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PARTICLE FRACTION AND VELOCITY MEASUREMENT IN GAS–POWDER STREAMS BY CAPACITANCE TRANSDUCERS

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Abstract—A simple, economical and accurate technique, based on the different dielectric constants of solids and gases, has been developed to determine instantaneous, *in-situ* void fractions and particle velocities in gas–powder streams. Two different electrode configurations were investigated for sensitivity and flow-regime dependency. Stationary, as well as high speed cinematographic, calibrations were performed. The technique is suitable for process control.

1. INTRODUCTION

Pneumatic conveying is an integral component in many processing plants, both for materials handling and for feeding a wide variety of chemical and metallurgical reactors. Typical applications are: coal combustion and gasification, steel desulphurization with powdered reagents and the flash smelting of copper concentrates. Optimization of such processes requires a knowledge of the trajectories of the particles which depend on the velocity of the particles and the volume fraction of the particles in the gas-particle stream at the point of injection. In most cases, the particle velocities are different from the gas velocities. The object of the present work was to develop a simple technique to measure the particle velocities and void fractions. This capacitance technique measures the instantaneous, volume-averaged *in-situ* velocity which makes it suitable for process control. The analog output of most capacitance meters provides another feature well-suited to process control.

Of all the void fraction, or particle fraction measurement techniques available (Hewitt 1978 and Banerjee & Lahey 1981), the conductance probe and γ-densitometer methods seem to have been the most widely used. Unfortunately, the conductance probe method is only applicable to electrically conductive particles and is significantly influenced by a space charge in the environment. The disadvantages of γ-densitometry are that it exhibits a strong flow-regime dependence, and requires a relatively strong source (and a large amount of radiation shielding), to observe fast transient phenomena.

The methods that have perhaps received the least amount of attention are capacitance probe techniques (Jones 1979 and Cimorelli & Evangelisti 1967) and fast or thermal neutron scattering methods (Moss & Kelly 1970 and Jackson *et al.* 1968). The fast or thermal neutron scattering methods also have shielding problems and the thermal neutron technique is particularly flow-regime dependent (Banerjee & Lahey 1981). On the other hand, the capacitance probe method has the following advantages:

(i) most economical,
(ii) simple installation,
(iii) the electrodes are external to the flow,
(iv) it is applicable to fast transient phenomena (up to a few μsec), and
(v) the output is an analog voltage suitable for process control.

Capacitance techniques have been investigated for diagnostics in packed and fluidized beds (Jones 1979), gas–liquid systems (Cimorelli & Evangelisti 1967 and Özgü *et al.* 1973) and for powder flow sensing in pneumatic conveying (Beck *et al.* 1969a, b). Beck & Wainwright (1969a) used a capacitance device to detect the flow of powder in a fluidized bed conveying system. Beck *et al.* (1969b) reported a cross correlation system for measuring particle velocities

employing capacitance transducers. This system measured the natural fluctuations in particle densities along the pipe by the capacitance transducer to determine average particle velocities.

In the present work, the value of the capacitance measurement, rather than changes in it, is used to determine particle fraction in the pipe. While this is a direct measurement, it does require calibration for the effects of electrode geometry and flow-regime dependence which are unknown for particle flow in pipes. The development of such a technique and the assessment of such problems are the subjects of this paper.

When particles having a dielectric constant, K_2, are inserted between two electrodes separated by a gas having a dielectric constant, K_1, one will measure an effective dielectric constant, K_{EFF}, which will depend on K_1, K_2, the proportion and size of the particles, the electrode spacing, and the particle shape and distribution. Theoretical analysis for evenly distributed particles has delineated two possible limits of behaviour: the so-called parallel and series limits. These are shown in figure 1 and correspond to the cases of the two materials acting as two capacitors in parallel and series. Other workers have proposed different behaviour between these two limits (Jones 1979). The present approach has been more practical in that the effective capacitance was measured as a function of the above-mentioned variables.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

2.1 *Stationary experiments*

In order to assess the effect of flow regime and electrode geometry, stationary experiments were first undertaken. The advantage of such experiments is that the void fraction and "flow regime" can be easily varied and reproduced. The flow regime was simulated by a variety of lucite shapes having different geometry and void fraction, which were inserted into tubes. Thus, extremes of solids distribution (core, annular and stratified) could be assessed for their effect on the capacitance measurement of solid fractions. The core pattern is one in which the solid is present in the middle of the tube, while the annular pattern is the reverse in which the solid is only present at the walls. The stratified pattern corresponds to situations in horizontal conveying where the particles settle to the bottom of the tube. The core and annular flow regimes are not observed in flowing solid–gas systems.

