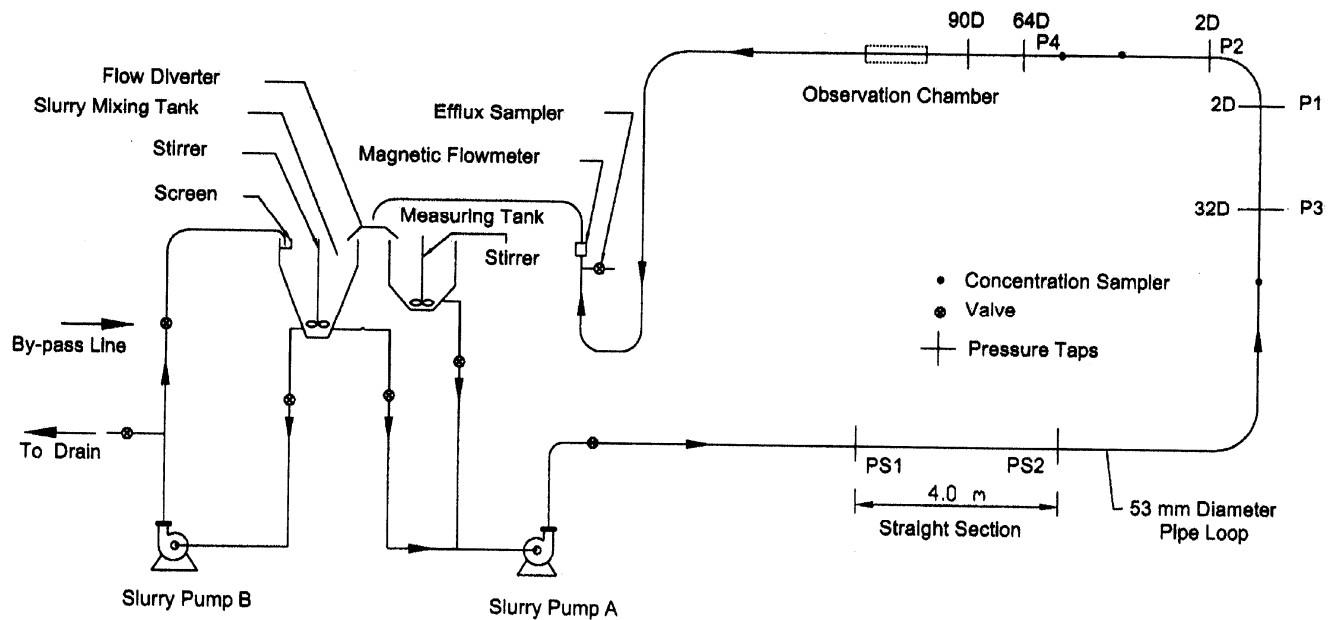


Fig. 1—Schematic diagram of the pilot plant test loop

mixed. The slurry is drawn from the mixing tank into 53 mm diameter pipe loop by a "50K WILFLEY" (Make: Hindustan Dorr Oliver Limited) model slurry pump having Ni-hard impeller and casing. The pump is driven by an induction motor of 22 kW, 415 V and 40 A (Type: ILA 2174-4, Make: M/s Siemens Limited). The capacity of the pump is sufficient to cover the entire range of head and discharge needed for simulating the conditions in the prototype pipeline. 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. For continuous monitoring of the flow rate, a pre-calibrated electromagnetic flow meter is installed in the vertical pipe section of the loop as shown in Fig. 1. 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 average efflux concentration is evaluated using the measured correlation between the slurry specific gravity and the solid concentration. Deposition velocity is estimated by visual observation of the flow in the transparent observation chamber. Different instruments and measuring systems such as isokinetic sampling tube for concentration measurement, separation chamber for pressure measurement and a diverter for flow rate measurement have been provided in the test loop.

