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Measurement of velocity profiles in multiphase flow using a multi-electrode electromagnetic flow meter

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ABSTRACT

This paper describes an electromagnetic flow meter for velocity profile measurement in single phase and multiphase flows with non-uniform axial velocity profiles. A Helmholtz coil is used to produce a near-uniform magnetic field orthogonal to both the flow direction and the plane of an electrode array mounted on the internal surface of a non-conducting pipe wall. Induced voltages acquired from the electrode array are related to the flow velocity distribution via variables known as 'weight values' which are calculated using finite element software. Matrix inversion is used to calculate the velocity distribution in the flow cross section from the induced voltages measured at the electrode array. This paper presents simulations and experimental results including, firstly the effects of the velocity profile on the electrical potential distribution, secondly the induced voltage distribution at the electrode pair locations, and thirdly the reconstructed velocity profile calculated using the weight values and the matrix inversion method mentioned above. The flow pipe cross-section is divided into a number of pixels and, in the simulations, the mean flow velocity in each of the pixels in single phase flow is calculated from the measured induced voltages. Reference velocity profiles that have been investigated in the simulations include a uniform velocity profile and a linear velocity profile. The results show good agreement between the reconstructed and reference velocity profiles. Experimental results are also presented for the reconstructed velocity profile of the continuous water phase in an inclined solids-in-water multiphase flow for which the axial water velocity distribution is highly non-uniform. The results presented in this paper are most relevant to flows in which variations in the axial flow velocity occur principally in a single direction.

1. Introduction

Conventional electromagnetic flow meters (EMFMs) have previously been used successfully in varieties of industries for measuring volumetric flow rates of conducting fluids in single phase pipe flows. At present, a conventional EMFM can measure the volumetric flow rate of a single phase flow with an error as low as $\pm 0.05\%$ of reading provided that the velocity profile is axisymmetric. However highly non-uniform velocity profiles are often encountered, e.g. just downstream of partially open valves. The axial flow velocity just downstream of a gate valve varies principally in the direction of the valve stem, with the maximum velocities occurring behind the open part of the valve and the minimum velocities behind the closed part of the valve. In such non-uniform velocity profiles the accuracy of the conventional EMFM can be seriously affected [1] but high accuracy volumetric flow rate measurements could be achieved by measuring the axial velocity profile and using this to determine the mean flow velocity in the cross section. Large variations in the axial flow velocity can also occur in multiphase flows e.g. horizontal and upward inclined multiphase flows in which axial velocity variations occur principally in the direction of gravity, with the minimum axial velocity at the lower side of the inclined pipe and the maximum velocity at the upper side of the inclined pipe. A specific example of a multiphase flow which is of great interest to the oil industry is upward inclined oil-in-water flow. Such flows are 'water continuous' and so the multiphase mixture is electrically conducting allowing the use of electromagnetic flow meters. However since the water velocity varies from a minimum at the lower side of the inclined pipe to a maximum at the upper side of the inclined pipe this causes erroneous readings from a conventional electromagnetic flow meter. Another flow of interest to the oil industry occurs during the drilling of inclined oil wells when rock cuttings flow co-currently with water based drilling mud. Mixture density variations in the flow cross section, caused by settling of the rock cuttings, can cause variations in the axial mud velocity from positive (upward) values at the upper side of

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the inclined well to negative (downward) values at the lower side. In view of the above, the objective of this paper is to describe a new non-intrusive electromagnetic flow metering technique for (i) measuring the axial velocity profile of single phase flows of conducting fluids and (ii) measuring the axial velocity profile of the conducting continuous phase of multiphase mixtures (such as horizontal and inclined oil-in-water flows and solids-in-water flows) in which the conductivity of the dispersed phase is very much lower than the conductivity of the continuous phase. [Note that in a previous paper [2] it has been shown that the relatively minor variations of fluid conductivity, which occur in the cross section of such multiphase flows, have only a minimal effect on the operation of electromagnetic flow meters. This is particularly true if the volume fraction of the non-conducting dispersed phase is less than about 0.4].

An alternative approach to accurate volumetric flow rate measurement in highly non-uniform single phase flows has been proposed by authors such as Horner [3] and Xu et al. [4] who described multi-electrode electromagnetic flow meters which are relatively insensitive to the flow velocity profile. However, this type of flow meter does not provide information on the local axial velocity distribution in the flow cross section. This can be a major drawback, particularly in a steady multiphase flow where, for example, the volumetric flow rate Q_c of a given phase can only be found by integrating the product of the steady local velocity v_c and the steady local volume fraction α_c of the phase in the flow cross section as follows

$$Q_c = \int_A v_c \alpha_c dA \tag{1}$$

where in Eq. (1) A refers to cross sectional area. The approach of Horner [3] would be of no benefit in determining the water volumetric flow rate in a highly inclined oil-in-water flow such as that described above—but in such a flow, the distribution of the local water velocity v_w could be determined using the electromagnetic flow metering method outlined in this paper and the distribution of the local water volume fraction α_w could be obtained non-intrusively using electrical resistance tomography (ERT) [5] enabling the water volumetric flow rate Q_w to be determined according to Eq. (1). Although previous work on velocity profile measurement using multi-electrode electromagnetic flow meters is reported in the literature (see for example [6] for a brief review) much of this previous work is not specifically aimed at multiphase flow measurement which is a major thrust of the work described in this paper. Also much of this previous work involves only simulations rather than the use of a practical device such as that described later in this paper.

