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Publication Date
1981-09-01

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Engineering & Technical Services Division

To be presented at the IEEE Nuclear Science Symposium,
San Francisco, CA, October 21-23, 1981

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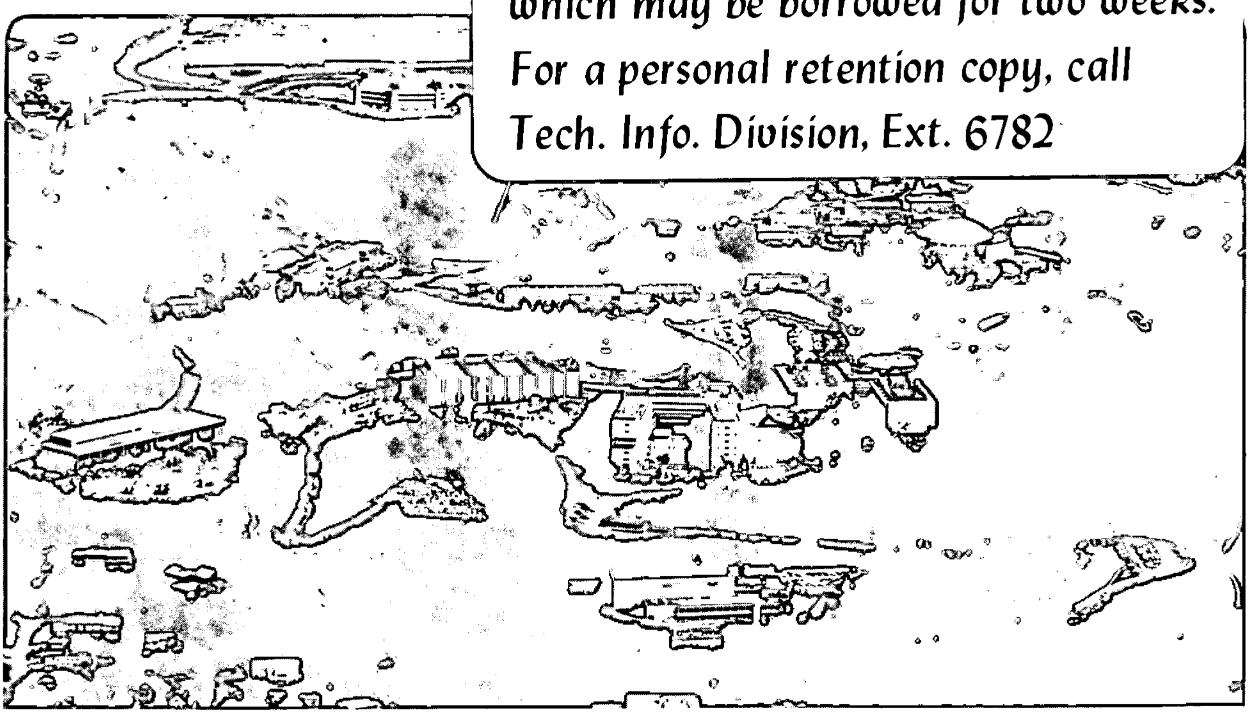

Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

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LBL-9470

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This work was supported by the Health and Environmental Research Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48, and the Electric Power Research Institute under Contract RP-1379-1.

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Abstract

A technique has been developed for measuring water film thickness in a two-phase annular flow system by the capacitance method. An experimental model of the flow system with two types of electrodes mounted on the inner wall of a cylindrical tube has been constructed and evaluated. The apparatus and its ability to observe fluctuations and wave motions of the water film passing over the electrodes is described in some detail.

Introduction

Some two-phase flow systems, in which the liquid and gaseous phases are confined to the interior of a cylindrical tube, are characterized by an annular film of liquid which flows along the wall of the tube, and by an interior dispersion of droplets and gaseous components. In order to study the properties of such systems it is important to measure, with some precision, the thickness of the annular film.

Previous studies have shown that this film may range in thickness from zero, or nearly zero, to several millimeters or more. Moreover, the film thickness is known to vary rapidly with time and position due to the presence of waves of various frequencies and forms of turbulent behavior.

A valid thickness measurement technique should satisfy several criteria. Because of the presence of wave motions and other disturbances, it should be capable of rapid response. For similar reasons it should average its measurement over as small an area as possible (unless only average data are desired). It should not require that the fluid, in this case, water, be unrealistically altered by the addition of seeding materials or ionic salts.

A number of techniques has been employed in the past to make film thickness measurements (1-10). Of these, the most common method (1) has been to exploit the difference in conductivity between the liquid and gaseous phase. Conductivity probes, flush mounted in the wall of the tube, sense the resistance of the fluid and, hence, the thickness. Penetrating conductivity probes (2) in the form of insulated needles with conductive ends have also been employed to estimate the film thickness. Unfortunately, the conductivity of pure water is so low that these methods have, for the most part, required the addition of ionic salts to make reliable measurement possible.

