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Using ERT for Multi-Phase Flow Monitioring

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Abstract *-- This paper describes a novel approach of measuring volumetric flow rate using Electrical Resistance Tomography. Conventional flow measuring techniques are flow-profile dependent and will not produce accurate results unless prior knowledge of the flow profile is known. A brief outline of the various aspects needed to realise an ERT flow meter are presented in this paper. Results produced by the ERT flowmeter were verified with two other independent flow measurement techniques. A brief description of these techniques is given. The results presented in this paper were obtained from experiments involving vertical flow and inclined flow.*

Keywords: Multiphase flow, Electrical Resistance Tomography, Flow Profile, Skew Flow.

1. INTRODUCTION

To date, there exist many types of flow meter utilising a range of different techniques [6, 5, 8, 17]. The accuracy and functionality of these meters are flow profile dependent. For these techniques to work, prior assumptions of the flow distribution have to be made, as the instruments themselves are not capable of providing local information on the flow. If the assumptions are wrong or inaccurate, the calculated flow rate will be inaccurate or may even be completely useless [5, 7, 11]. Tomography provide a means of 'looking' inside the flow region from which local flow information such as volume fraction and velocity can be extracted. This technique will provide a more accurate means of calculating flow rate and eliminate the uncertainty in measurement due to the inability to predict flow profile associated with existing flow measurement methods.

In order to measure the volumetric flow rate (*Q*), it is necessary to measure the distribution of the local volume fraction (a_c), of the solids and the distribution of the local axial velocity (V_c). The volumetric flow rate *Q* can then be taken as:

$$Q = \int_A a_c V_c dA \qquad (1)$$

Where *A* is the area of the cross-section

Measurement of the component fractions (a_c), and velocities (V_c), is particularly important in horizontal and inclined flows where these distributions are highly skewed.

In this paper, the discussion is limited to applying tomography to flows of non-conductive solids in conductive fluid although the same concept can be applied to non-conductive solids and liquids with different permitivity (e.g. oil, water, gas mixture). The use of the electrical resistance technique is best suited for measurement in conductive media.

2. ELECTRICAL RESISTANCE TOMOGRAPHY IN FLOW MEASUREMENT

Tomography is used to obtain cross-sectional images of objects by non-destructive means. Tomographic images were originally developed for medical purposes as an improvement to existing X-ray radiography practices. However, there is a growing interest in tomographic imaging for use in industrial processes to improve the design and operational efficiency of process plant operation. The general principle underpinning tomographic techniques is to enclose the objects to be studied by a number of non-intrusive sensors (transducers) and then acquire measurements from these sensors. The signals produced by these sensors depend on the position of the component boundaries within the sensing zone. A mathematical reconstruction algorithm is used to generate the respective cross sectional image based on the signals observed by the peripheral sensors.

As the experiments in this paper deals with conductive fluid, it was decided that the use of ERT to measure the local conductivity distribution (s_c), in the flow section was most appropriate. The local conductivity distribution can be converted to local volume fraction distribution (a_c), using the relationship such as that developed by Maxwell [14]. In order to measure the local axial velocity distribution V_c of the solids, the use of two planes of ERT sensors strategically placed some distance apart is required. Cross correlating the corresponding pixel conductivity from each plane would produce the velocity profile. Determining a_c and V_c allows the volumetric flow rate (Q), to be calculated easily as per equation 1.

2.1 ERT Hardware

In this preliminary work, an expected velocity discrimination of 10% was thought to be sufficient. Calculations as described in [1, 11] indicated that a sampling rate (d) of 50 samples per second from each plane would suffice for plane separation (L) of 50mm, maximum velocity (U_{Max}) of 0.5m/s and velocity discrimination ($\frac{\Delta U}{U_{Max}}$) of 10%.

$$d = \frac{1}{2\times\frac{L}{U_{Max}}\times\frac{\Delta U}{U_{Max}}} \qquad (2)$$

Conventional ERT systems such as those used in the medical field [4] and those used in the processes field [19] were considered to be too slow for flow monitoring application [11]. A new and faster ERT data acquisition system (DAS) known as the Mk2a was designed and built to meet these demands. The main features of the Mk2a ERT DAS is high acquisition rate (100 frames of 104 measurement in 1 second), high data transfer rate (> 1Mbytes per second), large data storage capacity (limited only by host computer primary and secondary storage). The functional blocks of the Mk2a are shown in Figure 1. Interested readers should refer to [11] for a more detailed discussion of the ERT DAS. Cross plane interference [7], where signals from either plane interfere with the other is also a problem that has to be addressed. The interleave data collection protocol [11] where data is collected from alternate planes was used to overcome this problem. The use of this method enables closer separation between the planes of electrodes to be achieved. This will enhanced cross-correlation especially if the flow is highly skewed.

