

Correlation of Electromagnetic Flow Meter, Electrical Resistance Tomography and Mechanistic Modelling for a New Solution of Solid Slurry Measurement

J. Y. Xu², M. Wang¹, B. Munir¹, H. I. Oluwadarey¹, H. I. Schlaberg¹, Y. X. Wu², and R. A. Williams¹

¹School of Process, Environmental and Materials Engineering, University of Leeds, Leeds, UK,
Email: M.Wang@leeds.ac.uk

²Institute of Mechanics, Chinese Academy of Sciences, Beijing 100080, China

ABSTRACT

The study presented here was carried out to obtain the actual solids flow rate by the combination of electrical resistance tomography and electromagnetic flow meter. A new in-situ measurement method based on measurements of EMF and ERT to study the flow rates of individual phases in a vertical flow is proposed.

The study is based on laboratory experiments that were carried out with a 50 mm vertical flow rig for a number of sand concentrations and different mixture velocities. A range of sand slurries with median particle size from 212 μm to 355 μm was tested. The solid concentration by volume covered was 5% and 15%, and the corresponding density of 5% is 1078 kg/m³ and for 15% 1238 kg/m³. The flow velocity was between 1.5 m·s⁻¹ and 3.0 m·s⁻¹. A total of 6 experimental tests were conducted. The equivalent liquid model was adopted to validate in-situ volumetric solids fraction and calculate the slip velocity.

The results show that the ERT technique can be used in conjunction with an electromagnetic flow meter as a way of measuring slurry flow rate in a vertical pipe flow. However, it should be emphasized that the EMF results must be treated with reservation when the flow pattern at the EMF mounting position is a non-homogenous flow. The flow rate obtained by EMF should be corrected considering the slip velocity and the flow pattern.

Keywords slurry measurement, electrical resistance tomography, electromagnetic flow meter, in-situ mean volumetric fraction, slip velocity.

1 Introduction

Slurry is an essential mixture of solid and liquid, and its physical characteristics are dependent on many factors such as the size and concentration distributions of solids in the liquid phase, the size of the conduit, level of turbulence, temperature, and absolute (or apparent) viscosity of the carrier. The transport of solid-liquid slurries over short and medium distances via pipelines is very important in many industrial applications. Local solid hold-up is one of the most important hydrodynamic characteristics that is needed for the design, analysis and performance estimation of liquid-solid two-phase flow and pipeline transportation systems.

Electromagnetic flow meters (EMF) have been successfully applied to measure mean velocities of single-phase liquid in various industries. Continuous efforts have been made to measure the characteristics of two-phase flow using electromagnetic flow meters, since such meters do not introduce a pressure drop and can provide a fast response to changes in the flow. Thus, there are many potential applications for electromagnetic flow meters in two-phase flow. However, due to the complexity of multiphase flow in solid slurry transportation, it is difficult to accurately measure solid concentration and flow rate using a conventional electromagnetic flow meter alone. Normally, a secondary sensor, e.g. gamma-ray density

meter, has to be employed.

Electrical resistance tomography (ERT) has been used successfully in predicting solid concentration, disperse phase velocity and flow regimes in both vertical and horizontal flows (McKee et al., 1995; Williams et al., 1996; Mann and Wang, 1997; G.P. Lucas et al., 1999; Wang and Yin, 2001). However, ERT is unable to measure the flow rate of the continuous phase and in its current form has difficulties in presenting an absolute value. In the present work, a new in-situ measurement method based on measurements of EMF and ERT to study the flow rates of individual phases in a vertical flow is proposed and the correlation of EMF-ERT measurements together with mechanistic modelling is studied.

