INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

Experimental investigation of Slurry flow

University of Leeds , 2 months internship
CZ.1.07/2.3.00/20.0139
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Contents

Host organisation

The most recent National Research Assessment Exercise confirmed that the University of Leeds is one of the most research intensive Universities and a leading member of the Russell Group of research intensive United Kingdom Universities. The School of Chemical and Process Engineering (SCAPE) is one of the largest integrated multidisciplinary engineering schools in Europe and was ranked 3rd in its subject category in the UK after Oxford and Cambridge in the 2008 Research Assessment Exercise (RAE). The Institute currently has an enrolment of 62 postgraduate students, 17 academic staff and a number of research fellows. Research activities within the School are organised into the following three research institutes: Energy Research Institute; Institute for Materials Research; Institute of Particle Science and Engineering. SCAPE also contributes to work in the Centre for Computational Fluid Dynamics, which has the most up-to-date CFD computing facilities. Currently, a Centre for Doctoral Training in Fluid Dynamics at the University is supported by the Engineering and Physical Sciences Research Council and University of Leeds, which makes it an excellent environment for the fellow's research in the area of fluid dynamics (PIV, EIT, CFD).

On-Line Instrumentation Laboratory

(OLIL) is the Research Group of Professor Mi Wang of Institute of Particle Science & Engineering. The current research interests of the group are in developments of Process tomography including instrumentation, algorithm and sensors; Colloid vibration potential imaging based on energy conversion and spectrum analysis due to colloidal vibration and Applications of these new technologies for multidimensional visualisation and characterisation of multiphase fluids and flows in research and engineering. As the nature of the research, the group has a multi-disciplinary background in Physics, Electronics, Biochemistry, Colloidal, Chemical and Flow Engineering.

The objectives of the group is to 'open up new dimensions' - enabling engineers to visualise materials and their physical and chemical states in dynamic process environment, in a new way offering enormous promise for the improvement of the engineering science which underpins many important industrial processes.

Objective

The main objective of internship was to deepen theoretical knowledge of fluid mechanics, and especially in the area of multiphase flow, gaining experience with the process tomography and use our own experience with the modelling of flow. The University of Leeds is one of the pioneers of industrial tomography, prof. Mi Wang is the holder of many important patents in this area. His working group is focused on application resistivity tomography to determine the concentration and velocity of flowing components with different electrical conductivity. Such cases include the flow of liquid phase (water) together with the solid phase (sand), called. Slurry flow.

Introduction

The transport of multiphase flows, in particular the transport of slurry (two-phase liquid-solid flow) through pipelines is widely encountered in many industries such as the energy and nuclear, petroleum, mining and chemical industries. Slurry transportation is highly complex due to the interactions between the phases (interfacial interaction) as well as the interactions between the phases and the walls of the pipes. Additionally, some other flow parameters, such as solids concentration, pipe orientations and so on, add to these complexities and the models and theories associated with slurry flow seem uncertain which has resulted in significant research being conducted on transport of slurries through pipelines.

In horizontal pipes, flow regimes such as homogeneous, heterogeneous, flow with moving bed and flow with stationary bed have been identified due to the separation of phases that occurs by gravity acting perpendicular to the flow. Similarly in vertical pipes, plug flow, slug flow and annular flow regimes are observed as a result of the slippage of phases. As a result of the slippage and separation of the phases, the solids tend to suspend and/or settle making the “flow unpredictable and time dependent.”

Inclined slurry flow is more complex than both horizontal and vertical slurry flow as separation and slippage of phases occur simultaneously. Furthermore, minimal research has been conducted on inclined flow as compared to vertical and horizontal flow even though the occurrence of inclined pipes in industry is unavoidable in some locations.

An understanding of slurry flow enables better slurry pump design and selection, can reduce the power output needed and can save operational costs. The suspension and settling of solids in time damages process facilities can cause equipment failures, environmental damage and pipe blockage that make use of slurry transport. Therefore, it is important to continuously monitor and measure flow through pipelines. Several intrusive methods and techniques of monitoring and measuring slurry flow parameters have been employed in the past, such as traditional probes and conventional electrical flow meters. However, these devices are intrusive and affect the internal flow and are unable to accurately measure flow parameters due to the complexity of multiphase flows. One of the methods widely used in industry to monitor and measure slurry flow parameters are Electrical Resistance Tomography (ERT). ERT is a non-intrusive measuring technique that enables the internal structure to be visualised, hence, ensuring safe and efficient transport and production of slurry flow systems. The internal structure of slurry flow is characterised by two main parameters the solids concentration distribution and solids axial velocity distribution.This paper reports the effects of pipe inclination angle, along with some other flow parameters, on solids concentration and solids axial velocity obtained from ERT.

Two phase solid – liquid flows

The transport of solid particles in a carrier liquid is widely encountered and used in several industries such as the mining, pharmaceutical, food processing, dredging, petroleum and chemical industries. The flow of solid particles held in suspension in the carrier liquid is usually referred to as slurry. In industry higher velocities are usually associated when transporting multiphase flows and this is no different in slurry transportation as low velocities will lead to the solid particles coming out of suspension which in turn can lead to pipe blockages, alter the flow conditions, slow down production and/or affect the energy requirements in pipeline transportation. This can be attributed to the different flow regimes that can occur in slurry flow which requires the flow velocity to be greater than the depositional critical velocity and viscous transitional velocity, unlike single phase flow which is homogeneous and independent of the flow velocity. However, it should be noted that too high a velocity can cause the particles to collide against the pipe walls and can lead to higher rates of abrasion which can then lead to erosion under specific conditions. (Hu, 2006; Abulnaga, 2002; Brown and Heywood, 1991)

Slurry Flow Regimes

Slurry flow in pipelines is complex as it is affected by many variables in particular the properties of the solid particles relative to the liquid. Due to this complexity and the uncertainties associated with the theories and models of slurry flow, significant investigations have been conducted on slurry flow with different particle concentration, pipe orientations, and operating conditions that have resulted in different flow regimes being identified. (Hu, 2006; Abulnaga, 2002) Initially, a classification was developed by Durand and Condolios (1952) and this was further refined by other investigators over the years. Shook et al. (2002) suggested that if particles greater than 50 mm are present in the flow and at low concentrations, the flow can be classified as heterogeneous. If the mean particle diameter is less than 50 mm it will exhibit homogeneous flow properties. However, many other investigators have noted that slurries of different concentrations and compositions exhibit different flow properties and thus produce different flow patterns. (Abulnaga, 2002; Zandi, 1971). Nevertheless, it is widely accepted slurry flow can be classified into four main flow patterns as shown in the figure 1 (Hu, 2006).

