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USE OF THE ELECTROMAGNETIC FLOWMETER IN A TWO-PHASE FLOW

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Abstract—The use of the transverse field electromagnetic meter for two-phase flows is investigated. It is shown both experimentally and theoretically that this device measures the average velocity of the continuous liquid phase provided this has some minimum electrical conductivity. The calibration is quite independent of void fraction, flow regime, axisymmetric velocity profile, or the electrical conductivity of the continuous liquid phase. The dynamic capability of the meter for use in measuring unsteady two-phase flows is also demonstrated to be considerable.

1. INTRODUCTION

The measurement of liquid velocity or liquid flow rate is often critical in experiments on liquid/vapor/gas mixture flows. Probes for local velocity measurement and/or volumetric devices which are reliable in single phase flows are often not suitable for a two-phase flow measurement. Frequently, the interpretation of the measurements is ambiguous and this results in poor accuracy. If good dynamic response is needed for experiments in unsteady flow, the problems become even more acute.

Among the devices commonly used in single phase flows for spatial averaged liquid velocity measurement, little attention has been devoted to the use of the electromagnetic flowmeter in two-phase flows. The first experimental study on the performance of a transverse field induction flowmeter in a two-phase flow was reported by Heineman *et al.* (1963). They succeeded in showing that the void fraction could be measured quite accurately by assuming that even in a two-phase flow, the output voltage of the induction flowmeter is proportional to the mean velocity of the conducting phase. Hori, Kobori & Ouchi (1966) presented further experimental evidence of this kind.

In the present paper we present both experimental and theoretical results which show that the electromagnetic meter has some significant advantages in two-phase flows for which the continuous phase has some minimum electrical conductivity. Not only does it measure the mean continuous phase velocity (as opposed to the continuous phase flow rate as erroneously assumed in some earlier studies), but this measurement appears to be quite insensitive to the distribution of the disperse phase.

2. THEORETICAL ANALYSIS FOR SINGLE PHASE FLOW

It is necessary to review briefly the equations and results pertaining to the use of a transverse field electomagnetic meter in single phase flow. The reader is referred to the classic text by Shercliff (1962) for further details. The meter consists of coils generating a nominally uniform magnetic field (magnetic flux intensity B) perpendicular to the axis of the circular pipe (radius b) containing the flow (figure 1). The induced electric potential in the fluid, $\phi(r, \theta)$ must then satisfy (see section 6 for possible error)

$$\nabla^2\phi = B \sin\theta \frac{du}{dr} \qquad [1]$$

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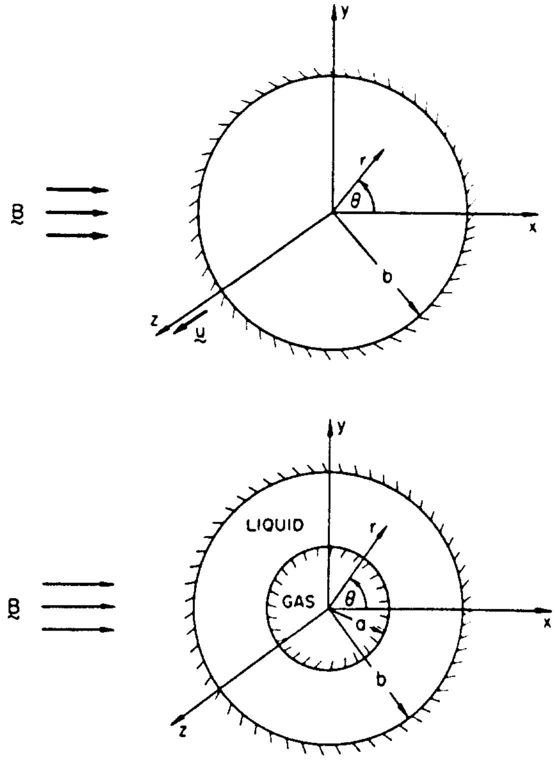

Figure 1. Schematic cross-sectional views of the transverse electromagnetic flowmeter in single phase (upper) and annular two-phase flow (lower).

provided the fluid velocity, $u(r)$, is purely axisymmetric. Then if the interior surface of the pipe is electrically insulated, the solution of [1] yields

$$\phi(b,\theta) = \frac{B\sin\theta}{\pi b}\int_0^b 2\pi r u(r)\,\mathrm{d}r. \qquad [2]$$

Hence the electric potential difference, $\Delta\phi$, generated between surface electrodes on either end of a diameter which is perpendicular to both the flow and the magnetic field (i.e. at $\theta = \pi/2$ and $3\pi/2$) is given by

$$\Delta\phi = \frac{2BQ}{\pi b}; \qquad Q = \int_0^b 2\pi r u(r)\,\mathrm{d}r. \qquad (3)$$