2 THEORETICAL CONSIDERATIONS

2.1 The slip velocity

Slip velocity is a phenomenon that usually occurs in a multi-phase flow. For a liquid–solid two-phase flow, the liquid phase moves much faster than the solid, except in a downward flow. The difference in the in-situ average velocities between the liquid and solid phases will result in a very important phenomenon; the “slip” of one phase relative to the other, or the “hold-up” of one phase relative to the other. This makes the in-situ volume fractions different to the solid loading volume fractions. It is of importance to study this in detail in order to obtain an accurate in-situ fraction. Therefore, the present work will use different models to study the influence of the slip velocity on the slurry measurement. The first of these models is the hindered settling velocity, proposed by Richardson and Zaki (1954), which can provide estimates for individual grains of sand. The hindered settling velocity, v_T , can be estimated by:

$$v_T = v_T' \cdot (1 - \varepsilon_{SD})^{n'} \quad (1)$$

where ε_{SD} is the delivered volumetric solids fraction. The index, n' , a function of the particle's Reynolds number, depends on the dimensionless particle diameter, which is $n'=4.6$ for particles settling in the range of Stokes' law and $n'=2.4$ in the range of Newton's law, respectively. v_T' is the terminal settling velocity obtained by Stokes' law and Newton's law.

When the Reynolds number is less than 0.1 in the Stokes region, the terminal settling velocity can be expressed by:

$$v_T' = \frac{g \cdot d^2 (\rho_S - \rho_L)}{18\mu_L} \quad (2)$$

where ρ_L is the fluid density, μ_L is the fluid viscosity, g is the acceleration due to gravity, d is the particle diameter, and ρ_S is the particle density.

When the Reynolds number is between 750 and 300,000, the drag coefficient is nearly constant at a value of 0.44 in what is known as the Newton's law region. The terminal settling velocity is then:

$$v_T' = 1.73 \sqrt{\frac{g \cdot d (\rho_S - \rho_L)}{\rho_L}} \quad (3)$$

2.2 The in-situ volumetric solids fraction

The frictional head loss can be described by the equivalent liquid model (ELM) (Matousek, 2002). For vertical upward flow, the force balance can be given by:

$$\frac{dp}{dx} = g \cdot \rho_L \cdot S_M + 4 \cdot \tau_M / D \quad (4)$$

where dp/dx is the pressure gradient, τ_M is the shear stress, D is the tube diameter, and S_M is the in-situ relative density, given by:

$$S_M = 1 + (S_S - 1) \cdot \varepsilon_S \quad (5)$$

where $S_S = \rho_S / \rho_L$ and ε_S represent the relative density of the solid and the in-situ volumetric solids fraction, respectively. According to this model the density of the mixture influences the liquid-like wall shear stress so that:

$$\tau_M = \tau_L \cdot \frac{\rho_M}{\rho_L} \quad (6)$$

where $\rho_M = \rho_S \cdot \varepsilon_{SL} + \rho_L(1 - \varepsilon_{SL})$, ε_{SL} is the solids loading volumetric fraction. The wall shear stress, τ_L defined as:

$$\tau_L = \frac{\rho_L \cdot f_L \cdot V^2}{2} \quad (7)$$

where V is the mixture velocity, and friction factors, f_L , in a smooth pipe can be approximated by:

$$f_L = C_L \cdot \text{Re}_L^{-n} \quad (8)$$

where $C_L = 0.079$, $n = 0.25$, for turbulent flow, and $C_L = 16$, $n = 1$ for laminar flow.

Substitution of Eq.(5) into (4) leads to:

$$\varepsilon_S = \frac{(dp/dx - 4\tau_M/D)/(g \cdot \rho_L) - 1}{S_S - 1} \quad (9)$$

where $\tau_M = \frac{\rho_M \cdot C_L \cdot \text{Re}_L^{-n} \cdot V^2}{2}$. Equation (9) may be used to calculate approximately the in-situ mean volumetric solid fraction.

