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EXPERIMENTAL INVESTIGATION ON PRESSURE DROP CHARACTERISTICS OF BI-MODAL SLURRY FLOW IN A STRAIGHT HORIZONTAL PIPE

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Abstract— In the present experimental investigation, the pressure drop measurements are done over a length of 4.0 m in 50 mm NB diameter pipe line under fully developed flow conditions using a pilot plant test loop for narrow sized silica sand slurry and bi-modal slurry. The bi-modal slurry consists of narrow sized silica sand and fly ash as fine particles in different proportions keeping the overall efflux concentration. The deposition velocity characteristics of the abovementioned slurries are also measured experimentally. For bi-model slurry, at an efflux concentration of 20.4% (by weight), the pressure drop reduces considerably with addition of the fine particles and the reduction in pressure drop is more at lower velocities. Further, at efflux concentration of 33.9% (by weight), the pressure drop reduces at higher rate for low velocity region as compared to high velocity region with addition of the fine particles. The bi-model slurry shows slight reduction in deposition velocity with increase in percentage of fines for both efflux concentrations.

Index Terms— Bi-modal, slurry flow, deposition velocity, fine particles, pressure drop, straight horizontal pipe, fly ash, silica sand
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1 Introduction

Solids transportation by pipelines, because of its low maintenance, round the year availability and being ecofriendly has been widely accepted by various industries as an extremely safe and attractive mode of transportation. These pipelines are also used for disposal of waste materials like tailing materials, fly ash etc. to the disposal sites in addition to transport solid materials using water or any other liquid as a carrier fluid for long distance haulage of bulk materials. Slurry pipeline design is a complex process and involves simultaneous optimization of various hydraulic parameters such as pressure drop, mixture velocity profile, solid concentration distribution and wear. The main conclusion drawn from the studies [1-7] done in the first half of 20th century which are primarily experimental is that pressure drop increases with increase in solid concentration and the mixture behaves as homogenous fluid at higher velocities. Durand and Condolios [8,9] have done pioneering and most exhaustive work to understand the frictional losses in solid liquid flow and subsequently several empirical correlations for pressure drop prediction based on experimental data on equi-sized and narrow size range particles have been proposed [10,11].

For optimum design of such type of pipelines, literature suggests that pressure drop and deposition velocity are two of the most important parameters and importance of these parameters further enhances with increase in need to transport solids at higher concentrations. The one of the methods suggested in the literature [10, 12] to reduce the values of these parameters is by addition of fine particles in small quantities to the slurry being transported. Kazanskij et al. [13] experimentally found that pressure drop reduces at lower velocities with the reduction being 30% close to the deposition velocities due to addition of fine particles in coarse slurries, Seshadri et al [14] suggested the need and requirement of more power for transportation of coarse particles due to higher velocity whereas presence of excessive amount of fine particles gives the slurry a strong non-Newtonian character giving rise to higher pressure drops. The de-watering cost also increases with the increase in the proportion of fines. It is therefore possible to get a good suspension and transportation of mixed slurry, at moderate velocities by proper choice of particle size distribution. Boothroyde et al. [15] based on study of very coarse slurries mixed with fine particles concluded that the coarse particles can be transported at a lesser velocity leading to reduction in specific energy consumption. Shook et al [16, 17] experimentally investigated the effect of addition of fine particles in coarse particles slurry and observed that the distribution of the particles across the pipe cross-section becomes more uniform. They concluded that it may be better to transport mixed size particulate slurry than equi-sized particulate slurry. Mishra et al [18] has modified the two-layer model of Gillis et al. [19] to predict the pressure drop for coarse slurry mixed with fine fly ash slurry. The model was further used to predict the pressure drop by using the experimental data collected by Kumar et al [20] for the mixed slurry of fly ash and bottom ash (fly ash as fine fraction and bottom ash as coarse fraction) mixed in different proportions. The prediction by Kumar et al [21] concluded that pressure drop and deposition velocity are affected considerably by the particle size distribution of the solid particles present in the slurry as suggested by the experimental data collected. Kumar et al [22] found that the model proposed by Mishra et al [18] for the pressure drop predicts the pressure drop quite well except in the region close to the deposition velocity, for narrow-sized as well as bi-modal slurry. From the scanty literature available, it is seen that no systematic experiments have been carried out to throw some light on the mechanism responsible for reduction in pressure drop and deposition velocity. In this view, Kumar et al [23, 24] based on the experimental data discussed the effect of addition of fine particles on pressure drop and deposition velocity at medium and high efflux concentrations. Hence, in the present experimental study an effort has been made to highlight the effect of addition of fine particles in a narrow-sized coarse slurry on the two flow characteristics i.e. pressure and deposition velocity in a combined way at medium and high efflux concentration. The fly ash is used as fine solid particles and silica sand as narrow-sized coarse slurry.