In the present study, a capacitance method (6) was elected to measure the film thickness, based upon the fact that the dielectric constant of pure water is very large, exceeding by a factor of about 80 that of the surrounding gaseous phase. The capacitance of two electrodes mounted on the interior surface of the tube covered by a water film will increase as the film thickness is increased. The method has the main advantage that it can be made to work reliably with pure water and, being non-intrusive, will not distrube the flow. The response time is determined by the performance of the capacitance meter which should be fast enough to observe wave motions and other fluctuations in the film.

Design of Capacitance Electrodes and Measuring System

A plexiglass tube of 1.25 inch inside diameter was used for the annular flow experiment. A convenient geometrical arrangement for the capacitance measurement of the film thickness consists of a pair of concentric metallic bands mounted coaxially around the wall of the flow tube and inset so that they do not disturb the liquid flow. Electrodes of this type (ring electrodes) have been described elsewhere (6). The dimensions of these electrodes are characterized by the perimeter of the rings, $\ell = \pi D$, where D is the diameter of the tube, the width of the rings, a, and their separation, d. Such electrodes will only average the film thickness measurement around the perimeter of the tube. Therefore, smaller electrodes capable of measuring the thickness at a point on the tube wall may also be required. These electrodes, (disk electrodes), are in reality a pair of small electrodes of a given configuration on the end of a small diameter (4 to 6 mm) cyclindrical rod. The ends of the electrodes are mounted flush with the inner surface of the flow tube and appear as two small metallic disk electrodes separated by an insulation gap.

To design the disk electrodes, it was necessary to consider the sensitivity and dynamic range of operation. Electrodes with a narrower gap and larger area will yield a larger capacitance and, consequently, greater sensitivity. On the other hand, the dynamic range of operation will be increased with the width of the gap because a thicker fluid film can be measured before saturation with a larger gap. To select a proper shape and size of electrode, a number of different patterns of electrode pairs was tried out using two different diameters, namely 6 mm and 4.5 mm (Fig. 1). A variety of geometrical sizes and shapes is given in Fig. 1, together with the curves that show the change in capacitance as a function of the water film thickness. The solid line, or dark area within the circle, is the gap between the electrodes.

The configuration C with a diameter of 6 mm and a gap of 0.8 mm along the diameter was the final selection. This kind of electrode pair can be made of copper plates separated by a thin layer of insulator of a given thickness. An alternative disk electrode pair uses a ceramic rod ground to a cylinder of proper dimensions, coated with nichrome, having a narrow insulated gap across the diameter at both ends and along the length of the rod. This kind of electrode pair has a low initial capacitance, a high Q, because of its high parallel resistance and is suitable for high temperature operation due to the good thermal stability of the substrate material. The inner metal ends, i.e. the disks, are a gold coat, curved to fit the inner wall of the tube. The disk electrodes are mounted in the tube by means of an attaching block shown in Fig. 2, which is provided with rubber O-rings to stop the leakage of water, with BNC connectors for the output signal, and a shielding metallic box to screen off local interference. Some of the disk electrodes are shown in Fig. 3.

The ring electrode pair which are the same size as the annular tube consist of copper rings, embedded in the inner wall of th tube, separated by a gap of the same material as the tube. Both the rings and the gap were designed to have the same width, i.e. 1/8". A shielding case surrounds the ring electrode section to screen against interference. The photo and sketch in Fig. 4 shows the construction in detail.

Calibration of Electrodes

The electrodes were calibrated in two ways. A static calibration was performed by covering the electrode with a stationary film of water of known thickness and the capacitance measured as a function of water film thickness. A specially constructed flow system was designed for a dynamic calibration. This system consisted of a section of pipe into which the electrodes, disk- or ring-type, were mounted. The capacitance of the electrodes was measured with running water of known thickness flowing along the inner wall of the pipe and over the surface of the electrodes. The water film thickness along the tube's inner wall is a function of the measured flow-rate of the water as explained below.

Static Calibration

The apparatus for static calibration consisted of water containers of carefully controlled dimensions. For the disk electrodes a cylindrical water container made of plexiglass was designed having a hole in the bottom into which the rod supporting the disk could be inserted so that the disk was flush with the bottom surface. The water film thickness on top of the electrode was determined by two independent methods, (1) by calculation from a known volume of fluid in the container and (2) by detection of the water surface with a microscope device which was specially designed to measure thickness down to 0.1 μ. Different kinds of water, namely low conductivity water (LCW), tap water (TW), distilled water (DW) and de-ionized water (DIW), were employed for the calibration. The conductivities, δ, of the different fluids are as follows: δ_{LCW} = 6.67 μS/cm, δ_{TW} = 66.7 μS/cm, δ_{DW} = 2.0 μS/cm and δ_{DIW} = 2.63 μS/cm. Among them the LCW and TW were used most frequently. For the static calibration of ring electrodes, a rectangular water tank, with a leveling screw for fine level adjustment, was used. Copper strips with an identical gap between them as that of the actual ring electrode pair, whose length equalled the tubes' circumference, were prepared on a printed circuit board which was adjusted and checked with a water-bubble gauge to make sure that it was parallel to the water surface. Since the electrode's surface was not flush with the bottom of the water tank, the elevation of the electrode's surface and thickness of the first water layer had to be determined by means of the microscope. Thereafter, the determination of the water thickness was carried out as described in the preceding paragraph. Because of the relatively large inner diameter of the tube, in comparison to the width and gap length of the electrodes, a pair of flat strips was considered adequate for this calibration. The tests were done mainly with low conductivity and tap water at room temperature.

