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Automated horizontal slurry flow regime recognition using statistical analysis of the ERT signal

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Abstract

Flow regime recognition is not only useful for characterisation of the flow, but also for the purpose of modeling, system controls and optimization and correction of flow regime dependent flow meters. This paper proposes a new indirect method for on-line recognition of the active horizontal slurry flow regime using statistical signal analysis of measurements obtained with a high performance Electrical Resistance Tomography system (ERT). Significant features of the ERT signal are extracted from both time domain and frequency domain. A set of experiments were carried out using a pilot-scale slurry flow loop, through which a mixture of sand and tap water was pumped into a 50 mm inner-diameter test section. All common slurry flow regimes are considered in the recognition scheme, including the transitional regime boundaries covering the transport velocity range of 1.5-5 m/s. Two types of sand are used in the experiments, medium (75-900 μm) and coarse (150-2200 μm), each with different throughput volumetric concentration, 2% and 10%. 1.2 m transparent pipe section was included into the test section, so as to visually inspect the prevailing flow regime and capture photographic images of the flow. A code was developed not only to render the recognition of the active flow regime, but also to visualise the distribution of the solid particles across the pipe cross-section and display the mean solids volume fraction. The evaluation of the proposed recognition method suggests 90.32% successful rate.

Keywords: Electrical Resistance Tomography, horizontal slurry flow, slurry flow regime recognition., ERT signal analysis.

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1. Introduction

Settling slurry flows cover a wide spectrum of applications and are the focus of considerable interest in engineering research. It is widely utilised in many industries such as mining, chemical, petrochemical, power generation, dredging and other industries. Flow of settling slurry in horizontal pipeline is complex and has been the subject of a vast number of studies from the early work of [1, 2, 3] and many others. The complexity of this type of flow is due to the influence of gravity, which gives rise to different flow regimes from pseudo-homogenous at high velocity to stationary bed and blockage at low slurry velocity. Flow regimes are normally described in terms of the distribution of solid particles within the pipe cross-section. In other words, they can be used to describe the motion of solid particles in horizontal or near horizontal slurry flows. These flow regimes have been the subject of numerous experimental studies such as [4, 5, 6, 7]. Since the settling slurry flow is very complex and the determination of a certain flow regime relies mostly on visual observation, the literature has shown different names and definitions to certain regime. Since 1952 different classifications have been used by many authors, some based on particle size and others based on solids concentration. These classifications were refined, based on the relationship between the particle size, concentration and deposition velocity, by [8, 9, 10, 11], who classified the slurry flow regimes into four main categories, "homogeneous flow", "heterogeneous flow", " moving bed" and "stationary bed". The schematic drawing of each flow regime, based on the definition of each flow regime in literature, is illustrated in Fig. 1.
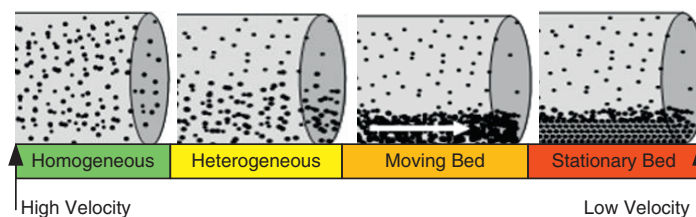

Fig. 1. Schematic drawing of slurry flow regimes in a horizontal pipe.

The emergence of these flow regimes affects the pressure drop, which causes partially or fully pipe blockage and reduces the efficiency, influences pipe wear and other performance characteristics. Then on-line identification of these flow regimes is of particular importance for the pipeline operator to ensure safe transport and maintaining acceptable control limits. They have also a negative impact on the performance of flow meters, which are flow regime dependent. Therefore, they have to be automatically recognized for optimisation and correction of these types of flow meters. The identification and evaluation of the information regarding these flow regimes are usually performed by visual inspection through graphic illustration, which sometimes difficult to interpret, either due to the system being opaque or with high velocity.

Over the years, since 1953, researchers have attempted to establish various methods to characterise and recognise the flow regimes encountered in horizontal pipeline such as [3, 12, 6, 13, 14, 15]. Pressure drop measurement has been one of the most common methods that adopted for flow regime recognition. Usually the flow regimes are recognised by either subjective operator judgments, which is done by visual inspections, although in some cases an analysis of the spectral content is performed, where the desired information cannot be extracted visually [16]. In some other cases they are identified by representing the boundaries between the flow regimes via flow regime maps. These flow regime maps represent the boundaries between various flow regimes under different conditions, though these boundaries are not distinctive lines, but rather poorly defined transition zones. However, there are limitations and problems with these flow regime maps that they are often dimensional and cannot be applied on a different operational condition. Despite the fact that some investigators have tried to generalise these flow regime maps, so they can be applied to different fluids and pipes of different sizes, but the total generalisation has not been achieved yet.