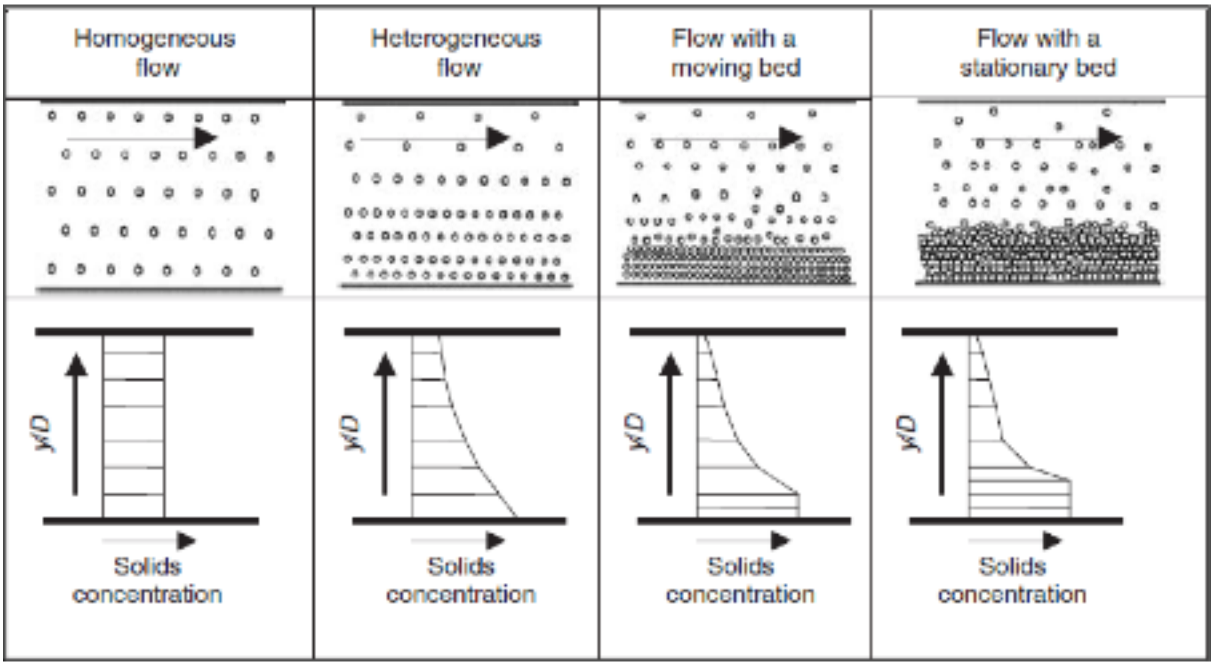

Figure 1: Flow regime classification in horizontal slurry flow. (Hu, 2006)

Homogeneous flow – as seen from the figure above, the solids are distributed uniformly in the carrier liquid about the horizontal axis of the pipe. Most slurry flows are considered homogeneous if they have a particle size smaller than 40mm to 70mm, however this also depends on the densities of the solid and liquid. Also, in order for homogeneous flow to persist, the mean velocity of the flow should be high enough to keep the fine and light (low density) solid particles in uniform suspension even at high particle concentrations of up to 60 wt%. When the solid particles concentration is more than 40 wt%, the mixture becomes more viscous and develops non-Newtonian properties but can still be considered and described by single phase models. Typical slurries which exhibit homogeneous flow are drilling mud and clays. (Hu, 2006; Abulnaga, 2002)

Heterogeneous flow – as the flow rate decreases or if there is a decrease in slurry velocity, the coarser and denser solid particles separate from the liquid forming a concentration gradient in the vertical plane, i.e. non-uniformity of solids in the horizontal plane. When there is a concentration distribution in pipe cross-section the flow is considered as heterogeneous, but no solid particles are deposited on the bottom of the pipe and most of the particles are still in suspension. As the concentration of the solids increase, it is expected that the solid concentration gradient will persist with the denser particles on the lower side. However, it should be noted that heterogeneous flow have typically low solid concentrations but can be as high as 35 wt%. (Abulnaga, 2002)

Flow with moving bed – as the flow velocity of the heterogeneous flow is reduced below a minimum velocity (limit deposition velocity), the denser, coarser particles deposit on the lower side of the pipe. A concentration gradient still exists where the finer less dense particles are still in suspension with the carrier liquid (homogeneous) and as there is a concentration gradient developed due to the denser particles, the concentration gradient increases near the bottom of the pipe (heterogeneous flow). Below the minimum velocity, the solid particles come out of suspension and are deposited on the pipe in the form of a bed. However, the shear forces exerted by the fluid are still capable of transporting this bed hence the term flow with moving bed. This moving bed increases pipe wear. (Lahiri, 2009; Peker et al., 2008; Hu, 2006)

Flow with stationary bed – when the flow rate is further decreased below critical velocity, the coarser solid particles become stationary and at the same time the height of the bed increases with motion due to the particles with the lowest settling speed present above the stationary bed and in the upper portion of the pipe. The motion of the particles in the upper pipe is that of the solid particles moving over on another (saltation flow) as the fluid tries to move the solids and this is said to move as an asymmetric suspension. Flow with stationary bed can lead to pipe blockages as the forces resisting motion are greater than those that cause the particle to move, i.e. the pressure required to continue flow motion becomes high. (Lahiri, 2009; Peker et al., 2008; Hu, 2006)

It is critical for operators to identify the flow regimes present in pipelines as they can affect pressure drop, other flow characteristics and influence pipe erosion.