Physical properties of material used

The solid material used in the study is fly ash obtained from a thermal power plant. The fly ash sample used has a specific gravity of 2.06 and pH value of 7.1 at 60% solid concentration. The maximum and the minimum particle sizes are 300 μm and 3 μm respectively with 84.4% particles are finer than 75 μm . The weighted mean diameter (d_{wm}) and the medium diameter (d_{50}) for the fly ash particles are 34.5 and 24.0 μm respectively which show that the fly ash particles are largely finer in size. The final static settled concentration of the fly ash slurry was 67.6% by weight.

Geometry of the bend

A commercially available circular mild steel pipe bend having 90° turn angle and radius ratio of 5.6 fitted in a horizontal plane is used to generate the pressure drop data experimentally. The detailed geometrical configuration of the test bends as well as the location of the pressure taps are given in Fig. 2.

Experimental Procedure

The pressure loss across the 90° horizontal bend having a nominal size of 50 mm is determined by incorporating the bend in the pilot plant test loop. To measure the pressure drop across the bend, pressure taps with separation chambers are provided at a distance of 2-pipe diameters both on the up-stream and the down-stream sides of the bend (Figs 1 and 2). To establish the permanent pressure loss across the

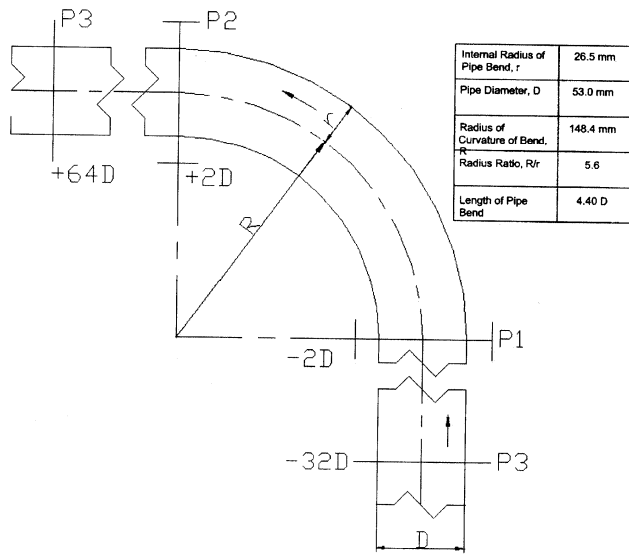


Fig. 2—Geometric details of 90° horizontal circular mild steel test bend

bend for the slurry flow at high concentrations, additional pressure taps are also provided at the distances of 32-diameters (reference point) on upstream side and 64-diameters on the downstream side (Figs 1 and 2). In order to account for the disturbed flow conditions downstream of the bend, two pressure taps are provided in the horizontal plane at each location, one on the inner side and the other on the outer side and an average value of pressure is measured. The pressure tap locations selected to establish the pressure drop across the bend and the permanent pressure loss are based on the findings of Kaushal⁶ and Kumar *et al.*⁹. For the comparative study of flow through the pipe bends and the straight pipeline, the pressure drop is also measured over a straight length of 4 m for fully developed flow. The head loss values obtained between different pairs of pressure taps are non-dimensionalized using dynamic head. The loss characteristics for the test bend is evaluated at selected flow velocities by suitably operating the plug valves provided in the pipe loop and the bypass line (Fig. 1).

Range of parameters studied

The aim of the study is to evaluate the pressure drop characteristics for conventional pipe bend for slurry flow at high solid concentrations. The pressure drop is measured across the bend at five efflux concentrations namely 50.42, 54.76, 60.06, 62.2 and 65.0 % (by weight). The analysis is also carried out for the estimation of the permanent pressure loss as a function of Reynolds number (1.5×10^3 – 2.0×10^5). The