Two basic electrode configurations designated, "ring" and "strip", as shown in figure 2, were evaluated in these tests for sensitivity and flow-regime dependency. The glass tube was

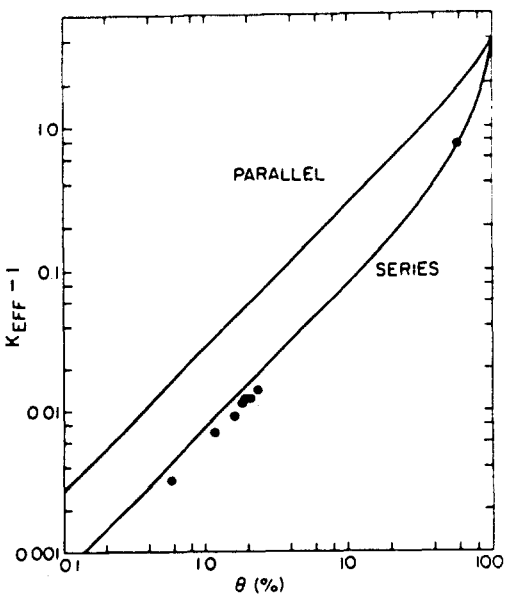

Figure 1. Calibration of strip electrodes for the dynamic experiments using high-speed cinematography. The theoretical parallel and series limits are also shown.

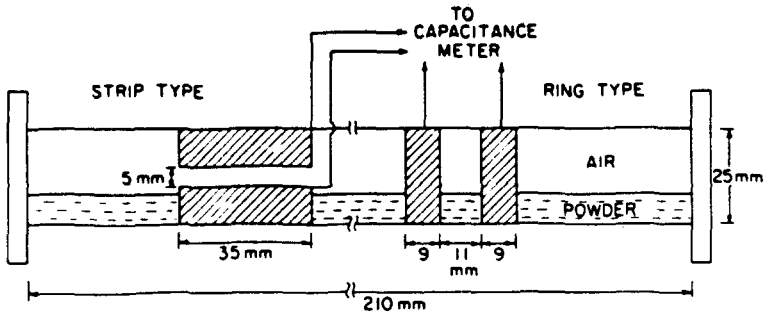

Figure 2. Schematic cross-sections of the strip and ring electrodes used in the stationary experiments.

210 mm long by 25 mm i.d. The ring electrodes consisted of two 9 mm wide aluminum strips attached circumferentially to the tube and separated by 11 mm. The strip electrodes consisted of two 35 mm long by 9 mm wide strips attached longitudinally and separated by 5.0 mm (A limited amount of experimentation with various configurations determined these dimensions.) The tubes were horizontal and far away from objects which would influence the readings.

2.2 *Dynamic experiments*

In pneumatic conveying, the particles are generally travelling more slowly than the gas; thus, in developing this capacitance technique, an accurate and direct calibration system was required. In these experiments, the particle velocities were measured by high speed cinematography, and compared with the particle velocities obtained by the simultaneous measurement of the solids flow rate and the *in-situ* solids fraction. However, preliminary calibration of the electrode configuration was required.

The most sensitive electrode configuration consisted of two brass plates 20 × 90 mm wrapped around the glass tube (12.6 mm i.d., 19.0 mm o.d.) through which the powder flowed, as shown in figure 3. This was wrapped with 5 mm of rubber and then electrostatically shielded with aluminum foil.

To determine K_{EFF}, and hence solids volume fraction θ, one must identify the effect of the capacitance of the glass tube and leads. This was done by filling the tube with liquids having known dielectric constants. The capacitance of the leads and glass tube was assumed to be C_1 and that of the air space in the tube C_2. The measured capacitance of the combination is denoted as C_A with the tube empty. When a fluid with dielectric constant K_2 completely fills the tube, C_2 will be changed to K_2C_2 and the measured capacitance will be C_B. For completely series behaviour

$$\frac{C_B}{C_A} = \frac{C_1 + C_2}{\frac{C_1}{K_2} + C_2} \qquad [1]$$

thus as K_2 is increased, C_B/C_A approaches a limiting value of $(C_1 + C_2)/(C_2)$. Tests with acetone, methanol and water were performed in this manner. From the results in figure 4, one can see that there is a very strong series component in the behaviour, and furthermore, the numerical values of C_1 and C_2 can be deduced from these tests.

