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A system to estimate coarse particle velocities at the pipe wall in settling slurry flow

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abstract

Understanding and modelling of coarse particle (settling) slurries in laminar flow in pipes is still not complete. Better analytical procedures will enable more efficient pipeline operation which could result in significant power savings in the transport of coarse materials. The depth and velocity of the settled bed significantly affect the pressure gradients required to pump these slurries and knowledge of these parameters is of importance. Existing measurement techniques that can be used for monitoring of these complex fluid systems are either very expensive, not easy to implement or mostly used under controlled laboratory conditions. A new measurement system was developed that is capable of detecting the deposition of solids, the depth of a settled bed and the velocity of coarse particles at the pipe wall, around the pipe circumference. Particle velocities were determined by cross-correlating modulated signals from pairs of electrodes mounted flush with the pipe wall, in contact with the slurry. Tests were conducted using a mixture of acetal beads in water, at bulk velocities between 0.5 and 4 m/s. Estimated particle velocities from the cross-correlation analyses were compared with those obtained using a 30 fps video camera combined with visual inspection, and found to be within 76%, thus validating the viability of the system. Particle velocity resolution using the cross-correlation technique is limited by block size, sample rate and the measurement distance between electrode pairs. Further test work with a range of real slurries (different particle sizes, solids concentrations and rheologies) needs to be conducted, along with more extensive verification of the results, to establish the limits of the system. Initial testing and evaluation of the system, which is capable of coarse particle flow monitoring in real time, showed significant potential for development of a new commercial sliding bed detector that can be used in a wide range of industrial applications in which particles are transported hydraulically.

1. Introduction

Flow of settling slurries is still generally not well understood and as a result slurry pipelines are often conservatively operated at high velocities (turbulent flow) in order to avoid pipe blockages [1]. However, due to water scarcity and the increasing cost of power there is a desire and need to operate these pipelines at lower velocities and higher slurry concentrations and viscosities [2], often in laminar flow. As a consequence a sliding or stationary (settled) bed of coarse particles forms (see Fig. 1), which further complicates flow predictions and pipeline design. Little information is available about friction conditions in settling slurry flows with deposits. The current understanding of the flow of settling slurries with deposits is still far from complete, as limited research has been conducted [3]. Appropriate experimental data will give more insight into flow patterns and behaviours of these suspensions and can be used to determine the sliding bed depth and local velocity. This information can then be used to improve existing theoretical models or to aid in the development of new and/or simplified models for more efficient pipeline design in industrial applications.

Electrical and thermal methods have been developed over the years and used with reasonable accuracy to determine multiphase quantities, such as solids concentration profiles. However, since the phases of a multiphase flow often display different electrical and thermal properties there is no universal probe that can be applied for measuring these multiphase quantities [4,5]. Magnetic resonance imaging (MRI) and electrical resistance tomography (ERT) are techniques that can be used to determine the particle wall velocity and the bed level in settling slurry flow, but these techniques are expensive to implement, require expert operators and are not easy to integrate into an industrial situation. To overcome these problems, an alternative measuring system is needed. Such a system should be inexpensive and easy to implement, and be able to reliably and accurately measure particle velocities in these complex fluids.

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Nomenclature

bn	block number *(samples)*
bs	block size *(samples)*
f_s	sampling rate (1/*s*)
inc	step size in samples
ID	inside diameter
K	offset, offset for max ρ_{xy} in cross-correlation calculation
L	cross-correlation distance (*mm*)
N	number of points in cross-correlation window
n	sample index
q	discrete estimated time delay
s_{xx}	auto correlation of signal *x*
s_{yy}	auto correlation of signal *y*
t, t_d	time, time delay (*sec*)
U_b	pipe bulk velocity (*m/s*)
v	velocity (*m/s*)
v_p	particle (bed) velocity (*m/s*)
$\bar{x}$	mean value of sampled signal $x[n]$
$\bar{y}$	mean value of sampled signal $y[n]$
ρ_{xy}	zero mean normalised cross-correlation coefficient

Ercolani et al. [6] describe an electric probe used to detect the critical velocity for particle deposition in settling slurry flow. Whilst this instrument supplied useful information on the limit deposition velocity, this information was qualitative only and no particle velocities were determined. Brown et al. [7] developed a measurement system in which a dc voltage was applied across electrodes mounted opposite each other, flush with the pipe wall and in contact with the conducting slurry. Two pairs of sensor electrodes at a known axial separation were located in the flow between these outer electrodes, using a small intrusive sting. Non-conducting particles in the flow changed the potential difference across each pair of sensor electrodes and so modified the measured signals. By cross-correlating the modified signals from each sensor pair the transit times were determined, from which local particle velocities were calculated. Nasr-El-Din et al. [8] used a similar probe to Brown et al. [7] to measure local ***in situ*** solids concentration. They placed the field sensors on the probe itself, not in the pipe wall, and also measured the modified potential difference between the sensor electrodes. They eliminated velocity effects on the measurements by using a dual electrode–sensor pair. Their system was used to determine only slurry concentrations across the pipe cross-section—no particle velocities were found. Shook et al. [9] investigated pipe wear by using a modified version of the system of Brown et al. [7] in a rotating spool to measure particle concentrations and velocities at the pipe wall at various radial positions. Two sensor electrode pairs were located at a known axial distance apart between field electrodes. All electrodes were flush with the pipe wall. Particle velocities were determined using cross-correlation.

