Velocity measurement in solid–liquid flows using an impact probe

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The use of a modified impact type of probe for velocity field measurement in the flow of multi-sized ($d_{50} = 71$ μm) particulate slurries is described. The impact probe has a sensor similar to a two hole offset probe but has a modified pressure sensing system which prevents blockage of the probe by the solid particles. The probe system has been successfully used in slurry flows over a wide range of solid concentrations (0–40% by weight) and flow velocities (1.67–2.95 m/s). The data presented in this paper have revealed some special features of velocity distribution in the flow of multi-sized particulate suspensions.

Keywords: impact probe; velocity measurement; solid–liquid flows; slurry pipelines

1. Introduction

Slurry pipelines are used to transport solid materials in crushed form using water or any other liquid which imparts the necessary energy to the solid particles to remain in suspension and move along with the flow. This mechanism is dependent on several parameters of which the most important are the flow velocity and particle size. These two parameters also determine the flow regime which exists when the transportation of solids takes place. A homogeneous regime exists if the solids being transported are fine and not too heavy and the velocity is sufficiently high. In actual practice, no particulate suspension of practical importance behaves like a homogeneous mixture. For commercial slurries, the flow regime is normally heterogeneous. Different types of flow patterns are encountered in this regime depending on the flow conditions. The distribution of solids across the pipe cross section under different flow patterns has been experimentally measured by researchers all over the world. But the experimental data on the velocity field is scanty due to the complexities associated with the measurement of velocity in solid–liquid flows.

Durand [1] measured the velocity profile in sand–water mixtures using a Pitot tube in a 150 mm diameter pipe. The particles were of two sizes (0.18 mm and 2.04 mm) and the concentrations was of the order 15% by weight. The experiments were performed at different average flow velocities in the range of 2.37–5.53 m/s. He observed that the velocity profile was symmetric and velocity deficiency curves ($(V_{\max} - V)/V_{\mathrm{av}}$ tended towards the Von-Karman universal curve at higher velocities. Newitt *et al.* [2] have reported measurement of velocity for sand–water mixtures in a 25.4 mm (1 in.) pipeline. They observed that particle and liquid velocity profiles were identical for fine particles, whereas for larger particles a local slip velocity existed which increased from zero in the upper one third or so of the pipe to a maximum value at the bottom of the pipe. Ayukawa [3] also measured the velocity profile in a horizontal, straight transparent duct with a square cross section of a side of 40 mm, using a Pitot tube. He found that the velocity ratio ($V_{\mathrm{av}}/V_{\max}$) decreases as Reynolds number reduces and this tendency is pronounced at high solid concentrations. Some other studies carried out with Pitot type probes are those of Jilan and Zhenhuan [4], Frankiewicz *et al.* [5], El Masry and El Halawany [6] and Asakura *et al.* [7].

Limitations of the conventional pressure probes to measure local velocity forced researchers to look for alternate mechanisms. Beck *et al.* [8] developed an electronic probe to measure velocity of particles in slurry flow. They tested this system in a 5% by weight sand slurry with two particle sizes (62 and 325 μm). They claim a high degree of accuracy in their velocity measurements for electrode spacing between 1.51 mm and 76.2 mm. However, the level of concentration used in this study was very small. This system was simplified by Brown *et al.* [9] by mounting the electrodes on a miniature probe which could be easily traversed across any diametrical plane. They have reported accurate measurement of local velocities for sand–water mixtures. However, they observed that this probe's performance is not satisfactory in high viscosity slurry flow, because the peak of the cross correlation function behaves erratically with time. They further mentioned that the probe will not be effective in a slurry with small size particles. Brown *et al.* [10]

further established the effect of particle size on the performance of this probe. They pointed out the limitations of this probe in measuring velocities in slurries with high settling tendencies. With such slurries, they could not measure velocities in the upper portion of the pipe, where the number of particles is too low. The other problem associated with such probes was the rapid erosion of the electrodes on the probe surface requiring frequent replacements.

Zisselmar and Molerus [11] used laser Doppler anemometry for measuring the flow field of glass balls in a 50 mm ID glass pipe. They observed both the horizontal and vertical velocity profiles to be identical and symmetrical. They also showed that longitudinal and lateral turbulence intensities are maximum near the wall. Nouri *et al.* [12] also used a laser Doppler anemometer for measuring particle velocity in two phase flows and found that the system can be used for measurement of velocity only up to solid concentrations of 0.5% by volume. With increased solid concentration the LDA system failed due to lack of transparency in the slurry pipe line. This limit of concentration could be increased up to 15% by using a refractive index matching technique. They employed this technique for downward solid–liquid flow and observed that mean particle velocity decreases and the profile becomes flatter as the solid concentration was increased.

Altobelli *et al.* [13] used a nuclear magnetic resonance (NMR) technique for velocity measurement in two phase flow for solid concentrations upto 39% by volume. The maximum flow velocity which could be measured was 0.25 m/s. They observed that the ratio (V_{max}/V_{av}) increased with an increase in concentration upto 10% by volume. For higher concentrations, there was a continuous decline in the value of this ratio. Sinton and Chow [14] also used the NMR technique for measurement of velocity field in Poiseuille flow upto solid concentration of 52% by volume.