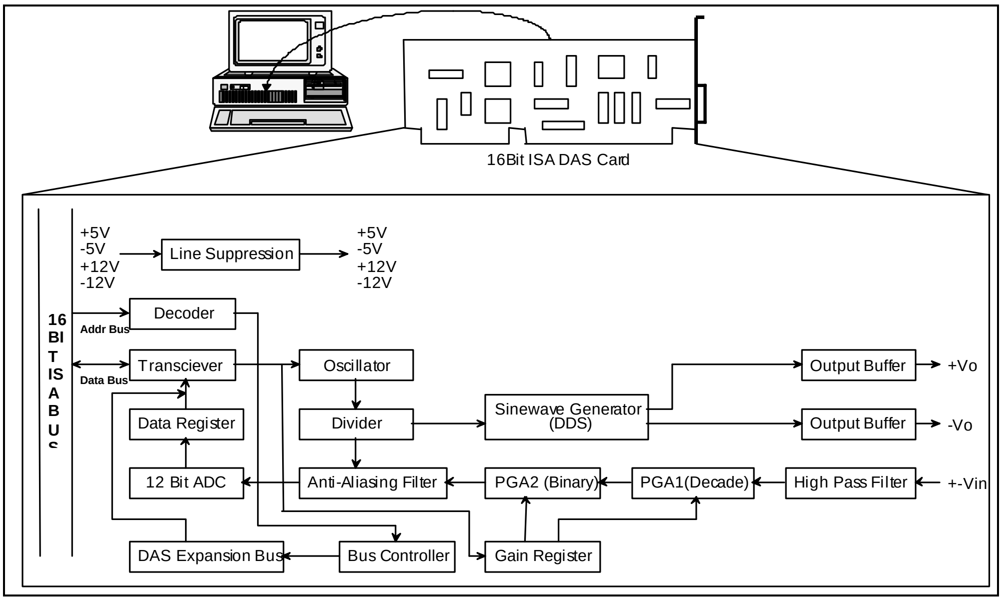


Figure 1 Functional Block Diagram of Mk2a System

2.2 Flow Parameter Calculation using ERT

The local volume fraction distribution (a_c), can be determined indirectly from the conductivity distribution by applying Maxwell's equation [14], shown below.

$$a_c = \frac{2s_1 + s_2 - 2s_{mc} + \dfrac{s_{mc}s_2}{s_1}}{s_{mc} - \dfrac{s_2}{s_1} + 2(s_1 - s_2)} \quad (3)$$

where s_1 is the conductivity of the first phase
s_2 is the conductivity of the second phase
s_{mc} is the local mixture conductivity distribution.

According to Maxwell, the validity of equation 3 is limited to small volume fraction, however, various researchers including Neale *et al.* [15] and Turner *et al.* [18] found that equation 3 , produced good agreement with experimental data over a wide range of void fractions.

Equation 3 can be simplified if the second phase is assumed to be non-conductive material, such as rock chippings (or plastic pellets, in this investigation).

$$a_c = \frac{2s_1 - 2s_{mc}}{s_{mc} + 2s_1} \quad (4)$$

Equation 4 requires the conductivity of the first phase and the mixture to be known. The conductivity of the first phase (s_1) can be found easily using a widely available commercial conductivity meter. The local mixture conductivity (s_{mc}), can be determined from the pixel conductivity as reported by a quantitative reconstruction algorithm such as the Modified Newton Raphson (MNR) [12, 20].

In this work, the MNR qualitative reconstruction algorithm, which was accepted to be the most accurate, was used to produce the quantitative conductivity profile. Details of this algorithm are widely documented and are available in the literature. [9, 12, 16]

Another main parameter, which needs to be determined in equation 1, is the local axial velocity. Applying cross-correlation techniques to determine the speed of moving profiles had been widely demonstrated [1, 3] and the mathematical principle behind this technique is also documented in statistical literature such as [2]. The basic function of the cross-correlation technique is to find the time offset between two signals where the similarities are most obvious. These signals can be of any value and is not limited to quantitative conductivity data. A back-projection-type qualitative reconstruction algorithm, which produces relative conductivity changes but requires very much less computational resources, would suffice. Although not limited to any one particular type of qualitative reconstruction algorithm, a back projection type algorithm as proposed by Kotre [10] is used in this investigation for the purpose of producing the conductivity signal for cross correlation purpose.