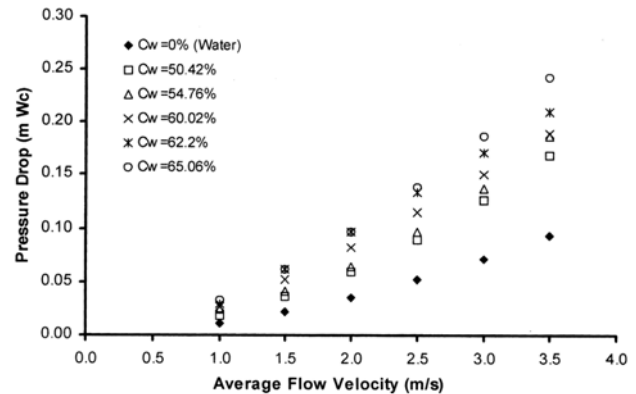


Fig. 3—Variation of pressure drop across the test bend with flow velocity in 50 mm NB

flow velocities are in the range of 0.5 m/s (minimum measurable value) to 3.0 m/s (maximum achievable value). The uncertainties in the pressure drop and flow rate measurements are $\pm 2\%$ and $\pm 0.5\%$ respectively.

Results and Discussion

Pressure drop characteristics across the bend

Pressure drop across the bend is defined as the pressure differential measured between pressure taps at $-2D$ and $+2D$ locations. To quantify the pressure drop across the conventional bend as a function of flow velocity and solid concentration, pressure drop is measured first for the water and then at the five efflux concentrations over the total range of flow velocities (0.5–3.0 m/s) achievable. Figure 3 shows the pressure drop across the conventional bend as a function of flow velocity. It is seen that at any given solid concentration, pressure drop increases with increase in the flow velocity. For all ranges of solid concentrations, it is observed that the pressure drop is always more than the single-phase water flow. It is also seen that at any concentration, the rate of increase of pressure drop is higher at higher velocities. It is further seen that pressure drop across the bend at a given flow velocity increases with increasing efflux concentration, the rate of increase being higher at higher efflux concentration. This can be attributed to the steep increase in density and viscosity of the slurries with increase in the efflux concentration. It is known from the literature that presence of solid particles results in the suppression of secondary flows, which is even depicted by the present results. There is no significant difference in pressure drop for 50.42% efflux slurry as compared to water more so at low velocities. The trends are similar to the ones reported by Mishra *et al.*¹⁰. At higher efflux

concentrations, there is significant increase in pressure drop even at low velocities, which could be attributed to abnormal increase in viscosity of the slurry.

Relative pressure drop

In order to analyze the results more quantitatively relative pressure drop in bend (P_{RB}) is calculated as:

$$P_{RB} = \frac{\Delta P_b}{\Delta P_{st}} \quad \dots (1)$$

where, ΔP_b is pressure drop across the bend, ($P_1 - P_2$), ΔP_{st} is pressure drop in straight pipe having a length equal to the distance between the two pressure taps 1 and 2.

Both ΔP_b and ΔP_{st} are measured for the same slurry at the same velocity. Thus, P_{RB} is a measure of increase in the pressure drop due to the bend. The pressure drop for the straight pipeline was measured over a distance of 4.0 m (Fig. 4) and ΔP_{st} is calculated from this data. Figure 5 shows the variation of relative pressure drop at selected flow velocities for the five efflux concentrations. It is seen that for water flow the relative pressure drop is almost constant at all velocities and it is close to 1.3. This value agrees with the values reported in literature¹⁰. The minor variation in the values is due to the experimental uncertainties. The relative pressure drops for the solid concentrations below 60% by weight are less than that of water flow at the lowest flow velocity of 1.0 m/s tested whereas at all other concentrations and flow velocities, the relative pressure drop is higher than that for water flow. The variation observed at lower velocities corroborates the fact that the presence of solid particles suppresses secondary flows in the bend, thereby resulting in lower pressure drop compared to water. Further, it is observed that for a given efflux concentration, the relative pressure drop approaches a constant value as the flow velocity increases. This trend is observed at all efflux concentrations tested. In the lower ranges of flow velocities, it is observed that the relative pressure drop increases with increase in the efflux concentration. This rate of increase diminishes at higher velocities, and at the highest selected velocity (3.0 m/s) the relative pressure drop is almost independent of the efflux concentration and it approaches almost a constant value of 1.4 with a variation of ± 0.1 . The trend is similar as observed by Mishra *et al.*¹⁰ at lower concentrations. For efflux concentrations of more than 60%, the relative pressure drop is nearly constant.