It is seen that techniques such as LDA and NMR have a great potential in unravelling complex flow mechanisms in slurry flow. However, as of now, these techniques have been used either for very small velocity flows and/or concentrations. These techniques, besides being expensive, are also complicated to handle. In-depth analysis of velocity measuring techniques in slurry flows show that the methods reported are either not very versatile in their use or are very expensive. In the present study, effort has been made to use a robust type of impact probe for the measurement of mixture velocity field in multi-sized particulate slurries at fairly high levels of solid concentrations, typically of those normally used in commercial applications. Some of the major considerations for the selection of the methodology for velocity measurement were:

1. The sensor should be robust and should be able to sense the velocity with reasonable accuracy.
2. The size of the sensing head should be small but still large enough as compared to the largest solid particles so as to avoid blockage.
3. The sensor should not have sharp bends as these are prone to blockage.
4. The differential pressure should be sensed at the same location as far as possible.
5. The sensor should be simple in design, easy to operate, should have the capability to operate at high solid concentrations and should retain its calibration.
6. The probe should be suitable for multi-sized particulate slurries with the particle sizes varying over more than three orders of magnitude.

A two hole offset probe (generally used in the measurement of velocity in chimneys, with simultaneous collection of air samples in the chimneys for chemical analysis) has been modified and adopted in the present study as a sensor to sense the differential pressure for measurement of local mixture velocity.

2. Experimental set-up and test section

The pilot plant test loop was a closed loop of 105 mm diameter pipe having a length of 60 m, a mixing tank with stirrer arrangement and different test fixtures [see Figure 1(a)]. The pilot plant has been described in detail by Mishra [15]. The slurry was prepared in the hopper shaped mixing tank which was provided with a suitable stirring arrangement for keeping slurry well mixed during the operation. The slurry was pumped from this tank into the 105 mm diameter pipe loop by means of a slurry pump having Ni-hard casing (Wilfley, Model 100K), coupled to a 50 HP motor through a pulley belt drive system. The flow rate of the slurry in the pipeline could be varied over a wide range by suitably operating the plug valves provided in the main pipe of the test loop as well as the bypass. After circulation through the pipe loop, the slurry could be diverted either to the mixing tank or to a measuring tank. The rate of flow was ascertained by measuring the rise in the level of the slurry in the measuring tank collected over a known interval of time. An agitator has also been provided in the measuring tank to keep the slurry in a properly mixed state. For continuous monitoring of the flow rate, a precalibrated electro-magnetic flow meter is installed in the vertical section of the pipe as shown in Figure 1(a). A transparent observation chamber was provided in the pipe loop to visually observe the movement of particles near the bottom of the pipeline. This allowed the estimation of the deposition velocity without disturbing the flow. The concentration of the slurry flowing through the pipeline was monitored by collecting efflux samples through the density sampler [Figure 1(a)] provided in the vertical section of the pipeline near the discharge end.

Figure 1(b) gives the details of the test section fabricated, and comprises a galvanized iron pipe line of 105 NB diameter, 500 mm long, fitted with two grooved flanges, two standard flanges, struts and O-rings etc. The G.I. pipe piece was fitted in the grooved flanges which in turn were fixed with standard flanges. Before fixing the flanges, O-rings were provided in the grooved flanges and the pipe to make a leak proof joint. This arrangement permitted the rotation of the pipe piece allowing the traversing of the velocity probe along different diametrical planes of the pipe. Struts were provided for fixing the test section in a particular

