Int. J. Multiphase Flow Vol. 14, No. 6, pp. 777–785, 1988
Printed in Great Britain.

0301-9322/88 \$3.00 + 0.00

AN IMPEDANCE METHOD FOR THE MEASUREMENT OF LIQUID HOLD-UP IN TWO-PHASE FLOW

P. ANDREUSSI, A. DI DONFRANCESCO and M. MESSIA
University of Pisa, 56100 Pisa, Italy

(*Received* 11 *September* 1987; *in revised form* 10 *July* 1988)

Abstract—A liquid hold-up gauge based on the measurement of the electrical impedance has been developed for application in gas–liquid pipe flow. The gauge consists of two ring electrodes mounted flush to the pipe wall. The impedance (capacitance or conductance) seen by the electrodes depends on the distance between them and on the liquid hold-up. For distances above three tube diameters, the impedance is independent of the flow configuration for all separated flow patterns and, with good approximation, also for intermittent flows. Moreover, capacitance or conductance are linearly related to the liquid hold-up. The impedance under bubble flow conditions closely follows the theoretical predictions due to Maxwell. Also for the other flow configurations (annular, stratified, intermittent) the results of static and/or dynamic calibration agree closely with theoretical models.

Key Words: two-phase flow, instrumentation, void meter, conductance probe

INTRODUCTION

A very common technique for the measurement of the liquid hold-up in two-phase gas–liquid flow is the impedance method. Details about this technique and main references can be found in a book by Hewitt (1978). Impedance probes can easily be used in large-scale experiments and in industrial applications, such as the continuous monitoring of the liquid hold-up in a gas–liquid pipeline.

This experimental technique is based on the measurement of the electrical impedance between two or more electrodes mounted on a specially designed section of the pipe. In general, according to the fluid pair, only capacitance or conductance is determined.

A major limitation of the impedance method, frequently reported, is its large sensitivity to the different flow patterns which may be encountered in two-phase flow. In order to overcome this perceived difficulty, a number of very complicated measuring sections have been designed and tested in recent years (Merilo *et al.* 1977; Auracher & Daubert 1985). In the present work, it is shown that a very simple, non-intrusive probe made of two ring electrodes mounted flush to the tube wall can be very effective for the measurement of the mean liquid hold-up under different flow conditions.

Only the hold-up relative to a continuous liquid phase can be determined by this probe when the impedance is given by a purely resistive term.

THE IMPEDANCE METHOD

The magnitude of the impedance between two electrodes immersed in a conducting liquid reaches a constant value and the phase angle goes to zero when the frequency of a.c. signals applied to the electrodes is sufficiently high. In this case the impedance is given by a purely resistive term, R_E. The high-frequency conductance, $G_E = 1/R_E$, between the electrodes is proportional to the capacitance in a non-conducting liquid between identical electrodes charged at a constant potential difference

$$G_E = \frac{\gamma}{\epsilon} C_E, \qquad [1]$$

where γ is the conductivity and ϵ the dielectric constant of the liquid.

In the present work the impedance technique has only been adopted with conducting liquids and in all cases the impedance was only given by a resistive term. By means of [1] the results obtained can be extended to the case of non-conducting liquids, when capacitance is measured.

A schematic diagram of the probe used in this work is shown in figure 1. In all our experiments the electrodes were stainless steel rings mounted flush to the tube wall. The length of the rings, L_E, is then equal to the tube circumference, πD.

Ring electrodes have been adopted by Asali *et al.* (1985) for the measurement of very thin liquid films. In these experiments the film thickness could be as low as 30 μm and in addition to the difficulties associated with the measurement of such small thicknesses, there was the problem of a possible non-uniform distribution of the liquid around the tube circumference. Therefore, it was decided to measure the mean thickness in a section of the tube rather than a local value.

When the distance between the electrodes, D_E, is large with respect to the film thickness, h_L, the capacitance and, from [1], the conductance between the electrodes can easily be calculated. The potential V^+ due to the positive electrode charged with a constant charge density per unit length, e, is given by

$$V^+ = \frac{e}{2\epsilon h_L} x \qquad [2]$$

where x is the distance from the electrode. In [2] it has been assumed that the electric field generated by the charge e is entirely contained in the liquid film and that its magnitude and direction are constant.