2 Physical Properties of Materials Used

2.1 Specific gravity of particles

The measured specific gravity of fly ash and silica sand is 2.17 and 2.65 respectively.

2.2 pH value of slurries

The pH value of both narrow sized silica sand as well as bi-modal slurries in the concentration range of 0-50% (by weight) exhibit a non-reactive nature at all concentrations tested.

2.3 Particle size gradation

The bi-modal slurry is prepared by using the two solid materials namely narrow-sized silica sand and fly ash. Fly ash is obtained from thermal power plant as fine particles. The narrow-sized silica sand is obtained from mining area . The particle size distribution for fly ash [Fig.1] shows that 97.5% particles are finer than 75 μm with largest particle size being 150 μm. The narrow-sized silica sand is sieved between two successive sieves to get the narrow-sized particles with a mean diameter of 448.5 μm. Based on the particle gradation, fly ash particles are used as fine fraction and are added in slurry of narrow-sized particles of silica sand which in turn helps to establish the effect of addition of fine particles on pressure drop and deposition velocity at required efflux concentrations in a straight pipe..

2.4 Settling characteristics

The settling characteristics of silica sand and fly ash slurry are presented graphically in Fig.2 by using standard experimental procedure. Fig.2 shows that the final static settled concentration of fly ash and silica sand are to be taken as 57.7% (by weight) and 69.4% (by weight) respectively. This confirms that narrow-sized slurry of silica sand is fast settling slurry in comparison to the. fly ash slurry, which is reasonably slow settling slurry..

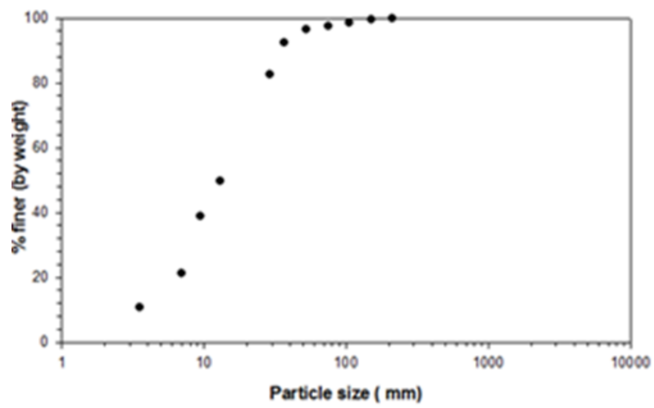

Fig. 1: Particle size distribution for fly ash used as fine fraction.

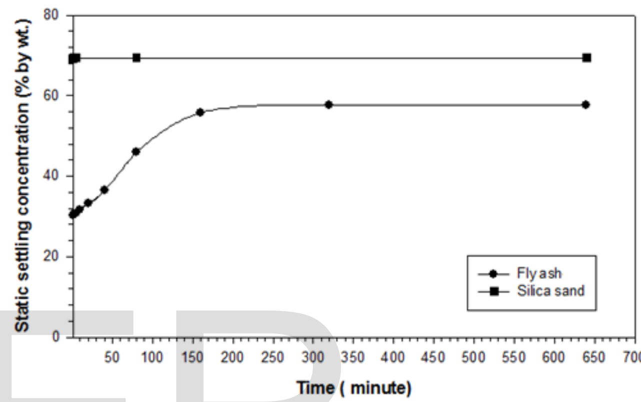

Fig.2: Settling characteristics for fly ash and silica sand in fresh slurry with initial concentration as 30(% by weight).

