Pressure drop across conventional and diverging-converging pipe bends in the flow of multi-sized particulate slurries

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Received 8 April 1997; accepted 20 January 1998

Pressure drop across a conventional long radius pipe bend and two wear resistive pipe bends have been presented for the flow of multi-sized particulate suspensions. Measurements have been made over a wide range of flow velocities and solid concentrations. The study has shown that diverging-converging pipe bend has marginally higher pressure drop but exhibit a much longer life. Quantitative data on relative pressure drop and bend loss coefficient for the three pipe bends are presented and analyzed.

Flow characteristics of solid-liquid mixtures through pipe bends is of great relevance to the slurry pipe line designers as they are an integral part of any pipeline system. For a slurry pipeline designer, bends have always been an important component due to the additional pressure drop across them and also their proneness to excessive wear resulting in short life. Flow in bends is quite complex and has been a focus of research all over the world for two decades. Ito has critically reviewed the literature in flow through bends for single phase fluid. Only limited information is available about flow characteristics in bends for solid-liquid flows. An extensive study has been conducted to develop pipe bends having reduced erosive wear. The study has shown that bends having a diverging-converging geometry exhibit considerably reduced erosion rate as compared to conventional long radius pipe bends. The details of these modified bends as well as their wear characteristics have been given by Mishra. It is also very important to establish the additional pressure loss in pipe bends to assess the extra energy requirements. A bend acts as an obstruction to flow, causing additional pressure losses. The pressure loss in a bend is a strong function of numerous parameters, like, concentration of solid particles, pipe diameter, mean flow velocity, radius of curvature of the bend, bend angle, specific gravity of the solid and the geometrical configuration of the bend. The data on the pressure drop in bends for multi-sized particulate slurry flow is very limited.

Experimental Procedure

A 90°C mild steel commercially available pipe bend (100 mm NB) having radius of curvature of 210 mm and a radius ratio of 4 along with two diverging-converging bends (Fig. 1) having same inner curvature but having an area ratio of 1.5 and 2.0 up to the middle plane (resulting in variable radius of curvature) have been used in the pilot plant test loop (Fig. 2) for the present study. The basic philosophy in the development of these bends was to initially diffuse the flow and then create an accelerating flow in the downstream, keeping the length same as that of a conventional bend. In these bends, the radius of the inner wall has been kept same as in the conventional bend. This was done to have diffusion toward the outer wall which is prone to excessive wear. The area of the modified bends was increased linearly from inlet to the middle of the bend (diffusion) and then area was reduced linearly up to the outlet. The cross-section was maintained circular at each location. The length of these bends was kept same as that of the conventional bend. For the measurement of the pressure drop across the bends, one pressure tap was provided at a distance of two diameters upstream of
the bend on the inner side of the pipe, whereas, two pressure taps were provided on the down-stream side at a distance of two diameters downstream of the bend (one on the inner side of the pipe and the other on the outer side of the pipe). This arrangement was used to enable the measurement of average pressure at the upstream and downstream locations of the bend.

For the present study, Zinc tailings (leftover material after the extraction of Zinc from the ore) from a processing plant having a specific gravity of 2.85 was used as the solid material. This material had a wide particle size distribution which is given in Table 1. Experiments were carried out at four efflux concentrations in the range of 9.82% and 44.26%, by weight and flow velocities were varied in the range of 0.96 m/s to 3.53 m/s for each solid concentration.

Results and Discussion

Pressure drop across three bends are presented in Figs 3-5. Fig. 6 gives the variation of bend loss coefficient for the three bends.

Pressure drop across the bends—Fig. 3a shows the pressure drop across the conventional bend. It is seen that at any given solid concentration, pressure drop increases with increase in the flow velocity and at any given velocity, same trend is observed with the concentration also. At the lowest efflux concentration (C_w = 9.82%), the pressure drop is lower than that for the clear water for velocities below 1.93 m/s and increases marginally for the higher velocities. Similar trends are noticed at 20.32% efflux concentration also. However, at 30.21% and 44.26% efflux concentrations pressure drop across the bends is always more than that of the clear water flow which increases with the increase in the efflux concentration at higher velocities. The trends observed above are in agreement with the trends observed by Mukhtar and Gupta.

In bends, the pressure drop is more than that in the straight pipe of equal length. The additional pressure drop in bends is due to the generation of pressure driven secondary flows caused by the centrifugal forces. Presence of solid particles has a tendency to suppress the secondary flows which results in decrease in additional pressure drop for low concentrations and velocities. However, at
higher velocities and concentrations due to increase in skin friction and density, pressure drop increases.