Heterogeneous flow of settling slurries in horizontal pipes

In oil and gas production and transportation and certainly in most of the other industries that utilise or involve slurry transport, the size of the particles vary from fine particles to coarser more dense particles. As the particles flow in a horizontal pipe orientation, there is a formation and/or settling of different layers that contain different size particles due to gravity acting perpendicular to the flow which results in the coarser denser particles to settle as the carrier fluid cannot suspend/lift those particles. When there is a settling of particles, the slurry flow is termed settling slurry. Several flow regimes are developed when the solid particles settle as these flow regimes have been published and discussed in the literature (Hu, 2006; Abulnaga, 2002)

Transitional velocities and critical velocity

The different flow regimes affect the mean flow velocity which in turn affects the pressure drop. Transitional velocities are the velocities that define a change from one flow regime to another. The regimes described in the previous sections can be represented by a plot of pressure gradient vs the average speed of the mixture as seen in figure 2.

The transitional velocities are defined as (Hu, 2006; Abulnaga 2002):V1 – this is the velocity at which stationary flow prevails in the lower half of the pipe. V2 – “is the velocity at or above where the mixture flows as an asymmetric mixture with coarser particle forming a moving bed.” (Abulnaga, 2002) , V3 – is the velocity region where particles move as an asymmetric suspension and is also defined by solids just beginning to settle and form a moving bed , V4 – is the velocity where solids move as a symmetric suspension. This can also be defined as the region where a homogeneous or pseudo homogeneous flow prevails.

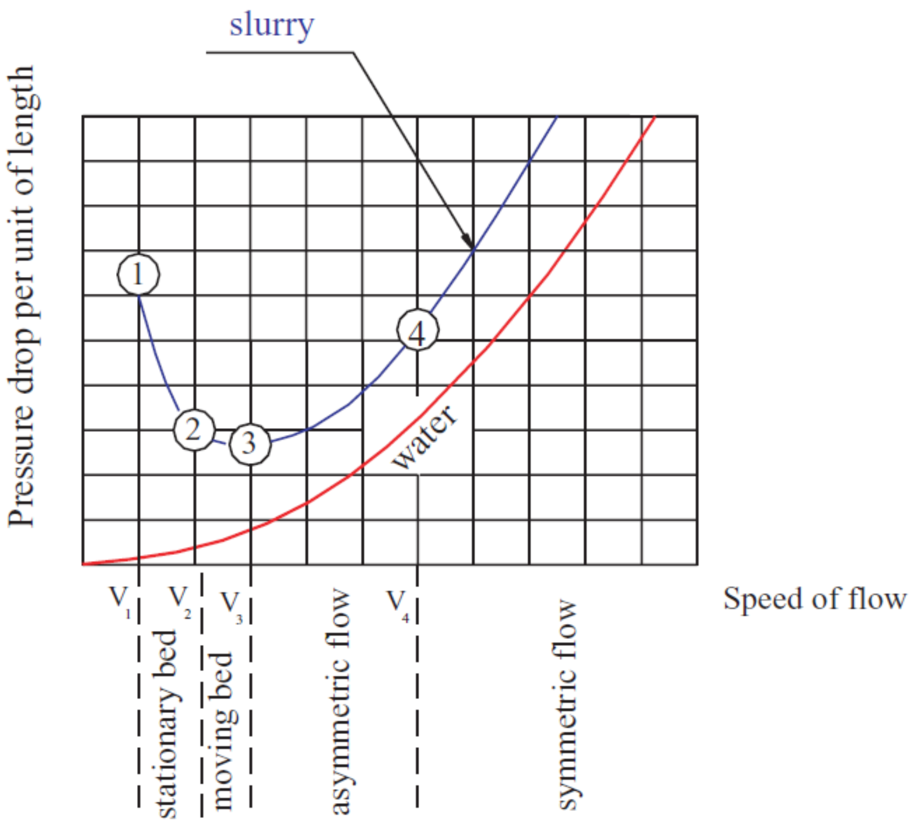

Figure 2: Plot of pressure gradient vs speed of mixture (Abulnaga, 2002)

The critical velocity, V_C, is defined as the "average mean flow velocity required to prevent accumulation of a layer of stationary or sliding particles on the bottom of a round horizontal pipe." (Hu, 2006) This definition can also be extended to the transitional velocity between stationary flow and flow with a moving bed known as the deposition critical velocity V_D or V_3 as shown in figure 2.2. Several experiments have been conducted in order to determine and predict the critical velocity and results based on empirical correlations are the most useful. However, several approaches by different investigators were used and that led to a discrepancy between those correlations. Nevertheless, the critical velocity is an important parameter as it represents the minimum flow that slurry can be transported in pipelines without causing pipe blockage. The critical velocity also corresponds to the lowest pressure drop as seen in the figure 2. (Hu, 2006; Wilson et al., 2006; Abulnaga, 2002) .
As stated before, several investigators have proposed different equations for determining the critical velocity and certainly the minimum velocities at the different flow regimes. However, the basis of their critical velocity equations are modified versions of the equations proposed by Durand and Condolios (1952) or Newitt et al. (1955). Durand and Condolios (1952) conducted an experiment to determine the critical velocity with solids concentration (Cv) of up to 15% for the transport of a sand-water mixture flowing through pipes with different diameters, mainly ranging from 38.1 mm to 508 mm. Based on the results they proposed the following equation (Hu, 2006; Abulnaga, 2002; Shamlou, 1988): $Vd = V3 = Fl\,2\,G\,Di\,\sqrt{\frac{\rho s - \rho l}{\rho l}}$

Where: V_D = V_3 is the deposition velocity. F_l – is the Durand factor.
Gibert (1960) recreated the experiments of Durand and Condolios (1952) and Durand (1953) using sand and gravel with solids concentration (Cv) between 2% and 22.5%. The pipe diameters used also ranged between 40 mm to 508 mm. Gibert (1960) noted that a similar resemblance to Durand and Condolios (1952) was observed for the critical velocity. However it should be noted that the experiment was carried out to correlate the results for the effect of solids on pressure loss. (Wilson et al., 2006)

Pressure Drop

Pressure drop is one of the most important parameters that operators are interested in, as it can provide information of the flow conditions in the pipe. In addition pressure drop can also provide some information on the solids concentration profile, the velocity of the suspensions, whether or not the pipe is about to get blocked (due to the build-up of the bed), etc. For operators and designers, the pressure drop can also provide information on suitable pump selection, designing pumps which can overcome the frictional losses anticipated and determining the power consumption. (Peker et al., 2008; Hu, 2006; Wilson et al., 2006)