The ERT system was used to estimate the in-situ volumetric fraction based on the average of volumetric fractions of individual pixels which constitute the entire image. The simple calculation is given by Eq.(10).

$$\varepsilon_S = \frac{\sum_{i=1}^{i=m} \varepsilon_{S,i} \cdot A_i}{A_{total}} \quad (10)$$

where A_i , A_{total} and $\varepsilon_{S,i}$ is the area of pixel, the area of image (the cross-sectional area of pipe) and in-situ local volumetric disperse phase fraction, respectively.

2.3 Electromagnetic flow meter

The theory of the voltage-sensing flow meter was first developed by Shercliff (1954). The weight function, which represents the degree of the contribution of the fluid velocity to the signal in the cross-section of a

conduit, was proposed and computed for single-phase flow. For two-phase flow with non-uniform but isotropic conductivity, Bevir (1970) concluded that ΔU_{TP} can be expressed as:

$$\Delta U_{TP} = \frac{4BQ_L}{\Lambda\pi d(1-\varepsilon_s)} = \frac{\Delta U_{SP}}{\Lambda(1-\varepsilon_s)} \quad (11)$$

Here, Q_L is liquid flow rate and ΔU_{TP} is the potential difference between electrodes for two-phase flow and ΔU_{SP} for liquid flow alone (at the same flow rate Q_L). Λ is a homogeneity factor based on the conductivity distribution over the cross section of the EMF sensor in accordance with the flow power law and asymmetric velocity profile.

Bernier and Brennen (1983) used an electromagnetic flow meter to measure a homogenous gas-liquid two-phase flow. They concluded that a homogenous flow would give rise to an equation:

$$\Delta U_{TP} = \frac{4BQ_L}{\pi d(1-\varepsilon_s)} = \frac{\Delta U_{SP}}{1-\varepsilon_s} \quad (12)$$

They also investigated $\frac{\Delta U_{SP}}{\Delta U_{TP}(1-\varepsilon_s)} = 1$ is also valid irrespective of flow regimes or the homogeneity of electrical conductivity.

The difference between the two approaches is obvious; whether the homogeneity of dispersive phase distribution (flow pattern) should be taken into consideration. Since ERT can present the dispersive phase in-situ distribution, we prefer to use equation 11 in the present work, which could be simplified as:

$$Q_L = \Lambda \cdot (1-\varepsilon_s) Q_{EMF} \quad (13)$$

where Q_{EMF} is the mixture flow rate obtained using EMF.

3 EXPERIMENTAL SETUP AND PROCEDURE

A slurry flow loop with 50mm inside diameter has been designed and built at the School of Process, Materials and Environmental Engineering at the University of Leeds as shown in Figure 1 (Pachowko *et al*, 2003). The total PVC pipe work is 22m in length, with a 3m long vertical and two 5m long horizontal testing sections in the loop. The loop consists of a main 500 litres mixing tank, where the solid and liquid are mixed homogeneously and introduced into the loop. A 250 litre measuring tank is used to determine the delivered volumetric solid fraction at high flow velocities, as well as for verification of flow rate readings. A 15kW Warman International 2/11/2 AH heavy-duty centrifugal pump is used to transfer the slurry at velocities between 0.3 and 5 m/s. A frequency inverter was used for the control of the pump and hence the velocity and type of flow pattern that are generated. The flow rate of the solid and liquid mixture was measured by an electromagnetic flow meter (EMF). The selected EMF was a Krohne Aquaflex unit because its body lining was manufactured to be resistant to the slurry material flowing through it. Therefore, an abrasive slurry can be investigated. Mounting the flow sensor on a vertical pipe allows the measured velocity to be interpreted as the mixture velocity.