There are several different cross correlation techniques [1, 3], however, all of these are derivatives of the first principle of cross-correlation, otherwise, known as *direct correlation*. *Direct correlation* suitable for implementation on a digital computer is show in equation 5.

$$R_{12}(n) = \sum_{m=0}^{M-n-1} f_1(m)\, f_2(m+n) \quad (5)$$

Where R_{12} is the cross correlation function
f_1 & f_2 are the signals to be correlated
$n = -(M-1), \ldots, -1, 0, 1, \ldots, (M-1)$
M = sample length

Alternative techniques of cross-correlation were developed, mainly to reduce the computation requirement and so to speed up the correlation process. However, depending on the speed requirement of the application coupled with present advances in microprocessor and digital signal processor (DSP) technology, using alternative methods of cross correlation may be unnecessary. For example, if the application has associated long time constants, like the monitoring of drill cuttings in several kilometres of oil well, and if fast DSPs such as the Texas Instrument TMS320C6x range of DSP capable of performing up to 1 billion calculations per second were used, direct implementation of equation 5 would be adequate.

3. VALIDATION

In order to determine the functionality of this concept and the prototype flow meter, some means of validating the results produced by the ERT technique are needed. Parallel investigations were carried out to validate the volume fraction and velocity profiles. This was achieved using two different independent techniques.

3.1 Volumetric Flow rate and Volume Fraction Validation using Weighing Hoppers and Gradiomanometer

As the solids and liquid phase were pumped around the flow rig, two weighing hoppers were used to determine the amount of solids and liquid collected in a given time. This will determine the overall flow rate. To determine the overall volume fraction at the test pipe section, a gradiomanometer was used. Details regarding the workings of the gradiomanometer were documented in literature such as [7, 11].

3.2 Local Volume Fraction and Velocity Profile using Miniature Intrusive Conductivity Probe

Recent developments at the University of Huddersfield have produced a miniature conductivity probe capable of probing small area within a region of interest. This device allows the conductivity and hence volume fraction distribution to be visualised. The profile generated by this device can be used to compare results generated by the ERT technique. In addition to measuring conductivity, this miniature device can also measure the local velocity of the solids. This is achieved via a set of identical conductivity sensors located along the device shaft (see Figure 2). The velocity distribution using this technique can again be used to compare with those generated by the ERT technique.

The basic principle of obtaining the volume fraction and solids velocity is the same as those discussed in section 2. Using the Maxwell equation, as shown in equation 3 and 4, the volume fraction can be determined. Cross-correlating the signals generated from both sensor electrode pairs (see Figure 2) will produce the solids velocity.

The invasive probe, with thin ring electrodes mounted on a 4 mm diameter plastic rod, is attached to a computer-controlled placement rig so as to allow it to be positioned anywhere in the region of interest (see figure 3). As movement of the probe within the region of interest is a mechanical process, each measurement position takes about one minute to complete, necessitating several hours to probe the entire region. Interested readers should consult [13] for a more detail discussion of this technique.