If the potential due to the second electrode charged by $-e$ and placed at a distance D_E is considered, the potential drop ΔV between the electrodes is given by

$$\Delta V = \frac{e}{\epsilon h_L} D_E \qquad [3]$$

and the capacitance by

$$C_E = \epsilon \frac{\pi D h_L}{D_E}. \qquad [4]$$

The conductance can finally be derived from [1] as

$$G_E = \gamma \frac{\pi D h_L}{D_E}. \qquad [5]$$

As shown by Asali *et al.* (1985), [5] is closely followed when $h_L \ll D_E$ and the frequency of the a.c. voltage applied to the electrodes is $\gtrsim 100$ kHz. The effects of the applied a.c. frequency on conductance has been analysed in detail by Coney (1973) and Brown *et al.* (1987).

Equation [5] can easily be generalized to different flow patterns. First, it can be noticed that in annular flow, for $h_L \ll D$, the flow area occupied by the liquid film is given by $\pi D \cdot h_L$. From [5] it can be seen that the conductance between ring electrodes is proportional to this product.

In many cases of separated gas–liquid flow, the liquid hold-up coincides with the fraction of the tube cross-section occupied by the continuous liquid phase, as the possible contribution of entrained droplets is negligible.

We now consider a duct of arbitrary cross-section equipped with two electrodes mounted flush all around the perimeter of the duct and separated by a distance D_E along the flow direction. Let the flow area of the duct be A, the fraction occupied by the liquid phase H_L and the wetted perimeter P_L. In this case the potential due to the positive electrode can be expressed as

$$V^+ = \frac{eP_L}{2\epsilon A H_L} x \qquad [6]$$

and the conductance between the electrodes as

$$G_E = \frac{\gamma A}{D_E} H_L. \qquad [7]$$

Equation [7] clearly shows that for all cases of separated gas–liquid flow in a duct (annular symmetric, annular non-symmetric, stratified etc.) the conductance between the electrodes is proportional to the mean liquid hold-up, the only limiting assumption being that the distance between the electrodes is large with respect to the characteristic size of the cross-section occupied by the liquid.

The electrical behaviour of rectangular electrodes for short separation distances can be predicted by the theoretical analysis developed by Coney (1973). This author found that the dimensionless conductance $\tilde{G}_E$, defined as

$$\tilde{G}_E = \frac{G_E}{\gamma L_E} \quad [8]$$

with L_E equal to the length of the electrodes, could be expressed by the function of the elliptical integrals $K(m)$,

$$\tilde{G}_E = \frac{K(m_1)}{K(1-m_1)} \quad [9]$$

with $K(m)$ defined as

$$K(m) = \int_0^{\pi/2} (1 - m\sin^2\theta)^{-1/2}\, d\theta \quad [10]$$

and m_1 given by

$$m_1 = \frac{\sinh|k(w_1-1)|\sinh|k(w_2-1)|}{\sinh|k(w_1+1)|\sinh|k(w_2+1)|}; \quad [11]$$

w_1 and w_2 are defined in figure 1, $k = 2\pi/h_L$.

It can easily be shown that for $h_L \ll D_E$, [9] converges to the approximate solution already determined. Equation [9] has been derived for a uniformly thick liquid layer flowing on a flat surface. Coney (1973) suggested that [9] could be extended to predict the conductance of annular liquid films by substituting for the actual film thickness the equivalent value

$$h_E = -\frac{D}{D_E}\ln\left(1 - 2\frac{h_L}{D}\right). \quad [12]$$

Equation [12] can only be used for small thicknesses. For $h_L \to D/2$, [12] gives $h_E \to \infty$, which is clearly an unrealistic correction to the actual value of the film thickness.