Recently, [17] used an acoustic probe to determine the flow regimes in horizontal pneumatic transport of fine powders. It is quite known that that probes are intrusive and subject to high wear within the pipeline, and may not be

applicable for larger particle size. More recently, [18] adopted a strategy to analyse slurry flow regimes based on the the direct interpretation of ERT measurement to identify homogeneous and heterogeneous flow without using image reconstruction. The slurry used in their experiment consisted of tap water and non-conductive glass beads (100 μm). It is apparent that using a direct method rather than indirect method may be may suffer some degree of subjectivity associated with the recognition of prevailing flow regime. It has also applicability limitation over a wide of range of conditions, such as solids concentration, particle size, slurry velocity, pipe diameter. More recently, Artificial Neural Network (ANN) based recognition method has been proposed by [19] to identify different flow regimes in a horizontal pipe. His method has shown a great success, as there is no need to calculate some parameters, such as the drag co-efficient and some empirical co-efficient, settling velocity and Froud number. However, the (ANN) based flow regime recognition requires a prior knowledge and information, which has an influence on the recognition scheme.

Therefore, this paper proposes a novel on-line ERT based technique, whereby the prevailing flow regime is indirectly and non-intrusively recognized regardless the condition, in which the flow operates, such as physical properties, pipe diameter etc.

2. Automated flow regime recognition

In order to achieve automatic recognition of the prevailing flow regime in horizontal slurry flow, two key stages are taken. First is developing a recognition method, and second is coding a program; to facilitate automatic recognition of the prevailing flow regime. All typical slurry flow regimes, Homogeneous, Pseudo-homogeneous, Heterogeneous, Moving Bed and Stationary Bed, including transitional boundaries, are considered in the recognition scheme. Statistical analysis of the conductivity data within each zone are carried out to provide a quantitative comparison of the flow regimes, thus reducing the subjectivity associated with recognising each flow regime. In order to achieve this objective the following steps are carried out;

2.1. ERT measurement

The ERT measurement of each horizontal slurry flow is taken to generate a measurement block. The measurement results are in the form of mean mixture conductivity in the each pixel within the generated averaged tomogram. Since each measurement block yields a huge amount of data (i.e. 8000 frames; each frame at 316 data pixel), then it is possible to use a tomogram with 21 cell zone scheme (Mesh/21 cell), as shown in Fig. 2. Mesh/21 cell zone represents the pipe cross-section and consists of 21 zones, which makes the basis for the statistical analysis of the conductivity data. Since the flow regimes in horizontal settling slurry flow are influenced by gravity, it is therefore, reasonable to consider only 5 cells within the vertical centerline of the tomogram. The analysis of only these 5 zones will obviously produce all of the characteristics relevant to the active flow regime.
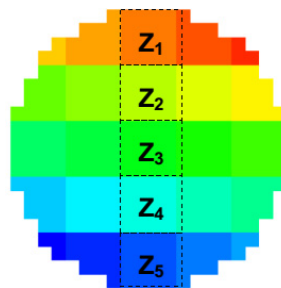

Fig. 2. A tomogram with Mesh/21 cell zone scheme.

2.2. Statistical signal analysis and flow feature extraction

In this study the statistical analysis and power spectral analysis are employed to extract the flow information from the time series and frequency domain respectively. The analysis of the ERT data for each cell mentioned within Mesh/21 cell is carried out, in the time domain, by considering the change in conductivity relative to the reference. It is apparent that the mean conductivity of each zone is related to the solids volume fraction distribution. This is based on the fact that by reducing the velocity, the solid particles migrate towards the bottom of the pipe, which results in higher conductivity at the top half of the pipe and lower at the bottom half. Based on this phenomenon, this feature is considered as an element in the recognition scheme. The relative difference between the slurry conductivity at the top half of the pipe and the bottom half of the pipe is used as a threshold for every flow regime, as shown below:

$$C = \frac{A}{(A+B)} \tag{1}$$

$$A = \frac{Z_1 + Z_2 + \left(\frac{Z_3}{2}\right)}{3} \tag{2}$$

$$B = \frac{\left(\frac{Z_3}{2}\right) + Z_4 + Z_5}{3} \tag{3}$$

Where; C represents the ratio of average conductivity of the top half of the pipe to the average conductivity across the pipe cross-section, A the average slurry conductivity at the top half of the pipe, B the average slurry conductivity at the bottom half of the pipe, Z_1-Z_5 the average conductivity of each zone denoted by the subscript.