Dynamic Calibration

The apparatus for the dynamic calibration of the capacitance probes is shown in Fig. 5. It consists of a porous plastic water injection tube mounted in a plexiglass water jacket. Attached beneath the injection tube is a length of 1.25" ID plexiglass tubing onto which short sections of plexiglass containing the probes are mounted. Water from the supply is passed through calibrated turbine flowmeters (Flow Technology Inc., Model FT-12N25-LJC and FTM-N10-LJS) having an error <1%, before being introduced into the test apparatus.

The thickness of a falling film of water flowing down the inside of the tube under gravity is quoted by Wallis (11). At low rates the film flow is laminar and obeys the equation

$$\delta = \left(\frac{3\mu_f Q_f}{\pi g \rho_f D}\right)^{1/3}$$

where δ is the film thickness, μ_f the water viscosity, Q_f the volumetric flow rate, g the gravitational acceleration, ρ_f the water density and D the tube diameter. At higher flow rates the film flow becomes turbulent and the thickness increases at a greater rate than the 1/3 power predicted under laminar conditions. The onset of turbulence is governed by the film Reynold's number defined as

$$Re_\Gamma = \frac{4\rho_f Q_f}{\pi D \mu_f}$$

Normally, the onset of turbulence is considered to occur for $Re_\Gamma > 2000$, but a reasonable fit to the entire flow region can be obtained if laminar flow conditions (δ proportional to $Q_f^{1/3}$) are assumed for $Re_\Gamma > 3000$ and turbulent flow conditions (δ proportional to $Q_f^{2/3}$) are assumed for $Re_\Gamma > 3000$.

If we insert the appropriate numbers for the pipe diameter and assume a water temperature of 17°C, we find with Q_f expressed in gal/min and δ in cm.

$$\delta = 0.0593\, Q_f^{1/3} \qquad Q_f < 1.28 \text{ gal/min}$$

$$\delta = 0.0546\, Q_f^{2/3} \qquad Q_f > 1.28 \text{ gal/min}$$

With this apparatus, film thickness ranging from less than 0.4 to 4 mm could be obtained with the existing water supply.

Instrumentation for Capacitance Measurement

In order to obtain sufficient accuracy and fast response, a Boonton capacitance meter Model No. 72BD, with a digital readout and a DC analog output was found satisfactory for both the static and dynamic measurements. The meter has a cut-off frequency of about 600 Hz, which is adequate for the dynamic detection of waves generated during the annular flow. The capacitance meter is sensitive enough to detect a capacitance change of 0.1 pF in 2ms. The stated requirement for the capacitance meter 72BD to give an accurate readout is that the Q factor be greater than 5. However, it had been tested and found that even with a Q as low as 0.9, the error in the result is still well within 1%. The high Q requirement, however, is not a problem, as a small external capacitor can always be connected in parallel with the electrodes to increase the figure of merit.

Experimental Results

Selection of Electrode Patterns for the Disk-Type Electrode Pairs

In order to optimize the geometrical configuration of the disk-type electrodes, preliminary measurements were first made using electrodes of various shapes and sizes. To simplify the measurements, these electrodes were generated photographically on printed circuit boards. The initial capacitance of these kinds of electrodes is always very low because of the small thickness (0.016") of the copper sheet. In Fig. 1 two families of curves are shown to illustrate that the characteristics of the electrode pairs depend very much on their shape. The solid curves (A, B, C, D, E) are for electrode pairs with an outside diameter of 6 mm, while the dashed curves (a, b, c, d, e) are for electrodes with a 4.5 mm diameter. The air-gap was about 0.8 mm for the large electrodes and 0.6 for the small electrodes. From these curves several conclusions can be drawn; namely, (1) the saturated capacitance increases with the size of the electrode (by comparing families I and II), (2) the sensitivity of the electrode $\Delta C/\Delta t$, increases with the length of the gap, (by comparing A, B, C, etc.) and (3) the dynamic range, i.e. the range of the water thickness from zero to the knee region of the curve, increases with the width of the gap, (comparing electrode E or e to the other electrodes in the same family).

The electrode C has a very simple geometric form and, in addition, has a relatively high sensitivity and a wide dynamic range. Based upon this investigation, it was decided to use pattern C with a diameter of 6 mm for the design of the disk electrodes.

Comparisons Between Static and Dynamic Measurements

There are two kinds of disk electrodes tested: the ceramic and the copper electrode. Since the data of the static measurements are taken by adding water to the container step by step, it is always possible to obtain a smooth curve with good consistency. In Fig. 6 two curves are shown which represent the measurement results for a ceramic and for a copper electrode. Obtained with low conductivity water, the curves differ from each other by about 20% (less than 1 pF), which is understandable since the geometrical dimensions of the two electrodes are not exactly identical. The small triangles and crosses are the measured points from dynamic measurements taken at different times. Misalignment of the rod electrode inside the tube will cause considerable deviation between the dynamic measured points and the static curve.