The theoretical results obtained by Coney (1973) can be extended to the flow configurations found in annular or stratified flow in a duct of arbitrary cross-section by defining an equivalent thickness of the liquid layer

$$h_L = \frac{A_L}{P_L}. \quad [13]$$

The use of this equation can be justified, to some extent, on theoretical grounds, but the most convincing support for its use will be a comparison with the results of the calibration of the conductance probe.

A convenient experimental procedure which can be adopted to determine directly the liquid hold-up without knowing the electrical conductivity of the liquid, consists of the measurement of the ratio, G_E^*, between conductance at a given hold-up and the conductance for the pipe full of liquid. This ratio can easily be predicted by the combined use of [9] and [13] for the cases of annular and stratified flow in a pipe.

In figures 2 and 3 the ratio G_E^* relative to different separation distances between the electrodes is plotted vs the liquid hold-up for the cases of annular and stratified flow, respectively. From these figures it can be seen that, for separation distances larger than two tube diameters, the calculated values of G_E^* are very close to the values of the liquid hold-up.

When ring electrodes are adopted for the determination of the liquid hold-up under dispersed flow conditions, it can be expected that the dielectric constant or the conductivity of the liquid will follow the equations given for ϵ or γ by Maxwell (1881),

$$\gamma = \frac{2H_L}{3 - H_L}\gamma_L, \quad [14]$$

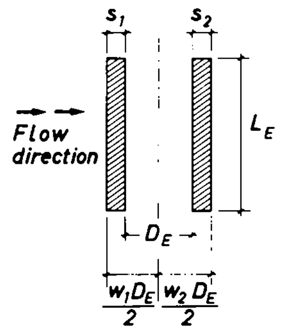

Figure 1. Scheme of flush-mounted electrodes.

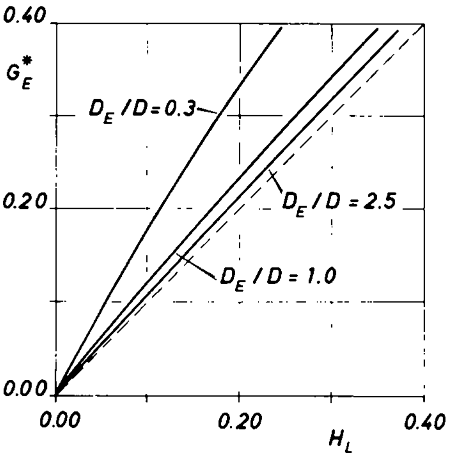

Figure 2. Predictions for annular flow at varying distances between the electrodes.

or by Bruggeman (1935),

$$\gamma = H_L^{3/2}\gamma_L. \qquad [15]$$

In the two cases G_E^* is given by

$$G_E^* = \frac{2H_L}{3 - H_L} \qquad [16]$$

and

$$G_E^* = H_L^{3/2}. \qquad [17]$$

Equations [16] and [17] are represented in figure 4. For a uniform void distribution across the pipe cross-section the dimensionless conductance is predicted to be independent of the distance between the electrodes.

PROBE DESIGN

A schematic diagram of the conductance cells used for the present investigation is shown in figure 5. The main dimensions of the cell are indicated in the figure. Similar probes with internal diameters of 32 and 90 mm have also been used in the present experiments.

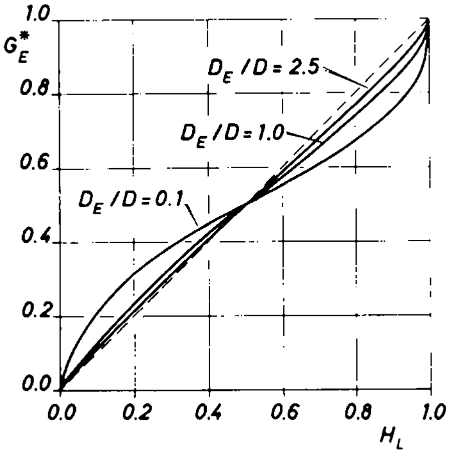

Figure 3. Predictions for stratified flow at varying distances between the electrodes.