3 Experimental setup and Range of Parameters

The pilot plant used for the present study consists of a closed recirculating Mild steel pipe test loop of 30 m length with inside diameter of 50 mm NB and is schematically shown in Fig. 3. The hopper shaped mixing tank having a capacity of 2.73 m^3 with a suitable stirring arrangement for keeping the slurry well mixed is used for the slurry preparation. The slurry is drawn from the mixing tank into 50 mm NB diameter transporting pipe loop by 50K "WILFLEY" (Manufacturer: M/s Hindustan Dorr Oliver Limited) model slurry pump having Ni-hard impeller and casing, and driven by a pulley belt drive system coupled to a 22 KW, 415 amp induction motor (Type: 2136 – 4, Make Siemens Limited). The pump capacity is sufficient to cover entire range of head and discharge needed for simulating the condition in the prototype pipeline. The flow rate in the loop can be varied over a wide range by suitable operation of plug valves provided in the loop as well as in the bypass pipeline. The bypass line operation helps in keeping the slurry well mixed in the mixing tank. A pre-calibrated electromagnetic flowmeter is installed in the vertical pipe section of the loop as shown in the Figure 3 for continuous monitoring of the flow rate. For collection of the slurry sample to monitor the solid concentration the test loop is provided with an efflux sampling tube fitted with a plug valve in the vertical pipe section near the discharge end,. The average efflux concentration is evaluated using standard correlation between the

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slurry specific gravity and the solid concentration [10, 12]. By observing the particle movement in the transparent observation chamber provided in the pipe loop, deposition velocity is estimated without disturbing the flow.

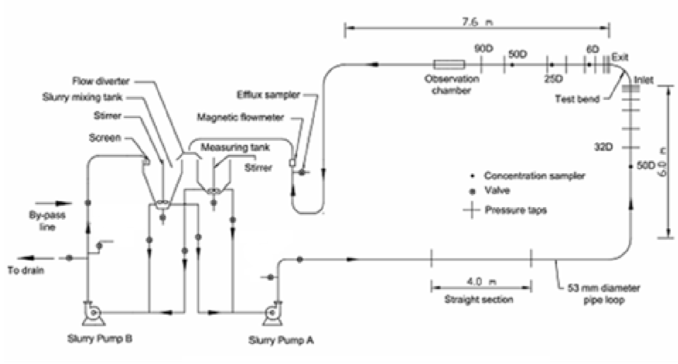

Fig. 3: Schematic diagram of the pilot plant test loop.

The pressure drop is measured in the straight pipe over a length of 4.0 m in a 50 mm NB diameter pipeline using the pilot plant test loop [Fig. 3]. The pressure taps provided with separation chambers are connected to U-tube differential manometer for measurement of pressure loss as a function of flow velocity. Deposition velocity is determined using the transparent observation chamber and efflux concentration by efflux sampler provided in the test loop. Pressure drop characteristics for the test loop are first established with water and then with slurry. The desired efflux concentration slurry for narrow-sized silica sand is prepared in the mixing tank. For preparing the bi-modal slurry, the finer particles of fly ash are mixed in the required proportion to achieve the desired ratios between narrow-sized silica sand and fine particles of 9:1, 8:2,7:3 and 6:4 keeping the overall efflux solid concentration nearly constant, based on the efflux concentration of narrow-sized silica sand slurry in the test loop,. The desired data for narrow sized silica sand slurry is measured for average efflux concentrations of 9.8, 20.4 & 33.9% (by weight). The average efflux concentrations selected for the bi-modal slurry are 20.4% and 33.9% (by weight). The various weight ratios of fine particles added to the total solids are 9%, 17%, 27% and 38% for an efflux concentration of 20.4% (by weight) and 8%, 18% and 27% for an efflux concentration of 33.9% (by weight)keeping the overall efflux concentration for the bi-modal slurry to be nearly equal to the initial efflux concentration. The pressure drop and deposition velocity in straight pipe are measured by varying the velocity between maximum achievable values and the deposition velocity, for each efflux concentration of narrow-sized silica sand slurry or bi-modal slurry.

