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# Two-phase flow meter for determining water and solids volumetric flow rate in stratified solids-in-water flows

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## INTRODUCTION

This paper describes a novel technique that can be used for measuring the local axial velocity distributions of the continuous and discontinuous phases and the local volume fraction distribution of both phases in highly non-uniform multiphase flows for which the continuous phase is electrically conducting and the discontinuous phase is an insulator. From these profiles the volumetric flow rates of both phases can be calculated. In the work described in this paper solids-in-water flows were investigated, the local axial velocity distribution of the water being measured using a novel instrument known as an Electromagnetic Velocity Profiler (EVP) [1]. The local axial velocity distribution of the solids and the local volume fraction distribution of both phases were measured using an Impedance Cross Correlation (ICC) device [2].

### 1. ELECTROMAGNETIC VELOCITY PROFILER

The fundamental theory of electromagnetic flow meters (EMFMs) states that charged particles, in a conducting material which moves in a magnetic field, experience a Lorentz force acting in a direction perpendicular to both the material's motion and the applied magnetic field. Shercliff [3] showed that the local current density  $\mathbf{j}$  in the fluid is governed by Ohm's law in the form

$$\mathbf{j} = \sigma(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \quad (1)$$

where  $\sigma$  is the local fluid conductivity,  $\mathbf{v}$  is the local fluid velocity, and  $\mathbf{B}$  is the local magnetic flux density. The expression  $(\mathbf{v} \times \mathbf{B})$  represents the local electric field induced by the fluid motion, whereas  $\mathbf{E}$  is the electric field due to charges distributed in and around the fluid. For fluids where the conductivity variations are relatively minor (such as the single phase and the multiphase flows under consideration in this paper) Shercliff simplified equation 1 to show that the local potential  $U$  in the flow can be obtained by solving

$$\nabla^2 U = \nabla \cdot (\mathbf{v} \times \mathbf{B}) \quad (2)$$

For a circular cross section flow channel bounded by a number of electrodes, with a uniform magnetic field of flux density  $\bar{B}$  normal to the axial flow direction, it can be shown with reference to Shercliff that, in a steady flow, the potential difference  $U_j$  between the  $j^{th}$  pair of electrodes is given by an expression of the form

$$U_j = \frac{2\bar{B}}{\pi a} \iint v(x, y) W(x, y)_j dx dy \quad (3)$$

where  $v(x, y)$  is the steady local axial flow velocity at the point  $(x, y)$  in the flow cross section,  $W(x, y)_j$  is the so-called 'weight value' relating the contribution of  $v(x, y)$  to  $U_j$  and  $a$  is the internal radius of the flow channel. It is shown in [1] that Equation 3 can be discretised to give

$$U_j = \frac{2\bar{B}}{\pi a} \sum_{i=1}^N v_i w_{ij} A_i \quad (4)$$

where  $v_i$  is the mean axial velocity in the  $i^{th}$  of  $N$  large regions (or 'pixels') into which the flow cross section is divided,  $A_i$  is the cross sectional area of the  $i^{th}$  large region and  $w_{ij}$  is a weight value relating  $U_j$  to  $v_i$ . Provided that the number of potential difference measurements  $U_j$  and the number of large regions are both equal to  $N$ , equation 4 can be inverted, as follows, to enable estimates of the local axial flow velocity  $v_i$  in each of  $N$  large pixels to be determined from the  $N$  potential difference measurements  $U_j$  made on the boundary of the flow

$$\mathbf{V} = \frac{\pi a}{2B} [\mathbf{W}\mathbf{A}]^{-1} \mathbf{U} \quad (5)$$

Where  $\mathbf{V}$  is a single column matrix containing the pixel velocities  $v_i$ ,  $\mathbf{W}$  is a square matrix containing the relevant weight values  $w_{ij}$ ,  $\mathbf{A}$  is a diagonal matrix containing information on the pixel areas  $A_i$  and  $\mathbf{U}$  is a single column matrix containing the measured potential differences  $U_j$  for a given imposed velocity profile. The electromagnetic flow meter geometry (Fig .1.a) was used to investigate the solids-in-water two phase flow described in this paper, with the flow cross section divided into seven pixels (Fig .1(b)). The geometry of these seven pixels was chosen such that the chords joining seven pairs of electrodes were located at the geometric centres (in the  $y$  direction) of the pixels (Fig .1(b)). The Helmholtz coil was used to generate a uniform magnetic field in the flow cross section [1]. The fluid pixels were categorized as pixel 1 at the top of the flow cross section to pixel 7 at the bottom. This pixel arrangement was chosen because, for many stratified flows of interest, variations in the axial velocity tend to occur in a single direction (i.e. in the  $y$  direction in Fig .1(b)). For making measurements in horizontal or inclined solids-in-water flows the line joining e5 to e13 would be in the direction from the uppermost side of the pipe to the lowermost side. For the experiments described in section 4, the EVP device was used to measure the mean in-situ water velocity  $v_w$  in each of the seven pixels shown in Fig .1.b.