With accurate adjustment the dynamic measured points fell on the static curve with good consistency. The data were repeatable. This implies that static calibration is applicable to dynamic conditions. This fact was further strengthened by measurements with the ring electrodes.

The results of the dynamic measurements carried out with the ring electrodes are given in Fig. 7, where the large number of points was also taken at different times, with TW or LCW. The most significant and important fact is that all the points fell on the static curve with little deviation, except those few points near 3 mm, which were, at the time, limited by the flow system. There appeared to be no problem of alignment, since the ring electrode pair was mounted flush with the inner wall of the annular tube section, and the dynamic data coincided with the static curve, as expected.

Influence of Water Temperature and Conductivity on Film Thickness Measurement

It is important to determine the influence of temperature on the capacitance measurement. The initial capacitance of the electrode pair did not change significantly when the electrodes were heated up by a hot air gun or cooled by a coolant spray. With LCW (conductivity $\delta = 6.67\ \mu S/cm$) the saturation capacitance changed by about 6% from 17°C to 49°C, while the capacitance within the dynamic range remained practically unchanged. When tap water ($\delta = 66.7\ \mu S/cm$) was used, the variation of the measured saturation capacitance can be as high as 50% within the same temperature range.

The temperature dependence is caused by the conductivity of the tap water, which increases rapidly with temperature. The capacitance meter requires a moderate quality factor, Q = 5. A highly conductive water film above the electrodes of small capacity of a few pF tends to deteriorate the quality factor. However, an external capacitor connected in parallel to the disk electrodes to increase the Q value will significantly reduce the temperature dependence. The temperature effect with disk electrodes in the form of solid rods and ring electrodes, which have large initial capacitances, was not observed.

Discussion

We have investigated two types of capacitance probes for making water film thickness measurements in annular two-phase flow configurations.

Capacitance probes of the disk-type are useful for making local measurements. However, as has been shown, their dynamic range is limited. For the probes considered in this report, the maximum, reliably measurable film thickness is approximately 1-2 mm. The only way the film thickness range can be increased is to enlarge the physical size of the probes. Thus, localization and thickness range are competing constraints subject to compromise. The disk-type electrodes have the advantage that they can be easily installed in the flow tube at any desired position.

The ring-type electrodes, on the other hand, have superior sensitivity and dynamic range. As shown above, they have the capability of making film thickness measurements up to 4-5 mm. Because they completely encircle the flow tube, measurements with these probes are averaged over a larger area. The ring-type probes are more difficult to construct and cannot be repositioned as easily as the rod electrodes.

As can be seen from the calibration curves, for example Fig. 7, the response of both types of probes to changing film thickness is non-linear. It is necessary to provide a linearizing transformation to the capacitance measurement to obtain the proper film thickness. This linearization can be accomplished either digitally by a data processing system, or in an analog fashion with appropriate electronic circuitry. An analog linearizer, which would provide immediate conversion, is presently under consideration. Because of the rapid response capabilities of the capacitance meter, it is possible to detect the fluctuations and wave motions of the water film passing over the capacitance probes. The oscilloscope photographs shown in Fig. 8 and 9 illustrate the variations in measured capacitance for each type of probe caused by fluctuations in film thickness. In the photographs the amplitude of capacitance fluctuations is shown together with the mean capacitance value and the calculated average film thickness as determined by measuring the total water flow rate. The fluctuations are due to turbulence in the film flow which occur for film Reynold's numbers in excess of about 2000, as noted above.

Summary

The capacitance method as a technique for making film thickness measurements in two-phase flow systems has been evaluated. Two types of probes have been tested: disk electrodes and ring-type electrodes. The former type permits the measurement of localized film thickness with a dynamic range of 1-2 mm and the latter enables us to measure cylindrically averaged thicknesses with greater precision and with a dynamic range in excess of 5 mm. With calibration and appropriate linearization, the capacitance measurements can be made to yield thickness data directly and with rapid time response. The latter capability makes it possible to observe fluctuations and wave motions in the film flow provided they are within the dynamic range of the probe used. Finally, it is pointed out that the probes are nonintrusive and do not require doping or other modification of the water supply.

Acknowledgement

This work was performed as part of the program of the Electronics Research and Development Group of the Lawrence Berkeley Laboratory, University of California, Berkeley, and was supported by the Electric Power Research Institute under Contract RP-1379-1 and by the Health and Environmental Research Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