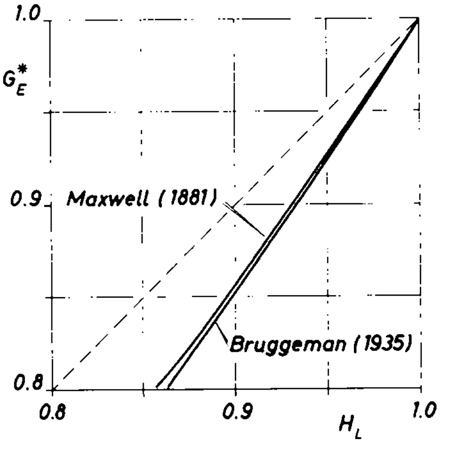

Figure 4. Predictions for bubble flow, using the Maxwell (1881) and Bruggeman (1935) equations.

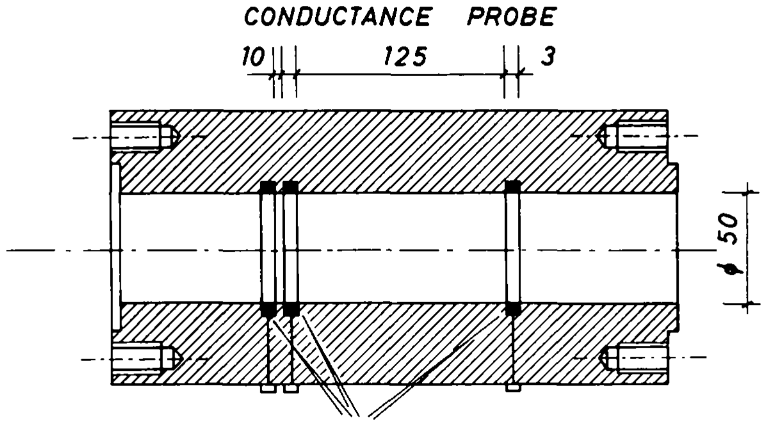

Figure 5. Ring electrodes for hold-up measurements in a 50 mm i.d. pipe.

As can be seen from figure 5, the probes were equipped with three rings and the distance between the rings could be varied. A three-ring probe permits three electrode paris to be used in the actual measurements. This feature of the probe has already been adopted for the determination of slug velocity.

The electronic circuit developed to measure conductance is shown in figure 6. The choice has been to excite the probe with a 100 kHz signal in order to avoid the double-layer effects described by Brown *et al.* (1978). The operational amplifier adopted in the circuit gives an output voltage V_o proportional to the voltage of the signal generator, V_s, and to G_E:

$$V_o = -R_f \cdot V_s \cdot G_E; \qquad [18]$$

R_f is indicated in figure 6.

When conductance is simply proportional to the liquid hold-up, this feature of the electronic circuit permits us to obtain H_L as the ratio between the actual signal and the signal relative to full pipe flow.

In order to attain better precision, the hold-up was, in general, obtained using calibration lines which related the signals from the amplifier to hold-up measurements taken with very precise absolute methods.

In addition to the electronic circuit shown in figure 6, impedance magnitude and phase were measured using a Hewlett–Packard impedance meter (model 4800 A). As already mentioned, in all the present experiments the phase of the impedance was very close to zero.

Signals from the amplifier could be sent to a digital voltmeter, which gave the instantaneous or the mean voltage from the probe, or to an AD converter connected to a computer.

PROBE CALIBRATION

Annular flow

Annular liquid films were simulated by inserting Plexiglas rods of known diameter into the pipe. A similar procedure was adopted by Asali *et al.* (1985). Calibration lines for two probe

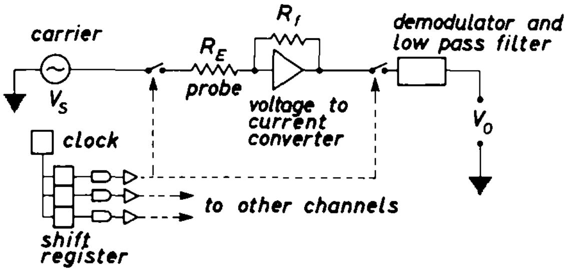

Figure 6. Electronic circuit for the measurement of conductance.

configurations are compared with the theoretical predictions in figure 7. As can be seen, the agreement between theory and the experiments is good. In particular, it can be noted that, for a distance between the electrodes of less than two pipe diameters, good linearity is attained between G_E^* and H_L.