A range of sand slurries with median particle size from 212 μ m to 355 μ m was tested. The solid concentration by volume covered was 5% and 15%, and the corresponding density of 5% is 1078 kg/m³ and for 15% 1238 kg/m³. The flow velocity was between 1.5 m·s⁻¹ and 3.0 m·s⁻¹. A total of 6 experimental tests were conducted. ERT results presented in this paper were obtained from an ITS 2000 ERT system (Industrial Tomography Systems Ltd, Manchester, U.K.) in monitoring slurry transport in vertical pipes at several velocities. The ERT sensor was mounted in the working section at a distance of approximately 1.0 m from the tube bend. The dual-plane ERT Sensor with two dummy rings was configured so that the axial separation of the image planes was 50mm. On each plane, sixteen stainless steel electrodes are mounted flush to the surface of the pipe at equal intervals. The electrodes were designed to have a length to width ratio of 3, giving an electrode size of 18mm by 6mm. The voltage potential differences for tomography

images were collected based on the normal adjacent protocol, with a data collection speed of 5 frames per second for the dual planes, at an AC current injection frequency of 9600Hz and a current value of 15mA. This produces 104 independent measurements for each tomographic image. The reconstruction of the image was carried out by the use of the Linear Back Projection (LBP) algorithm (Wang, 2000). The volumetric solids fraction was determined from the Maxwell relationship (Dyakowski et al., 2000). In this work, prior to experiments we calibrated the ERT system and took the reference frame when the sensor was full of liquid only so that the reference measurement error could be controlled within 1%.