Simkhis et al. [10] used an array of strip electrodes around one half of a pipe circumference and a common electrode around the other half to measure local slurry electrical resistance. After calibrating the system they sequentially measured the resistance between each strip electrode and the common electrode, to research the behaviour of dunes in solid–liquid flows. From their measurements they determined the local chordal concentration which enabled them to compile dune profiles. By cross-correlating the signals from two sensors spaced 175 mm apart, dune translational velocities were estimated. These were verified by video results. Yang and Beck [11] gave useful detail on the cross-correlation technique and how they used it to measure pipeline flow velocities. They indicate how their system was made "intelligent" in that transducer selection, circuit gain, sampling frequency, pre-delay and interpolation around the cross-correlation peak were implemented. They achieved a measurement accuracy of around 1% for the flow velocity. Ilgner et al. [5] described the development of a thermal system that can detect (at the pipe invert) bed-load activity and transition to a stationary bed. The system, however, does not determine the velocity of the sliding bed.

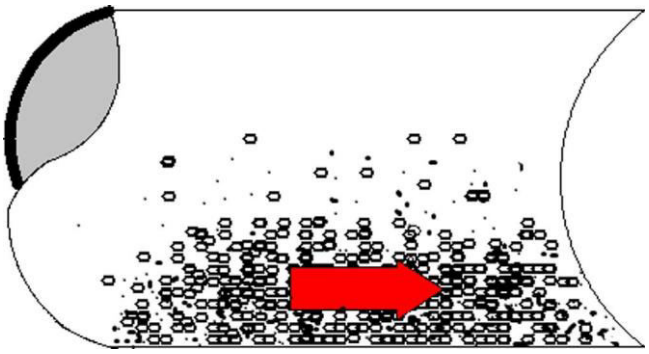

Fig. 1. Schematic showing settled bed.

From the literature it is clear that electrical conductivity methods in conjunction with the cross-correlation technique can be used successfully for particle velocity estimation in multi-phase fluid systems. However, there is still no reliable, low cost and easy to implement system available to do this, as reported in Ilgner et al. [5]. The aim of the work described in this article was to develop and evaluate a non-invasive system capable of estimating coarse particle bed depth and bed velocity gradient in settling slurry flow. A conductance based system, referred to as "deposition probes" as in Refs. [12,13], was implemented and developed at the Flow Process Research Centre (FPRC) of the Cape Peninsula University of Technology (CPUT). The system was designed to measure particle velocities at different positions around the pipe wall circumference, at slurry bulk velocities up to 4 m/s, using simple electrodes and signal processing techniques. The system was evaluated in a model fluid (water and black acetal beads) that contained some white acetal (tracer) particles for initial verification of particle velocities using a camera and visual inspection.

2. Theory

This section describes the implementation and limitations of using cross-correlation analysis in this particular application in order to obtain time delays between signals acquired from the sensors (axially separated electrode pairs).

2.1. Cross-correlation analysis

The relationship between signals from inline electrode pairs, spaced axially a short distance *L* apart, can be written as:

$$y(t) = x(t - t_d) \quad (1)$$

where $x(t)$ is the signal generated at the upstream electrode pair and $y(t)$ (a delayed version of $x(t)$) is the signal generated at the downstream electrode pair. Eq. (2) was used to calculate the

particle velocity:

$$v = L/t_d \quad (2)$$

Since the acquired signals are sampled the system becomes discrete and Eqs. (1) and (2) can be written as Eqs. (3) and (4) respectively:

$$y[n] = x[n-q] \quad (3)$$

$$v = Lf_s/q \quad (4)$$

Cross-correlation enables the determination of the similarity of two signals separated by a time delay, using multiplication to compare the linear relationship between two variables [14]. In signal processing, data lengths are finite, so the correlation process is an estimation [15]. In this application, the velocity of the conveyed coarse particles (at any of the given radial positions) was estimated by using cross-correlation to determine the delay between the voltage time series $x[n]$ from the first electrode pair and the voltage time series $y[n]$ from the second electrode pair (n being the sample index). The calculation required sliding a windowed portion of one sequence over the other to find the time delay t_d at which the correlation is a maximum. For sampled data, the zero mean normalised cross-correlation coefficient ρ_{xy} ($-1 \le \rho_{xy} \le 1$) is given by Eq. (5):