Consequently, measuring $\Delta\phi$ leads to a measurement of the volume flow rate, Q or mean fluid velocity, $u_M = Q/\pi b^2$, which is independent of *both* the form of the axisymmetric velocity profile *and* the electrical conductivity of the fluid. The first feature makes this instrument very valuable for unsteady or oscillatory flow where boundary layers may have complicated velocity profiles (see Brennen *et al.* 1980). The second feature means the instrument could be used for fluids with low electrical conductivity. In practice, however, the impedance through the fluid must be low compared with the input impedance of the signal processor used to measure $\Delta\phi$, and this usually places a lower limit on the electrical conductivity of the fluid; with alternating magnetic fields the Cushing effects discussed in section 6 can also create practical lower limits to the fluid conductivity.

3. DISPERSED TWO-PHASE FLOW WITHOUT RELATIVE MOTION

A homogenous two-phase flow with a fine uniformly dispersed second phase which has zero velocity relative to the continuous phase must clearly yield exactly the same result as the single phase flow. Although the electrical conductivity may be a function of the void fraction, α, the result [3] does not depend upon the electrical conductivity (except possibly as described in section 6) and hence the relation [3] should hold with Q being the total volume flow rate. Consequently in the absence of relative motion, the measurement $\Delta\phi$ is related to the mean dispersed phase (liquid) velocity, u_L, or dispersed phase flow rate, Q_L, by

$$\Delta\phi = 2Bb\,u_L = \frac{2B}{\pi b}\frac{Q_L}{(1-\alpha)}. \qquad [4]$$

This case has previously been considered by Fitremann (1972). His analysis was based on a perturbation of the electrical current within the fluid due to the presence of electrically nonconducting spheres which are small and finely dispersed. Due to some inconsistencies in his analysis, our interpretation of his results is that $\Delta\phi$ is smaller than $2Bb\ u_L$. This appears inconsistent with either the present argument or the experimental results of the present paper (Heineman *et al.* 1963, Hori *et al.* 1966).

4. ANNULAR TWO-PHASE FLOW

Another simple, but radically different case is that of annular liquid/gas flow in which there is a concentric core of gas which may move at a different velocity from the surrounding annulus of liquid. We shall assume for simplicity that the gas is electrically nonconducting. In Bernier (1981) this problem is shown to have the following exact solution

$$\Delta\phi = \frac{2bB}{\pi(b^2-a^2)}\int_a^b 2\pi r u(r)\,\mathrm{d}r \qquad [5]$$

provided, again, that the liquid velocity profile, $u(r)$, is axisymmetric. Consequently, since $\alpha = b^2/a^2$, it follows that the relation [4] also represents the calibration in the case of annular flow. Note that this result is independent of the gas flow rate or velocity. This useful feature of the electro-magnetic flowmeter has not been utilized in annular flow experiments as far as we can determine.

5. RESULTS FOR OTHER TWO-PHASE FLOW CONFIGURATIONS

The results of sections 2 and 3 suggest that the transverse electromagnetic meter might provide a means to measure the flow rate of a continuous conducting phase (liquid) in the presence of a nonconducting phase (gas) in a way which is quite insensitive to the flow pattern. To substantiate this further, it would be valuable to solve the combined fluid flow/electromagnetic problems involving dispersed nonconducting spheres with relative motion. This has not been accomplished as yet. A model consisting of many long *cylindrical* voids parallel with the direction of flow is somewhat more tractable. If these cylinders have a radius, $c \ll b$, then the first order disturbance, $\Delta\phi^*$, to the electrical potential caused by each of them is found (Bernier 1981) to be related to the liquid flow rate by

$$\Delta\phi^* \simeq \frac{2B}{\pi b}\frac{c^2}{b^2}Q_L$$

Summing up the contributions from each each of the cylindrical voids, one obtains

$$\Delta\phi = \frac{2B}{\pi b}(1+\alpha)Q_L \qquad [6]$$

which is identical to expression [4] to first order in α. It should be noted that cylindrical insulators were used by Hori *et al.* (1966) in a calibration experiment.

6. EFFECTS OF FREQUENCY: CUSHING EFFECT

Before leaving the theoretical analysis, one other possible limitation of the use of the electromagnetic flow meter should be mentioned. Cushing (1958) has observed that the use of an alternating magnetic field (as in most flow meters including that used in the present experiments) leads to an attenuation factor, X, multiplying the right hand sides of [1]–[3] of the form

$$X = \frac{\left[1 + \left(\frac{\omega\epsilon_0}{\sigma}\right)^2 \epsilon(\epsilon - 1)\right] + i\left[\frac{\omega\epsilon_0}{\sigma}\right]^2}{1 + \left(\frac{\omega\epsilon_0\epsilon}{\sigma}\right)^2}. \qquad [7]$$

If this were significantly different from unity, the calibration of the instrument would no longer be independent of the electrical properties of the fluid as represented by its dielectric constant, ϵ, and conductivity, σ. Moreover, the factor X has a quadrature component which may have a detrimental effect on the sensitivity of the flowmeter whenever a demodulation process is used to recover the amplitude of the signal. In a dispersed two-phase flow the dependence of the effective mixture values of ϵ and σ on the void fraction might cause further difficulties.