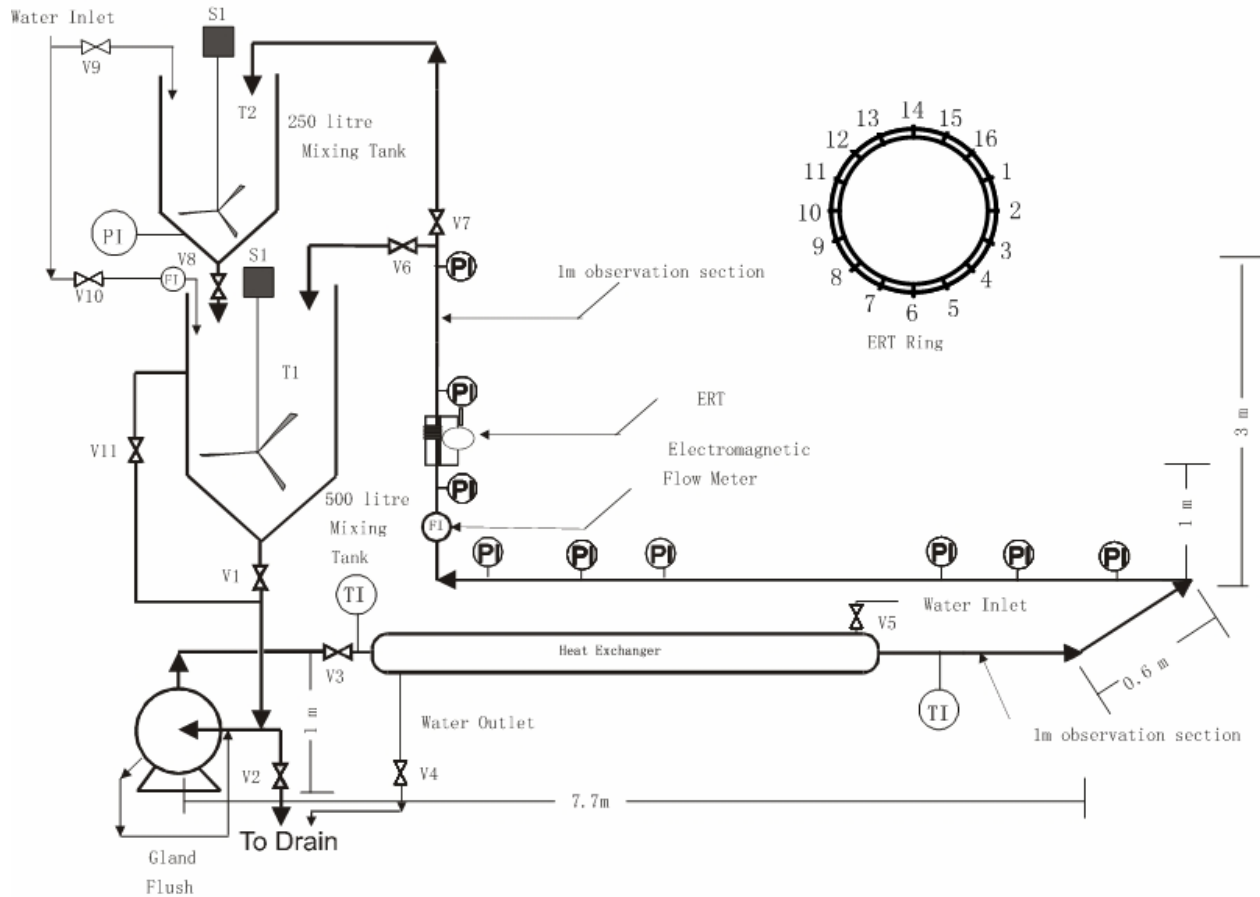


Figure 1: Schematic of the test flow loop

4 RESULTS AND DISCUSSION

4.1 In-situ volumetric solids fraction measurement obtained by ERT

For each experiment, 350 conductivity images were continuously collected over approximately 5 minutes, for all loading volumetric fraction. These images were averaged and merged and then the volumetric fraction profile was obtained using the Maxwell relationship. The results are presented in Figure 2. The solid curves represent theoretical results predicted by equation 9 and the points indicate the measured values using ERT system. It is shown that the ERT system gives reasonable estimates of the mean volumetric fraction in vertical flow. It also demonstrates that it is possible the mean concentration in the test section to be higher than that of the loading sand concentration. It is also observed that the decrease of in-situ volumetric fraction as mean mixture velocity (as well as the slip velocity) increases in the solid-water two-phase upward flow. This phenomenon is well known and can be explained with the principle of mass conservation and flow continuity. Furthermore, the comparison with the results obtained by ELM

showed that ERT system provided a reasonable estimation of the average volumetric fraction for the mixture flow of the vertical liquid-solid slurry flow.

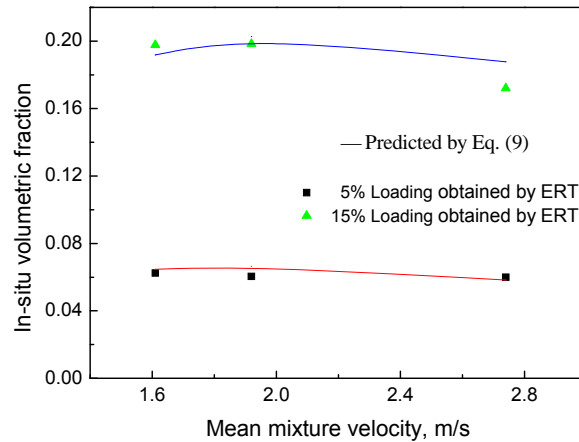


Figure 2: Comparison of volumetric solids fractions obtained using the ERT system and the ELM model.

4.2 Slurry flow rate measurement obtained by electromagnetic flow meter

In order to investigate the effect of the mixture flow rate on the electromagnetic flow meter, we studied equation 13 using a loading volumetric sand fraction of 0.15. Two groups of data are presented in Figure 3. One set of data was obtained using the EMF readings corrected with a constant loading volumetric fraction, 0.15, and the experimental measurement using a measurement tank, respectively. Another data set were obtained using the EMF reading corrected with the in-situ volumetric fractions measured using the ERT system at relevant mixture flow rates, respectively.