$$\rho_{xy}[k] = \frac{1}{N}\sum_{n=0}^{N-1} \frac{x[n]-\bar{x}}{s_x} \cdot \frac{y[n+k]-\bar{y}}{s_y} \qquad k = k_{min}, \ldots, k_{max} \quad (5)$$

where the interval $[k_{min}, k_{max}]$ defines the correlation delay range and:

$$s_{xx} = \frac{1}{N}\sum_{n=0}^{N-1} (x[n]-\bar{x})(x[n]-\bar{x}) \quad (6)$$

$$s_{yy} = \frac{1}{N}\sum_{n=0}^{N-1} (y[n]-\bar{y})(y[n]-\bar{y}) \quad (7)$$

Normalising the correlation coefficient in this way removes the scale dependence on slurry concentration and carrier fluid conductivity, makes the correlation coefficients insensitive to amplifier gain settings in the data acquisition process and allows a simple threshold to be used for accepting or rejecting correlation results [14,15]. The value of k at which the peak in a plot of ρ_{xy} vs. k occurs is denoted by q, and it is related to t_d by Eq. (8), where s_e is the sampling error:

$$t_d = q/f_s + s_e \qquad (-1/f_s < s_e < 1/f_s) \quad (8)$$

If the sampling rate is high enough s_e is negligible and Eq. (8) can be approximated by Eq. (9):

$$t_d = q/f_s \quad (9)$$

The aim is therefore to find q. To do this a relatively long data block was acquired, then processed by stepping through it in increments of inc samples, doing the cross-correlation calculation for each of these smaller overlapping blocks of data until the complete acquired signal was analysed. This series of calculations gave the variation of particle velocity v_p with time. In doing this analysis Eq. (5) was applied as follows [11]:

$$\rho_{x_{bn}y_{bn}}[k] = \frac{S_{x_{bn}y_{bn}}[k]}{\sqrt{S_{x_{bn}x_{bn}} \cdot S_{y_{bn}y_{bn}}}} \quad (10)$$

$$x_{bn}[n] = x[n-(bn)(inc)] \quad \text{for } 0 \le n-(bn)(inc) < bs \quad (11)$$

$$y_{bn}[n] = y[n-(bn)(inc)] \quad \text{for } 0 \le n-(bn)(inc) < bs \quad (12)$$

$$bn = 0, 1, 2, \ldots (N-bs)/inc \ ; \ inc \le bs \quad (13)$$

The delay q_{bn} for each block is then the value of q for which $\rho_{x_{bn}y_{bn}}[k]$ is a maximum, and the velocity v_{bn} for each block is given by Eq. (14):

$$v_{bn} = Lf_s/q_{bn} \quad (14)$$

The variation of the particle (equivalently bed) velocity with time was then compiled via Eq. (14):

$$v[t_{bn}] = v_{bn} \quad (15)$$

2.2. Cross-correlation limitations

Since the system is discrete the estimated time delays can only take on discrete values which are in increments of the sampling period [14]. This means that the system is unable to detect delays that fall in-between sample points. This is the sampling error, which can be reduced by increasing the sampling rate. The percentage error PE between the estimated and actual time delay can be calculated using Eq. (16):

$$PE = ((t_d - q/f_s)/t_d) \cdot 100 \quad (16)$$

So by Eqs. (8) and (16):

$$-100/f_s t_d < PE < 100/f_s t_d \quad (17)$$

The percentage error can be defined to fall in the range $-PE_T \le PE \le PE_T$, where PE_T is the maximum tolerable percentage error so:

$$PE_T = 100/f_s t_d \quad (18)$$

Eq. (18) can be used to determine the sample rate for a given time delay and allowable percentage error. The minimum allowable sample rate of the system must at least be equal to two times the cut off frequency of the anti-aliasing filters in order to satisfy the Nyquist criteria, which is 6400 Hz. The optimum sample rate for each bulk flow rate is then determined by a percentage error that falls between the limits of 75%, however if this calculated sample rate falls below the minimum sample rate the latter must be used. From Eq. (14) it can be seen that the cross-correlation block size determines the minimum velocity the system can measure, since a measured time delay cannot be equal to or greater than the block size. Thus the system is only capable of estimating velocities greater than the limit defined by Eq. (18):

$$v_{min} = Lf_s/bs \quad (19)$$

This limitation was evaluated experimentally.

3. Experimental methods and material

3.1. Pipe loop

The FPRC pipe loop used in this work consists of a centrifugal pump with a variable speed drive (VSD), diameter 42 mm (ID) class 16 PVC pipes, a diameter 50 mm Krohne Optiflux 4000 electromagnetic flow meter, a 500 l mixing tank and the deposition probe spool pieces (see Section 3.2). The flow rate was controlled by varying the speed of the centrifugal pump via the VSD. When the desired solids concentration is reached in the pipes, the mixing tank can be bypassed and the loop run as a closed system. The pipe bulk velocity (U_b) was measured using the electromagnetic flow meter. The deposition probe spools are installed in the out leg of the loop, and are shown in Fig. 2.