As the significant feature and relevant information regarding every flow regime is also contained in zone 3, therefore, this zone, which is located at center of the pipe cross-section, is also taken into account in the analysis. One half of zone 3 is included into the top half of the pipe, whereas the other half is incorporated into the mean conductivity of the bottom half of the pipe.

In order to remove or at least reduce the subjectivity in recognising the active flow regime, further features of the signals is extracted, which makes another condition in decision making within the flow recognition scheme. These features are taken from the frequency component of the signal. In order to make the basis of the recognition scheme, distinctive features are required to be identified. A journey through literature revealed that there is a handful of method available for extracting flow features from flow process measurements, such as Signal-to-Noise ratio (SNR), Power Spectral Density Functions (PSDF), Probability Density Functions (PDF), Auto Correlation Functions (ACF) etc. [20].

The spectrum analysis of the signal, in which an attempt is made to measure the signal power, is carried out. The spectrum of a signal shows how much power is contained in each of its components or frequency [21]. In order to estimate the power of any component of a signal a plot is required, in which the x-axis is the frequency components and on y-axis presents the power spectrum of the signal. Some of the most important methods of the spectrum objects are Power Spectral Density (PSD), Mean Square Spectrum (MSS) and Pseudo-spectrum. The power spectrum is also referred to as the Power Spectral Density (PSD). PSD is one of the most important methods of spectrum analysis, as it highlights the strong and weak variations (energy) of a signal and also can be used for oscillatory and non-oscillatory signals in the time series data [22]. In statistical signal processing, the frequency content of the signal is characterised through spectral density. The spectrum of a signal is defined by the plot, in which the magnitude and phases of different frequency components are clearly indicated. In order to find spectrums of a signal the Fast Fourier Transform (FFT) has to be employed [23]. In the analysis used in this study, the periodgram technique is adopted, which is considered as a non-parametric method and a common spectral estimator. The selection of periodogram is based on the fact that it is robust, simple, it can provide reasonably high resolution

for a very long data length and computationally cheap for estimating the power spectrum of a signal. It is worth pointing out that the power spectrum does not readily determine the average power of the signal, but only power of a frequency component. Therefore, the area under the curve of PSD of a signal has to be integrated to obtain the average power of the signal under analysis. In other words, the area under the PSD curve renders the average power of the signal. The PSD of the signal is estimated by the periodogram, which uses directly sampled FFT. The PSD is a measure of power per unit of frequency; hence it has units of power/frequency. The MSS, on the other hand, is a measure of power at a specific frequency and has units of power. As previously mentioned the spectrum view clearly has more information than the time domain. In order to determine the statistics of each signal in each zone, the plot of MSS is produced so as to estimate the relationship of the signal power and transport velocity at a specific frequency. Since any reduction in slurry velocity can influence the amplitude, and the difference can clearly be seen from one zone to another or one flow condition to another, thus a distinctive feature can be extracted to make the basis of the recognition scheme. This feature is used to relate the signal power at the top half of the pipe to the signal power at the bottom half of the pipe. This is based on a phenomenon that the average signal power decreases with increase of solid particles in each zone. Therefore, a threshold is assigned, based on the relative difference between the signal power at the top half of the pipe and the bottom half of the pipe for each flow regime. Once the average power of each zone is calculated, then the comparison is made between the signal power at the top half of the pipe and the power at the bottom half of the pipe. This can be done by calculating the ratio of the average power at the top of the pipe (P1, P2 & P3/2) to the average power across the five zones (or pipe cross-section); as shown below:

$$D = \frac{E}{(E + F)} \tag{4}$$

$$E = \frac{P_1 + P_2 + \left(\frac{P_3}{2}\right)}{3} \tag{5}$$

$$F = \frac{\left(\frac{P_3}{2}\right) + P_4 + P_5}{3} \tag{6}$$

Where; D represents the ratio of average signal power of the top half of the pipe to the average signal power across the pipe cross-section, E the average signal power at the top half of the pipe, F the average signal power at the bottom half of the pipe, P_1-P_5 the average signal power in each zone denoted by the subscript.