Fig. 3b depicts the variation of pressure drop across the wear resistive bend having an area ratio of 1.5. The trends indicate that at any given efflux concentration pressure drop increases with the increase in flow velocity. Further, at any given flow velocity pressure drop also increases with efflux concentration. A comparison of Figs 3a and 3b indicates that the pressure drop is approximately 50% higher for the 1.5 area ratio wear resistive bend (Figs 3a & 3b). The modification in the geometry in the wear resistive bend has various effects—(i) increase in the area of cross-section reduces the local flow velocities thereby reducing the intensity of pressure driven secondary flows which should result in a lower pressure drop, (ii) the diverging passage causes increase in secondary flows due to diffusion which results in higher pressure drop, (iii) interaction of secondary flows and turbulence keeps the solid particles under suspension resulting in more homogeneous solid distribution, and (iv) increase in the area of cross-section results in an increase in surface area causing higher frictional losses.

Thus, the pressure drop across the diverging-converging bend depends on the relative contributions from the above mechanisms. The increased pressure drop in this bend (AR = 1.5) may be due to increased intensity of the secondary flows and increase in the exposed surface area, despite flow velocities being smaller as compared to the conventional bend.

Fig. 3c depicts the variation of pressure drop across wear resistive bend with area ratio 2. Overall trends observed are in agreement with those observed for conventional and wear resistive bend, i.e. at any given efflux concentration it increases with the flow velocity and at any given flow velocity it increases with efflux concentration. The pressure drops across the wear resistive bend with area ratio 2 is however seen to be smaller than those observed for the bend with area ratio 1.5 and are much closer to conventional bend values, for the same efflux concentrations and flow velocities. The reduction in pressure drop across the wear resistive bend with area ratio 2.0 as compared to wear resistive bend with area ratio 1.5 could be due to the dominating effect of reduced velocity as compared to that due to increased secondary flow.

*Relative pressure drop across the bends*—In order to analyze the result more quantitatively
relative pressure drop across bends ($R_{pb}$) has been calculated as follows,

$$R_{pb} = \frac{\Delta P_b}{\Delta P_{st}}$$

where, $\Delta P_b$—pressure drop across the bend, and $\Delta P_{st}$—pressure drop in straight pipe of equal length.

Both $\Delta P_b$ and $\Delta P_{st}$ are measured at the same velocity for the same slurry. Thus, $R_{pb}$ is a measure of increase in the pressure drop due to the bend. The pressure drop ($\Delta P_{st}$) was calculated from the measured pressure drop in a straight pipeline over a length of 45.5 m. Fig. 4 depicts the variation of pressure drop across the straight pipe line with flow velocity for water as well as slurry flow. The figure shows that pressure drop for slurry flow is higher than that for the water flow, at all velocities and efflux concentrations. Further, at any given flow velocity pressure drop in slurry flow increases with increasing efflux concentration. The dependence of the pressure drop on flow velocity is also clearly visible from the figure for water as well as slurry flow i.e. pressure drop increases with increasing flow velocity.

Fig. 5a shows the variation of relative pressure drop with flow velocity for the flow of zinc tailing slurry in the conventional bend at various efflux concentrations. It is seen that for the water flow, relative pressure drop is almost constant with respect to velocity with value being close to 1.45. The small scatter in the data at low velocities can be attributed to experimental uncertainties. For solid-liquid flows at different solid concentrations, it is seen that up to a velocity of 2.57 m/s relative pressure drop is smaller than that observed for water flow. Beyond 2.57 m/s flow velocity for all solid concentrations, relative pressure drop is nearly same to that observed for water flow at corresponding velocity. The trends observed above for the slurry flows are in agreement with the trends reported by Mukhtar et al. This phenomenon can be explained from the dependence of pressure drop in a straight pipe on the flow velocity. Reduction of slurry flow velocity in the straight pipe, results in progressive skewed concentration profiles and consequently the pressure drop does not decrease with velocity at the same rate as in the case of water. In the pipe bends, however, due to the presence of secondary flows concentration profiles are not affected significantly even at low flow velocities (near deposition velocity in straight pipe) and hence, the rate of fall of pressure in bend is higher as compared to the straight pipe. Thus, at low velocities, the values of

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**Fig. 4**—Pressure drop in the straight pipe for zinc tailing slurry at different efflux concentrations

**Fig. 5**—Variation of relative pressure drop in the bends as a function of flow velocity for different efflux concentrations (a) conventional bend (b) bend with area ratio 1.5 (c) bend with area ratio 2
The relative pressure drop across bends starts decreasing. The relative pressure drop is minimum near the deposition velocity (approximately 1.5 m/s) in the straight pipe. At higher concentration and high velocity, solid-liquid mixture behaves like a homogeneous mixture and thus, relative pressure drop is close to that with the clear water. Similar results have been obtained in the earlier studies.