There are several problems in determining the equivalent circuit when granular materials are in the pipe: in general the instrinsic dielectric constant of the material can only be estimated, and the material can be distributed in many ways. For practical purposes, it was assumed that the particles acted in series with the air in the pipe, both in the evenly dispersed and packed states, and that for the silica used in the tests the dielectric constant was 4.0 (Weast 1971). By filling the tube with the particles of known packing density (58% measured independently), C_1

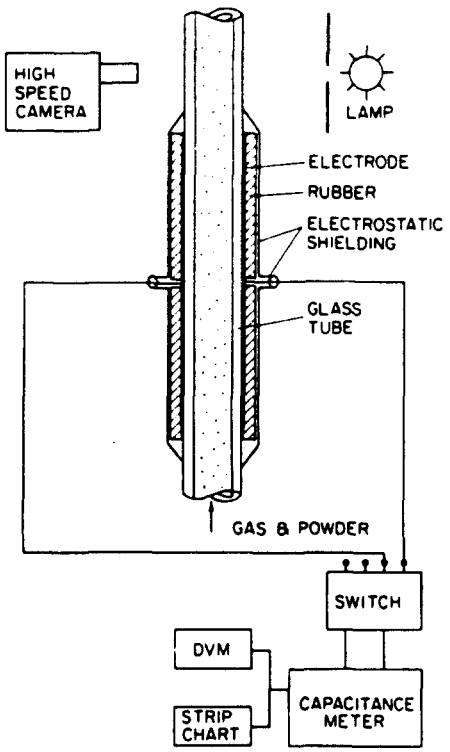

Figure 3. Schematic cross-section of the strip electrodes used in the dynamic experiments.

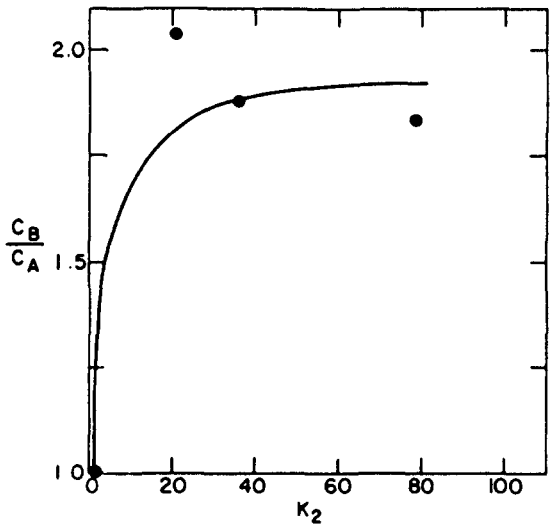

Figure 4. Ratio of measured capacitance when tube filled with a fluid to that when filled with air as a function of the dielectric constant of the fluid.

and C_2 were calculated (10.96 and 21.40 pF). Thus this fixes the point in figure 1 for a solids fraction, θ of 58%.

Since the particle fraction, θ, for dispersed flow is much smaller than in the packed states, separate calibration was undertaken. The powder feeder was conventional in design, having a pressurized hopper which discharged material through its bottom. The gas–powder stream could be further diluted with gas introduced through a "tee" junction under the hopper. The hopper was approx. 4 m from the test section, the last 0.6 m being vertical and free from bends and connections. In these tests, the capacitance, particle mass flow rate (by weighing the discharge), and particle velocity (by high speed cinematography) were measured simul-

taneously. The solids fraction is: $\theta = U_{ps}/U_p$ where U_{ps} is the superficial particle velocity. The results in figure 1 show that a good working relationship between K_{EFF} and θ was obtained over a wide range of θ. It should be noted that this analysis does not prove the equivalent circuit is series.

For the quantitative results reported in figures 8 and 9, the random experimental error was mainly due to drift and fluctuations in the readings. A reasonable value for the error is considered to be one-half of the worst possible error (i.e. the average reading *plus* two standard deviations combined with the empty readings *minus* two standard deviations) which was on average 8% of the θ value, and is analogous to one standard deviation.