2.3. Threshold indication for each flow regime

In order to assign the values of C and D to every flow regime some initial information regarding the boundaries between the investigated flow regimes is required. In order to define these boundaries it is paramount to know the transitional velocities for the conditions used in this investigation. The information regarding the boundaries of flow regimes was experimentally obtained. It is worth mentioning that, due to the opacity of slurry and complex nature of slurry flow, the identification of these boundaries, at which one flow regime changes to another, can be quite difficult by conventional visual observation of flow through a transparent pipe section. Therefore, the transitional regime boundaries were arbitrary widened (±0.3 m/s), within which one flow regime changes to another. The information obtained from literature and visual observation of flow regarding the transitional velocities has been used to determine the boundaries between flow regimes and the range of C and D values for each flow regime. The threshold of C was determined by plotting the transport velocity against the relative difference between the top and the bottom of the pipe for every condition; see Fig. 3 (left-hand side). Similarly, the threshold of D value is determined by plotting the transport velocity against the ratio of average power at the top of the pipe to the average power at the bottom of the pipe for every condition; see Fig. 3 (right-hand side). The shaded areas in both figures

represent the transitional regime boundaries. Based on these two plots, the threshold values of *C* and *D* is assigned for each flow regime/transitional region, as shown in Table 1.
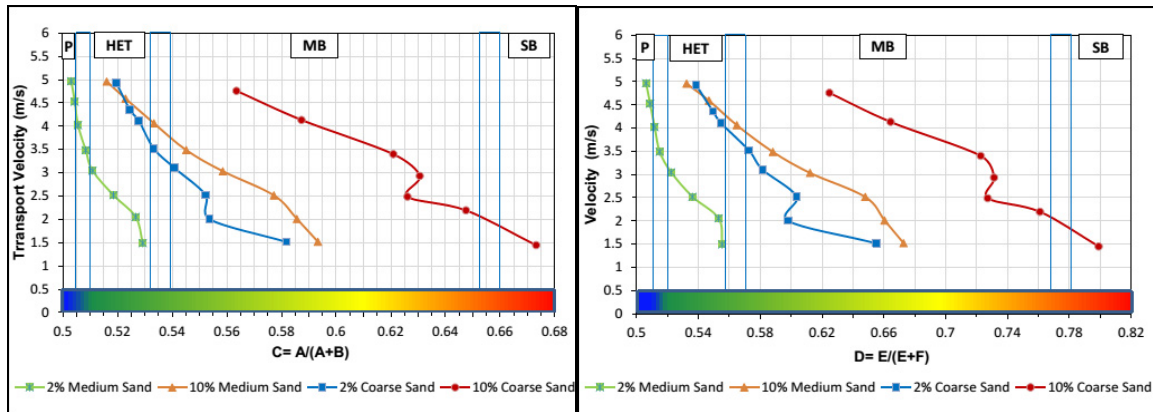

Fig. 3. The threshold of the signal; (left-hand side) the threshold values of *C*, (right-hand side) the threshold values of *D*. (P) Pseudo-homogeneous, (HET) Heterogeneous, (MB) Moving Bed, (SB) Stationary Bed.

Table 1. The range of *C* and *D* value for every flow regime or transitional region.

Flow Regimes	Threshold Value of *C*	Threshold Value of *D*
Homogeneous	$0.499 \leq C < 0.501$	$0.496 \leq D < 0.504$
Pseudo-homogeneous	$0.501 \leq C < 0.505$	$0.504 \leq D < 0.510$
Transition (Pseudo-homogeneous & Heterogeneous)	$0.505 \leq C < 0.510$	$0.510 \leq D < 0.520$
Heterogeneous	$0.510 \leq C < 0.532$	$0.520 \leq D < 0.555$
Transition (Heterogeneous & Moving Bed)	$0.532 \leq C < 0.540$	$0.555 \leq D < 0.570$
Moving Bed	$0.540 \leq C < 0.652$	$0.570 \leq D < 0.770$
Transition (Moving Bed & Stationary Bed)	$0.652 \leq C < 0.657$	$0.770 \leq D < 0.780$
Stationary Bed	$0.657 \leq C$	$0.780 \leq D$