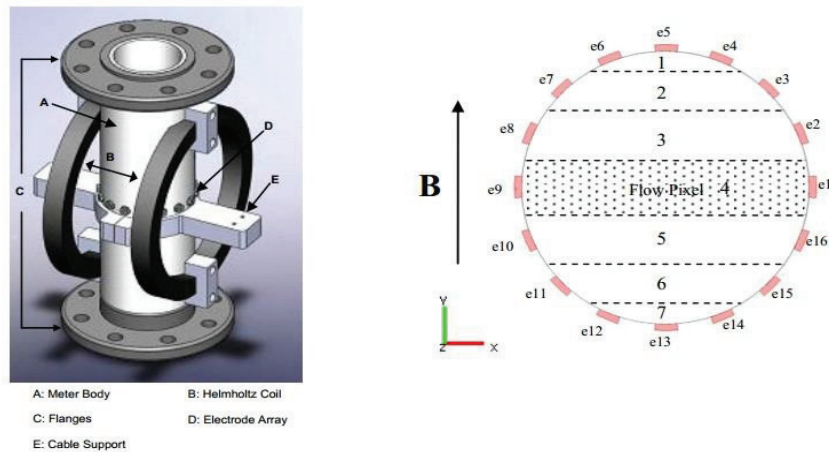


Fig .1 .(a) Design of the Electromagnetic Velocity Profiler ; (b) Schematic diagram of the flow pixels, the electrode arrangement and the direction of the magnetic field

## 2. IMPEDANCE CROSS-CORRELATION DEVICE

The Impedance Cross Correlation (ICC) device is used to determine the distribution of the local solids velocity and the distributions of the local solids volume fraction and the local water volume fraction (where  $\alpha_w = 1 - \alpha_s$ ) [2]. The ICC flow meter consists of two electrodes arrays, separated by an axial distance of 50 mm and each array contains eight electrodes mounted over the internal circumference of the pipe carrying the flow. Every electrode in each array can be selected to be either “excitation”, “measurement” or “earth”. In the present study of solids-in-water flow, water which is conductive, is the continuous phase while the solids are the dispersed phase and have effectively zero electrical conductivity. Since the ICC device has two electrode arrays, the electrode selection circuits were designed to be able to select any electrodes from a given array (A or B) and connect them to excitation, measurement or to earth in the corresponding channel (A or B) of the conductance measurement circuit. In order to produce sensing regions inside the pipe, the states of each array are changed according to three defined configurations, These configurations can each be rotated (in steps of  $45^\circ$ ) to eight rotational positions ( $n=1$  to 8) to cover the measurements entire cross-section area of pipe, see [4]. **Config.\_I**: one electrode is selected as excitation. The second electrode is selected as virtual earth measurement (**ve**). The remaining electrodes are selected as earth (**E**). **Config.\_II**: one electrode is selected as excitation. Two electrodes are selected as **ve**. The remaining electrodes are selected as **E**. **Config.\_III**: two electrodes are selected as excitation; two electrodes are selected as **ve**. The remaining electrodes are selected as **E**. In order to calculate the sensitivity distribution for each configuration and rotational position, a model of a ‘single plane’ of an 8-electrode

sensor was produced in COMSOL. For a given plane the sensitivity of the sensing field of a given electrode configuration was calculated at numerous positions (or elements) in the flow cross section. In these simulations, the flow cross-section was assumed to be filled with water (the conducting medium) and material of zero conductivity was assumed to be inserted, in turn, into each element to simulate the presence of a non-conducting particle of the dispersed phase.[2] The sensitivity parameter  $S_i$  can be calculated by  $S_i = (Vout)_w - (Vout)_0$ .