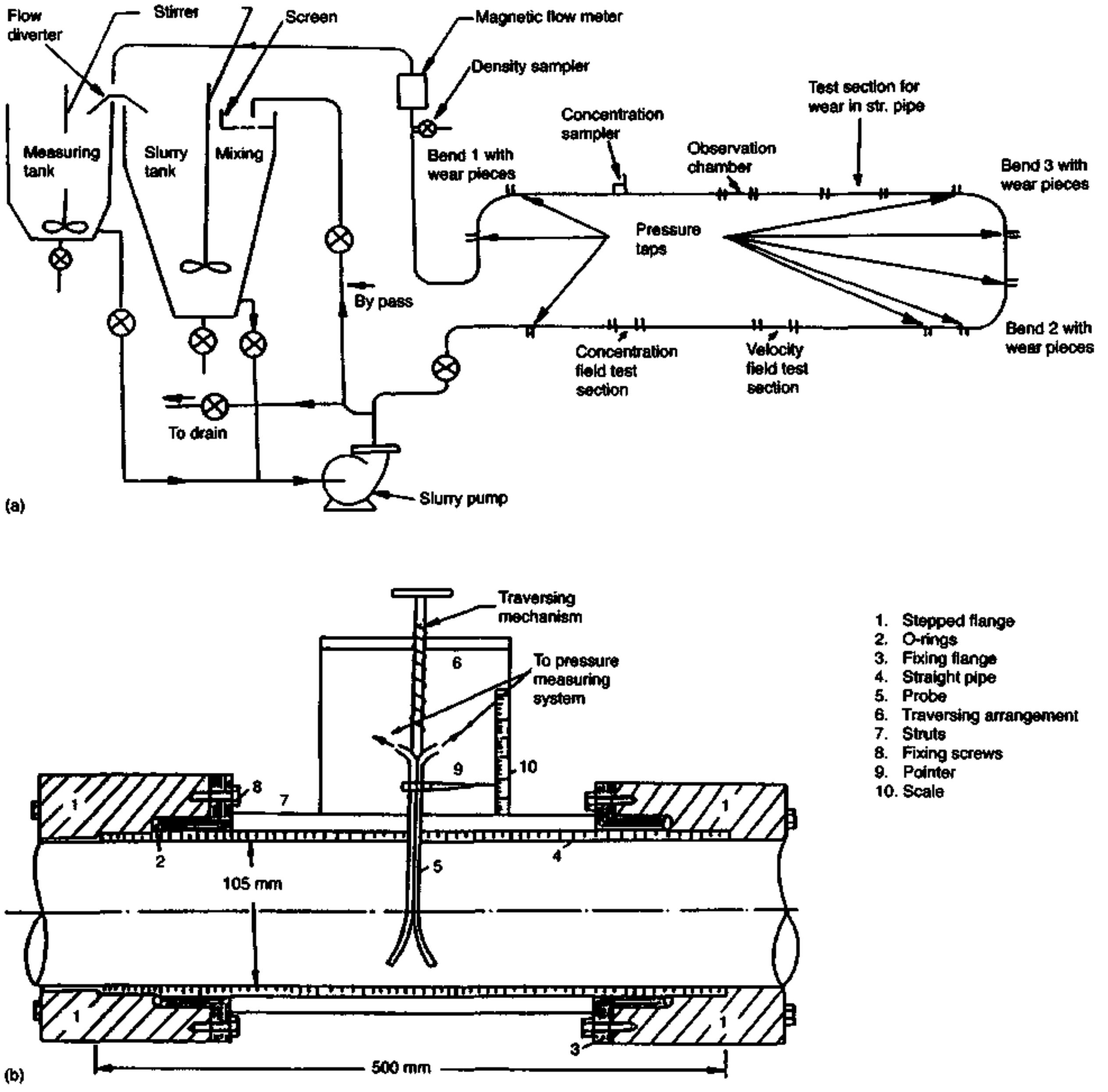

Figure 1 (a) Schematic diagram of the pilot plant test loop. (b) Schematic diagram of the test fixture for velocity measurement

orientation. For holding the probe in position, a supporting frame was fixed as shown in Figure 1(b) which could be rotated along with the pipe test section. A scale was also provided along the lead screw to locate the position of the sensing head of the probe accurately. Another scale (protractor) was fixed with the grooved flange to adjust exactly the plane of measurement. This test section was fitted in the straight portion of the pilot plant loop far away from any disturbances in upstream (150 diameter) and downstream (50 diameter) directions [Figure 1(a)].

3. Impact probe, pressure measuring system and calibration

The probe has been fabricated by soldering two stainless steel tubes of 3 mm internal diameter side by side. The ends of the two tubes were bent by 90° in opposite directions and cut parallel to the outer surfaces of the two tubes. The two openings thus created had major and minor diameters of 4 mm and 3 mm, respectively. The dimensional details of the probe are given in Figure 2. Since the impact probes in solid–liquid mixtures are susceptible to blockage, a methodology for the measurement of the differential pressure was developed and used in the present study. Figure 2 also gives details of the pressure measuring system. The improvised pressure measuring system includes an inverted U-tube differential manometer, high pressure water source, flow direction indicating devices and valves (V_1 and V_2).

The modified probe along with the pressure measuring system was calibrated against a standard Pitot-static tube in clear water flow. Valves V_1 and V_2 were kept closed during calibration. The velocity at the point of measurement is related to the differential pressure indicated by the probe by

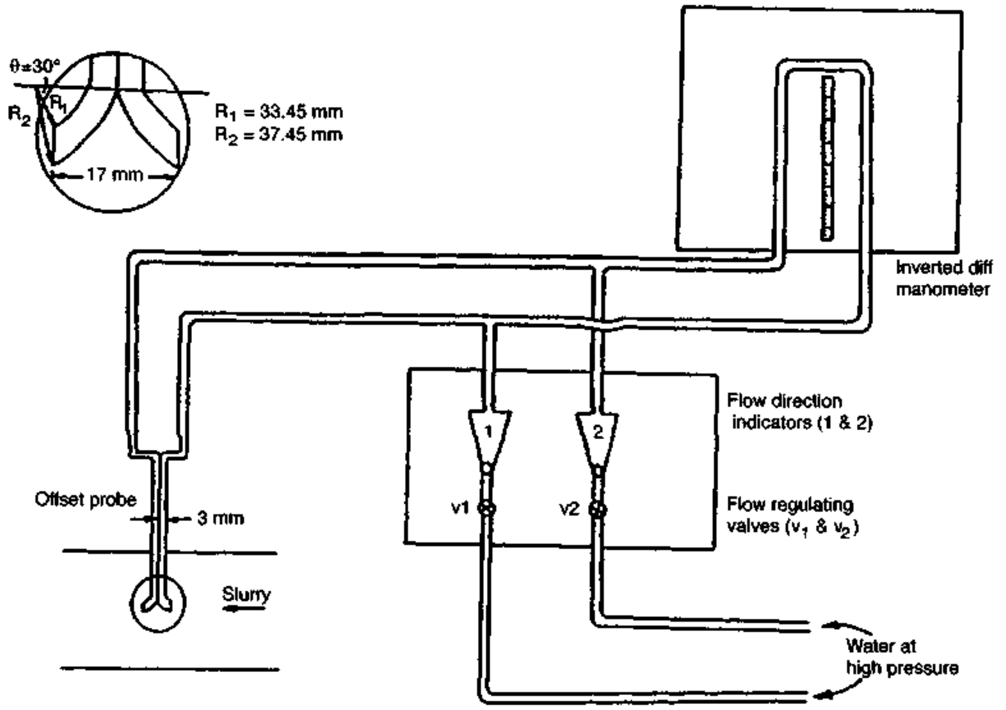

Figure 2 Schematic diagram of the measuring system for slurry velocity

$$V = K\sqrt{2g\Delta h_w} \quad (1)$$

where K is the probe coefficient.