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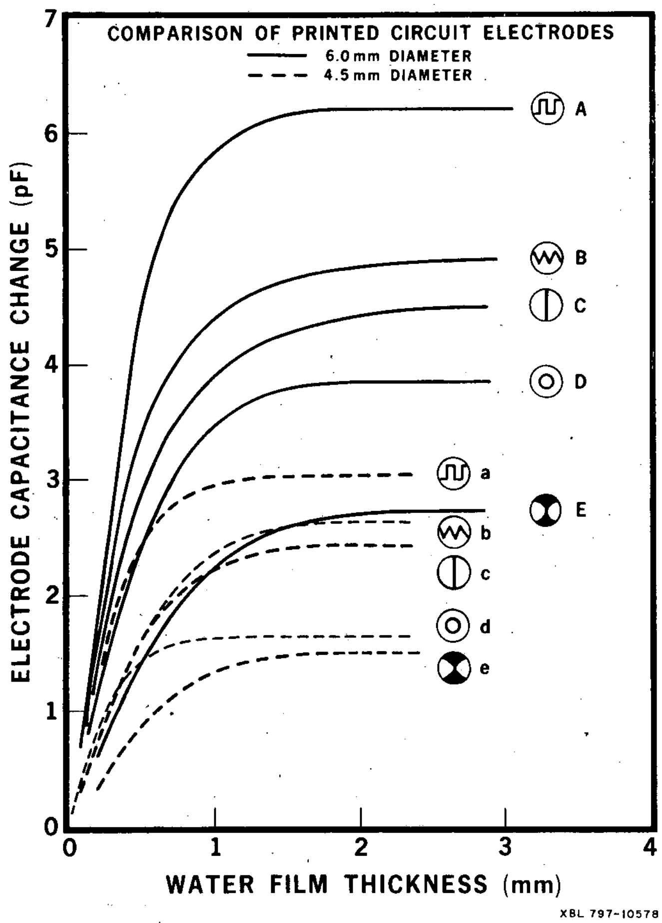