For liquid hold-ups typical of annular flow, $H_L < 0.1$, G_E^* coincides with H_L.

Non-symmetric annular films were created by moving the Plexiglas rods toward the tube wall. No appreciable effects on conductance were noticed.

Stratified flow

Stratified flow was simulated by pouring known volumes of liquid into a short horizontal section of pipe.

Dynamic calibration of the probe was also performed by measuring the height of free-falling liquid layers in a slightly inclined pipe by a needle mounted on a micrometer head.

The experimental results are compared with the theoretical predictions in figure 8 for two probe configurations.

The agreement between theory and the experiments appears to be satisfactory. It is interesting to note that, for both annular and stratified flow, the experimental results tend to be closer to the line at 45° than the theoretical predictions.

Bubble flow

Bubble flow conditions were simulated by a number of plastic spheres of known diameter (1–10 mm). The spheres were suspended at fixed positions.

Bubble flow was also established in a vertical tube filled with water by a small air flow fed through a large number of 2 mm holes drilled close to the bottom of the tube.

The hydrostatic head of the areated liquid was measured close to the conductance probe by a manometer. The liquid hold-up was obtained as the ratio between the manometer readings and the height of the areated liquid column.

As shown in figure 9, the experimental points almost coincide with the theoretical predictions only when the electrodes are spaced far apart (probe A). This result can be explained by recalling that in these experiments the bubbles were mainly located close to the pipe axis.

When the electrodes are closely spaced (probe B), the flow configuration appears to be intermediate between annular and bubble flow.

If the behaviour of closely spaced electrodes in bubble flow is confirmed by more extensive experiments, this electrode configuration, which gives a linear dependence between G_E^* and H_L can eventually be adopted for the measurement of small void fractions in bubble flow.

Bubble flow conditions were also tested for probe A by moving the spheres, which simulated gas bubbles, close to the pipe wall. This flow configuration is encountered, for instance, in bubble and slug flow in a horizontal pipe. For a void fraction of about 0.05 the maximum variation of

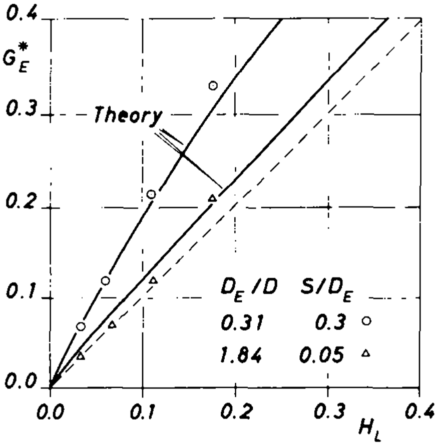

Figure 7. Comparison between theory and experiments: annular flow.

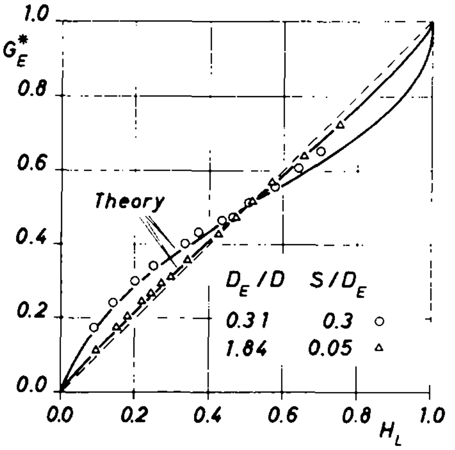

Figure 8. Comparison between theory and experiments: stratified flow.

void fraction detected with all the spheres at the wall was 10%. All measurements were included in the range 0.048 (spheres uniformly distributed) to 0.052 (spheres at the wall). This variation is appreciable when the gas phase is considered, but becomes negligible when the liquid hold-up is the important parameter to be measured.