It can be seen from Figure 3 that the data corrected by a constant volumetric fraction gives a linear relationship between the mixture and water phase flow rates. However a non-linear correlation is presented from both the experimental measurement and the data with correction made using in-situ volumetric fractions. The gradient of the curve decreases gradually with increased mixture flow rate. The difference may be caused by two reasons: (a) the decrease of volumetric solids fraction due to the increase of slip velocity between solid phase and liquid phase, which are demonstrated in Figure 2; (b) the flow pattern trends to non-homogenous flow when slurry flow rate is increased, namely the homogeneity factor, Λ , may not be constant for a non-homogeneous system. The EMF reading corrected with in-situ volumetric fraction has a consistent tendency similar to that obtained by the experimental method.

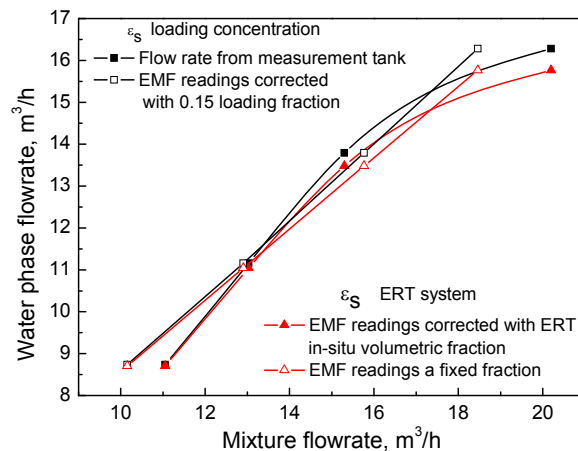


Figure 3: Flow rates obtained from EMF, EMF corrected with in-situ volumetric fraction and experimental measurements at a loading volumetric fraction of 0.15.

4.3 In-situ volumetric solids fraction and velocity obtained by four different methods

For the sake of the studies of slip velocity in solid-liquid vertical flow, four different methods to obtain the slip velocity v_T were attempted. If ε_{SD} is defined as the delivered volumetric solids fraction, then we can obtain from continuity equation:

$$v_T = V_M \cdot \frac{\varepsilon_S - \varepsilon_{SD}}{\varepsilon_S} \quad (14)$$

v_T plays a very important role in vertical hoisting. Due to the different flow pattern in horizontal and vertical pipes under the same entry conditions, the delivered volumetric solids fraction is different in different pipes, especially for the experiment loop of the present work. The solid and liquid are mixed homogeneously and first introduced into the horizontal pipe and then flows into the vertical pipe section. Thus the delivered volumetric solids fraction ε_{SD} in vertical pipe would be re-measured with T2 as is shown in Figure 1. Table 1 shows the results calculated by different models.

15% loading sand volume ($\varepsilon_{SD} = 0.134$)			
Methods	ε_S		v_T
Stokes' law ($n' = 4.6$)	0.138	←	0.051
Newton' law ($n' = 2.4$)	0.140	←	0.073
ERT system	0.198	→	0.520
ELM	0.192	→	0.486

Table 1: A comparison of the mean in-situ volumetric solids fraction obtained and the slip velocity, v_T by four methods
(The mixture velocity, V_M , is 1.61 m/s). The arrow shows the derivation direction.

It is seen in Table 1 that Stokes' law obtained the lowest ε_S and v_T values. It should be emphasized that in practice Stokes and Newton models were based on the properties of single particles, so they only provide a rough estimate of the expected in-situ volumetric solids fraction. Furthermore, due to the size, velocity and density of the solid phase there will be segregation at the bottom of the vertical pipe. The two models did not take into account the interaction between different sized particles, either. Thus it would be better that the results of ELM are used to validate the ERT system. It can be seen in Table 1 that the slip velocities in the test section reach to 0.52 m/s so that we should consider the effects of the slip velocity on slurry measurement. This aspect of the work will be studied further to correct the measurement results of EMF in the future.