The essential 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. Williams [7] applied a uniform transverse magnetic field perpendicular to the line joining the electrodes and the fluid motion and his experiments revealed that for a uniform velocity profile the flow rate is directly proportional to the voltage measured between the two electrodes. Subsequently Shercliff [8] showed that the local current density $\boldsymbol{j}$ in the fluid is governed by Ohm's law in the form of

$$\boldsymbol{j} = \sigma(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}) \tag{2}$$

where σ is the local fluid conductivity, $\boldsymbol{v}$ is the local fluid velocity, and $\boldsymbol{B}$ is the local magnetic flux density. The expression $(\boldsymbol{v} \times \boldsymbol{B})$ represents the local electric field induced by the fluid motion, whereas $\boldsymbol{E}$ 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 [8] simplified Eq. (2) to show that the local potential U in the flow can be obtained by solving

$$\nabla^2 U = \nabla \cdot (\boldsymbol{v} \times \boldsymbol{B}) \tag{3}$$

For a circular cross section flow channel bounded by a number of electrodes, with a uniform magnetic field of flux density $\overline{B}$ normal to the axial flow direction, it can shown with reference to [8] 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

$$U_j = \frac{2\overline{B}}{\pi a} \iint v(x,y) W(x,y)_j dxdy \tag{4}$$

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. Eq. (4) can be discretized as follows by assuming that the flow cross section can be divided into $\hat{I}$ elemental regions

$$U_j = \frac{2\overline{B}}{\pi a} \sum_{n=1}^{\hat{I}} \hat{v}_n \hat{W}_{n,j} \hat{A}_n \tag{5}$$

where $\hat{v}_n$ and $\hat{A}_n$ are respectively the local axial velocity in, and the cross sectional area of, the nth elemental region. $\hat{W}_{n,j}$ is the weight value describing the contribution of the axial velocity in the nth elemental region to the jth potential difference U_j. If the axial flow velocity is now assumed to be constant in each of N large regions, Eq. (5) can be written as

$$U_j = \frac{2\overline{B}}{\pi a} \sum_{i=1}^{N} v_i \sum_{n=\hat{I}_{i-1}+1}^{\hat{I}_i} \hat{W}_{n,j} \hat{A}_n \tag{6}$$

where v_i is the axial flow velocity in the ith large region. In Eq. (6) when the subscript n is in the range $\hat{I}_{i-1}+1 \le n \le \hat{I}_i$ it refers to the elemental regions lying within the ith large region. [Note also that there are $\hat{I}_i - \hat{I}_{i-1}$ elemental regions within the ith large region and that, by definition, $\hat{I}_0 = 0$]. An 'area weighted' mean weight value w_{ij} relating the contribution of the velocity v_i in the ith large region to the jth potential difference U_j is given by

$$w_{ij} = \frac{\sum_{n=\hat{I}_{i-1}+1}^{\hat{I}_i} \hat{W}_{n,j} \hat{A}_n}{A_i} \tag{7}$$

where A_i is the cross sectional area of the ith large region. Combining Eqs. (6) and (7) gives

$$U_j = \frac{2\overline{B}}{\pi a} \sum_{i=1}^{N} v_i w_{ij} A_i \tag{8}$$

It will be shown later in this paper that Eq. (8) can be inverted to enable estimates of the local axial flow velocity v_i in each of N large pixels to be determined from N potential difference measurements U_j made on the boundary of the flow. Furthermore, although Eq. (8) was derived on the assumption that the axial velocity in each large pixel is constant, it will be seen that when this inversion method is used to solve for the velocity in each large pixel then the values of v_i obtained give a good approximation to the mean axial velocity in each of the large pixels, in situations where there is some axial velocity variation within each large pixel.

In Section 2 of this paper it is shown how the weight values w_{ij} can be calculated, for a particular magnetic flow meter geometry, using finite element techniques. In Section 3 values of U_j are calculated for a number of different simulated velocity profiles in the EMFM. In Section 4 of the paper, a reconstruction technique is outlined which enables the pixel velocities v_i to be determined from the weight values w_{ij} and the boundary voltage measurements U_j. In Section 5 a practical EMFM is presented and in Section 6 results