EXAMPLE OF APPLICATION

Static and dynamic calibration of the ring electrodes showed that this probe can be employed for accurate measurements of the liquid hold-up under different flow configurations. In two-phase flow, three main flow regimes can be identified: separated dispersed and intermittent.

Ring electrodes have been tested under carefully controlled, separated and dispersed flow conditions. In the following application, intermittent flow in a near-horizontal tube is analysed.

This flow regime can be considered as a combination of the other two flow configurations. In a horizontal tube, areated liquid slugs flow over a continuous liquid layer. Intermittent flow can then be analysed by separating the slugs from the base film and using the calibration lines identified for these flow patterns.

An example of the voltage output from the electronic circuit is shown in figure 10. In this example the distance between the electrodes was close to two pipe diameters. This distance is not negligible if compared with slug lengths. For this reason, the arrival of a liquid slug does not cause a steep change of hold-up, as can be expected from visual observations, but the high signal which characterizes the passage of a slug is preceeded (and followed) by a gradual increase (decrease).

The mean liquid hold-up was determined using the calibration lines relative to bubble and stratified flow above and below a threshold value V_S (shown in figure 10), intermediate between the maximum and the minimum signal. The hold-up in the slugs or in the base film was determined without considering rising or decreasing signals before and after any slug.

In figure 11, the mean liquid hold-up and the hold-ups in the slug and in the base liquid layer are represented as functions of the gas velocity for one liquid velocity. It can easily be verified that these measurements are in good agreement with previously published data (see Barnea & Brauner 1985).

An interesting result of the measurements shown in figure 11 is that if we compare the mean dimensionless conductance G_E^* (time-averaged voltage signal divided by the signal relative to full pipe flow) with the mean hold-up determined following the procedure outlined above, it is found that these two values almost coincide. These results are shown in figure 12 and can be justified considering that in intermittent flow slugs move very fast and can be recorded for short times. Time-averaged hold-ups are then mainly determined by stratified flow conditions. It follows that the calibration line relative to stratified flow can also give the mean hold-up under slug flow conditions.

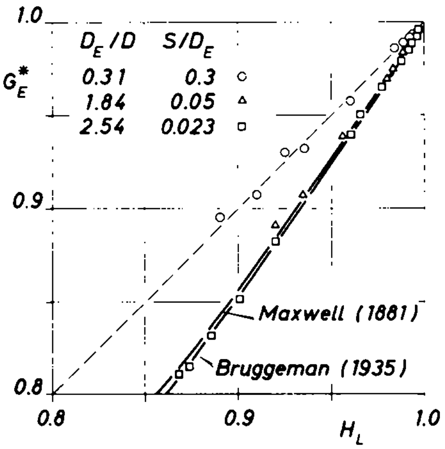

Figure 9. Comparison between theory and experiments: bubble flow.

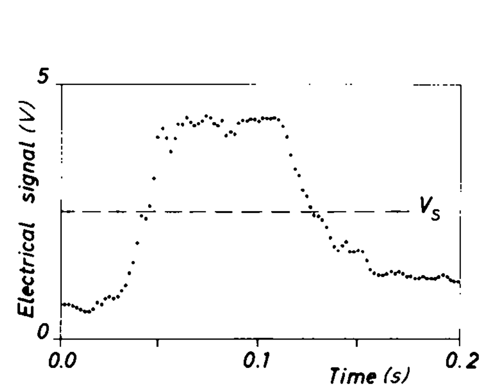

Figure 10. Conductance measurements in slug flow.

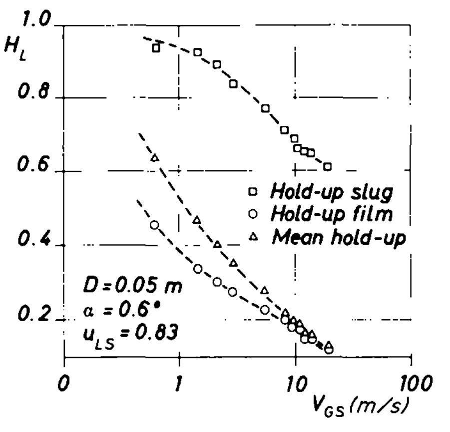

Figure 11. Mean liquid hold-up in the slug, in the base film and overall mean hold-up.