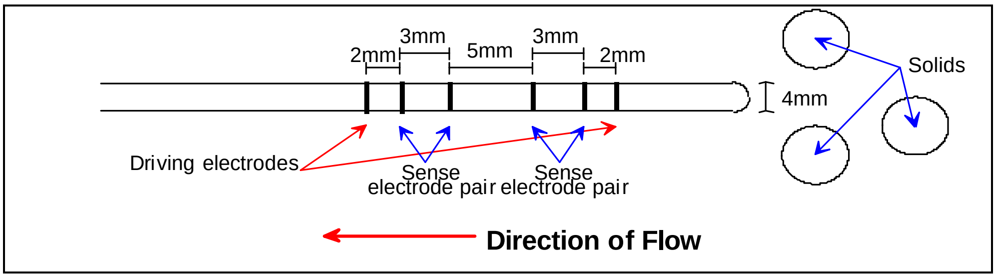


Figure 2 Miniature Conductivity Probe

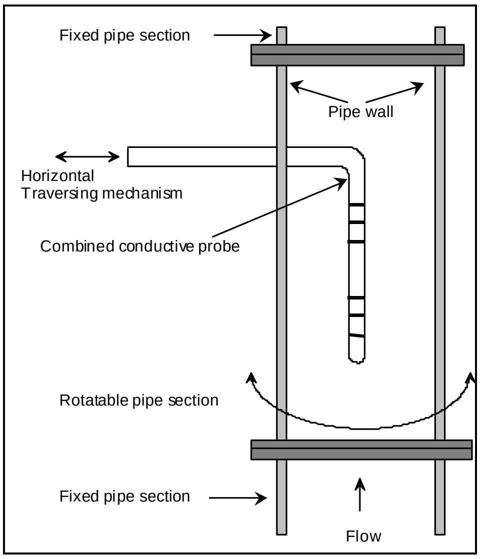


Figure 3 Miniature Conductivity Probe

The experiments presented in this work were conducted on a laboratory-scale flow rig at the University of Huddersfield. For the ERT experiments, a total of 2000 frames of data each consisting of 104 measurements were recorded in a period of 20 seconds. The results were compared with those from the weighing hoppers and the miniature conductivity probe, both of which requires a longer acquisition time, due to their mechanical nature. It is important to stress that the experiments involving the miniature probe and the ERT system were not conducted simultaneously, as different time scales were involved, hence, slight differences in results were expected.

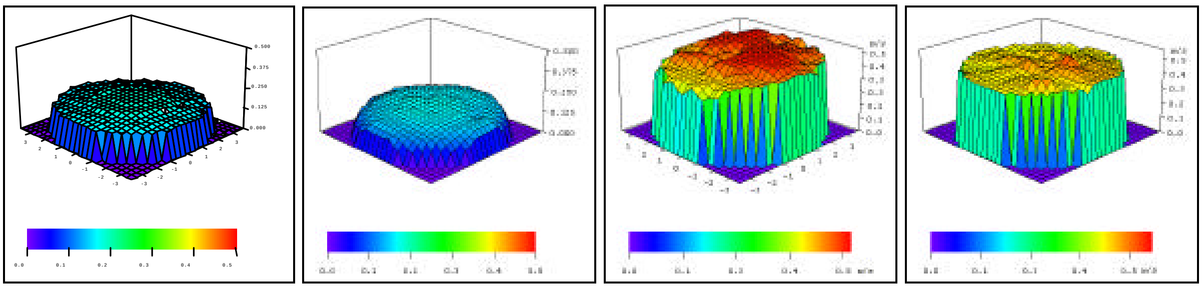
The flow conditions investigated in this paper involve almost "homogeneous" and skew profiles produced by inclined flow.

4. RESULTS

4.1 Vertical Flow Condition 1

	ERT			Local Conductivity Probe (LCP)	
	Reference	**ERT**		**Reference**	**LCP**
Global Void Fraction (%)	14.90	16.70		17.00	14.00
Global Mass Vel. (m/s)	0.47	0.46		0.45	0.44
Vol. Mass Flow rate (m^3/hr)	1.27	1.30		1.37	1.12

Table 1 Results for vertical Flow Condition 1



(ERT)a **(LCP)b** **(ERT)c** **(LCP)d**

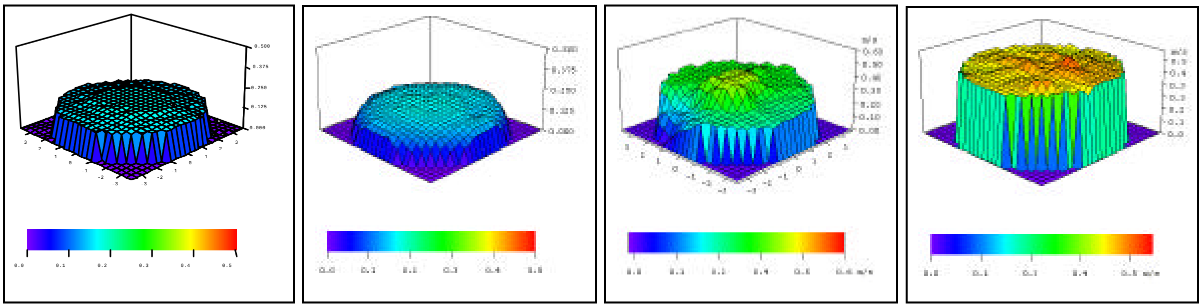
Volume fraction Profiles **Velocity Profiles**

Figure 4 Volume Fraction and Velocity Profile Plots

4.2 Vertical Flow Condition 2

	ERT			Local Conductivity Probe (LCP)	
	Reference	**ERT**		**Reference**	**LCP**
Global Void Fraction (%)	15.33	15.85		18.00	14.00
Global Mass Vel. (m/s)	0.28	0.29		0.22	0.28
Vol. Mass Flow rate (m^3/hr)	0.76	0.82		0.70	0.72