4 Results and Discussion

The variation of pressure drop with flow velocity are presented in Figs. 4 to 6. Figs. 7 to 9 shows the variation of deposition velocity as a function of average efflux concentration of solids for both narrow-sized and bi-modal slurries

4.1 Pressure Drop Characteristics

The variation of pressure drop with flow velocity at various efflux concentrations for narrow-sized silica sand slurry and bi-modal slurries are presented from Figs. 4 to 6.

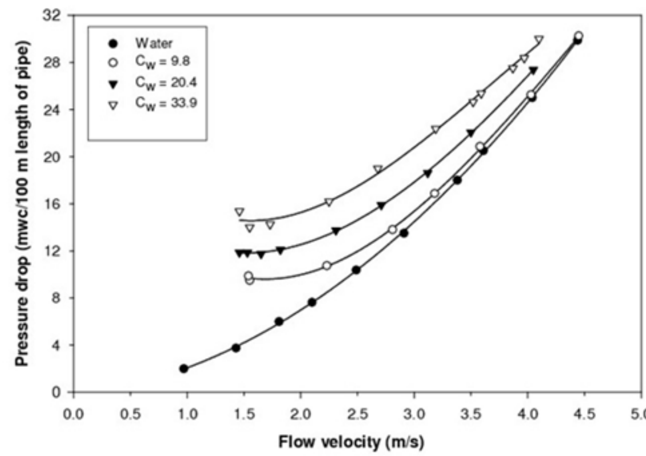

Fig.4: Pressure drop variation with flow velocity for narrow-sized silica sand slurry at various efflux concentrations (% by weight).

For narrow-sized silica sand slurry, Fig. 4 shows that at any given average efflux concentration of 9.8%, 20.4% and 33.9% (by weight), the pressure drop increases with increase in velocity. The pressure drop for slurry has a tendency to get closer to the value of water at higher flow velocities, which can be attributed to the uniform distribution of solids expected at higher velocities. It is further seen that at any given flow velocity, pressure drop increases with increase in the solid concentration, the rate of increase of pressure with concentration being higher at lower velocities. This may be attributed to the settling behaviour of solids at low velocities. It is seen that pressure drop is significantly higher for slurries in comparison to water at velocities close to deposition of solids, and further reduction in velocity also increases the pressure drop which may be due to the reduction in effective flow area due to settling of particles.

Fig. 5 depicts the pressure drop characteristics for the bi-modal slurry having an average efflux concentration of 20.4% (by weight) with varying concentration of finer particles of 0, 9, 17, 27 and 38% of the total solids. It is seen that the pressure drop at any given velocity reduces with increase in concentration of fine particles, the drop being more pronounced at lower velocities. Close observations of the pressure drop characteristics of the bi-modal slurry highlights two velocity regions namely low velocity region and high velocity region (velocities higher than 2.5 m/s). In the low velocity region, addition of fine particles reduces the pressure drop considerably, the reduction being around 30% for 38% fine particles at 1.5 m/s and around 15% at 2.5 m/s. Further increase in the percentage of fines particles from 27% to 38% the reduction in pressure drop is only marginal. In the high velocity region, the pressure drop reduction is seen only up to 17% of fine particles and the reduction is nearly around 10% in this velocity region. Further increase in percentage of fine particles, results in increase in

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pressure drop in the high velocity region as a result of increased viscosity of the slurry mixture which leads to higher pressure drops at higher velocities.