The two hole offset probe was calibrated with water as the fluid medium against a standard Pitot-static tube in a 105 mm pipeline to determine the probe coefficient. The sensing head of the Pitot static tube and upstream sensing head of the two hole offset probe were kept at equal distance (11 mm) from the centre line of the pipe in the same diametrical plane. This was done to avoid interference between the probes while still allowing measurement of the same velocity. The range of velocities covered during calibration was from 0.77 m/s to 4.41 m/s. Figure 3 gives the calibration curve for the two hole offset probe. The average value of the probe coefficient (K) at different velocities was determined as 0.847 with a standard deviation of 0.009. The values of the probe coefficient at various velocities lie within ± 1% of the average value of the probe coefficient (Figure 3). After calibration, the probe was traversed across the diameter of the 105 mm pipe to determine the velocity profile for clear water flow. Figure 4 depicts the normalized velocity profile at three different flow rates (average flow velocities being 1.67 m/s, 2.31 m/s and 2.95 m/s). The profiles at all three flow rates merge into one curve. The Reynolds numbers corresponding to the three flow rates were from 1.75×10^5, 2.42×10^5 and 3.1×10^5. The ratio of the average flow velocity to maximum velocity was measured as 0.820, which agrees well with the values quoted in standard text books (Schlichting [16]). Further, the flow rate obtained by the integration of the velocity profile was within ± 2% of the actual flow rates as measured by the direct volumetric method (Table 1).

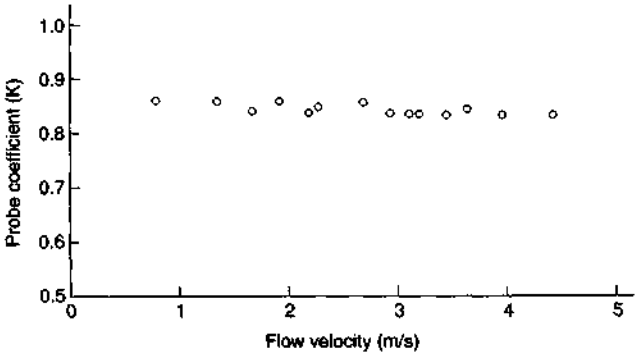

Figure 3 Variation of the probe coefficient as a function of flow velocity

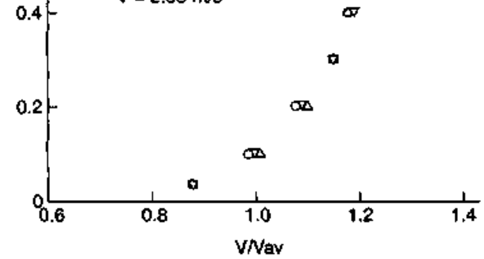

Figure 4 Velocity profile in 105 mm pipe for water flow at different flow velocities

Table 1 Comparison between measured flow rate (magnetic flow meter) and computed flow rate using velocity area method for clear water and slurry flow

S. No.	Efflux concentration (% by weight)	Measured flow rate (m^3/h)	Computed flow rate (m^3/h)
1	0.0	52	53.04
2	0.0	72	73.30
3	0.0	92	93.63
4	8.78	52	51.37
5	8.85	72	71.78
6	8.57	92	92.06
7	19.91	52	52.34
8	22.47	72	72.84
9	20.55	92	93.21
10	31.88	52	52.75
11	30.31	72	73.25
12	30.31	92	93.56
13	39.25	52	52.56
14	40.23	72	73.40
15	38.8	92	93.56

For measurement of the slurry velocity, valves V_1 and V_2 were first kept open and the high pressure water source was adjusted to pressurize the probe and the manometer limbs. A small amount of back flow (purging flow) was maintained through the probe. For this purpose, flow indicating devices were installed downstream of valves V_1 and V_2 to make sure that the pressure from the external source was slightly more than the pressure which the impact probe was subjected to by the solid–liquid flow. Flow direction indicators have a shape similar to a rotameter and were fabricated out of transparent perspex sheet. The inner diameter of the tube increased from 3 mm to 6 mm over a length of 40 mm, and has a float for indicating the direction of flow. These also act as non-return valves. This arrangement prevented the entry of solid particles into the probe. Extra care was taken to ensure that connections were leak proof. After adjusting the location of the impact probe for velocity measurement of slurry in the pipe, both valves V_1 and V_2 were closed to cut off the external pressure supply to the probe and manometer. This resulted in release of the locked-in pressure of the manometer which prohibited the solid particles from entering into the probe. After equilibrium was reached, the difference in the levels of the manometric fluid (water) in the two limbs was measured which corresponded to the local slurry velocity.