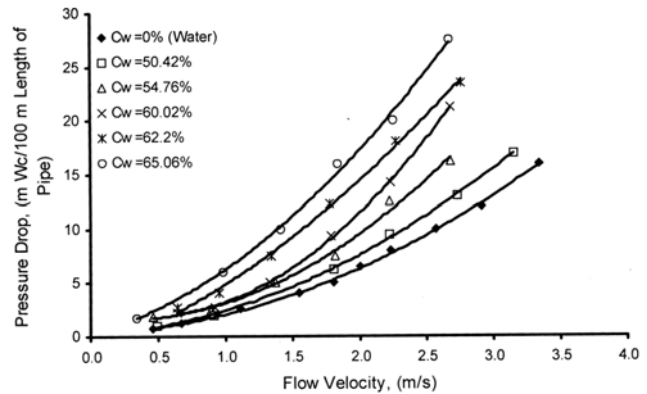


Fig. 4—Pressure drop variations in 50 mm NB diameter pipeline for fly ash slurry with flow velocity at different concentrations (% by weight)

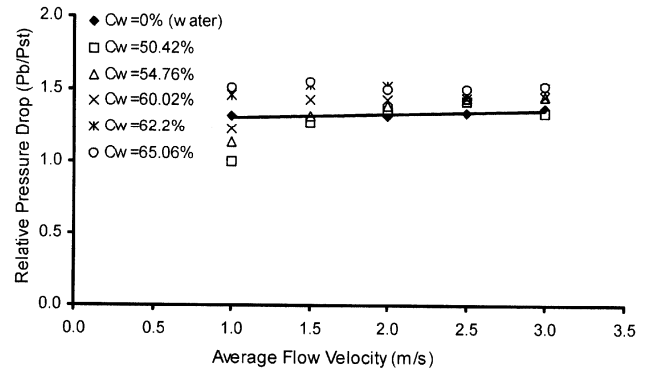


Fig. 5—Variation of relative pressure drop across the bend with flow velocity for different efflux concentrations

Bend loss coefficient

The parameter, which represents the effect of density and viscosity of the fluid on the pressure drop across the bend, is the bend loss coefficient. For slurry flow, bend loss coefficient (K_b) can be defined as:

$$\frac{\Delta P_b}{\rho_m g} = \Delta H_b = K_b \times \frac{V_m^2}{2g} \quad \dots (2)$$

where, ΔP_b is pressure loss in bend in $N/m^2 = (P_1 - P_2)$, ρ_m is density of slurry in kg/m^3 , ΔH_b is pressure drop across bend in 'm' of slurry column, V_m is mean flow velocity of slurry in m/s

The bend loss coefficient as a function of efflux concentration and flow velocity is shown in Fig. 6. For water flow, the bend loss coefficient decreases from 0.219 to 0.156 with increase in the flow velocity. The trends are in agreement with the data available in literature^{9,10}. For slurry flow the trends observed are similar to that observed for the water