3.2. Electrode configurations

Four deposition probe spools, each having four rings of electrode pairs spaced at known axial distances and radial positions around the pipe circumference, for both inline and adjacent configurations, were installed in the out leg of the pipe loop. In the adjacent configuration (Fig. 3) the electrodes (signal and common earth) are fitted side-by-side, symmetrically about each nominal radial position. In the in-line configuration (Fig. 4), at

Fig. 2. FPRC pipe test loop with deposition probe spool pieces (ID 42.6 m) [17].

each radial position the signal and common earth electrodes are respectively the 1st and 2nd, 3rd and 4th, 5th and 6th and 7th and 8th electrodes. Each electrode is made from diameter 1.6 mm grade 316 stainless steel. Two spool pieces of each configuration were developed to allow testing with variable probe spacing, required for different size coarse particles. The four spool pieces were fitted in the pipe loop at axial increments of 140 mm (Fig. 2), which allowed comparison of results between the adjacent and in-line configurations for cross-correlation distances of 10, 20, 30, 110, 120, 130, 140, 150, 160 and 170 mm.

3.3. Deposition probe system

The electronics of the deposition probe system implemented at the FPRC, CPUT, is based on information obtained from CSIRO during the P599 project [13] and is described more fully in Ref. [17]. Only minor changes were made to the circuits, but the data acquisition and analysis software was re-written completely, using both LabView^{s} and Matlab^{s}. A common 58 kHz sinusoidal carrier signal is applied to each signal/common earth electrode pair. The impedance of the mixture between the electrodes creates the electrical load/channel, and the voltage across this load is measured. The concentration and structure (size and packing) of the non-conducting particles flowing past the electrode pair varies this impedance, which amplitude modulates the measured signal. The modulated, rectified, filtered and amplified signal from each channel is sampled and stored as a time series of voltages. The individual signals from each channel give an excellent indication of the state of particle deposition at each position, but no other information. All the acquired data are time series of potentials at different levels for each channel. Determining the velocity of coarse particles at the pipe wall was done as explained in Section 2.1, based on the assumption that the particles flow in a straight line past the axially separated electrode pairs, causing the same time delayed disturbance at each adjacent electrode pair. Data acquisition was done using two NI6070E (16 SE/8 DI, 1.25 MS/s, 12 bits) cards simultaneously and software developed in LABVIEW^{s} for online monitoring and processing of the acquired signals. This enabled real-time monitoring and visualisation of particle wall velocity and bed depth around the pipe circumference. Post processing was done using MATLAB^{s}, and was crucial in developing the system because it provided valuable insight into the behaviour of the system under different flow conditions. The system is shown schematically in Fig. 5.

3.4. Test material

For the work reported here a "model" suspension of diameter 3 mm black acetal beads (with a limited number of white acetal beads as tracers) in tap water was used. The solids content was varied arbitrarily and the flow loop was run as both an open and closed system in order to vary the depth of the bed. Specific solids concentrations were not relevant and so are not stated.

4. Results and discussion

This section presents and discusses some typical results to indicate the capability of the system and the effect of processing parameters on the estimated particle velocity. Examples of initial verification results using video are also given.

4.1. System evaluation

Figs. 6–9 show results from some of the tests. Fig. 6 shows the effect of block size on the cross-correlation calculations between two adjacent electrode pairs located at the pipe invert. The pipe invert is located at an angle of 0l in Figs. 2 and 3. If the block size is too small then randomly spaced short segments of data can correlate well, giving wildly fluctuating and significantly incorrect time delays, hence incorrect estimated velocities. This phenomena is emphasised by the vertical scale in Fig. 6. If the block size is too large then the calculated velocity is averaged too much and small but real variations in particle velocity are missed. When a suitable block size is used these small variations in the bed velocity can be captured. Block size alone though does not determine the velocity resolution, which also depends on the sampling rate, as shown in Fig. 9.

Fig. 7 shows a 0.25 s segment of data (levels adjusted to separate the plots) from which the adjacent electrode velocity plots for U_b¼4.0 m/s in Fig. 8 were determined. In Fig. 7 channel three and four are signals acquired from two adjacent electrode