The velocity at any point in the pipe cross-section for slurry flow (V_{slurry})is evaluated from the equation

$$V_{slurry} = K\sqrt{2g(\rho_w/\rho_s)\Delta h_w} \quad (2)$$

The local slurry density (ρ_s) is obtained from the solid concentration measurements done through a specifically designed sampling tube under near isokinetic conditions [15]. In these measurements K is assumed to be a constant and independent of slurry density, and has been experimentally verified as described subsequently in the paper.

4. Material properties, range of parameters and accuracy

The information available in the literature about the velocity field in horizontal slurry flow is very limited. The objective of the present study was to measure the velocity field in the pipe flow of multi-sized particulate slurries to understand the flow mechanics and generate a database which will be helpful in the development of better flow models for designing slurry pipelines. The slurry used in the present study was prepared by mixing copper tailings (waste material after the extraction of copper from the ore) obtained from a processing plant with water. The physical properties of the solid and rheological properties of the slurry are given in Tables 2–6. The overall specific gravity of the solid was 2.82 and the maximum particle size was 0.85 mm with a continuous size distribution below this value (see Tables 2–6) with d_{50} = 71 μm. The static settled concentration of the slurry was measured as 58.67% by weight and the suspensions were found to be Newtonian up to a concentration of 40% by weight.

The velocity field in the slurry pipeline has been measured for various combinations of flow rates and efflux concentrations. Efflux concentration was varied between 8.57% and 40.23% by weight, which was wide enough to cover the normal operating range of a slurry pipeline. The selection of flow rates was based on the expected solid distribution pattern in the pipe transporting slurry. The lowest flow velocity of 1.67 m/s was quite close to the deposition velocity of 1.60 m/s and was expected to give a highly skewed distribution of solids and hence vital information on the effect of such a distribution pattern on he velocity profile may be obtained. Experiments were performed at two higher velocities for each concentration namely, 2.31 m/s which is about 0.7 m/s above the deposition velocity and 2.95 m/s at which solid particles are expected to be more uniformly distributed. The choice of the above mentioned flow rates ensured measurement of the velocity profile in widely varying flow conditions characterized by different patterns of solid particle distribution.

For each combination of flow rate and efflux concentration, velocity profile was measured along four diametrical planes namely vertical, horizontal and two 45° planes. Along any diametric plane, velocity was measured at 10 radial locations and hence data on mixture velocity was obtained at 40 locations across the pipe cross-section at any given flow condition. Measurements were made with the impact probe and the probe coefficient was assumed to be same in both water and slurry as it was not possible to calibrate the probe in slurry flow. Hence, it was essential to establish the accuracy of this assumption for slurry flows. It is to be noted that in the slurry flow the velocity field is not axisymmetric. From the measured velocity field at 40 locations, flow rate was evaluated by integrating the measured velocity profiles using the software package "SURFER" with velocity being taken as zero at the pipe wall. For analysing the present data a 25 × 25 grid was selected for accurate interpolation and the grid locations falling outside the pipe cross-section were blanked out. These computed flow rates were compared with the flow

Table 2 Properties of the solid material. (1) Overall specific gravity of solids: 2.82; (2) specific gravity of different size fractions

B.S. Mesh size	+ 52	− 52 + 100	− 100 + 200	− 200
Specific gravity	2.84	2.82	2.80	2.76

Table 3 Specific gravity of slurry at various concentrations

Concentration (% weight)	10	20	30	40	50
Specific gravity	1.07	1.15	1.24	1.35	1.48

Table 4 Particle size distribution

Particle size (μm)	850	600	300	210	150	106	75	53	48	31	16	8
% Finer	100	99.6	97.36	90.83	80.64	71.24	52.01	40.5	37.62	32.42	16.61	4.07

Table 5 Static settled concentration

Time (min)	0	1	2	5	8	12	25	60	120	250	2640
Settled concentration (% weight)	25.9	26.95	27.69	30.54	33.37	37.89	49.9	56.62	58.67	58.67	58.67

Table 6 Rheological parameters of the slurry

C_w (%)	T (°C)	Viscosity of slurry (cp)	Viscosity of water (cp)	Relative Viscosity	Remarks
0	19	—	1.03	1.0	Newtonian
10	19	1.141	1.03	1.108	Newtonian
20	19	1.271	1.03	1.234	Newtonian
30	19	1.509	1.03	1.465	Newtonian
40	19	1.982	1.03	1.924	Newtonian

rates measured from the precalibrated electro-magnetic flow meter. Table 1 compares these flow rates at different efflux concentrations and flow velocities. The minimum deviation of 0.06% between the two flow rates is observed at the lowest efflux concentration (8.57% by weight) and at a maximum flow velocity of 2.95 m/s. The maximum deviation of 1.97% is found at the highest efflux concentration (40.23% by weight) and at a velocity of 2.31 m/s. The deviations are random and of the same order of magnitude as the accuracy of calibration of the electro-magnetic flow meter. Hence, it can be concluded that the proposed methodology is capable of measuring slurry velocity with reasonable accuracy.