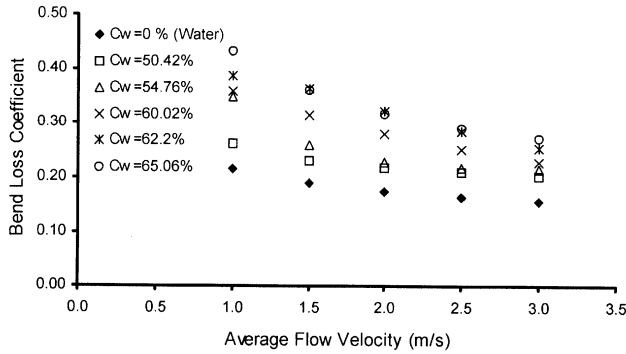


Fig. 6—Bend loss coefficient as a function of flow velocity

flow at different effluent concentrations and it is always higher than the corresponding water data. At a given velocity, the bend loss coefficient increases with increase in the effluent concentration. It is observed that the rate of increase with effluent concentration is maximum at the lowest velocity and minimum at the highest velocity. This variation could be attributed to the change in the rheological characteristics of the slurry. So, in general it can be concluded that for the fly ash slurry flow, the bend loss coefficient at any given velocity increases with increase in effluent concentrations and decreases with increase in the average flow velocity. The increase in the bend loss coefficient with increase in the effluent concentrations is due to the higher increase in the pressure drop across the pipe bend which is attributed to the change of rheological nature of the slurry at higher concentrations. For fly ash slurries, experience shows that the slurry above a solid concentration of 60% (by weight) exhibits strongly non-Newtonian behaviour and the viscosity of the suspension increases exponentially which causes an increase in the pressure drop in the pipe network, i.e., both across the pipe bend as well as in the straight pipeline. The bend loss coefficient decreases with increase in the flow velocity for both water and slurry flow. It is well known that in single phase fluid flow through bend, the loss coefficient depends on Reynolds number generally showing a decreasing trend with increasing Reynolds number, attaining a constant value at very high Reynolds numbers. Further, the nature of the flow (laminar/turbulent) has also a major effect on the values of K_b . It is to be noted that at any given velocity, Reynolds number reduces as solid concentration increases due to increase in viscosity. Hence, increasing trend of K_b with concentration at any given velocity could be partially due to decrease in Reynolds number.

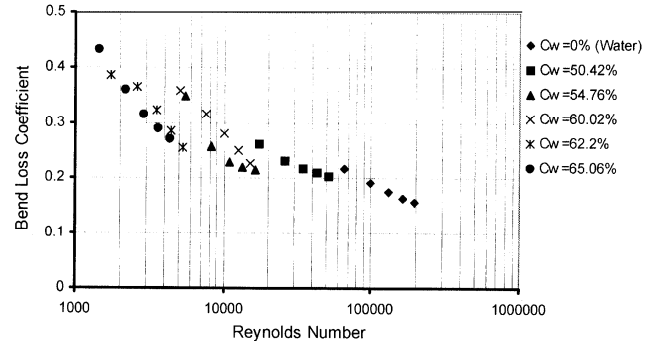


Fig. 7—Bend loss coefficient as a function of Reynolds number

Hence, K_b has been plotted as a function of Reynolds number in Fig. 7. For fly ash slurries, Bingham Reynolds number (Bingham viscosity is used in Reynolds number) is used for the plot and the details of calculation are available elsewhere¹³. It is seen from the figure that the value of ' K_b ' decreases with increasing Reynolds number, with the data points corresponding to all concentrations more or less falling on a single curve. Thus, the effect of solid concentration on K_b appears to be some what secondary and the effect of the Reynolds number is predominant.

Permanent pressure loss

Permanent pressure loss due to bend is of interest to a pipeline designer. For this purpose, two pressure taps, one at 32D (P_3) on the up-stream side and other at 64D (P_4) on the downstream side of the bend are provided. The pressure drop between these locations is measured. It was observed that this pressure drop is higher in comparison to the pressure drop measured in straight pipeline over the same length without the bend. The net increase in the pressure drop due to the introduction of the bend is therefore determined. The non-dimensionalized form of the net increase in the pressure drop due to the introduction of the bend is termed as permanent pressure loss coefficient. The permanent pressure loss coefficient (K_p) is defined as:

$$K_p = \frac{\Delta P_{BEND} - \Delta P_{St.}}{\frac{1}{2} \rho_m V_m^2} \quad \dots(3)$$

where, $\Delta P_{BEND} = (P_3 - P_4)$, with bend, in N/m^2 , $\Delta P_{St.}$ is pressure drop in a straight pipeline of equal length, in N/m^2 , ρ_m is density of slurry in kg/m^3 , V_m is mean flow velocity of slurry in m/s

Figure 8 has been plotted to show the variation of pressure drop between the locations at 32D on the upstream side and 64D on downstream side from the test bend at selected flow velocities. The trends are similar to the ones observed just across the bend (2D upstream and 2D downstream) with higher magnitudes.