5 CONCLUSIONS

To understand the performance of a liquid-solid slurry flow in a vertical pipe and measure the individual phase flow rate, the presented study was carried out conducting an experimental and theoretical investigation of the slurry vertical flow with EMF and ERT techniques. A series of experiments were carried out. As has been shown above, in the present work the flow rates of the continuous phase and two-phase mixture are measured using EMF, the volumetric disperse phase fraction is obtained with an ERT system, and the slip velocity can be predicted with ELM in a vertical pipe transporting slurry. Some significant results are obtained:

For the measurement of flow rate it should be noted that the mounting position of the EMF instrument would have an important effect on results displayed by the EMF. In this study the EMF was mounted in the working section at a distance of about 0.1 m from the tube bend. As the mixture flows through a pipe bend this will result in an accumulation of particles at the bottom so that the accuracy of measurement is affected and there will be a distortion of velocity distribution in the pipe cross-section. In future work the EMF should be installed in a position where the vertical slurry flow is developed. Otherwise the EMF measurement has to be revised due to the influence of non-homogenous flow.

For the measurement of the disperse phase, a new in-situ measurement method based on ERT in a vertical flow is proposed. The results were checked by the ELM. Figure 5 shows that axial solids volume fraction distribution obtained using the ERT system at various mixture velocities at the loading solid concentration of 5% and 15%. It can be seen that there is an accumulation of particles at the outer wall of the pipe. Due to the ERT sensor being mounted in the working section at a distance of approximately 1.0 m from the tube bend and solid particle inertia, the mixture flow through a pipe bend will result in an accumulation of particles at the bottom and outer wall of the bend. In the connecting vertical pipe, the accumulation will disintegrate due to the secondary flow induced by the bend and due to flow turbulence. Similar results were also found by N. Huber and M. Sommerfeld (1994) in a gas-solid two-phase flow. The results further prove the flow pattern of non-homogenous flow in the test section showing that inevitable errors exist for the measurement of non-homogenous a two-phase flow using the EMF. Furthermore for non-homogenous flow the slip velocity has to be considered to correct the results of EMF, and the equivalent liquid model (ELM) was used to calculate the slip velocity and validate the ERT system.

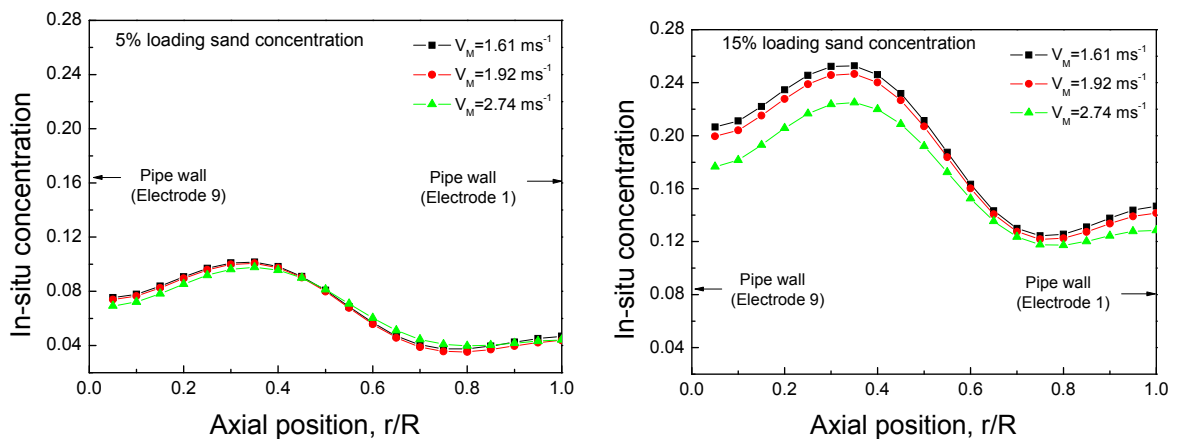


Figure.5: Axial solids volume fraction distribution obtained using the ERT system

In summary, it should be emphasized that the EMF must be treated with reservations when the flow pattern at the EMF mounting point is a non-homogenous flow. The slip velocity and flow pattern have to be considered to correct the results using the equivalent liquid model. The results have demonstrated that the ERT technique can provide in-situ volumetric fraction and therefore can be used in conjunction with an electromagnetic flow meter as a way of measuring slurry flow rate in a vertical flow.