Having established independently the accuracy of velocity measurement using the measured local concentration, it is desirable to establish the accuracy of concentration measurement also. To achieve this the efflux concentration has been calculated from the measured concentration and velocity fields and compared with measured efflux concentration. The efflux concentration is calculated by the relation

$$C_{\mathrm{eff}} = \int_{\mathrm{AREA}} c(x,y)\,V_s(x,y)\,\mathrm{d}x\,\mathrm{d}y/Q \qquad (3)$$

where c is the local concentration and V_s is the local solid velocity. In this expression, local mixture velocity has been used as the velocity of the solids. The measured values of local *in-situ* concentrations and mixture velocities were multiplied over a grid of 25 × 25 after blanking out the grid locations falling outside the pipe cross-section. The computed flux values were again numerically integrated, using software package "SURFER". The computed and the measured values of efflux concentrations are given in Table 7. It is seen that computed values of efflux concentration are reasonably close to the measured values over the entire range of efflux concentrations and flow velocities. The deviations observed are within the experimental uncertainties and accuracy of numerical integration. Hence, it can be concluded that both concentration sampler and velocity measuring system are capable of measuring local concentration and flow velocity with reasonable accuracy.

5. Results and discussion

Mixture velocity field measurements have been made along four planes for four solid concentrations at three velocities. Detailed presentation of the experimental

Table 7 Comparison between measured efflux concentration and computed efflux concentration from the measured concentration and velocity profiles

S. No.	Measured efflux concentration (% by weight)	Computed efflux concentration (% by weight)
1	8.78	8.77
2	8.85	8.97
3	8.57	8.73
4	19.91	20.76
5	22.47	23.47
6	20.55	20.83
7	31.88	33.09
8	30.31	31.21
9	30.31	31.28
10	39.25	40.30
11	40.23	41.70
12	38.8	40.39

data is available elsewhere [15]. For brevity, velocity profiles are presented only for the lowest and the highest concentrations at all three velocities (Figures 5 and 6). Figure 5 shows the velocity profiles along different planes at an efflux concentration of 8.78% by weight. It was observed that the measured velocities along 45° and 135° degree planes at corresponding locations were almost identical hence the average values of both have been plotted at various elevations. Therefore, velocity profiles along three planes namely, vertical, horizontal and average of the 45° and 135° plane have been plotted. It is seen that the velocity profile along the mid-vertical plane for the lowest flow rate [Figure 5(a)] is highly asymmetric. The velocity close to the bottom wall is considerably lower than that at the corresponding location near the top wall. The peak velocity is slightly shifted from the pipe centre towards the top. The velocity profile along the 45° plane is also asymmetric but the extent of asymmetry is reduced. The velocity profile along the horizontal plane is, as expected, symmetric. Three distinct profiles along three different diameters at the same cross-section of the pipe can be explained on the basis of different patterns of solid distribution along the three planes. The corresponding concentration profiles are shown in Figure 6(a). The concentration at the bottom is very high (32% by weight) which increases both the local density and viscosity of the mixture. This results in the retardation of flow close to the bottom wall. The increased concentration at the bottom also reduces the effective area of flow forcing the flow to shift upwards. This results in the skewness of the vertical velocity profiles. Similar results have been obtained by many investigators [2,6,17] for slurries with narrow particle size distribution. Along the 45° plane the extent of asymmetry has reduced because concentration gradients along that plane are not so pronounced. The concentration along the horizontal plane is almost uniform and this is the reason for the symmetric velocity profile along this plane. Another important feature which can be seen is that the ratio of maximum local velocity to the average velocity at this efflux concentration is 1.26, whereas for clear water flow this ratio is approximately 1.22 for the same flow rate. This increase may also be due to an increase in bottom concentration and increased viscosity of the mixture. Similar findings have been reported by Roco and Shook [17]. Figure 5(b) depicts the velocity profiles along different planes at an average velocity of 2.31 m/s at almost the same efflux concentration (C_w = 8.85%). The figure indicates the nature of the curve to be more or less similar to the one observed at lower velocity. Closer observation shows that the extent of asymmetry along the vertical plane has reduced. Along the 45° plane similar behaviour is observed. This is expected if one sees the