Figure 9 shows the variation of the permanent pressure loss coefficient, (K_p) as a function of average flow velocity. At any given flow velocity the permanent pressure loss coefficient increases with the increase in the solid concentration. It is also seen that for the flow of water, the permanent pressure loss is minimum, which gradually increases as the fly ash solid is added and the increase is of the order of 50% at the lowest velocity (1.5 m/s), to 25% at the highest velocity (3.0 m/s) tested. Figure 9 also shows that the permanent pressure loss increases almost linearly with the average flow velocity for any given solid concentration, with increase being steeper at higher concentrations. These trends are in agreement with the data given by Kumar⁹, Mishra¹⁰ and Ahmed¹¹. Further, the values of bend loss coefficient for water are in good agreement with the data available in literature^{1,2}.

Effect of bend on flow on downstream pipe

Flow of slurry inside the pipe bend is very much complex due to the presence of secondary flows. Secondary flows play a dominant role in determining the flow regime, i.e., homogeneous or heterogeneous, within the pipe bend. The presence of bend also affects the flow behaviour in the downstream side in the pipeline where the flow is disturbed due to the bend. It is very difficult to analyze this phenomenon mathematically. However, Ito^{1,2} and Kumar⁹ have shown that the disturbances downstream to the bend exist up to the distance of the order of 40 to 50 pipe diameters from the exit of the bend. Since the flow in this region is disturbed, the pressure drop will be different from the corresponding value in a fully developed flow in a straight pipe. The analysis is based on the comparison of permanent pressure loss coefficient, K_p (Eq. 3) and excess pressure loss coefficient, K_b , defined as,

$$K_b = \frac{\Delta P_b - \Delta P_{st}}{\frac{1}{2} \rho_m V_m^2} \quad \dots (4)$$

It is to be noted that K_p is a measure of total pressure loss due to the bend whereas K_b represents

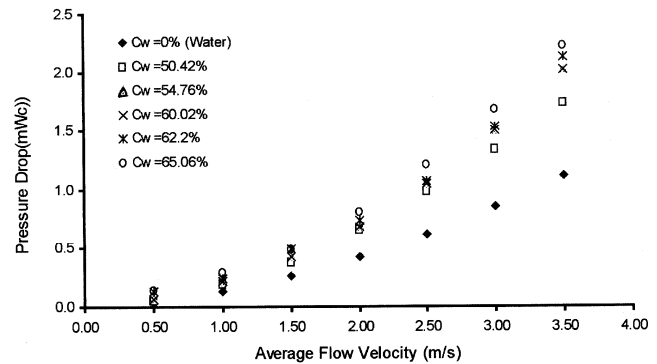


Fig. 8—Variation of pressure drop between 32D u/s and 64D d/s of test bend with flow velocity at various fly ash concentrations

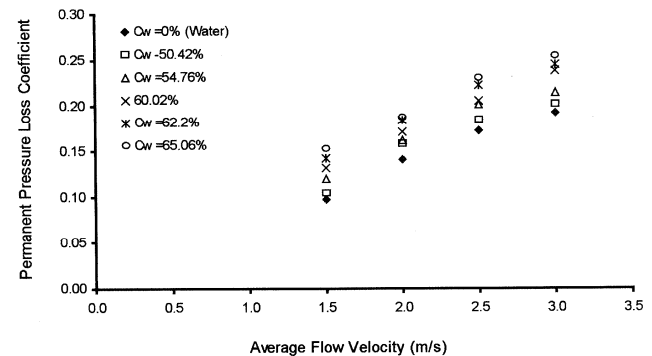


Fig. 9—Permanent pressure loss coefficient as a function of average velocity

Table 1— The values of K_p and K_b at higher velocities obtained for various concentrations