Fig. 1 Comparison of Printed Circuit Electrodes of Different Patterns

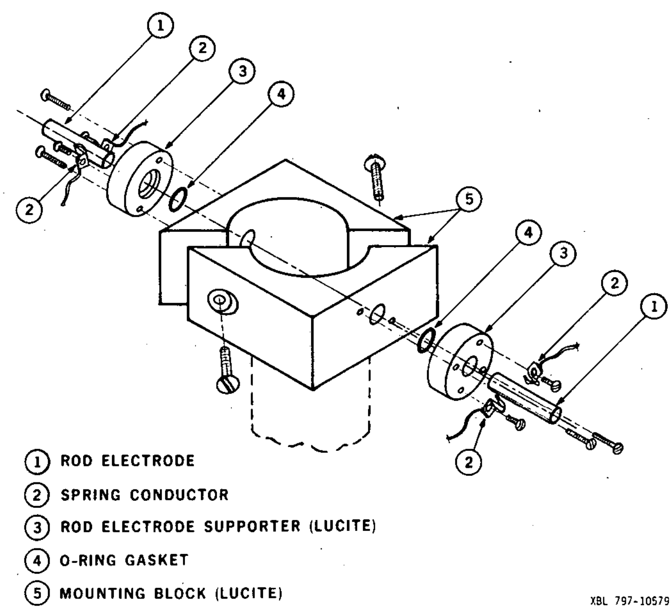

Fig. 2 Construction of Rod Electrode Mounting Block

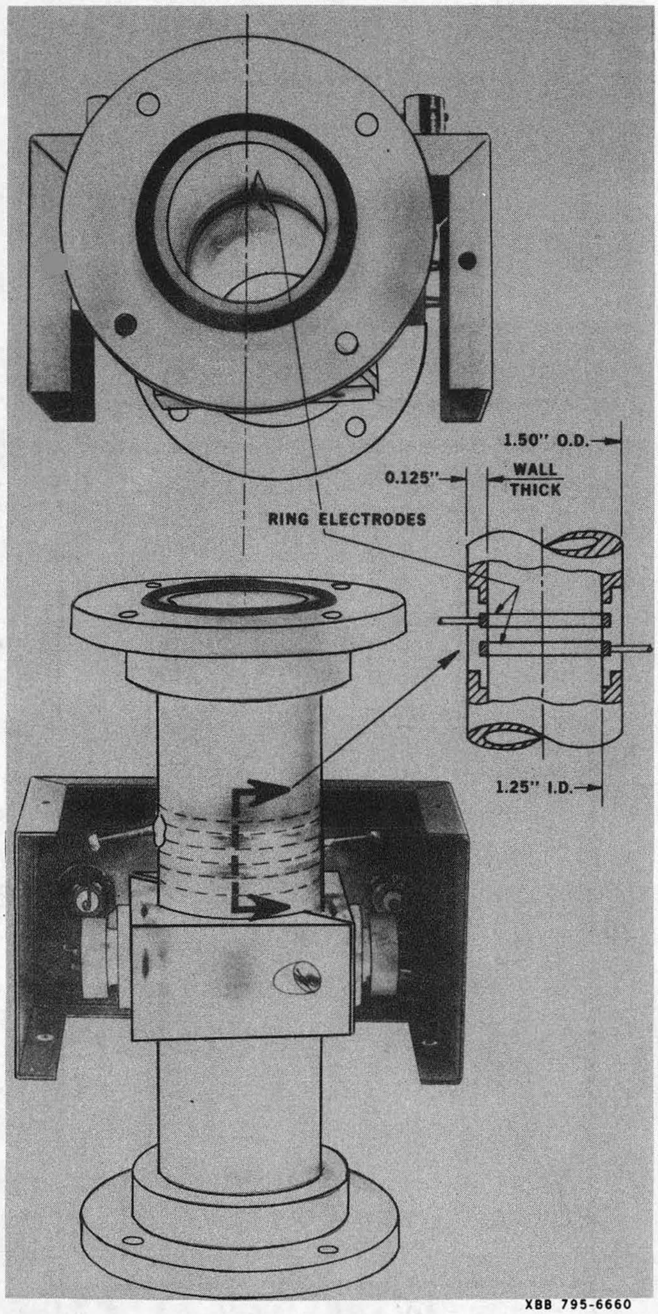

Fig. 4 Construction of Ring Electrode Mounting Section