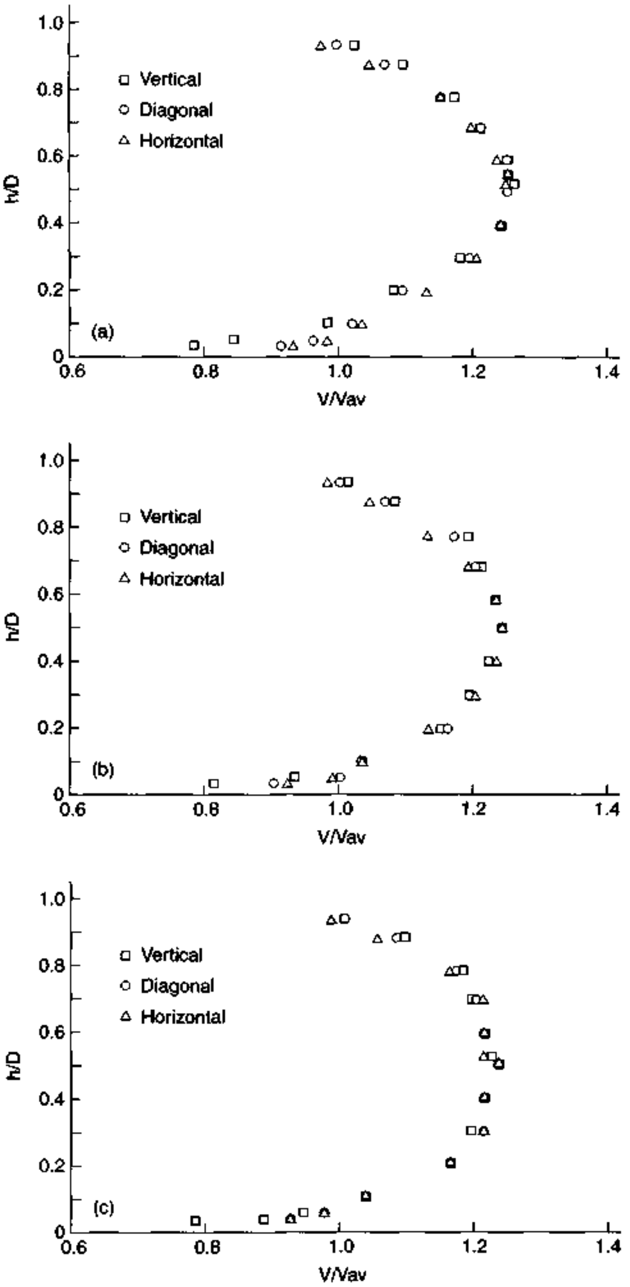

Figure 5 (a) Velocity profile along different planes at an average flow velocity of 1.67 m/s for an efflux concentration of 8.87%. (b) Velocity profile along different planes at an average flow velocity of 2.31 m/s for an efflux concentration of 8.85%. (c) Velocity profile along different planes at an average flow velocity of 2.95 m/s for an efflux concentration of 8.57%

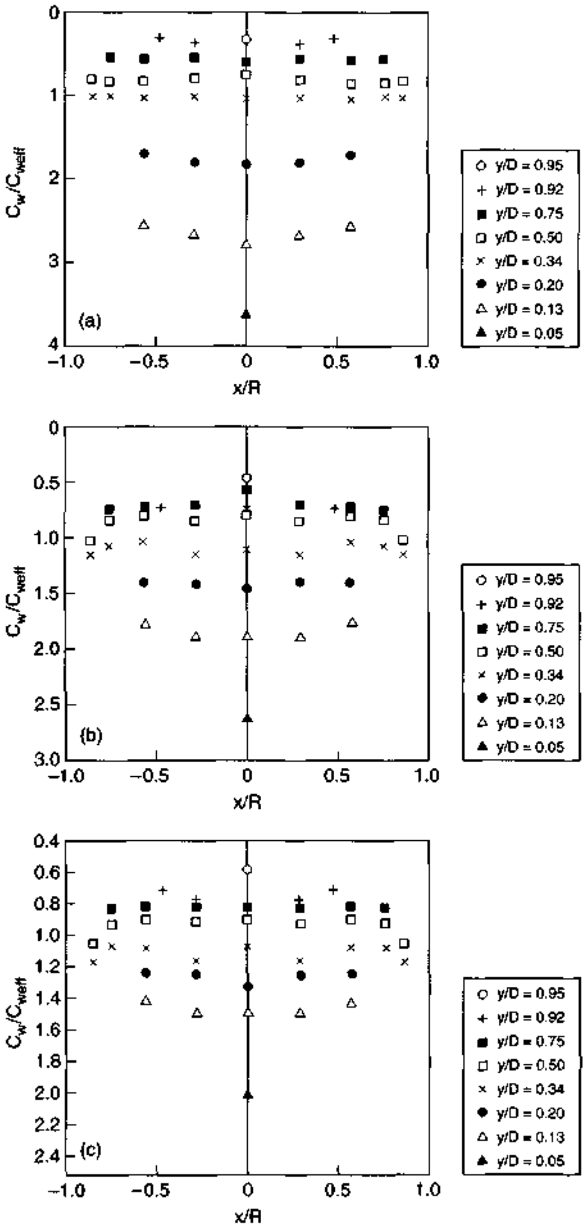

Figure 6 (a) Overall concentration field at an average flow velocity of 1.67 m/s for an efflux concentration of 8.78% (by weight). (b) Overall concentration field at an average flow velocity of 2.31 m/s for an efflux concentration of 8.85% (by weight). (c) Overall concentration field at an average flow velocity of 2.95 m/s for an efflux concentration of 8.57% (by weight)

change in concentration profile [Figure 6(b)]. For increased flow rate the extent in skewness of the concentration profile decreases which results in a reduction of asymmetry in the velocity profile. The location of peak velocity also shifts towards the centre. Similar observations have been reported by Newitt *et al.* [2], El Masry and El Halawany [6] and Roco and Shook [17] for slurries with narrow particle size distribution. The ratio of maximum velocity to average velocity has also reduced from 1.26 to 1.24 but is still higher than that for clear water flow. Figure 5(c) depicts velocity profiles at almost the same efflux concentration (C_w = 8.57%) for the highest flow rate (V_{av} = 2.95 m/s). The nature of the velocity profile is also similar to that for the lowest flow rate but the extent of asymmetry has more or less disappeared even along the vertical plane. This can be attributed to a more uniform concentration distribution at this flow rate [Figure 6(c)]. The value of (V_{max}/V_{av}) is equal to 1.23 which is reasonably close to that for clear water flow and this small change can be attributed to a fall in Reynolds number due to a change in density and viscosity of the suspension.