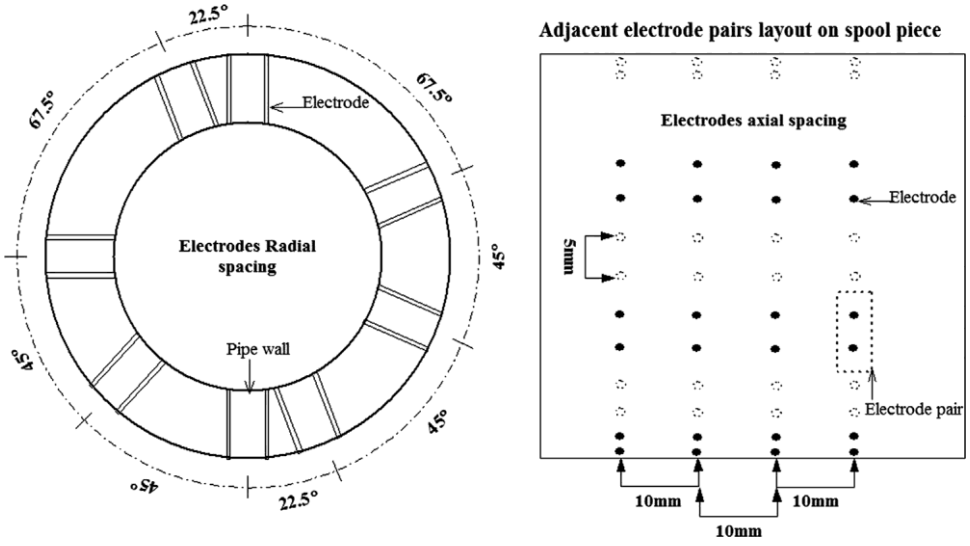

Fig. 3. Adjacent electrode pair configuration.

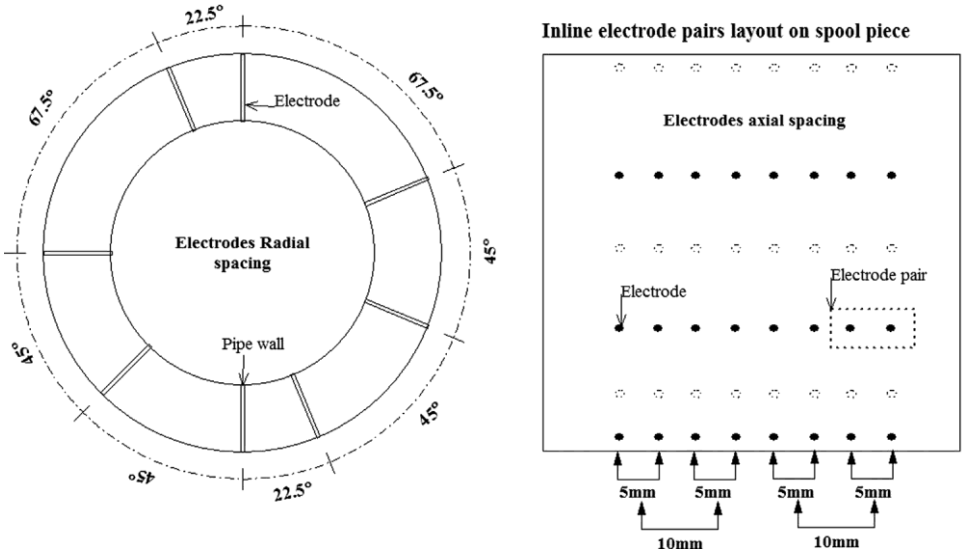

Fig. 4. Inline electrode pair configuration.

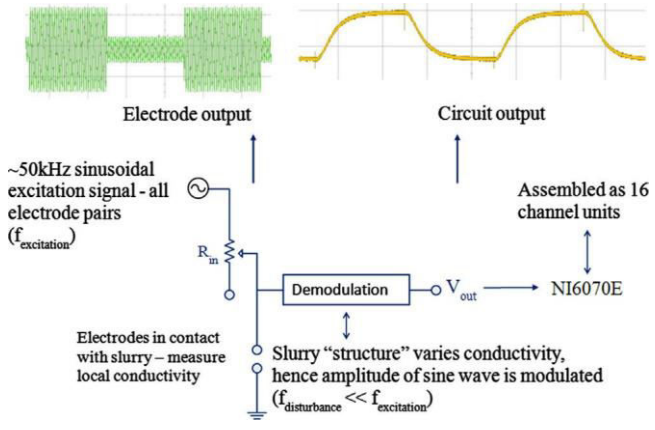

Fig. 5. Deposition probe principle of operation.

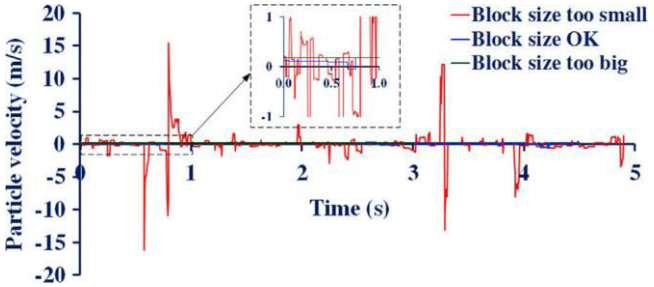

Fig. 6. Effect of block size on calculation of particle velocity—water/3 mm acetal beads at U_b¼0.5 m/s [17].

pairs and it is difficult to see any similarities between the two signals. A moving average filter (effectively a low pass filter) for each signal was therefore applied to more easily identify the similarities between the two time series. The filtered data (bold plot) are displayed on top of each raw signal (normal plot) in Fig. 7. When observing the filtered data it is clear that the two signals 'follow' (similar amplitude variations) one another after some time delay, thus validating the original assumption of particles causing the same disturbance at each adjacent electrode pair (see Section 3.3).