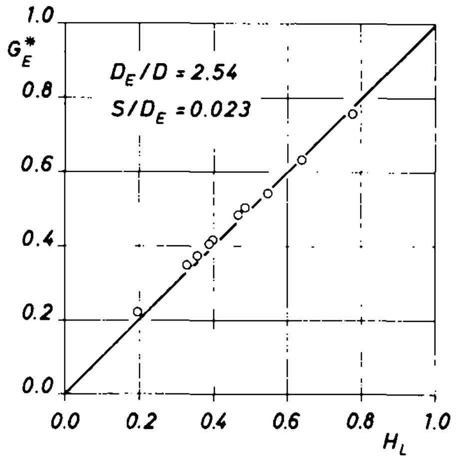

Figure 12. Comparison between the overall mean liquid hold-up in slug flow and the mean dimensionless conductance.

A more precise analysis of slug flow can be performed by the use of a three ring probe. Two rings can be closely spaced to allow a precise determination of the slug arrival time. The third ring, spaced far apart, allows the measurement of the mean slug void fraction.

CONCLUSIONS

The impedance method can be very effective in determining the liquid hold-up in two-phase flow. In particular, this method appears to be convenient when a specially designed section of the flow apparatus can be easily installed.

The dependence of conductance from the electrical conductivity and of capacitance from the dielectric constant of the two phases can be eliminated determining, when possible, the conductance or the capacitance relative to the flow of only one phase at a time.

The distance between the electrodes can be chosen in the range 1.5–2.5D in order to have a good compromise between the conflicting requirements of a localized measurement and a reading independent of the flow configuration. For these values of D_E, it may be useful to use static calibration lines in case a precise measurement of hold-up is required. When $D_E > 2.5D$, the hold-up is linearly related to the conductance both for stratified and annular configurations.

The static and dynamic calibration of the probe showed that the theory developed by Maxwell (1881) and Bruggeman (1935) for dispersed flows and by Coney (1976) for separated flows can easily be adapted to describe the electrical behaviour of the ring electrodes analysed in this paper.

The use of a third electrode allows a more precise characterization of the various flow regimes and the determination of the velocity at which disturbance waves or slugs travel along the tube.

REFERENCES

ASALI, J. C., HANRATTY, T. J. & ANDREUSSI, P. 1985 Interfacial drag and film height for vertical annular flow. *AIChE Jl* **31,** 895–902.

AURACHER, H. & DAUBERT, J. 1975 A capacitance method for void fraction measurements in two phase flow. In *Proc. 2nd Int. Conf. Multiphase Flow*, London.

BARNEA, D. & BRAUNER, N. 1985 Hold-up of the liquid slug in two phase intermittent flow. *Int. J. Multiphase Flow* **11,** 43–49.

BROWN, R. C., ANDREUSSI, P. & ZANELLI, S. 1987 The use of wire probes for the measurement of liquid film thickness in annular gas–liquid flows. *Can. J. chem. Engng* **56,** 754–757.

BRUGGEMAN, D. A. G. 1935 Calculation of different physical constants of heterogeneous substances. *Annln Phys.* **24**, 636–679.

CONEY, M. W. E. 1973 The theory and application of conductance probes for the measurement of liquid film thickness in two phase flow. *J. Phys. E: Scient. Instrum.* **6**, 903–910.

HEWITT, G. F. 1978 *Measurement of Two Phase Parameters.* Academic Press, London.

MAXWELL, J. C. 1881 *A Treatise on Electricity and Magnetism.* Clarendon Press, Oxford.

MERILO, M., DECHENE, R. L. & CICOWLAS, W. M. 1977 Void fraction measurement with a rotating electric field conductance gauge. *J. Heat Transfer* **99**, 330–332.