The meter employed in the present experiments utilized a fairly high frequency (328 Hz) in order to obtain good dynamic response. In order to evaluate possible Gushing effects, Maxwell's formulae values of ϵ and σ were used for the air/water flows examined in the experiments to calculate X for the entire range of void fractions, α:

$$\frac{\sigma}{\sigma_w} = 1 - \frac{3\alpha}{\alpha + \left(\frac{2\sigma_w + \sigma_A}{\sigma_w - \sigma_A}\right)}; \qquad \frac{\epsilon}{\epsilon_w} = 1 - \frac{3\alpha}{\alpha + \left(\frac{2\epsilon_w + \epsilon_A}{\epsilon_w - \epsilon_A}\right)}$$

Though the validity of these formulae is limited to $\alpha \ll 1$, the results shown in figure 3 can be used for qualitative evaluation of the Cushing effects. It is seen that over the low void fraction range used in the present experiments, the in-phase attenuation factor is unity for typical tap water conductivities of 10^{-2} mhos/m. Even for 10^{-6} mhos/m the factor is minor. However, these effects may become important for liquids with conductivities less than 10^{-6} mhos/m.

7.7. EXPERIMENTS

As part of an experimental study on the unsteady behavior of an air/water bubbly mixture, the performance of a 10.2 cm (4 in.) i.d. transverse field Foxboro electromagnetic flowmeter with insulated walls was investigated. To accommodate a 328 Hz excitation frequency for good dynamic response, a variable A.C. power source in line with an oscillator was used instead of the 60 Hz commercial version. The low noise signal processor consisted of a 68 dB preamplifier and a demodulator.

The flowmeter was installed in a vertically upward flow 1.37 m above an air injector. A second flowmeter was used upstream of the air injector to monitor the water flow rate. The void fraction, α, was measured by means of an impedance void fraction meter developed as part of the same research program (Bernier 1981). For various selected water flow rates up to superficial velocities of 1.14 m/sec, measurements were made for different void fractions by varying the air injection rate. The resulting flow patterns were observed through the lucite tube upstream and downstream and downstream of the flowmeter; they ranged from bubbly flow through transition and into the churn-turbulent regime. The output signals of the two flowmeters and the void fraction meter were monitored by a tape recorder and a digital Fourier analyzer for the purpose of evaluating both the D.C. signal and the r.m.s. noise.

The mean signal output from the electromagnetic flowmeter monitoring the two-phase flow ($\Delta\phi_{TP}$) is presented in figure 3 where the values have been divided by $(1 - \alpha)$ and the output of

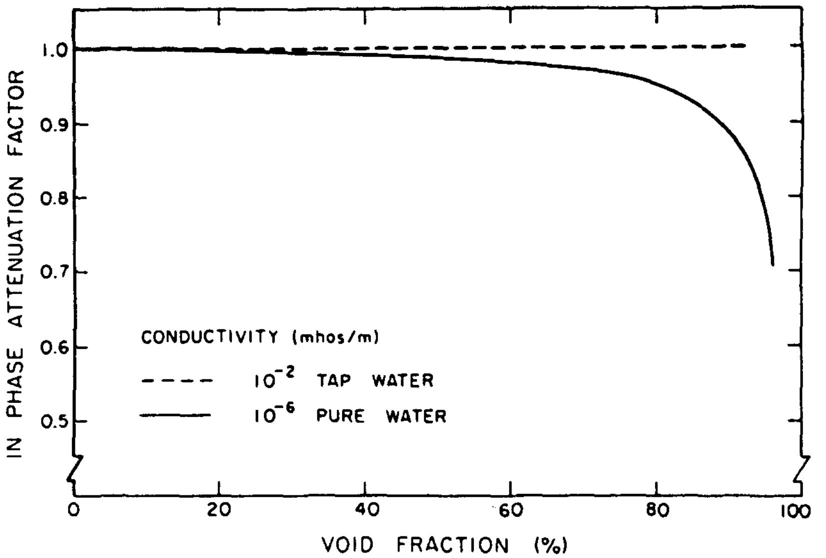

Figure 2. In-phase attenuation factor due to the effective electrical properties of a homogeneous two-phase flow mixture in an oscillating magnetic field. Water dielectric constant: $\epsilon_w = 80$, magnetic field frequency: 328 Hz.