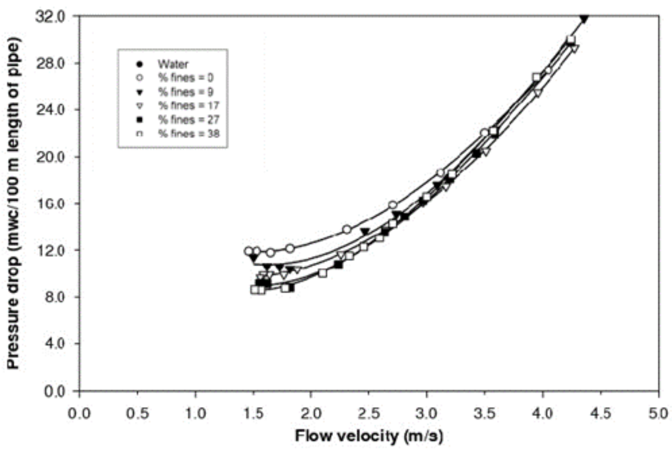

Fig.5: Pressure drop variation with flow velocity for bi-modal slurry of silica sand slurry and fly ash mixed in different proportions of fly ash having average efflux concentration 20.4 (%by weight).

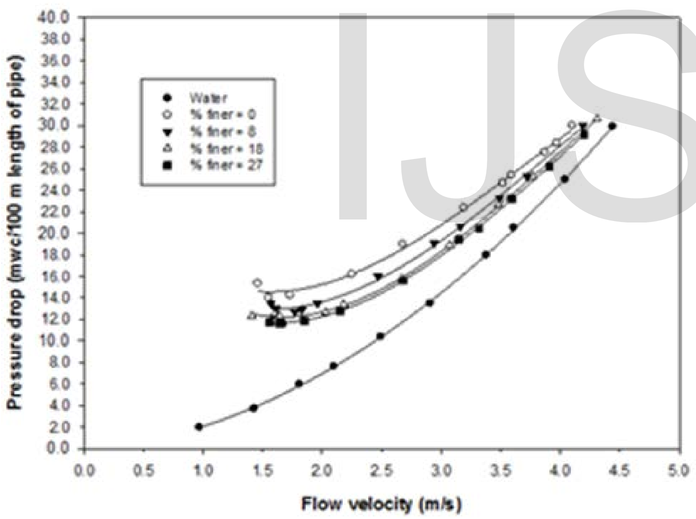

Fig.6: Pressure drop variation with flow velocity for bi-modal slurry of silica sand slurry and fly ash mixed in different proportions of fly ash having average efflux concentration 33.9 (%by weight) .

Fig. 6 presents the pressure drop characteristics for the bi-modal slurry having a high average efflux concentration of 33.9% (by weight) with varying concentration of finer particles of 0, 8, 18 and 27% of the total solids. Nearly similar behavior is observed as for average efflux concentration of 20.4% (by weight) For 33.9% efflux concentration, the pressure drop reduction occurs up to 27% of fines over the complete velocity range tested. In the low velocity region, addition of fine particles reduces the pressure drop considerably, and is in the range of 15-20% in this region and being around 8 to 10% in the high velocity region.

A close scrutiny of the above discussion for narrow-sized as well as bi-modal slurries, leads to conclusion that the higher reduction in pressure drop due to addition of fine particles in low velocity region compared to high velocity region can be attributed to the comparatively more uniform distribution of coarse particles in the low velocity region as well as the increased interaction between particles and better suspension of coarse particles due to increased viscosity of the carrier fluid.

4.2 Deposition velocity Characteristics

The variation of deposition velocity with efflux concentration for narrow sized silica sand slurry is shown in Fig.7. Figs. 8 and 9 presents the variation of deposition velocity with fine particles percentage at efflux concentrations of 20.4 and 33.9 (%by weight) respectively for bi-modal slurries.