2.4. Decision making

The decision on the type of the active flow regime, including transitional regions, is based on the assigned threshold values of *C* and *D*. In order to remove or reduce the subjectivity in recognizing the prevailing flow regime, or to make the best decision, the two threshold values were considered together at the same time, i.e. based on the assigned threshold values for each flow regime, the value of *C* and *D* must apply to the output recognized flow regime. This implies that if one of the values is incorrect then it will not return any result. Since *A* is the product of the ratio of the mean conductivity of the top half of the pipe to the mean conductivity of the pipe cross section (*A+B*), ideally one would think that at homogeneous flow regime, *A* should be equal to 0.5. However, as this is highly unlikely to happen in real world, therefore, a range of threshold values of *C* and *D* has been assigned, within which homogeneous flow regime would be returned. The threshold values of *C* have been extended by ±0.001 and *D* by 0.004. Thus, in order for the recognition scheme to return homogeneous flow regime, the value of C has to be between 0.499 and 0.501 and the value of *D* has to be between 0.496 and 0.504.

Since the stationary bed is the most sensitive flow regime and undesirable, then another condition has been assigned along with both conditions (*C & D*). The third condition is the standard deviation (STDEV) of the signal. As previously discussed, once a packed stationary bed is formed at the bottom of the pipe (zone 5), then the signal in

zone 5, unlike any other zones or conditions, does not show a turbulent fluctuation. Therefore, in order to determine that the flow regime is stationary bed, three conditions have to be met (*C*, *D* and *G*). *G* returns the standard deviation of the signal in zone 5. Based on the experimental data and visual observation, the threshold for the standard deviation of the signal in zone 5 is assigned as an arbitrary value (*G<0.003*).

3. Experiment facility

A set of experiments were carried out using a pilot-scale slurry flow loop shown in see Fig. 4. The horizontal line of the flow loop made the test section of the experiments, in which different flow regimes were generated by altering the slurry velocity. In order to cover all four typical slurry flow regimes, a relatively wide range of superficial velocity were selected to pump two sands, medium and coarse, each with different throughput volumetric concentration, 2% and 10%. At the beginning of each test the transport velocity was nominally set to 5 m/s, then it was incrementally decreased until the transport velocity reached 1.5 m/s. After a steady state pressure gradient was observed the use of high performance ERT system (Fast Impedance Camera System-FICA) is attempted to measure the average conductivity, across the pipe cross-section, by collecting blocks of 8000 frames for each flow condition. The data collection speed for FICA system is around 1.15 ms/frame, which means 9.2 seconds are required for collection of 8000 frames in real time. The details of the dual-plane ERT sensor and the high performance ERT system can be found in [24]. A 1.2 m transparent pipe section was included into the test section, so as to visually inspect the active flow regime in real time and capture photographic images of the flow for later comparison and evaluation of the proposed method.
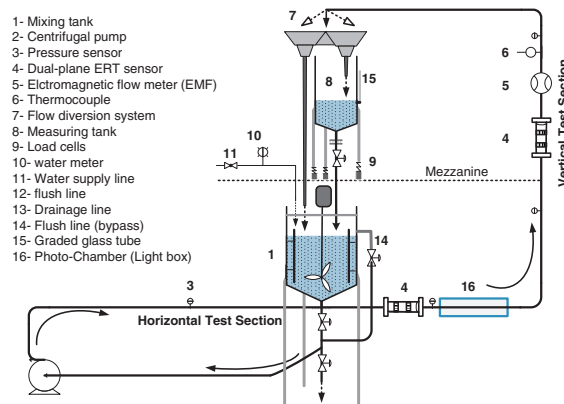

1- Mixing tank
2- Centrifugal pump
3- Pressure sensor
4- Dual-plane ERT sensor
5- Electromagnetic flow meter (EMF)
6- Thermocouple
7- Flow diversion system
8- Measuring tank
9- Load cells
10- water meter
11- Water supply line
12- flush line
13- Drainage line
14- Flush line (bypass)
15- Graded glass tube
16- Photo-Chamber (Light box)

Fig. 4. Schematic drawing of the flow facility.