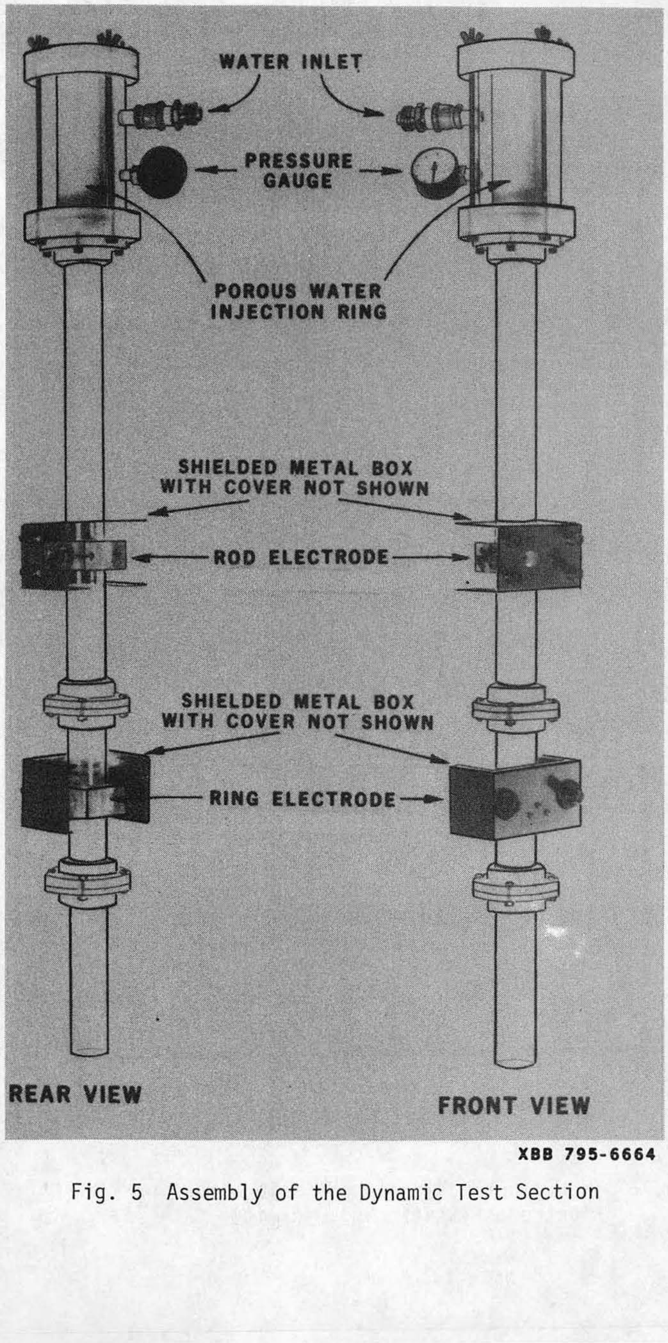

Fig. 5 Assembly of the Dynamic Test Section

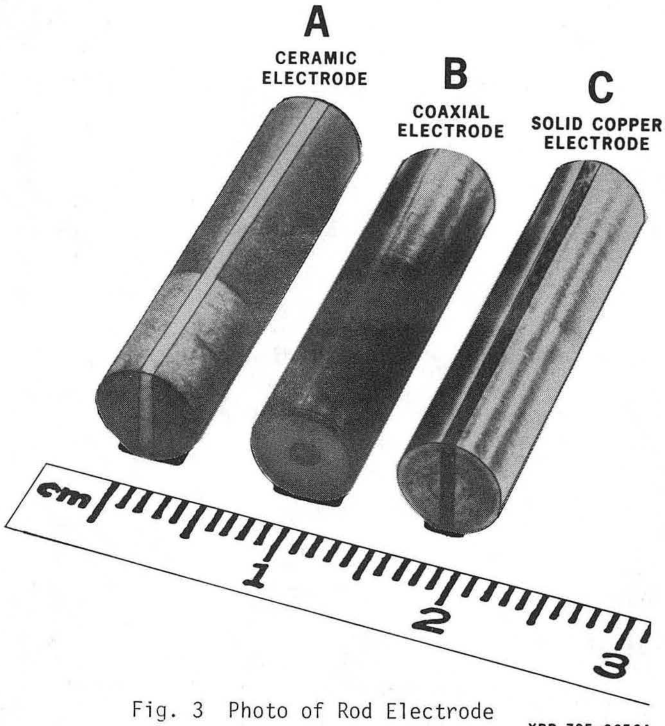

Fig. 3 Photo of Rod Electrode

XBB 795-6656A

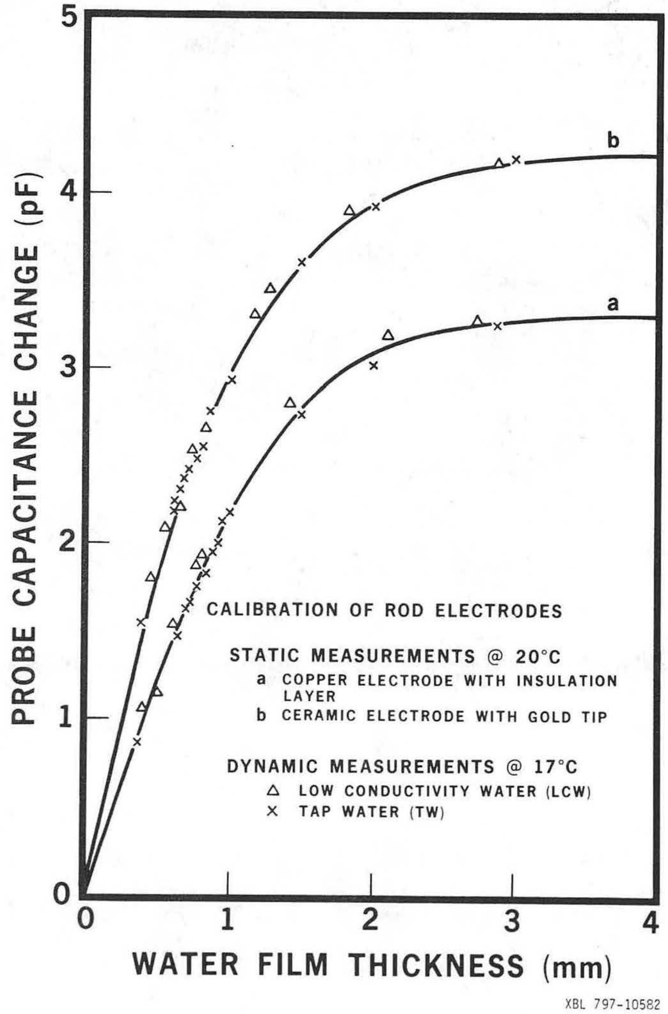

Fig. 6 Experimental Results of Calibrations on Rod Electrodes (Static and Dynamic)