Coefficient	0 % (water)	50.42 %	54.76 %	60.02 %	62.2 %	65.06 %
$V_m = 2.5$ m/s						
K_p	0.173	0.185	0.201	0.203	0.223	0.230
K_b	0.154	0.177	0.200	0.212	0.227	0.239
$V_m = 3.0$ m/s						
K_p	0.193	0.201	0.214	0.238	0.245	0.254
K_b	0.132	0.206	0.209	0.218	0.223	0.255

pressure loss across the bend only. Since the upstream effect of the bend is usually small, the difference in the value of K_p and K_b is a measure of additional losses in the downstream of the bend due to disturbances caused by it. The values of K_p and K_b at comparatively higher velocities ($V_m = 2.5$ and 3.0 m/s) obtained for all concentrations tested are given in Table 1.

The data shows that in the case of water the permanent pressure loss coefficient is much higher than the excess pressure loss coefficient for the bend. This implies that the additional pressure loss due to

the flow disturbances downstream of the bend also contributes significantly to the total permanent loss due to the bend. Due to the curvature of the bend, centrifugal forces are generated, which create large disturbances resulting in skewed velocity profile downstream of the bend. Hence, the pressure loss in this region contributes significantly to the total pressure loss due to the disturbed flows conditions. For slurry flow the presence of solids suppresses the secondary flows leading to lower pressure losses in the bend at low concentrations^{11,12}. Further as concentration increases, viscous effects also increase, resulting in higher loss across the bend. The contribution of the downstream disturbance, to the permanent pressure loss reduces at higher concentrations of the solids, since flow tends to stabilize much faster due to increased viscous effects. At higher concentrations, both pressure drop in the bend region as well as at the downstream side increases but increase in the former is at higher rate than the latter, and at any concentration for instance, $C_w = 50.42\%$ the difference between the permanent pressure loss coefficient and the excess pressure loss coefficient (at 3.0 m/s flow velocity) is almost negligible, (i.e. values almost equal). At higher concentrations, i.e., $C_w = 54.76\%$, it is achieved even at lower flow velocity, i.e., 2.5 m/s. The data also reveals that further increase in concentrations ($C_w > 60.0\%$), the similar type of trend is observed and the values of permanent pressure loss coefficient are almost equal to the excess pressure loss coefficients within the experimental uncertainties. Thus, it can be concluded that the contribution of disturbed flow conditions downstream of the bend to the total pressure loss is not very significant in the case of homogeneous slurries having high concentrations.

Conclusions

The present study on the flow characteristics of high concentration slurry through 90° horizontal circular pipe bend (radius ratio = 5.6) has established the following conclusions

- (i) The relative pressure drop across the pipe bend increases with increase in velocity and approaches a constant value at high velocity for all solid concentrations studied. The asymptotic value increases with increase in solid concentration. At very high efflux

concentration, the dependence of relative pressure drop on velocity is rather weak.

- (ii) The bend loss coefficient shows a reducing trend with increase in flow velocity (over the range tested) for the slurry flow at all concentrations tested. The bend loss coefficient is predominantly decided by the Reynolds number of the flow.
- (iii) The permanent pressure loss coefficient for bends increases marginally with the increase in the flow velocity at all concentrations tested. The increase in bend permanent loss with concentration is more at lower velocity as compared to that at higher velocity.
- (iv) The flow disturbances downstream of the pipe bend result in additional losses and their contribution to permanent pressure loss is substantial for single phase fluids. However, in the case of highly concentrated slurries, this contribution is rather insignificant.

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