2.3 *Materials*

The silica materials were at least 99% SiO_2 and were obtained from a foundry supply company. The 450 μm SiO_2 sand was Ottawa silica sand having nearly spherical particles. The iron powder, at least 99% Fe, is the type used in scarfing operations in steelmaking. The sizes quoted are the weighted average size interpolated from a cumulative per cent passing screen analysis.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 *Stationary experiments*

The relationship between measured output capacitance of the ring electrodes and void fraction in stratified systems are shown in figure 5 for 40 μm diameter iron, and 44 and 450 μm diameter silica powders. Figure 5 shows that the output capacitance is only linearly dependent on the void fraction when θ/θ_F is between approx. 0.1 and 0.5 (θ_F is the particle fraction for a packed bed). Figure 5 also shows that conductive particles such as iron can be measured with the present technique.

The flow-regime dependence of the output capacitance is shown in figure 6 for ring and strip electrodes. By comparison, one can see that the ring electrode geometry is less influenced by

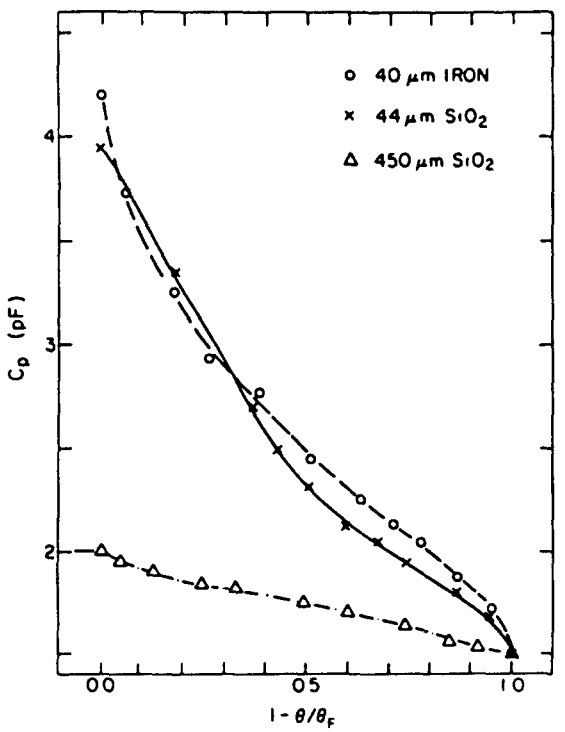

Figure 5. Output from the ring electrode as a function of θ in stationary, stratified configuration.

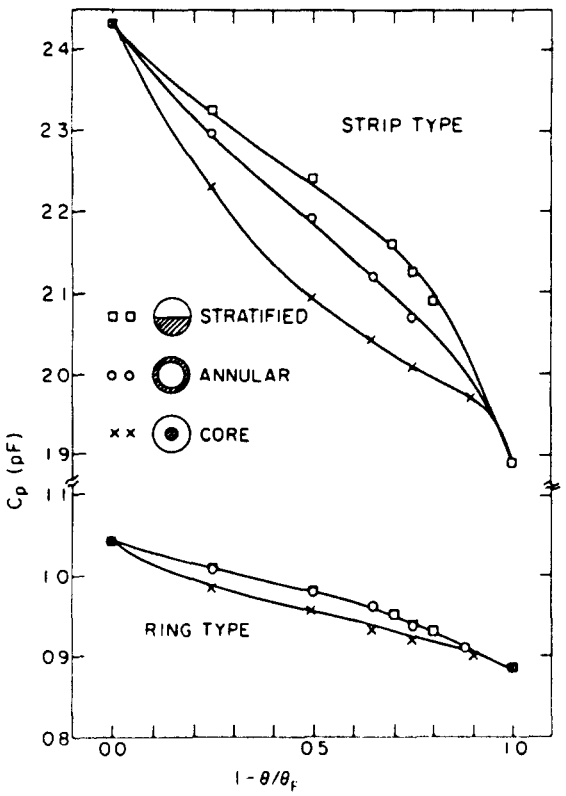

Figure 6. Output from strip and ring electrodes for stationary, lucite simulations of stratified, annular and core flow.

the flow-regime than the strip geometry. However, the ratio of the capacitance of a full tube to an empty one is much larger in the case of the strip electrode geometry than the ring electrode geometry. From this, one can conclude that the strip electrodes are more sensitive and are most useful when the flow-regime is known, whereas the ring electrodes are most useful when the flow-regime is unknown or rapidly changing.