6 REFERENCES

- BERNIER R.N., and BRENNEN C.E., (1983) Use of the electromagnetic flow meter in a two-phase flow, *Int. J. Multiphase Flow* 9, 251–257.
- BEVIR M.K., (1970) The theory of induced voltage electromagnetic flow meters. *J. Fluid Mech.* 43, 577–590.
- DYAKOWSKI T., JEANMEURE L.F.C., and JAWORSKI A.J., (2000) Applications of electrical resistance tomography for gas-liquid and liquid-solids flows- A review. *Powder Technology* 112, 174-192.

GIDASPOW D., (1994) Multiphase flow and fluidization - Continuum and kinetic theory descriptions. *Academic press*.

HEYWOOD N.I., MEHTA K.B., and POPLAR D., (1993) Evaluation of seven commercially available electromagnetic flow meters with Newtonian and non-Newtonian china clay slurry in pipe flow. *12th Int. Conf. Slurry Handling and Pipeline Transport-Hydrotransport 12. BHRG*, 353-76

HEYWOOD N.I., MEHTA K.B., (1999), Performance evaluation of eight electromagnetic flow meters with fine sand slurries. *Hydrotransport 14. BHRG*, 413-31

HUBER N., and SOMMERFELD M., (1994) Characterization of the cross-sectional particle concentration distribution in pneumatic conveying systems. *Powder Technology 79*, 191-210.

LUCAS G.P., et al., (1999) Measurement of the solids volume fraction and velocity distributions in solids-liquid flows using dual-plane electrical resistance tomography. *Flow Measurement and Instrumentation 10*, 249-258.

LUCAS G.P., CORY J.C., and WATERFALL R.C., (2000), A six-electrode local probe for measuring solids velocity and volume fraction profiles in solids-water flows. *Measurement Science and Technology 11*, 1498-1509.

MANN R., and WANG M., (1997) Electrical process tomography: simple and inexpensive techniques for process Imaging. *Measurement and Control 30*, 206-211.

MATOUSEK V., (2002) Pressure drops and flow patterns in sand-mixture pipes. *Experimental Thermal and Fluid Science 26*, 693-702.

MCKEE S.L., WILLIAMS R.A. and BOXMAN A., (1995), Development of solid-liquid mixing models using tomographic techniques. *Chemical Engineering Journal 56*, 101-107

PACHOWKO A.D., WANG M., POOLE C., and RHODES D., (2003), The use of electrical resistance tomography (ERT) to monitor flow patterns in horizontal slurry transport pipelines, *Proceedings for 3rd World Congress on Industrial Process Tomography*, Banff, VCIPT, pp.305-311

RICHARDSON J.F., and ZAKI W.N., (1954) Sedimentation and fluidisation. *Transactions of the Institution of Chemical Engineers 32*, 35-53.

SHERCLIFF J.A., (1954) Relation between the velocity profile and the sensitivity of electromagnetic flow meters. *J. Appl. Phys. 25*, 817-818.

WANG M., and YIN W., (2001) Measurement of the concentration and velocity distribution in miscible liquid mixing using electrical resistance tomography. *Transactions of the Institution of Chemical Engineers 79*, 883-886.

WANG M., (2002) Inverse solutions for electrical impedance tomography based on conjugate gradients methods, *Meas. Sci. & Tech.*, IOP, 13, pp.101-117

WILLIAMS R.A., JIA X., and MCKEE S.L., (1996) Development of slurry mixing models using resistance tomography. *Powder Technology 87*, 21-27.

WILSON K. C. et al., (2006) Slurry transport using centrifugal pumps. Third edition, *Springer*.