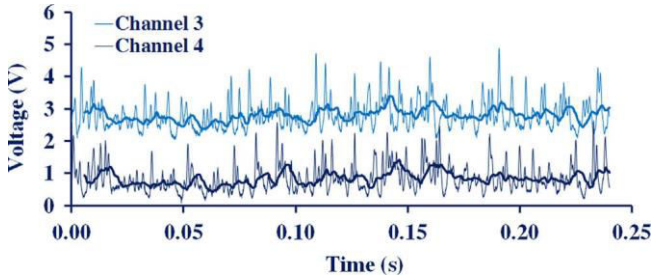

Fig. 7. Sampled data at CH3 and CH4 (adjacent, 0.25 s)—water/3 mm acetal beads at U_b¼4.0 m/s [16].

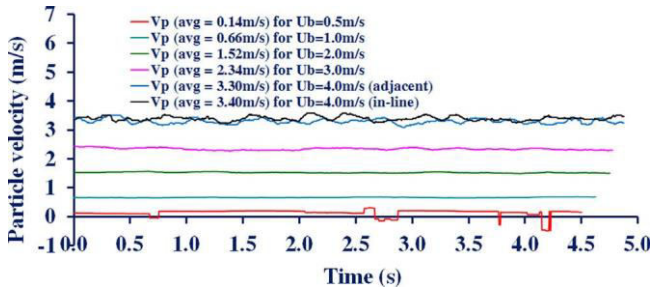

Fig. 8. Water/3 mm acetal beads: calculated particle velocities (0l) for various U_b (bs¼17,000) [6].

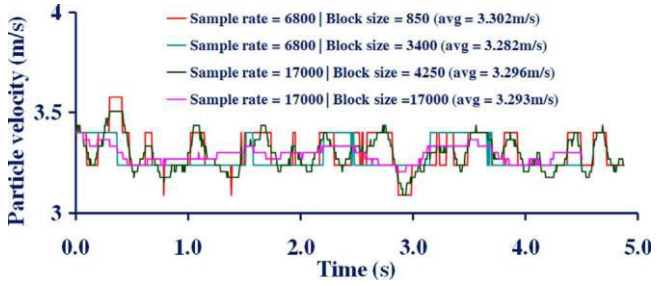

Fig. 9. Effect of sampling rate/block size on calculated particle velocity: 3 mm acetal beads in water at U_b¼4.0 m/s [7].

Fig. 8 shows particle velocities in the pipe invert (radial position of 0l) for different bulk velocities. At U_b¼0.5 m/s the bed motion was unstable and very sudden accelerations/decelerations were observed. The combination of sampling rate and blocksize used in this particular analysis was unable to correctly track the velocity over these short times. When the bed was stable a reasonable velocity was calculated, for example between 0.8 and 2.0 s. The plots for U_b¼4.0 m/s compare results from adjacent and inline probes. Since the spool pieces were spaced 140 mm apart, the estimated particle velocities would not be an exact match, but are clearly similar and give average velocities of 3.296 m/s (adjacent) and 3.396 m/s (inline), a difference of only 3%. Tests conducted at other bulk velocities gave similar results and showed that either electrode pair configuration works equally well.

Fig. 9 compares the effect of sampling rate and block size on the calculated velocities. At a higher sample rate the time step between two estimated points occur in smaller increments than at a lower sample rate (sampling error effect) and the resolution of the vertical axis decreases with the decrease in the sampling frequency. This is due to the percentage error that increases between the estimated time delay and the actual time delay as the sampling frequency is decreased. At the lower sampling rate the velocity resolution was approximately 0.17 m/s, and this improved, as expected, to 0.03 m/s at the higher sampling rate. The averaging effect of the block size is also evident in the plots.

However, the average estimated velocities for each analysis over the time period are similar, all within 0.6% of each other [16].

The sampling rate is important for a better velocity resolution. In general the higher the sampling rate the better the velocity resolution, however the higher the sampling rate the more computational expensive it is to calculate the cross-correlation function. The shorter the block size a finer time resolution can be achieved, but if the block size is too small for a given flow condition it will yield incorrect results. Selecting the optimum sample rate and block size at this moment is depended on observing the acquired signals from the sensors. Future work is required to develop a method to automate the selection of the sample rate and block size for different flow conditions; however, this was not part of the main objectives during this research work.

4.2. Dynamic response of measurement system

In order to evaluate the dynamic response of the measurement system, the pump speed was varied to produce a change of flow velocity. The bulk velocity was slowly decreased from 4 m/s to approximately 0.5 m/s and then slowly increased again over a 120 s period. Fig. 10 shows that at each radial position the system properly tracked the changes in velocity. After about 40 s, when the bulk velocity became too low to suspend particles right across the pipe cross-section, the velocity dropped to zero at the radial positions of 180l and 202.5l, and remained there for the rest of the test period. This demonstrates that the system is capable of correctly detecting when there is no particle interaction at the pipe wall.