Due to the complexity of two phase solid – liquid flow, several investigators have proposed a wide range of different empirical equations to determine the pressure drop under different operating conditions. Several factors affect the pressure drop and in a horizontal pipe the pressure drop correlations are more complex than in vertical slurry pipe flows. (Wilson et al., 2006) Some of these factors include but are not limited to the types of flow regime present across the pipe cross-section, the effect of gravity acting perpendicular on the particles in horizontal pipes, the concentration of the particles, particle size and diameter and the velocity of the particle/flow.
Therefore, this section will review the fundamentals of pressure drop and hydraulic friction based on the more prominent models and/or correlations used in determining pressure drop in slurry flow.
The pressure drop is mainly due to the interactions of the solid particles with the pipe wall, particle-particle collisions and fluid friction acting on the pipe wall (viscous shear), i.e. "the pressure drop due to the resisting/frictional forces is due to the structure of the flow." (Peker et al. 2008) As the slurry flows in the pipe, a hydraulic friction gradient (im) is observed throughout the pipe whereby friction acts. The hydraulic friction gradient represents the head loss per unit length due to friction. Since the frictional losses were determined to increase with an increase in the solids volumetric concentration. Therefore, it is assumed that the frictional losses are directly proportional to an increase in concentration of solids. (Peker et al., 2008; Hu, 2006; Wilson et al., 2006) Additionally, the hydraulic friction gradient for the slurry (i_m) is larger than the hydraulic friction gradient of the carrier fluid in terms of equivalent volume of water (i_l), Durand and Condolios (1952) proposed the

following expression for an increase in friction head loss due to an increase in volumetric solid concentration (Hu, 2006; Abulnaga, 2002): $\phi = \frac{im-il}{\alpha v\ il}$,
where:
Φ – dimensionless pressure loss
im – is the frictional pressure loss of the slurry, mwater/mpipe.
il – is the frictional pressure loss for an equivalent volume of carrier liquid, mwater
α_v – is the solids volumetric concentration.

Slurry flow modelling

Three-layer model

Doron, Simkhis and Barnea (1997) conducted experiments of solid-liquid flow at pipe inclinations of up to 7° upward and downwards to verify the applicability of the three-layer. Doron and Barnea (1993) model when the effect of pipe inclination was considered by accounting for the pipe tilt. It was concluded that the three layer model could be extended for inclined slurry flow in critical velocity and pressure drop determination.
The three layer model assumes that at low bed velocities a stationary layer is formed at the bottom. Above the stationary bed, flow with a moving bed is present and finally there is a heterogeneous mixture or pseudo homogeneous layer that is present in the upper part of the pipe. Another governing assumption is the hypothesis of a minimal bed velocity for the moving bed, i.e. the bed located above the stationary bed height has a minimum velocity. Doron et al. (1997) considered this velocity to be the minimum velocity required to induce motion in stationary particles. Therefore if the velocity of the moving bed is below this velocity, the coarser particles will settle and form a stationary bed and the upper part of the bed with the finer particles will move at this minimal velocity. (Doron et al., 1997).

Two-layer model

Unlike the three layer model, the two layer model is based on the concept of two separate layers. Shook and Roco's (1991) extension of Wilson's (1970) mechanistic model approach of two layer slurry flow has been shown to be applicable in horizontal and inclined slurry flow by Khan and Richardson (1996) (Abulnaga, 2002).

Electrical Resistance Tomography

Electrical resistance tomography (ERT) is one of the methods of measuring slurry flow through pipelines that has gained a lot of interest in recent times. ERT is a simple cost effective invasive but non-intrusive method of monitoring slurry flow that also allows for on- line measurements and a reasonable margin of accuracy. The opaque nature of pipes and slurry make it impossible to know what is occurring within the pipe, therefore the use of ERT enables the user to visualise the internal structure of the solid-liquid flow by creating images/tomograms based on conductivity currents. (Sharifi and Young, 2013; Dyakowski et al., 2000)

Figure 3: EIT sensor installed in 2inch pipeline

A typical ERT system consists of sensors (see Figure 3), data acquisition system and an image reconstruction system. The sensor system consists of number of electrodes that are equally spaced and of optimal design so as sit flush on the inner pipe wall circumference and not cause any interference with the flow. The data acquisition system consists of various electrical components such as voltmeters, electrode multiplexer array, signal sources and signal demodulators. The data acquisition system is a critical component of the ERT system as it is connected to the electrodes and also to the image reconstruction unit. The ERT system collects data depending on the data collection strategy. An adjacent data collection strategy is commonly used in most ERT systems where an alternating current, usually 15 mA, is injected to a pair of electrodes via the data acquisition system and the resulting voltage from the other electrodes is than measured. This process is continued until all conductivity measurements are mapped from all the independent pair electrodes. (Sharifi and Young, 2013; Faraj and Wang, 2012) For a dual plane electrode system with a 16 electrode configuration, Lucas et al. (1999) state that 104 independent differential voltage measurements can be obtained using the adjacent strategy. The recorded voltage output from the other electrodes passes through the phase sensitive demodulator where both the amplitude and the phase of the measurement can be obtained. Lucas et al. (1999) also state that in order to use an ERT system to map the solids velocity profile and the volume fraction, data needs to be acquired at a rate of 100 frames per second. At the end of acquisition, each data block is transferred to the image reconstruction system whereby images for both the phase and the amplitude are obtained for analysis. It is to be noted that the image reconstruction system can generate images based on either a Linear Back Projection (LBP) algorithm or Newton-Raphson technique. (Lucas et al., 1999) .

From the above technique, the local solids concentration profile can be determined from the conductivity maps. Using the simplified Maxwell's relationship for sand-water flow, the solids volume fraction (a) within a pixel is determined as (Lucas et al., 1999): $\alpha = \frac{2(\delta v - \delta m)}{\delta m + 2\delta w}$, where δ_w is the pixel conductivity of the continuous water phase and δ_m is measured pixel conductivity.

Lucas et al. (1999) suggest the use of pixel to pixel cross-correlation technique to determine the solids velocity profile. Faraj and Wang (2012) explained the process of cross-correlation technique to determine the solids axial velocity distribution using the figure 4 below.