4. Experiment results and discussion

The ERT measurements were taken for each type of the sand used in the experiments at two different throughput concentrations, 2% and 10%, and at different slurry velocity so as to generate a range of flow regimes considered in the study. The analysis of the ERT signal, for the 5 zones along the vertical centreline of each tomogram was carried out, by considering the change in conductivity relative to the reference (i.e. conductivity of carrier liquid). The signal, which is in time domain were plotted for each condition, an example of which is shown in Fig. 5. By observing Fig. 5, it can be seen that by reducing the slurry velocity the difference or gap between the conductivity of slurry at the top of the pipe and the conductivity at the bottom half of the pipe increases. In other words, by altering the transport velocity the mean conductivity goes through changes in each zone. It is apparent that the mean conductivity of each zone is related to the solids volume fraction. This is due to the fact that by reducing the velocity the solid particles migrate towards the bottom of the pipe, which results in higher conductivity at the top half of the pipe and lower at the bottom half. Based on this phenomenon, this feature was considered as an element in the recognition scheme. Moreover, it is quite evident that at 1.5 m/s slurry velocity; the signal of zone 5 decreases its fluctuation significantly.

It can be seen almost as a straight line. It is worth pointing out that the visual observation of the flow during the experiment revealed that there was a packed stationary bed at the bottom of the pipe. It can then be concluded that, based on the form of the signal in zone 5 at 1.5 m/s, the flow regime is stationary bed. By further analysis of the signal of zone 5 it was found that the standard deviation decreases with decrease of velocity. This is an indication of reduction of turbulent fluctuation in the conductivity. For example, for the velocity range 1.5-4.5 m/s the standard deviation range was found to be within 0.0019-0.2. Therefore, a threshold was assigned for stationary bed, based on the standard deviation of zone 5.
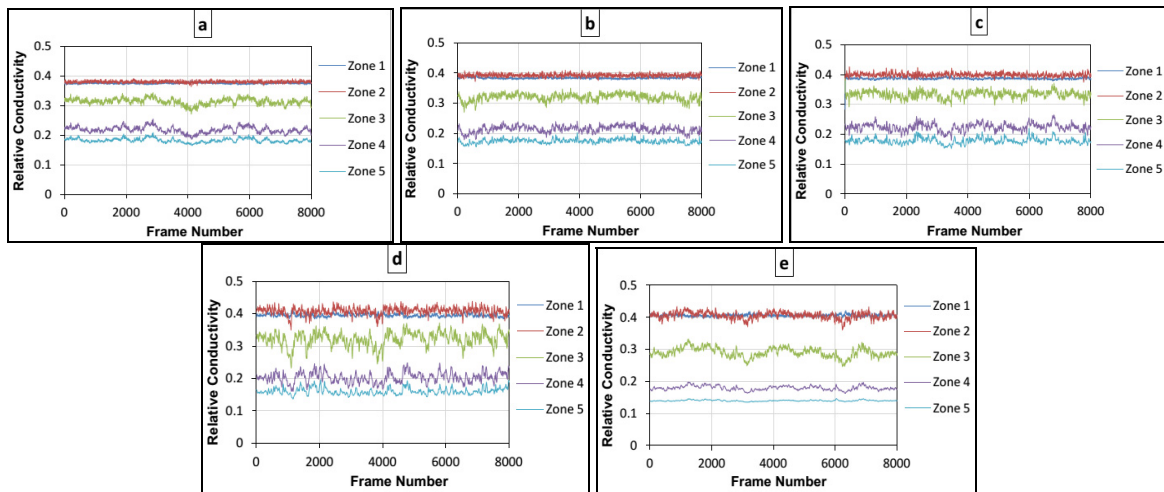
Fig. 5. Time domain signal of the ERT measurement for coarse sand at 10% throughput concentration; (a) 3.5 m/s, (b) 3.0 m/s, (c) 2.5 m/s, (d) 2.0 m/s, (e) 1.5 m/s.

The ERT signal was converted from time domain to frequency domain using FFT, which was used to render the Power Spectral Density (PSD) and the average power of the ERT signal within each zone. It was apparent that from the results of PSD the significant feature and relevant information regarding every flow regime can clearly be extracted by comparing the top half with the bottom half of the pipe. This can clearly be seen in the plot of power against the 5 zones, an example of which is shown in Fig. 6, which is showing the average signal power, for 10% coarse sand, against each zone as a function of velocity. It is evident that the velocity influences the signal power. By observing the plot, it can be seen that at the bottom of the pipe the average power of the signal decreases with decrease of velocity. At the top of the pipe, on the other hand, the average power of the signal increases with increase of velocity. This is clearly due to the difference in solids concentration between the top and bottom of the pipe.
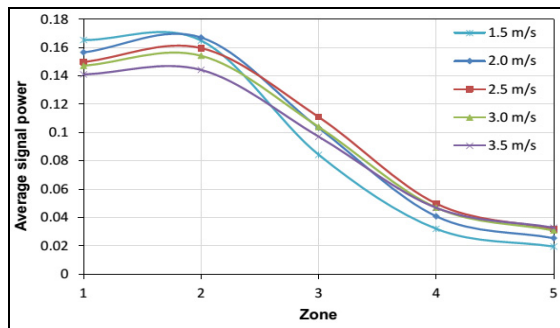
Fig. 6. Average signal power against the 5 zones as a function of transport velocity.