Fig. 5b shows the variation of relative pressure drop for bend with area ratio 1.5. For water flow, it is observed that beyond 1.93 m/s relative pressure drop shows little variation with flow velocity, with an average value being close to 2.3. Below this value of velocity, relative pressure drop shows an increasing trend. This may be due to the Reynolds number effect since inside the bend the local values of Reynolds number will be smaller as compared to those in the straight pipe. Hence, viscous effects will become more predominant inside the bends. For slurry flow through area ratio 1.5 bend, relative pressure drop values do not show any predominant dependence on either the efflux concentration or the flow velocity. It is further evident from the figure that at all the flow velocities and efflux concentrations relative pressure drop for slurry flows is marginally less than that in the water flow. This could be attributed to suppression of strong secondary flows due to the presence of solid particles. The phenomenon of decreasing trend in the relative pressure drop observed in the conventional bend, as deposition velocity is approached, is not present in this case. This is possibly due to the fact that reduction in energy losses due to more uniform solid distribution in bends is offset by increase due to enhanced secondary flows caused by changes in the cross-sectional area.

Fig. 5c shows the variation of relative pressure drop with flow velocity for the water flow as well as slurry flow with different solid concentrations in wear resistive bend with area ratio 2. For clear water, the trend observed is similar to the one observed for wear resistive bend with area ratio 1.5. The constant value of relative pressure drop beyond 1.93 m/s is approximately 1.5 and is marginally more than the conventional bend. For slurry flows with different solid concentrations, the relative pressure drop values do not show any dependence on either the efflux concentration or the flow velocity with values being marginally smaller than that of the water flow as seen for 1.5 area ratio bend. The plausible causes for this trend have already been discussed.

Bend loss coefficients for conventional as well as wear resistive bends

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

\[
\Delta P_b / (\rho_m g) = \Delta H_b = K_b \left( \frac{V_m^2}{2 g} \right)
\]

where, \( \Delta P_b \) is the pressure loss in bend in N/m², \( \rho_m \) is the density of slurry in Kg/m³, \( \Delta H_b \) is pressure drop across bend in m of slurry column, and \( V_m \) is the mean flow velocity of slurry in m/s.
The bend loss coefficient for conventional bend at various efflux concentrations and flow velocities is depicted in Fig. 6a. For clear water, the bend loss coefficient decreases marginally from 0.29 to 0.26 with increase in the flow velocity. This trend is in agreement with that reported in literature\textsuperscript{10}. For slurry flow, the trends observed are similar to that observed for water flow at different solid concentrations. At higher velocities (more than 1.93 m/s) bend loss coefficient increases with solid concentration. The maximum increase is however, limited to 10% of the loss coefficient in water. At the low flow velocities (below 1.93 m/s) trends indicate bend loss coefficient for water flow to be higher than the slurry flow. This is due to the reasons already explained.

For area ratio 1.5 bend, the trend of bend loss coefficient (Fig. 6b) with flow velocity for water flow is similar to the one observed for conventional bend i.e. with increase in the flow velocity bend loss coefficient decreases. The loss coefficient value is observed to be 0.49 at 1.6 m/s and 0.44 at 3.53 m/s for water flow. For slurry flow also, the trends are similar with bend loss coefficient values being close to that of clear water flow. The overall variation in bend loss coefficient values is within ±5%.

Fig. 6c depicts the variation of bend loss coefficient for wear resistive bend with area ratio 2. For water flow trend is similar to the one observed for area ratio 1.5 bend, with the values being smaller to that observed for area ratio 1.5 bend. The values change from 0.32 at 1.6 m/s to 0.28 at 3.53 m/s. For slurry flow the same trend is seen for all concentration. The values indicate increase in loss coefficient with efflux concentration. Although this increase is about 10% at the lowest flow velocity where uncertainty in measurements could be larger. At higher velocity this variation is limited to ±5% which is same as that in the 1.5 area ratio bend.

Conclusions

Pressure drop studies in bends have shown that modified bends have higher pressure drop than a conventional bend. The extent of increase of pressure drop in area ratio 2 bend over conventional bend is marginal. The pressure drop increase is highest for bend with area ratio 1.5. Based on the above findings it is concluded that diverging-converging bend with area ratio 2 offers many attractive features and can be used in practice for slurry pipelines. Mishra\textsuperscript{2} has shown that in slurry flows, wear at the mid-plane in the wear resistant bend, with area ratio 2.0, is even less than that observed at the bottom of a straight pipe. Thus, with such bends it is possible to achieve longer life without appreciable additional energy loss as compared to conventional bends.

References