For the  $\phi^{th}$  electrode configuration ( $\phi = \text{I, II or III}$ ) and the  $n^{th}$  rotational position ( $n = 1$  to  $8$ ) the co-ordinate for the "Centre of Action" (CoA) for the effective sensing region in can be defined as:

$$(Cx)_{\phi,n} = \frac{\sum_{i=1}^N x_i a_i S_i}{\sum_{i=1}^N a_i S_i} \quad (Cy)_{\phi,n} = \frac{\sum_{i=1}^N y_i a_i S_i}{\sum_{i=1}^N a_i S_i} \quad (6)$$

the coordinates of 24 different CoA were calculated as shown schematically Fig. 2(a). In practical operation, for a given configuration  $\phi$  and a given rotational position  $n$ , a conductance measurement circuit is used to measure the local mixture conductivity  $(\sigma_m)_{\phi,n}$  and this value of local mixture conductivity is assigned to the corresponding centre of action at position  $(Cx)_{\phi,n}$ ,  $(Cy)_{\phi,n}$  [4]. The local volume fraction  $(\alpha_s)_{\phi,n}$  can be expressed as: [5]

$$(\alpha_s)_{\phi,n} = \frac{2\sigma_w - 2(\sigma_m)_{\phi,n}}{2\sigma_w + (\sigma_m)_{\phi,n}} \quad (7)$$

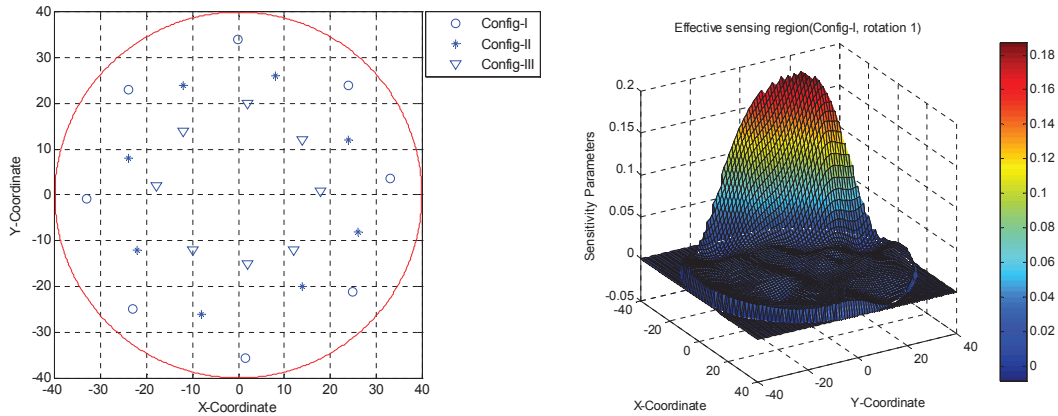


Fig. 2. (a) Location of CoA for Config-I, II and III for each of the eight possible electrode rotational positions per configuration; (b) Effective sensing region associated with Config-I, rotation 1

The output signals from the channel A (array A)  $(V_A)_{\phi,n}(t)$  and channel B (array B)  $(V_B)_{\phi,n}(t)$  were cross correlated to provide information on the local dispersed phase velocity of the flow at the CoAs in the flow cross section 'interrogated' at planes A and B. The cross correlation function  $R_{\phi,n}(\tau)$  for the dispersed phase at each interrogated CoA was calculated as follows:

$$R_{\phi,n}(\tau) = \frac{1}{T} \int_0^T (V_A)_{\phi,n}(t)(V_B)_{\phi,n}(t + \tau) dt \quad (8)$$

where  $\phi$  is the configuration type,  $n$  is the rotation number,  $\tau$  is time delay and  $T$  is the total time period for which data is acquired. The local dispersed phase velocity  $(v_s)_{\phi,n}$  at each interrogated CoA is given by[6]:

$$(v_s)_{\phi,n} = \frac{L}{(\tau_p)_{\phi,n}} \quad (9)$$

where  $L$  is the axial distance between arrays A and B and  $(\tau_p)_{\phi,n}$  is the time delay corresponding to the peak of the relevant cross correlation function  $R_{\phi,n}(\tau)$ .