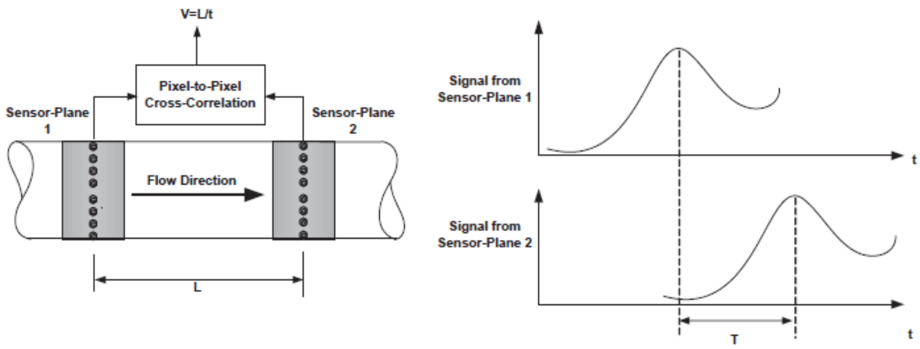

Figure 4: Faraj and Wang's (2012) schematic explanation for the principle of cross- correlation

Ultrasonic Doppler Velocity Profiler

Ultrasonic Doppler Velocity Profiler (UDVP) can measure the velocity of multiphase flow. The UDVP measures the instantaneous velocity profiles in a flow field by detecting and processing the Doppler shift frequency of an echo caused by reflected signals of the moving particles. Generally, the Doppler shift frequency is difficult to determine from the reflected signals as the basic frequency is much larger than the shift frequency and thus making it difficult to resolve. Another factor as to why it is difficult to resolve the shift frequency is due to the broad spectrum of the ultrasonic signal. Quadrature shift detection is used to determine the shift frequency by measuring the phase change between successive echo signals. (Murakawa et al., 2012)

In order to determine the velocity distribution as a function of time, the UDVP makes use of a small piezoelectric transducer placed at an angle of inclination (α) along the measuring line. An ultrasonic pulse is emitted by the piezoelectric transducer and the pulse is then transmitted through the fluid. When the pulse comes into contact with the particles, the pulse's energy (frequency) is scattered and reflected. After a time delay, the reflected frequency from the pulse's interaction with the particles is recorded by the same transducer as an echo. Therefore, a velocity component in the measuring line can be obtained, i.e. the amount that the frequency of the reflected echo has been altered is proportional to the speed of the moving particle. (Murakawa et al., 2012)

The position of the echo that is received on the measuring line due to the time delay between the applied pulse and the received frequency (echo) is given as (Murakawa et al., 2012): $X = \frac{C\,\tau}{2}$, where *X* is the measurement distance from the transducer, *c* is ultrasound speed in carrier liquid and *Tau* is time-of-flight of the ultrasonic pulse.

The Doppler shifted echo from the particles give information on the instantaneous velocity distribution. After the signal has been filtered and compared with the transmitted frequency, the velocity (V) is computed from the following equation (Murakawa et al., 2012): $V = \frac{C\,fd}{2\,fo}$

where:

f_d – is the Doppler shifted frequency (Hz)

f_0 – is the basic transmitted ultrasonic frequency (Hz) .

The figure below from Murakawa et al., (2012) schematically presents the measurement principles of UDVP, see Figure 5 . Part (a) of the figure shows the measurement system where the transducer is placed at an angle on the surface of the pipe/channel wall which is the velocity component within the measurement line that will be determined. Part (b) shows the reflected signal/frequency from the pipe wall, at the extremes of the profile, and shows the frequency of the refracted signals from the particles, profile in between the pipe wall reflection profile, along the measuring line. Part (c) shows the reconstructed velocity profile where the instantaneous velocity at the different frequencies were computed from the Doppler shifted velocity equation.

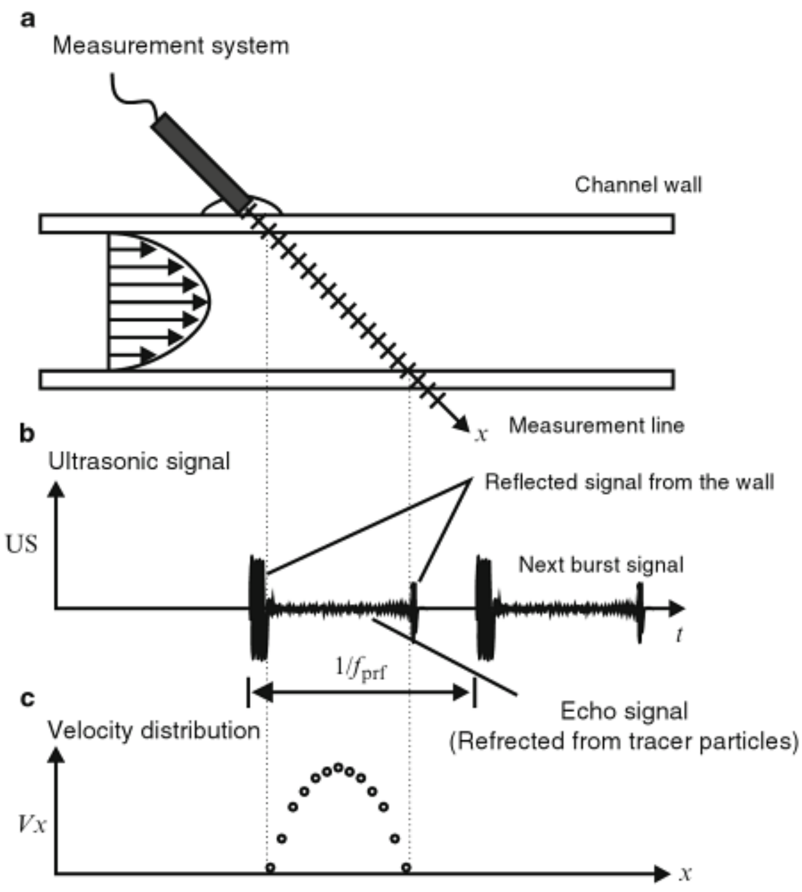

Figure 5: Murakawa et al., (2012) representation of the principle of UDVP measurement.

Experimental Procedure

The main objective of this study is the measurement of the solids velocity and solids concentration distribution in inclined slurry flows through the use of an ERT system. Furthermore, the effect of the particle size and the delivered solids concentration on the concentration profiles and velocity profiles will also be investigated for various pipe inclination angles. The effect of the settling characteristics of slurry in an inclined orientation will be investigated.