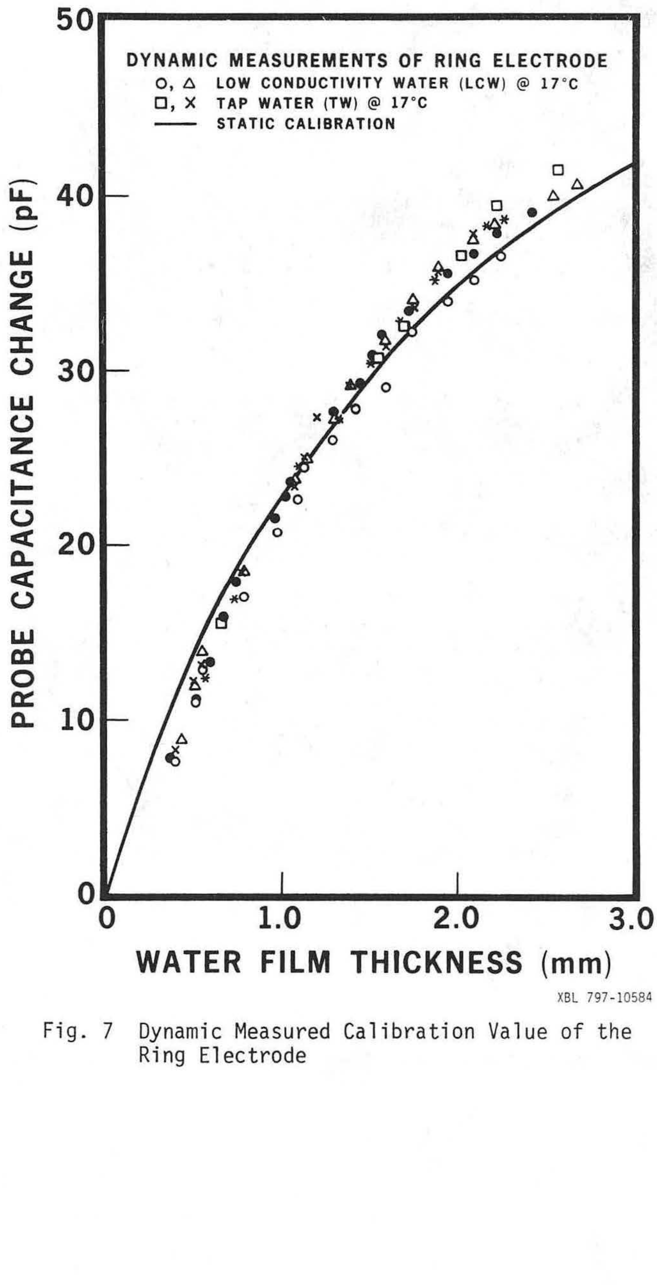

Fig. 7 Dynamic Measured Calibration Value of the Ring Electrode

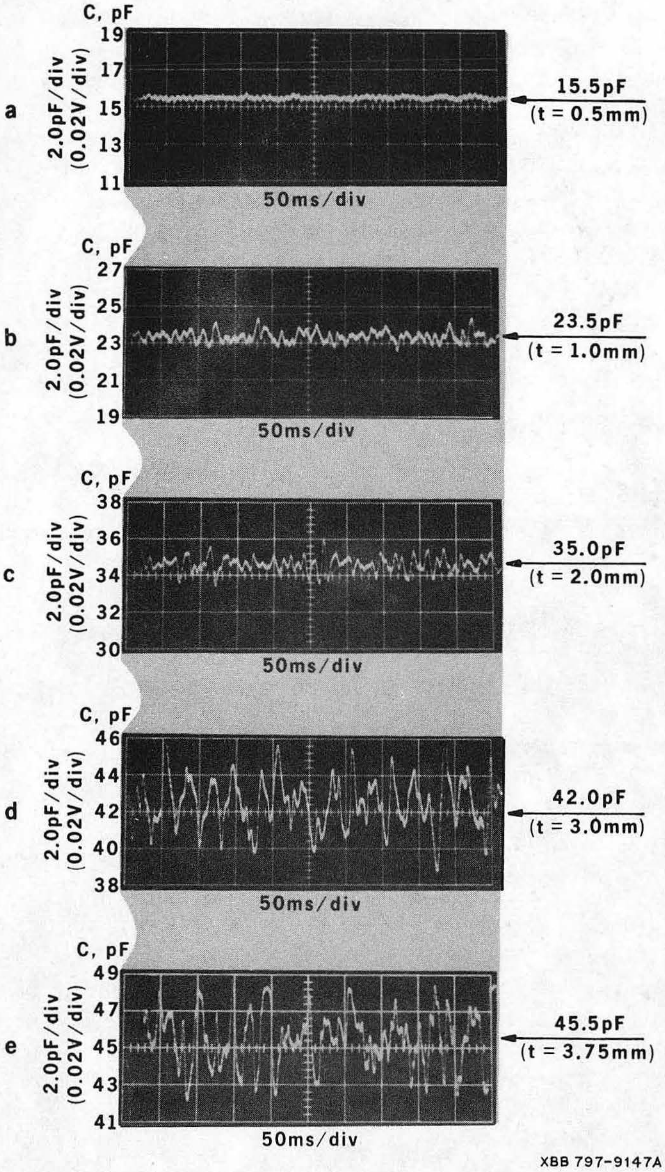

Fig. 8 Transient Measurement of Film Thickness with Ring Electrodes

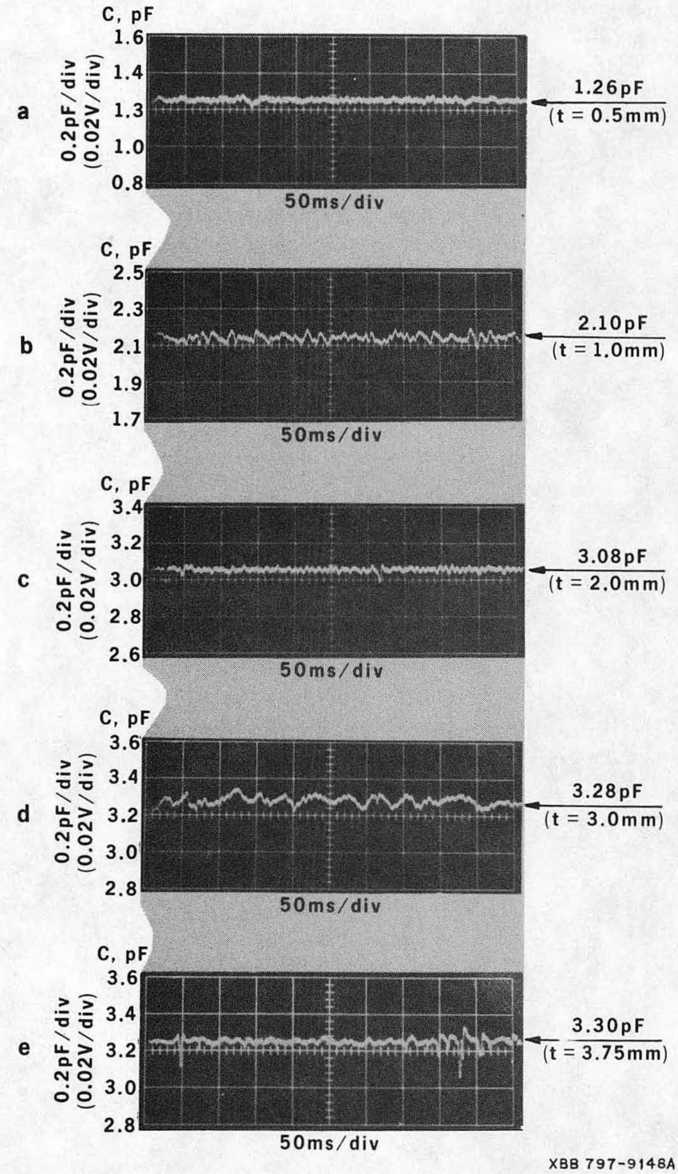

Fig. 9 Transient Measurements of Film Thickness with Rod Electrodes

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