3.2 *Dynamic experiments*

The capacitance transducers can be used in the characterization of flow regimes, in both steady and unsteady states. Figure 7(b) shows the capacitance output for the various flow regimes in figure 7(a) for upward-flowing powder. The regime was determined by visual observation. The powder flow rate was increased in steps and the solids fraction, θ, can be seen to increase as well. With this particular apparatus, the flow became unsteady at $\theta = 0.03$, as seen by the variations in the output and visually by a "wavy" or "ropy" pattern. With further increases in solids loading, the particles could not be moved continuously and slugging of powder started. The slug loading and duration can be measured from figure 7(b). Thus this transducer could be placed at critical positions in pneumatic conveying systems to signal incipient slugging or saltation, so that corrective action could be taken.

This transducer is a very useful diagnostic tool in the dispersed regime, as shown in figure 8, where the solids fraction θ, was measured at various solid mass flow rate W, and gas volumetric flow rate Q, combinations at the lower transducer. If the particles and gas were travelling at the same speed (homogeneous equilibrium flow) (Wallis 1969), then θ would be given by

$$\theta_H = \frac{U_{ps}}{U_{gs} + U_{ps}} \qquad [2]$$

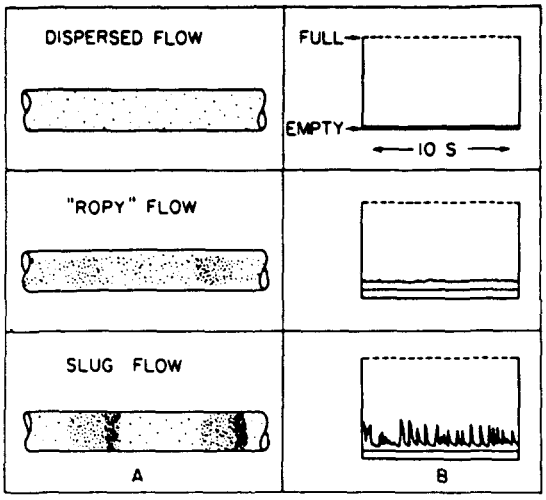

Figure 7(a). Visual appearance of upward, vertical flow in the pipe with increasing solids flow rate (top to bottom).

Figure 7(b). Traces from strip chart (output proportional to capacitance) for the various flow regimes.

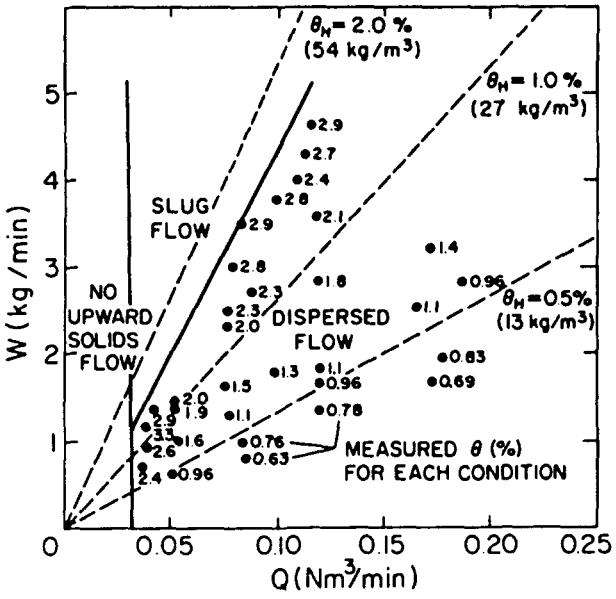

Figure 8. Measured θ in % at various solids mass flow rates, W, and gas volumetric flow rates, Q. Solid lines delineate the regimes, the transition from dispersed to slug was judged when θ fluctuated significantly from the average. Dotted lines indicate various θ in homogeneous equilibrium flow.

shown by the dotted lines in figure 8. Figure 8 shows that θ values are generally higher than predicted by homogeneous equilibrium flow. This is more clearly understood by transforming the variables to actual average gas and particle velocities.