The points labelled "*j*" in Fig. 10 could be spurious results, or could be due to some erratic, transient behaviour of the particles, which was sometimes observed at the lower flow rates. They were not investigated further in this work. Between 80 and 95 s, the region labelled "*h*" in Fig. 10, estimated velocities at all radial positions dropped to zero because v_{min} for this analysis configuration was reached.

Knowing when coarse particles begin to settle out is crucial in coarse particle pipeline flows. It is clear from Fig. 10 that the system is capable of indicating the onset of particle settling, which will provide a warning of potential pipe blockage.

4.3. Verification of measurement system

To provide some preliminary verification of estimated particle velocities a video camera (maximum 30 fps) was placed 200 mm away from the pipe, with the centre of the camera lens in-line with the 270l radial position. White and black acetal beads were inserted into the pipe loop, where the white beads were used as

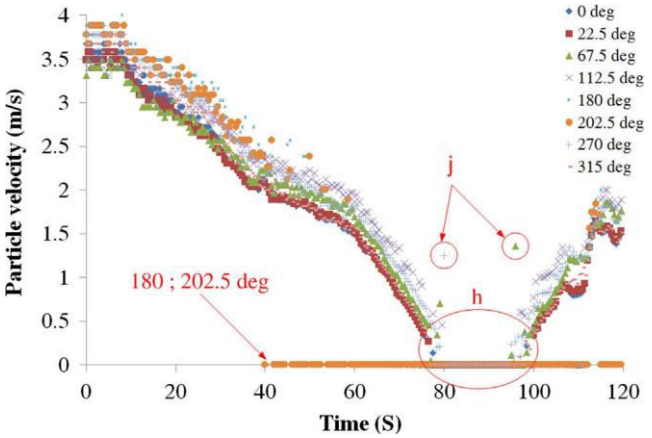

Fig. 10. Example of estimated velocities for changing flow rate.

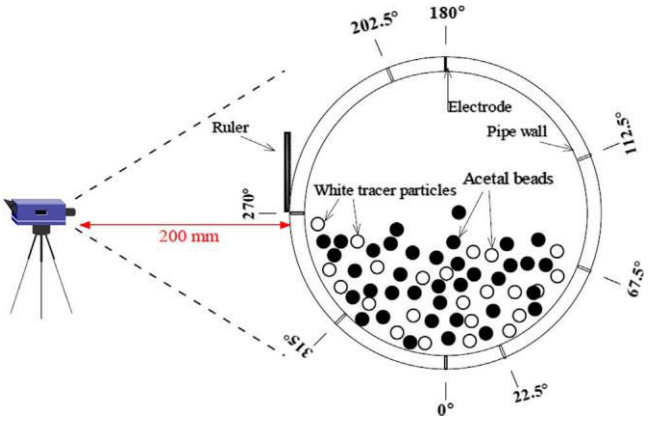

Fig. 11. Video camera measurement setup.

tracer particles. An arc between radial positions 202.5l and 315l was covered, as shown in Fig. 11. Rulers were placed above the radial positions of 270l and 315l to enable measurement of the distances travelled by the white tracer acetal beads. With the knowledge of the distance travelled and the video frame rate the particle velocity was estimated using Eq. (2).

Fig. 12 shows an example of four consecutive video frames (colours of images inverted) at the radial position 315l. The red lines were aligned with the trailing edge of a tracer particle and used to measure the distance travelled between two consecutive frames. Measurements where done between 10 consecutive frames to yield a total of eight particle velocity estimations, which were used for verifying results obtained from the deposition probe system. The elapsed time between each consecutive frame was 0.033 s and the total measurement time for this sequence was therefore 0.33 s. During tests the flow rate was kept constant and data were recorded using both methods simultaneously and over the same measurement time.

Verification results at bulk velocities of 0.58 and 0.8 m/s are presented in Tables 1 and 2, respectively. Tables 1 and 2 show the average values calculated over 0.33 s for both techniques (video and deposition probe system). Particle velocities for bulk velocities greater than 0.8 m/s could unfortunately not be compared as they were too high for the frame rate of the available video camera.

Results from the electrode measurement system and the video camera showed reasonable agreement. For all test points checked the percentage difference was within 76%, which indicates that the deposition probe system can determine particle velocities at the pipe wall with acceptable accuracy. However, verification tests were only done at two (low) bulk velocities, with a slow video frame rate, and deposition probe results depend on sampling rate and cross-correlation block size. Further more extensive verification tests using a high speed camera must be done.