Based on the objectives set out and the aims of the experimental work, the following tests will be carried out:

- 2% volumetric concentration sand-water mixture flowing through the flow loop at mixture velocities between 1.5 m/s to 5.0 m/s.
- 10% volumetric concentration sand-water mixture flowing through the flow loop at mixture velocities between 1.5 m/s to 5.0 m/s.

Both 2% and 10% volumetric solid concentration sand-water mixtures will be pumped through the flow loop at the selected inclination angles; 0° (horizontal), 5° and 15°. The selected angles are inclined from the horizontal. The mixture velocities were selected to ensure that each flow regime is covered and, therefore it should be noted that the measurements will be carried out for each mixture velocities (or transport velocity which will be used interchangeably) used for the different pipe inclination angles.

In order to measure the effect of inclination angle on the solids concentration and velocity profile, a set of experiments are conducted in an inclinable flow loop located in lab G.56 of the School of Chemical and Process Engineering, University of Leeds, as shown in figures 6 and 7.

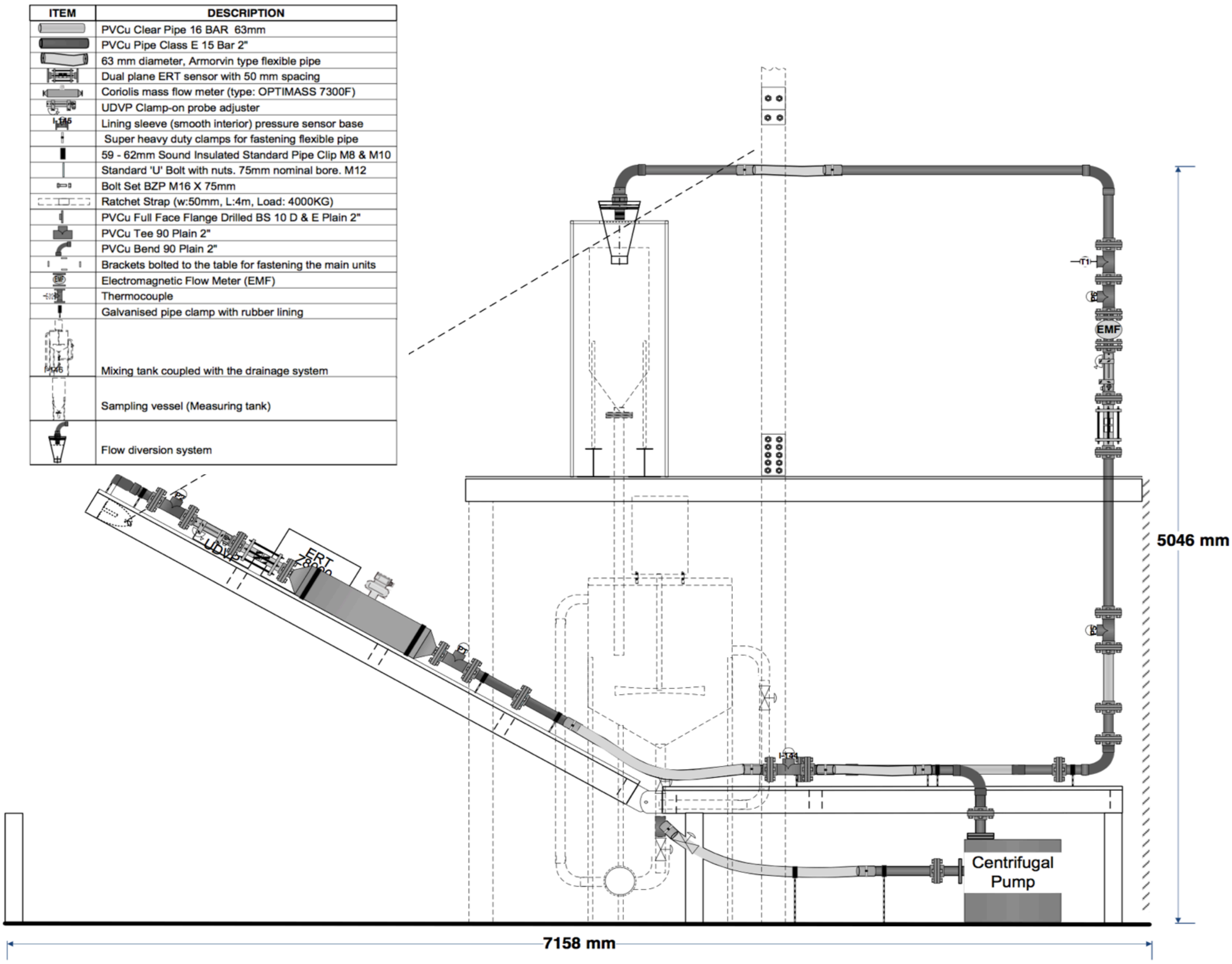

Figure 6: Scheme of the inclinable slurry test bed, flow measurement vessel 50 mm, Y. Faraj 2010

Figure 7: Coriolis mass flow meter (CMF), slurry mixing tank

Strategy of slurry experiment is apparent from Figure 8. Validation and comparison of results are shown on the scheme. Four principally different instrumentations are used for solid-liquid flow estimation.