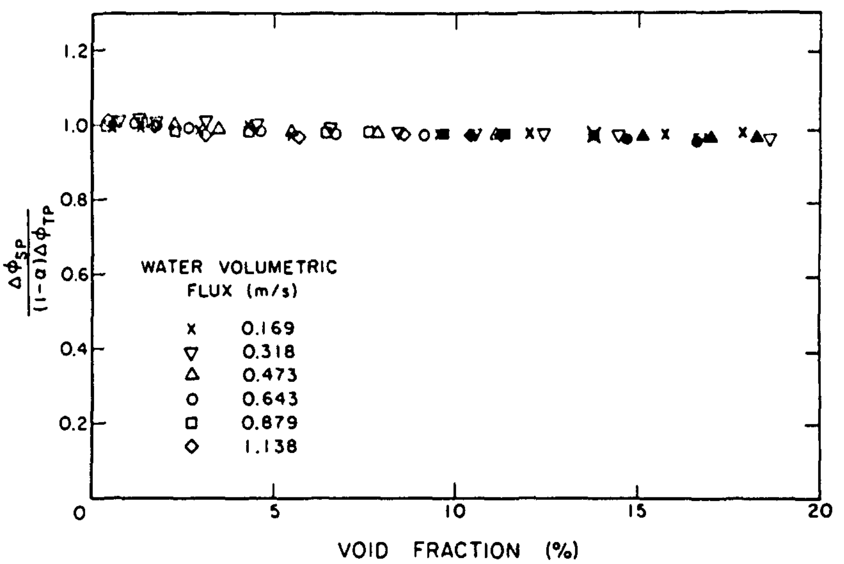

Figure 3. Steady-state performances of a 10.16 cm (4 in.) i.d. Foxboro transverse field electromagnetic flowmeter in air/water bubbly (open symbols) and churn turbulent (solid symbols) two-phase flows.

the flowmeter monitoring the water flow rate ($\Delta\phi_{SP}$). According to the theory in sections 3, 4 and 5, the result should be unity and, indeed, the experimental results fall within a narrow band ($\pm 2\%$) on either side of unity over a wide range of void fractions and superficial water velocities. Some of the flows were clearly observed to be in the churn-turbulent regime as opposed to the bubbly flow regime. These are shown by the solid symbols and indicate no corresponding change in the flowmeter calibration.

We conclude that the electromagnetic flowmeter measures the average water velocity over a substantial range of void fractions, water flow rates, slip ratios, and flow regimes.

The r.m.s. noise generated by the meter was also monitored during each experiment. The higher frequency field excitation (328 Hz) would allow flow noise at frequencies up to about

50 Hz to be detected. It was found that the r.m.s. noise was virtually independent of the void fraction or water flow rate and it was concluded that the flow noise was insignificant compared with the electronic noise. The noise-to-signal ratio therefore decreased as the water flow rate increased. Typical values were of the order of 0.05 for the higher flow rates (Bernier 1981).

We conclude that the electromagnetic meter has excellent dynamic capability for unsteady two-phase flows provided the field excitation is set at a frequency about ten times higher than the required dynamic response. Noise is not a problem.

8. CONCLUSIONS

It has been shown that a transverse field electromagnetic flowmeter has considerable potential in two-phase flows in which the continuous liquid phase has some modest electrical conductivity. Insofar as the present study is concerned, it appears to monitor the average liquid velocity independent of void fraction, flow rate, or flow regime. The insensitivity is demonstrated theoretically for both bubbly flow and annular flow (independent of axisymmetric velocity profile). It has been demonstrated experimentally for bubbly flow and churn turbulent flow.

Furthermore, it has been shown that the instrument will have good dynamic capability in unsteady two-phase flows provided the field excitation frequency is increased to a value about ten times the required response frequency.

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NOMENCLATURE

- a radius of gas core in annular flow
- b electromagnetic flowmeter internal radius
- B magnetic flux intensity
- c small cylindrical bubble radius
- i imaginary index
- r radial position
- Q volumetric flowrate
- u axial fluid velocity
- u_M average velocity, $Q/\pi b^2$
- X electrical property factor
- α void fraction
- ϵ dielectric constant
- ϕ electric potential
- $\Delta\phi$ electric potential difference
- $\Delta\phi_{TP}$ output of the E.M. flowmeter monitoring the two-phase flow in the experiments
- $\Delta\phi_{SP}$ output of the E.M. flowmeter monitoring the water flow rate in the experiments
- σ electrical conductivity
- θ angular position measured from the magnetic flux direction
- ω radian frequency

Subscripts

- A air
- L liquid
- W water

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