### 3. TWO-PHASE FLOW METER SYSTEM DESIGN

The two-phase flow meter system includes the measurement instruments described above for EVP (see section 1) and ICC (see section 2). This system is limited to operation in flows in which the continuous phase is electrically conducting. In two-phase solids-in-water flow, the ICC device is used to obtain the local volume fraction and the local flow velocity distribution of the dispersed phase. The volumetric flow rate of the dispersed phase can be expressed according to:

$$Q_{s,ICC} = \int_A \alpha_{s,ICC} v_{s,ICC} dA \quad (10)$$

The EVP is used to obtain the local axial velocity distribution of the electrically conducting continuous phase. The local volume fraction distribution of the dispersed phase obtained using the ICC device is used with the measured continuous phase velocity distribution to obtain the continuous phase volumetric flow rate as expressed in

$$Q_{w,EVP} = \int_A (1 - \alpha_{s,ICC}) v_{w,EVP} dA \quad (11)$$

### 4. EXPERIMENTAL RESULTS

The ICC device was mounted in the inclinable multiphase flow loop for testing using solids-in-water flow inclined at  $30^\circ$  to the vertical. The measurement techniques described in section 2 were implemented in order to determine the local solids volume fraction distributions and local axial solids velocity distributions in the cross-section for various flow conditions. Fig. 3.(a) shows the interpolated local volume fraction distribution for flow condition fm8 corresponding to  $30^\circ$  pipe inclination to the vertical, a water volumetric flow rate equal to  $8.66 \text{ m}^3 \text{ h}^{-1}$  (cubic metres per hour) and a solids volumetric flow rate of  $0.467 \text{ m}^3 \text{ h}^{-1}$

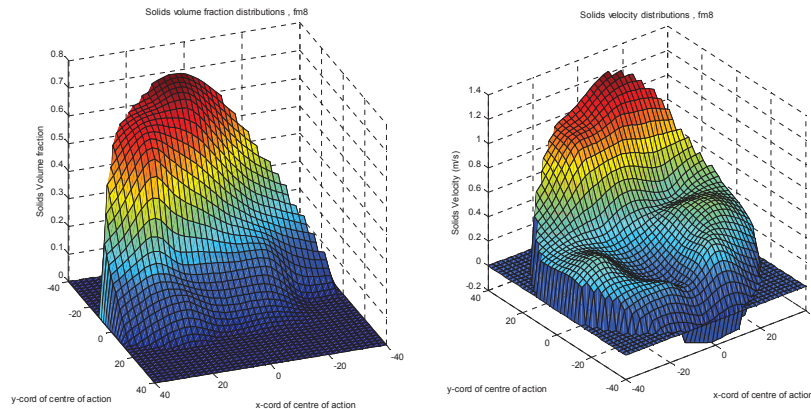


Fig. 3. (a) The solids volume fraction distribution using ICC device, fm8 condition; (b) The solids velocity distribution using ICC device, fm8 condition. [Note the reversal of the x and y axes compared with Fig.3. (a)].

Fig. 3.(a) shows that the solids volume fraction at the lower side of the inclined pipe is much greater than at the upper side. Fig. 4 presents the mean solids volume fraction in the regions 1 to 7 (shown in Fig. 1(b)) for the 5 different flow conditions. The results shown in Fig. 4 were obtained from data such as that presented in Fig. 3.(a). Fig. 3.(b) shows the interpolated local axial solids velocity profile obtained from the ICC using the cross correlation technique described in section 2. The solids volume fraction profiles shown in Fig. 4 demonstrate that in a flow inclined at  $30^\circ$  to the vertical, the upper regions of the flow cross-section at fluid regions 1, 2 and 3 (Fig. 1(b)) had a very small proportion of solid particles present i.e. they were mostly occupied by water. For each flow condition, the local solids volume fraction was integrated over the flow cross-section to give the mean solids volume fraction  $\overline{\alpha_s}$ . [Note that it was found that there was good agreement between the mean ICC solids volume fraction  $\overline{\alpha_s}$  and the mean solids volume fraction  $\overline{\alpha_{s,dp}}$  measured using the  $dp$  cell technique].