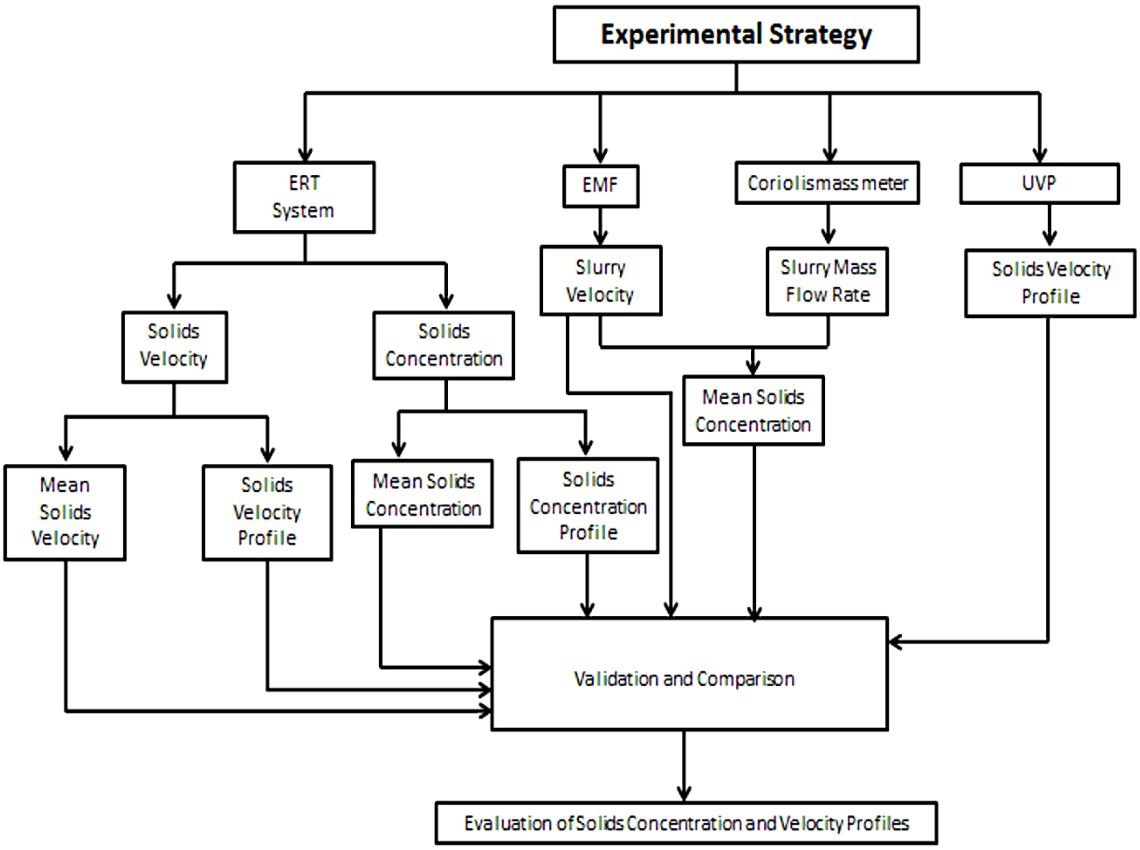

Figure 8: Strategy of Slurry experiment

Results of measurement

A typical result of tomographic measurement of electrical conductivity, concentration and axial speeds, see Figure 9.

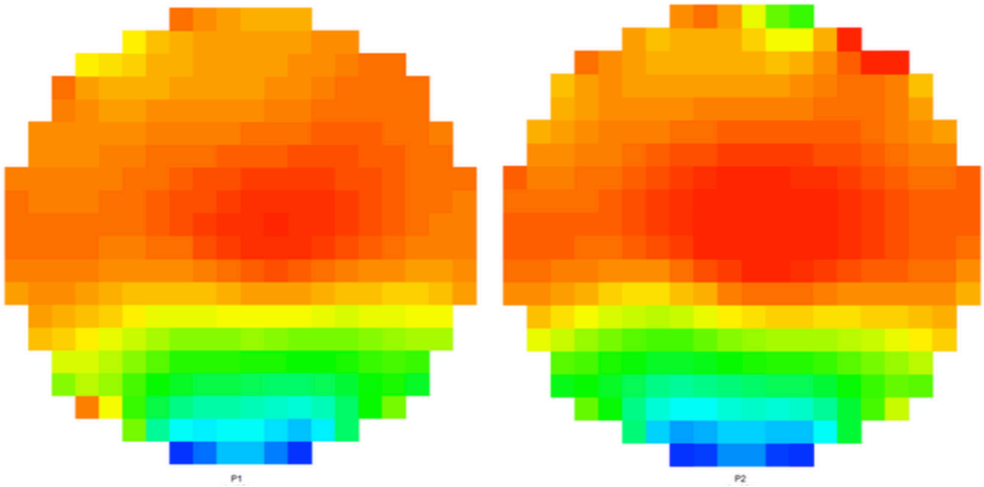

Figure 9: Conductivity map, moving bed

Different conductivity characterizes different concentration in the cross section of pipeline. From the figure forming suspension guests at the channel bottom, which moves at a lower speed than the slurry at the top of the pipeline. Measurement planes give us a profile of concentration and axial velocity, see Figure 10. These profiles were acquired for superficial speed of 3.5 m / s.

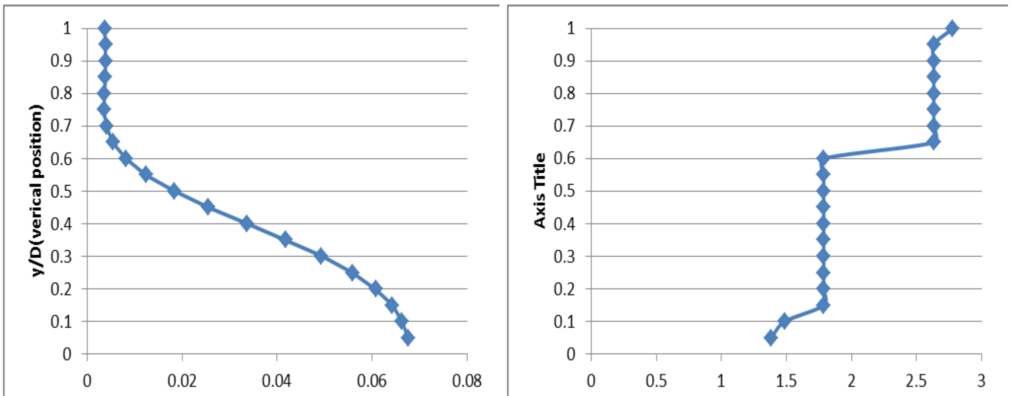

Figure 10: Concentration profiles, axial velocity

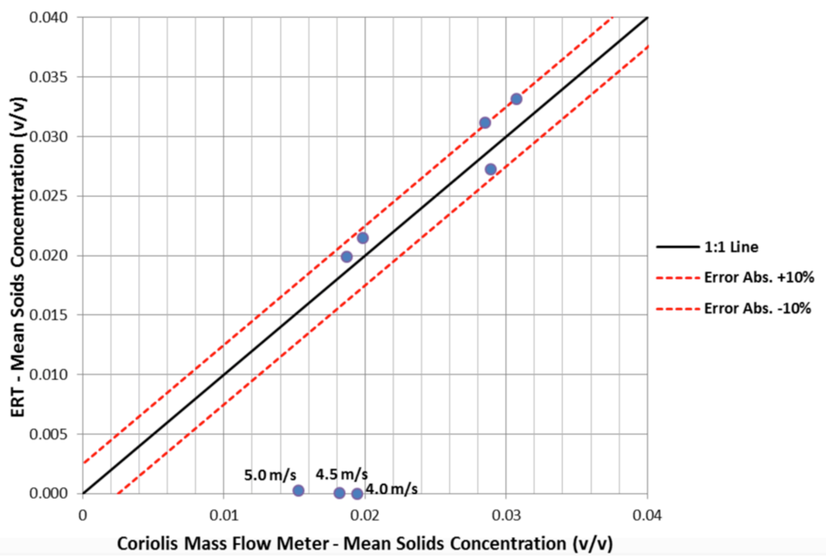

Figure 11: Error analysis for solids concentration generated between ERT and Coriolis mass flow