The maximum concentration upto which experiments were performed was approximately 40% by weight. These values are approximately 70% of the static settled concentration of the slurry. The velocity profiles at these efflux concentrations and at various flow rates [Figure 7(a–c)] are similar to those observed in the case of lower efflux concentrations. A closer look at the vertical velocity profiles however indicates that *although* (V_{max}/V_{av}) *value has increased at all flow* rates as compared to the values obtained at lower efflux concentrations at corresponding flow rates, the point of maximum velocity has shifted slightly towards pipe centre. This means that after the bottom concentration reaches a constant value, due to a decrease in heterogeneity of the concentration profile, the point of maximum velocity does not move further away from the pipe centre. Profiles along the 45° and horizontal plane also show similar behaviour for the maximum value of local velocity. The reason for this may be due to the increase in the viscosity of the suspension.

6. Concluding remarks

An impact probe (two-hole offset probe) with a modified pressure measuring system has been designed, fabricated and successfully used for measuring velocity field in slurry pipelines. The instrument developed is robust and can measure local velocities for solid–liquid mixtures with an overall accuracy of better than ± 2%. The measurements have revealed some special features of velocity distribution in the flow of multi-sized particulate slurries.

7. Nomenclature

C_w	concentration by weight, %
C_{weff}	efflux concentration by weight, %
d_{50}	median particle size, m
D	diameter of the pipe, m
g	acceleration due to gravity, m/s^2
h	distance along any diametrical plane from lower surface of the pipe, m (for a horizontal plane, the distance is from the outer surface)
Δh_w	differential pressure in meters of the water column
R	radius of the pipe, m
V	local flow velocity, m/s
V_{av}	average flow velocity, m/s
V_{max}	maximum flow velocity, m/s
x	distance along any horizontal chord from the vertical diameter, m
y	distance along the vertical diameter from the bottom of the pipe, m
ρ_w	density of the liquid, kg/m^3
ρ_s	density of the solid particles, kg/m^3

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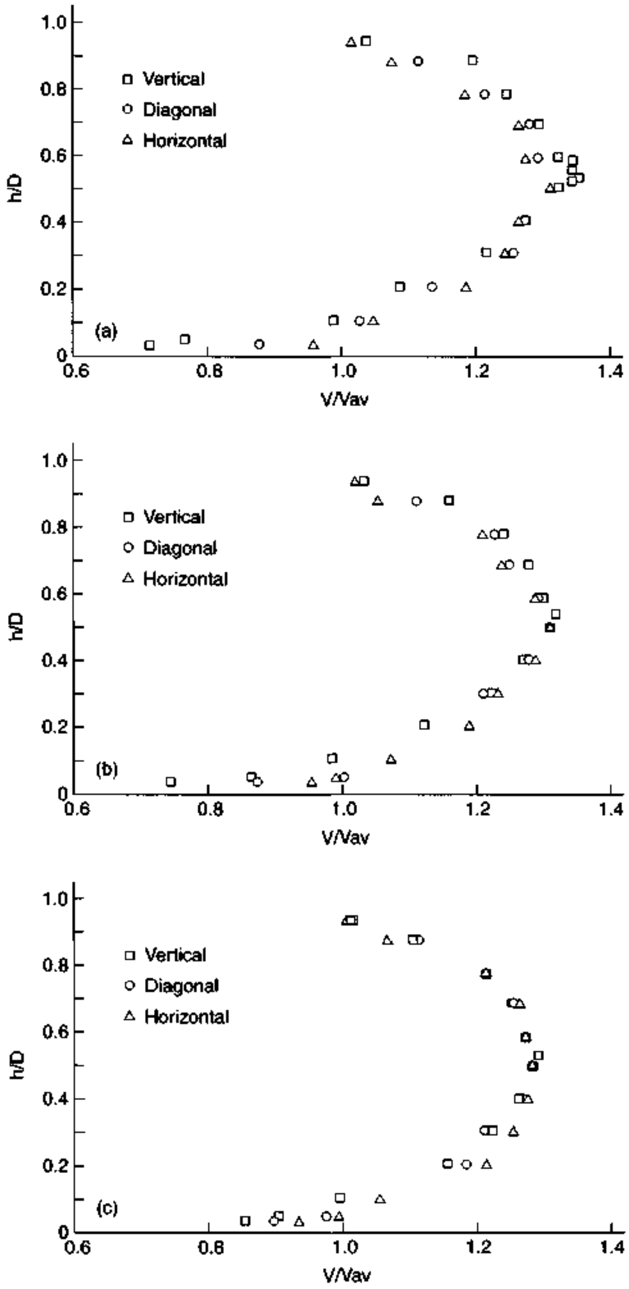

Figure 7 (a) Velocity profile along diffrent planes at an average flow velocity of 1.67 m/s for an efflux concentration of 39.25%. (b) Velocity profile along different planes at an average flow velocity of 2.31 m/s for an efflux concentration of 40.23%. (c) Velocity profile along different planes at an average flow velocity of 2.95 m/s for an efflux concentration of 38.8%

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