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A two-phase flow meter for determining water and solids volumetric flow rates in stratified, inclined solids-in-water flows

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ABSTRACT

This paper describes the design and implementation of a two-phase flow meter which can be used in solids-in-water two phase pipe flows to measure the in-situ volume fraction distributions of both phases, the velocity profiles of both phases and the volumetric flow rates for both phases. The system contains an Impedance Cross Correlation (ICC) device which is used in conjunction with an Electromagnetic Velocity Profiler (EVP). Experimental results were obtained for the water and solids velocity and volume fraction profiles in upward inclined flow at 30° to the vertical, in which highly non-uniform velocity and volume fraction profiles occur.

1. Introduction

Measurement of the different phase flow rates in multiphase flow is highly important in oil and gas recovery, chemical, mining, food processing and nuclear industries. Around the world, scientists with diverse backgrounds, as well as engineers from different specialities, have engaged with the problem of how to measure the different parameters of multiphase flow.

Local probes have been used by previous researchers including Cory [1], Nasr-El-Din et al. [2], MacTaggart et al. [3] and Xie et al. [4] to measure the local mixture conductivity σ_m at a given point in a multiphase flow. Cory [1] used a 6 electrode local probe to measure the solids velocity distribution and solids volume fraction distribution in vertical and inclined solids-in-water flows. According to Cory, solids volume fraction α_s profiles in vertical flow show only small variations across the flow cross-section. While in pipes inclined at 30° to the vertical α_s varied strongly from the lower side of pipe being much higher than on the upper side. Yet inserting an intrusive measuring device into the pipeline is generally not acceptable with multiphase flows containing solids since it will be liable to damage by abrasion, and blockages may build up around it [5].

To avoid such limitations, a non-invasive measurement technique (Process Tomography) is used to provide the concentration, or density distribution and/or velocity distribution of at least one phase of a multiphase system.

Electrical Resistance Tomography (ERT) [6] is a non-intrusive technique used to map the flow conductivity across the interior of a flow pipe. In ERT systems the electrodes are mounted around the pipe circumference and are in direct contact with the flow. An electrical current is injected into the flow between pairs of electrodes and the resulting potential distribution is measured between other electrode pairs. The larger the number of sources and receivers the higher spatial resolution of the image produced. Dual-plane ERT can be used also to determine the dispersed phase velocity by adding a second plane with a known axial distance L from the first plane. By using point-by-point cross correlation techniques, the dispersed phase velocity distribution can be obtained in multiphase flows in which the continuous phase is electrically conducting [7]. However the accuracy of ERT can be effected by the type of reconstruction algorithm that employed.

Xu et al. [8] present a new in-situ measurement method based on measurements of the Electromagnetic flow meters (EFM) and ERT to study the performance of a solids-in-liquid slurry flow in a vertical pipe and measure the individual phase flow rate. He concluded that the ERT technique can be used in conjunction with an electromagnetic flow meter as a way of measurement of slurry flow rate in a vertical pipe flow. However he stressed that the EFM results must be treated with reservation when the flow pattern is a non-homogenous flow.

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

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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) [9]. 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 [5].

2. Electromagnetic Velocity Profiler

2.1. Background theory of the 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 [10] showed that the local current density $\mathbf{j}$ in the fluid is governed by Ohm's law in the form

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

where σ 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 multiphase flows under consideration in this paper) Shercliff [3] simplified Eq. (1) to show that the local potential U in the flow can be obtained by solving the following expression:

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

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 [3,4] that, in a steady flow, the potential difference U_j between the jth pair of electrodes is given by an expression of the form

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

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. For single phase flow of a conducting liquid or for multiphase flows in which the continuous phase is conducting and the dispersed phase(s) are insulating it is shown in [1,4] that Eq. (3) can be discretized to give

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

where v_i is the mean axial velocity of the conducting continuous phase in the ith of N large subdomains into which the flow cross section is divided, A_i is the cross sectional area of the ith large subdomain 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 subdomains are both equal to N, Eq. (4) can be inverted, as follows, to enable estimates of the local axial flow velocity v_i of the conducting continuous phase in each of the N large subdomains to be determined from the N potential difference measurements U_j made on the boundary of the flow [11]:

$$\mathbf{V} = \frac{\pi a}{2\bar{B}} [\mathbf{WA}]^{-1} \mathbf{U} \tag{5}$$

where $\mathbf{V}$ is a single column matrix containing the subdomain 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 subdomain areas A_i and $\mathbf{U}$ is a single column matrix containing the measured potential differences U_j for a given imposed velocity profile.

2.2. Electromagnetic Velocity Profiler Device

A simple electromagnetic flow meter geometry (Fig. 1(a)) was

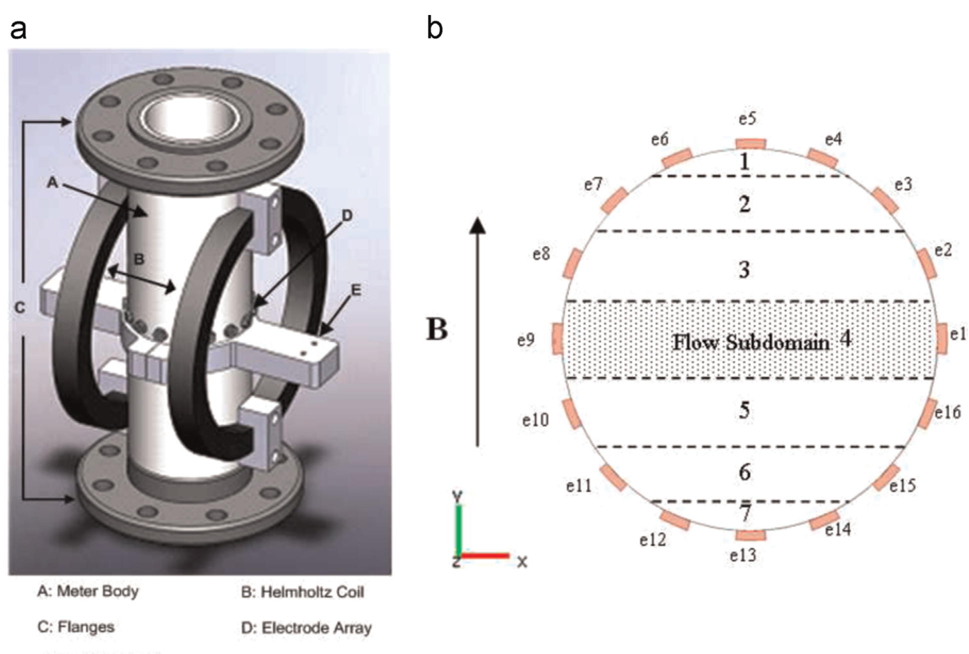

Fig. 1. (a) Design of the Electromagnetic Velocity Profiler the internal pipe diameter is 80 mm; (b) schematic diagram of the flow subdomains, the electrode arrangement and the direction of the magnetic field.