Applications

Examples of slurries

- Cement slurry, a mixture of cement, water, and assorted dry and liquid additives used in the petroleum and other industries
- Soil/cement slurry, also called Controlled Low-Strength Material (CLSM), flowable fill, controlled density fill, flow able mortar, plastic soil-cement, K-Krete
- A mixture of thickening agent, oxidizers, and water used to form a gel explosive
- A mixture of pyroclastic material, rocky debris, and water produced in a volcanic eruption and known as a lahar
- A mixture of bentonite and water used to make slurry walls
- Coal slurry, a mixture of coal waste and water, or crushed coal and water
- Slurry oil, the highest boiling fraction distilled from the effluent of an FCC unit in a oil refinery. It contains large amount of catalyst, in form of sediments hence the denomination of slurry.
- A mixture of wood pulp and water used to make paper
- Manure slurry, a mixture of animal waste, organic matter, and sometimes water often known simply as "slurry" in agricultural use, used as fertilizer after ageing in a slurry pit
- Meat slurry, a mixture of finely ground meat and water, centrifugally dewatered
- An abrasive substance used in chemical-mechanical polishing
- Slurry ice, a mixture of ice crystals, freezing point depressant, and water
- A mixture of raw materials and water involved in the raw mill manufacture of Portland cement
- A mixture of minerals, water, and additives used in the manufacture of ceramics
- A bolus of chewed food mixed with saliva
- A composite slurry, formed from a combination of no less than three of the aforementioned slurries

Fundamentals calculations

Determining solids fraction

To determine the per cent solids (or solids fraction) of a slurry from the density of the slurry, solids and liquid

$$\phi_{sl} = \frac{\rho_s(\rho_{sl} - \rho_l)}{\rho_{sl}(\rho_s - \rho_l)}$$

where

ϕ_{sl} is the solids fraction of the slurry (state by mass)
ρ_s is the solids density
ρ_{sl} is the slurry density
ρ_l is the liquid density

In aqueous slurries, as is common in mineral processing, the specific gravity of the species is typically used, and since is taken to be 1, this relation is typically written:

$$\phi_{sl} = \frac{\rho_s(\rho_{sl} - 1)}{\rho_{sl}(\rho_s - 1)}$$

Liquid mass from mass fraction of solids

To determine the mass of liquid in a sample given the mass of solids and the mass fraction: By definition

$$\phi_{sl} = \frac{M_s}{M_{sl}} * 100$$

therefore

$$M_{sl} = \frac{M_s}{\phi_{sl}}$$

and therefore

$$M_s + M_l = \frac{M_s}{\phi_{sl}}$$

where

M_s is the mass or mass flow of solids in the sample or stream
M_{sl} is the mass or mass flow of slurry in the sample or stream
M_l is the mass or mass flow of liquid in the sample or stream

Volumetric fraction from mass fraction

$$\phi_{sl,v} = \frac{V_s}{V_{sl}}$$

Equivalently

$$\phi_{sl,m} = \frac{M_s}{M_{sl}}$$

and in a minerals processing context where the specific gravity of the liquid is taken to be one:

$$\phi_{sl,v} = \frac{\frac{M_s}{SG_s}}{\frac{M_s}{SG_s} + \frac{M_l}{1}}$$

respectively

$$\phi_{sl,v} = \frac{M_s}{M_s + M_l SG_s}$$

Then combining with the first equation:

$$\phi_{sl,v} = \frac{1}{1 + \frac{M_l SG_s}{\phi_{sl,m} M_s} \frac{M_s}{M_s + M_l}}$$

we conclude that

$$\phi_{sl,m} = \frac{M_s}{M_s + M_l} = 1 - \frac{M_l}{M_s + M_l}$$

$\phi_{sl,v}$ is the solids fraction of the slurry on a volumetric basis
$\phi_{sl,m}$ is the solids fraction of the slurry on a mass basis
M_s is the mass or mass flow of solids in the sample or stream
M_{sl} is the mass or mass flow of slurry in the sample or stream
M_l is the mass or mass flow of liquid in the sample or stream
SG_s the bulk specific gravity of the solids

Conclusion

In conclusion, the local solids concentration plotted against the vertical cross-section of the pipe displayed the characteristic trend of settling slurry flow for each pipe inclination angle tested. The presence of the different flow regimes, pseudo-homogeneous, heterogeneous and flow with a moving bed were clearly identified by the solids concentration profiles. Furthermore, the development of the shear layer when moving bed flow prevailed was clearly highlighted from the results generated by the ERT. As the pipe is inclined, local solids concentration profile is much smaller at 15 degrees inclination angle compared to horizontal slurry flow. This was accounted for by the axial cross-pipe component of particle weight causing a thicker and more effective shear layer capable of suspending more solid particles. The local solids velocity profile is much larger at a higher inclined slurry flow than for horizontal slurry flow. The ERT system is adequate in visualisation and measurement of the solids concentration profile where an average overestimation of approximately 0.01 to 0.02 (v/v) from coriolis mass flow meter was determined. ERT can also satisfactorily measure solids velocity profile where it overestimates the local solids velocity profile by 0.2 m/s to 0.5 m/s anywhere along the vertical position of the pipe (y/D) at the lower transport velocities and anywhere between 0.8 and 1.3 m/s along y/D at the higher transport velocities. The ERT system is suitable to measure both the solids concentration profile and velocity profile but is highly sensible to any changes in temperature by more than 4 °C. Error analysis for solids concentration was estimated as well, see example Figure 11.

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