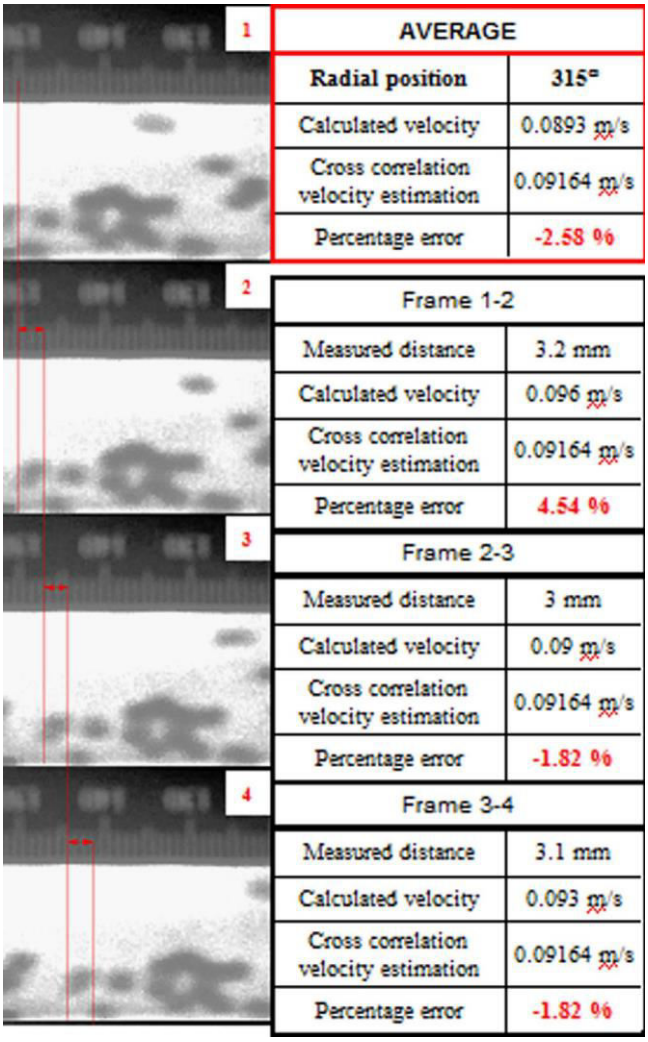

Fig. 12. Video camera verification of estimated particle velocity (U_b¼0.36 m/s). (For interpretation of references to colour in this figure, the reader is referred to the web version of this article.)

Table 1
Video verification of deposition probe particle velocity estimations for U_b¼0.58 m/s.

Radial position	270l	315l
Video velocity	0.350	0.291
Electrodes velocity	0.362	0.295
% difference	−3.43	−1.37

Table 2
Video verification of deposition probe particle velocity estimations for U_b¼0.8 m/s.

Radial position	270l	315l
Video velocity	0.775	0.516
Electrodes velocity	0.819	0.533
% difference	−5.68	−3.29

5. Conclusions and recommendations

The aim of the project was to develop and implement a system that can reliably determine the velocity of particles in a settled bed and in partially suspended (stratified) flow, around the pipe wall circumference, at bulk velocities up to 4 m/s. The system is conductivity based and relies on the assumptions that over the measurement distance the structure of the slurry remains constant and that the particles are non-conducting. For the slurries and flow regimes of interest these assumptions are reasonable. Theoretical analysis and experimental results showed how the accuracy and resolution of the system, and the minimum velocity that can be measured, depend on the sample rate and cross-correlation block size. The system was found to be capable of detecting initial settling of coarse particles as well as the depth of a settled bed. This showed that the system can be used in industrial pipelines as an early warning system to indicate both critical deposition velocity and the build up of a settled bed which could indicate pipe blockage. Results obtained from the two different

electrode configurations yielded similar results under the same flow conditions and it was concluded that one configuration works just as well as the other. Initial verification tests showed that all velocity estimates from cross correlation agreed to within 76% of those derived from analysis of video frames.

The system is capable of real-time particle velocity monitoring around the pipe circumference, and shows potential for the development of an in-line measurement system that can monitor coarse particle flow and concentration distributions in settling slurry flow under dynamic flow conditions.

However, further work is required to fully reach the potential of the deposition probe system. This should include increasing the update rate of the online velocity estimations, simplifying the user interface, incorporation of interpolation into the analysis to minimise physical sampling rates and data storage, automatic choice of sampling rates and block sizes, gains and pre-delay and a feedback loop for automatic flow rate control based on the particles settling behaviour. Minor modifications to the electronic circuits could also enable determination of mixture concentration profiles that can be used for more accurate monitoring of complex slurry flows. Moreover, a range of real slurries covering different particle sizes and fluid properties (rheological behaviour) need to be tested using the deposition probe system in order to establish its performance and limits of operation. In parallel with these improvements extensive verification tests using a high speed camera or alternative techniques will have to be done. Such modifications and improvements to the deposition probe system could result in a new cost-effective, easy to implement, robust and accurate instrument for in-line flow measurements of coarse particle suspensions.

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