MATLAB was used to code the program for automated flow regime recognition. It was remarked that the elapsed time for determining the active flow regime is 30-35 s. This is due to the large amount of conductivity data (8000 frames). However, for on-line recognition of the flow regime, it is not necessary to input such a large data. Therefore, in order to continuously determine the flow regime, every 1000 frames would be sufficient. Since the high performance ERT system (FICA) measures 8000 frames per second, then 1000 frames can be acquired in 0.125 s. The code has been developed not only for rendering the recognition of the active flow regime, but also to visualise the distribution of the solid particles across the pipe cross-section and measure the mean solids volume fraction across the pipe cross-section. Fig. 7 illustrates the local solids concentration, which is calculated and displayed in real time.
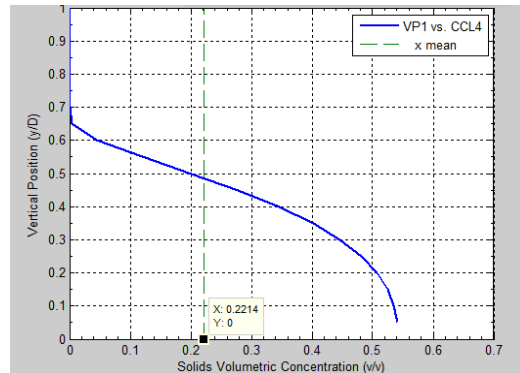

Fig. 7. Local solids volume fraction distribution for 10% coarse sand at 1.5 m/s.

In order to evaluate the recognition method, 31 test conditions were carried out within the range of velocity 1.5-5 m/s, which would undoubtedly cover all flow regimes considered in this recognition scheme. Different solid particle size (coarse & medium) at two different throughput concentrations (2% & 10%) were used to evaluate the effect of particle size and solids concentration upon the recognition scheme. The results of the recognition method have been compared to those established in literature [25] along with photographs of the flow and visual observation. The rate of recognition was determined as 90.32% for the conditions used in this study. A summary of the evaluation results is shown in Table 2. Since the recognition decision is based on the analysis of the zones across the vertical centerline of the pipe cross-section, therefore it is possible to be applied on any pipe size conveying slurry.

Table 2. Summary of recognition test results.

Flow Regimes	Actual Flow Regime	Recognised Flow Regime
Pseudo-homogeneous	2	2
Transition (Pseudo-homogeneous & Heterogeneous)	2	2
Heterogeneous	9	8
Transition (Heterogeneous & Moving Bed)	2	1
Moving Bed	15	14
Stationary Bed	1	1
Recognition Rate		**90.32%**

5. Conclusions

This paper has presented a novel method for slurry flow regime recognition, which is based on the statistical signal analysis of the ERT data in both time and frequency domain. It considers all common slurry flow regimes in the recognition scheme, including the transitional regime boundaries. Since the principle of the method is based on the distribution of solid particles across the pipe cross-section, then its applicability is quite reasonable to any particle size, 50% solids concentration and any internal diameter pipe. The test results suggest a recognition rate of 90.32% based on the test conditions used in this study. Since the recognition decisions are based on the statistical ERT signal analysis as an indirect recognition method, it is believed that it removes the subjectivity associated with recognition of the prevailing flow regime. This recognition method can be applied on any two-phase solid/liquid flow, as long as one of the phases is non- or less conductive than the other one. It can be useful for optimisation and correction of flow meters that are flow regime dependent. It can also be used in a non-intrusive and on-line fashion for distinguishing the boundaries between different typical settling slurry flow regimes and visualisation of solids distribution across the pipe cross-section, so as to enable the operator to take appropriate control actions for other downstream operations such as separation, mixing etc.

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