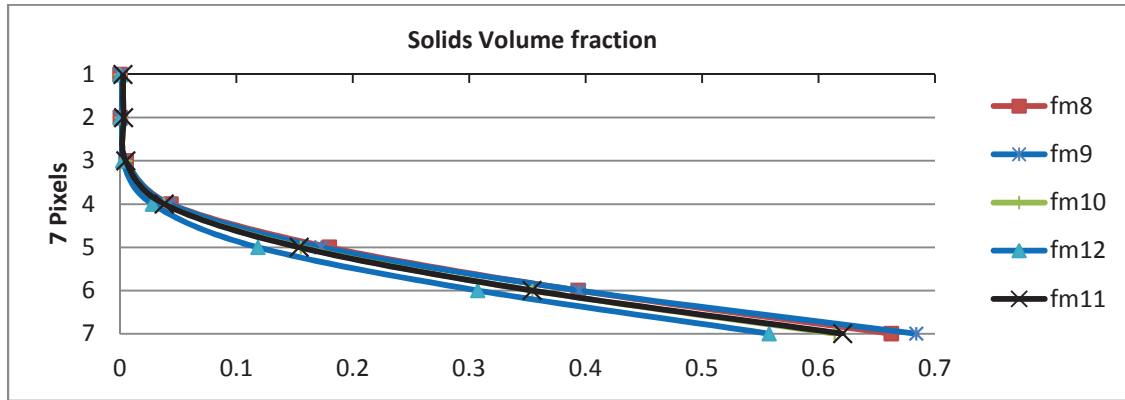


Fig. 4 Solid volume fraction profiles for flows inclined at 30° to the vertical

For inclined upward flow, the distribution of the measured local axial solids velocity  $v_s$  is highly non-uniform with the solids velocity varying from a minimum value at the lower side of the inclined pipe to a maximum value at the upper side. Using data such as that shown in Fig. 3.(b), the mean solids velocity in each of the seven regions which are shown in Fig .1.b was calculated and the results presented in Fig. 5(b).

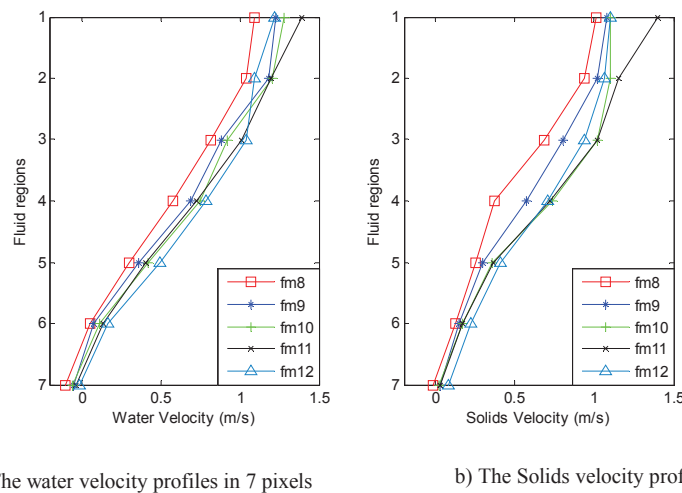


Fig. 5 Reconstructed water velocity and solids velocity in solids-in-water flow at a 30° inclination to the vertical

Fig. 5(a) shows the reconstructed local axial water velocity profiles obtained using the EVP flow meter for flow conditions fm8 to fm12. It is seen that at the lower side of the inclined pipe, in fluid region 7, the water velocity is negative (reverse flow). As we move towards the upper side of the pipe the velocity becomes positive.

Fig. 5(b) shows similar behaviour for the local axial solids velocity profiles - where the solids have a much lower velocity at region 7 than they do in region 1 (Fig .1(b)).

The solids volumetric flow rate  $Q_{s,ICC}$  for each flow condition was obtained by integrating the interpolated local solids volume fraction and local solids velocity data (such as that shown in Fig. 3) in the flow cross section according to equation 10. The water volumetric flow rate  $Q_{w,EVP}$  for each flow condition was obtained by integrating the water volume fraction and water velocity data for the regions 1 to 7 shown in Fig .1(b). The error  $\epsilon_{Q_s}$  in  $Q_{s,ICC}$ , as compared with  $Q_{s,ref}$ , varied from -8.8% to +11.4%. Furthermore the error  $\epsilon_{Q_w}$  in  $Q_{w,EVP}$ , as compared with  $Q_{w,ref}$ , varied from +11.2% to +5.4%. However it should be stressed that the gravimetric methods used for obtaining  $Q_{s,ref}$  and



$Q_{w,ref}$  were also prone to error and it is expected that, when more reliable reference measurements can be made, the errors in  $Q_{s,ICC}$  and  $Q_{w,EVP}$  will be shown to be much smaller.

### CONCLUSIONS

A combined ICC/EVP two phase flow meter has been designed and built which can be used in solids-in-water two phase pipe flows to measure the volume fraction distributions of both phases, the velocity profiles of both phases and the volumetric flow rates for both phases. For solids-in-water pipe flows inclined at 30° to the vertical the solids and water velocity profiles and the solids and water local volume fraction distributions are all highly non-uniform. Nevertheless the two phase flow meter can measure solids and water volumetric flow rate to about +/-10% of reading. It is expected that the magnitude of these errors will be substantially reduced when better reference measurements of the solids and water volumetric flow rates can be made.

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