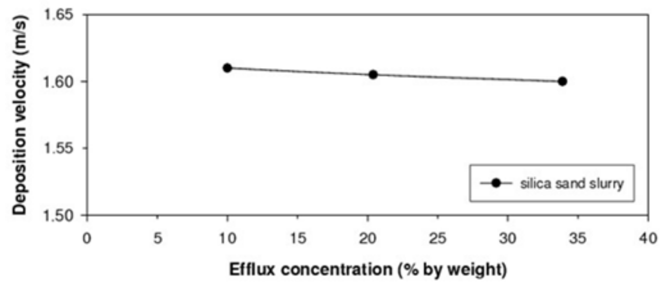

Fig.7: Deposition velocity for narrow-sized silica sand slurry.

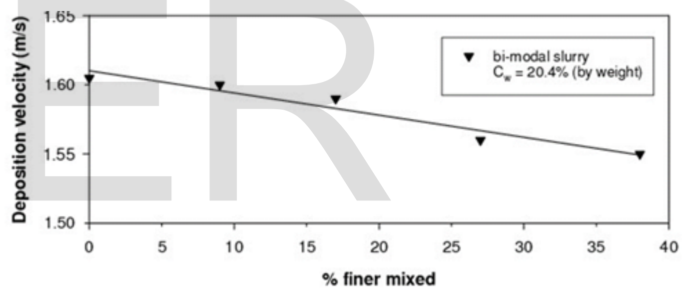

Fig.8: Deposition velocity for bi-modal slurry having average efflux concentration 20.4 (%by weight).

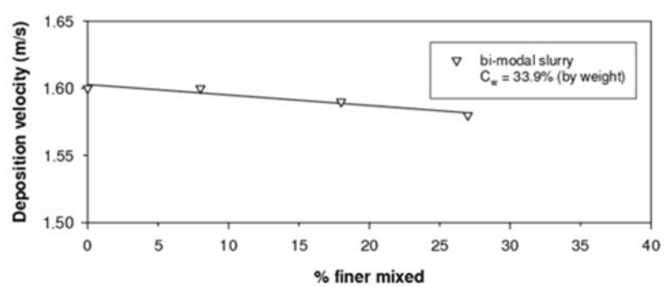

Fig.9: Deposition velocity for bi-modal slurry having average efflux concentration 33.9 (%by weight).

For the narrow-sized silica sand slurry [Fig.7], there is marginal drop in the deposition velocity with concentration. For the bi-modal slurry [Fig.8, 9], the deposition velocity reduces with increase in percentage of fines, but over the range tested, the addition of fines has only marginal effect on deposition velocity.

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5 CONCLUSIONS

Based on the present experimental study, the main conclusions can be summarized in the following points:

(i) For narrow-sized silica sand slurry, at any given solid concentration, pressure drop increases with increase in velocity and at any given flow velocity, pressure drop increases with increase in solid concentration, the rate of increase of pressure with concentration being higher at lower velocities.

(ii) For the bi-modal slurry having a high average efflux concentration, the pressure drop reduction occurs with addition of fines over the complete velocity range tested as well as the pressure drop at any given velocity reduces with increase in concentration of fine particles, the drop being more pronounced at lower velocities. It is also seen that the reduction in pressure drop is higher in the low velocity region compared to high velocity region.

(iii) The higher reduction in pressure drop due to addition of fine particles in low velocity region compared to high velocity region may be attributed to the comparatively more uniform distribution of coarse particles in the low velocity region as well as the increased interaction between particles and better suspension of coarse particles due to increased viscosity of the carrier fluid.

(iv) For the narrow-sized silica sand slurry, there is marginal drop in the deposition velocity with concentration.

(v) For bi-modal slurry over the range tested, the deposition velocity reduces with increase in percentage of fines, but the addition of fines has only marginal effect on deposition velocity.

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