Table 2 Results for Vertical Flow Condition 2



(ERT)a **(LCP)b** **(ERT)c** **(LCP)d**

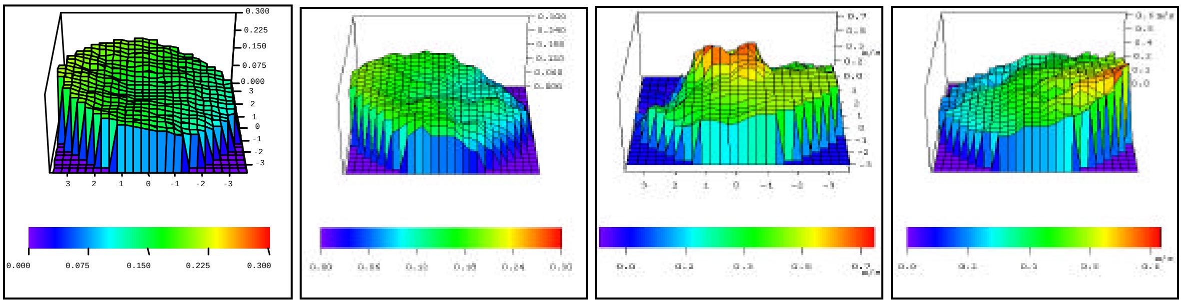
Volume fraction Profiles **Velocity Profiles**

Figure 5 Volume Fraction and Velocity Profile Plots

4.3 Inclined Flow Condition 3

	ERT			Local Conductivity Probe (LCP)	
	Reference	**ERT**		**Reference**	**LCP**
Global Void Fraction (%)	18.32	16.37		18.00	11.00
Global Mass Vel. (m/s)	0.26	0.33		0.26	0.30
Vol. Mass Flow rate (m^3/hr)	0.86	0.89		0.86	0.57

Table 3 Results for Vertical Flow Condition 3



(ERT)a **(LCP)b** **(ERT)c** **(LCP)d**

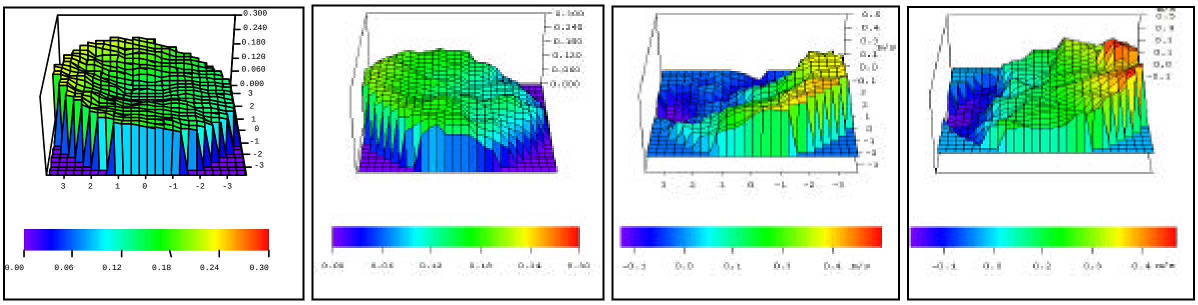
Volume fraction Profiles **Velocity Profiles**

Figure 6 Volume Fraction and Velocity Profile Plots

4.4 Inclined Flow Condition 4

	ERT		Local Conductivity Probe (LCP)	
	Reference	**ERT**	**Reference**	**LCP**
Global Void Fraction (%)	18.90	17.40	21.00	14.00
Global Mass Vel. (m/s)	0.12	0.13	0.09	0.11
Vol. Mass Flow rate (m^3/hr)	0.41	0.34	0.35	0.27

Table 4 Results for Inclined Flow Condition 4



(ERT)a **(LCP)b** **(ERT)c** **(LCP)d**

Volume fraction Profiles **Velocity Profiles**

Figure 7 Volume Fraction and Velocity Profile Plots

5. CONCLUSION

The results show good correlation between those produced by the ERT meter and those produced by two other independent reference methods. Both volume fraction and velocity profiles produced by the ERT system match those indicated by the intrusive probe. Homogeneous and skew profiles of inclined flow were investigated. The results indicated that tomographic technique can be used to measure flow rates independent of flow regime.

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