$$U_p = \frac{U_{ps}}{\theta} = \frac{W}{A\rho\theta} \qquad [3]$$

$$U_g = \frac{U_{gs}}{(1-\theta)} = \frac{Q}{A(1-\theta)} \qquad [4]$$

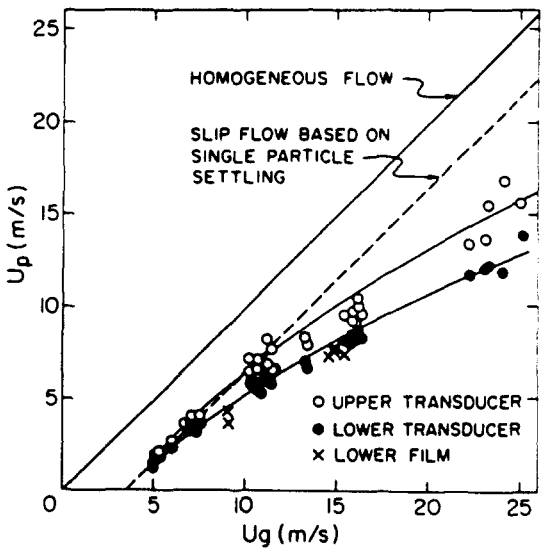

Figure 9. *In-situ* gas and particle flow rate from experiments in figure 8. Upper and lower transducers were 0.6 m apart.

where A is the cross sectional area of the pipe, W is the solids mass flow rate, Q is the volumetric gas flow rate and ρ is the density of the solid material.

From such a transformation, figure 9, one can observe that these particles (with an average diameter of 450 μm, and a density of 2640 kg·m^{-1}) have an appreciable relative velocity, which is in good accord with that which can be calculated from single particle correlations (Clift *et al.* 1979) at lower velocities used. The high speed cinematography results also agree reasonably well. There is considerable divergence at higher velocities because the particles do not have sufficient time to accelerate to the fully developed flow case, although one can see that the particles passing a higher transducer are closer to the single particle slip line.

4. CONCLUSIONS

(1) A simple, reliable technique with an accuracy of approx. 8% for a particular configuration has been developed to measure instantaneous, *in situ* particle velocities and void fractions when the solids flow rate is known.

(2) The "strip" electrode configuration was more sensitive than the "ring" type, which was less-flow regime dependent.

(3) High-speed cinematographic calibration proved the technique to be accurate in the dispersed flow regime.

(4) Different flow regimes can easily be distinguished.

(5) Because of the analog output available on most capacitance meters, the technique is suitable for process control.

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REFERENCES

BANERJEE, S. & LAHEY, R. T. JR., 1981 Advancements in two-phase flow instrumentation. *Adv. Nucl. Sci. & Tech.* 13, 227–414.

BECK, M. S. & WAINWRIGHT, N. 1969a Current industrial methods of solids flow detection and measurement. *Powder Tech.* 2, 189–197.

BECK, M. S., DRANE, J., PLASKOWSKI, A. & WAINWRIGHT, N. 1969b Particle velocity and mass flow measurement in pneumatic conveyors. *Pneumatic Tech.* **2**, 269–277.

CIMORELLI, L. & EVANGELISTI, R. 1967 The application of the capacitance method for void fraction measurements in bulk boiling conditions. *Int. J. Heat Mass Transfer* **10**, 277–288.

CLIFT R., GRACE, J. R. & WEBER, M. E. 1979 *Bubbles, Drops and Particles.* Academic Press, New York.

HEWITT, G. F. 1978 *Measurement of Two-Phase Flow Parameters.* Academic Press, New York.

JACKSON, C. N., ALLEMAN R. T. & SPEAR, W. G. 1968 Neutron densitometer for measuring void fraction in steam–water flow. *Trans. Am. Nucl. Soc.* **11**, 366–367.

JONES, T. B. 1979 Dielectric measurements on packed beds. General Electric Technical Information Series, *Rep. No.* 79*CRD*131, Schenectady, New York.

MOSS, R. A. & KELLY, A. J. 1970 Neutron radiographic study of limiting planar heat pipe performance. *Int. J. Heat Mass Transfer* **13**, 491–502.

ÖZGÜ, M. R., CHEN, J. C. & EBERHARDT, N. 1973 A capacitance method for measurement of film thickness in two-phase flow. *Rev. Sci. Instrum.* **44**, 414–416.

WALLIS, G. B. 1969 *One-Dimensional Two-Phase Flow.* McGraw-Hill, New York.

WEAST, R. C. 1971 [Ed.] *Handbook of Physics and Chemistry.* CRC, Cleveland, Ohio.