MICROWAVE CHARACTERIZATION OF LIQUID FILMS

R. P. Roy*, J. Ku*, and I. Kaufman*, and S. P. Kalra**
* Arizona State University
Tempe, AZ
** Electric Power Research Institute
Palo Alto, CA

Abstract

A simple microwave technique is described that measures the instantaneous local thickness of a film of liquid flowing down the inner wall of a tube while at the same time a current of gas flows in the opposite direction. Such a measurement technique is significant because of the extensive occurrence of such liquid/gas flows in chemical process and energy industries.

Introduction

We have developed a simple microwave technique that measure the instantaneous local thickness of a film of liquid flowing down the inner wall of a tube while at the same time a current of gas flows in the opposite direction. Such a measurement technique is of significance because of the extensive use of such liquid/gas flows in chemical process and energy industries (e.g., solar energy conversion systems and nuclear reactor systems). Specifically, the heat and mass tranfer at a liquid film/gas interface depends upon, in addition to the flow fields in the gas stream and the liquid film, the structure of the interface itself (e.g., presence of ripples or waves on the interface). While there are competing measurement techniques (such as x-ray beam attenuation (1), conductivity probes (1), capacitance probes (1)(2), etc.), each of these is either quite expensive or subject to other limitations.

Experimental Work

A schematic of the experimental apparatus is shown in Fig. 1. The liquid film/gas flow test section is located in this wave guide. Except for this wave guide, which was a TE_{10} mode guide 19.7 cm wide and 1.3 m long, the microwave system was coaxial line. Two wave guide heights were used: 1.5 cm and 0.8 cm, internally. To make certain that the test section was subjected to a travelling wave field, for possible comparison of the test results with theory, the input and output coax-to-waveguide transitions were matched with tuners. The absence of reflections from these transitions were verified by probing the waveguide fields between the test section and the transitions when power was supplied to the opposite end. The incident microwave power was kept constant during the measurements.

The liquid used in our work was water, which has a dielectric constant of about 80 and a high loss tangent (0.065 at 1 GHz 0.49 at 10 GHz). Since a combination of water and 10 GHz microwave would have a wavelength in the water of 3.7 mm and a skin depth of 2.6 mm, this would preclude the use of a test column of reasonably large diameter (1.5 cm or larger). Therefore, our tests were conducted near 1 GHz instead. The actual frequency used was 1.22 GHz, for which the wavelength in water is 2.8 cm and the skin depth is 13 cm.

When the system was first operated, it was noticed that some microwave energy leaked out of the apertures of the test section (at top and bottom). This leakage was eliminated by using plexiglass for the test section only inside the guide and then continuing it as a copper tube external to the guide (both top and bottom). This then was effectively a cylindrical waveguide below cut-off.

The combination of the detector-amplifier-bias circuit and the data acquisition system shown in Figure 1 was arranged to process the microwave output signal to produce:

(1) a distribution curve of the local thickness of the liquid film, which we have called the ''probability density function'';
(2) a frequency spectrum of the local film thickness fluctuation energy, obtained by taking the Fast Fourier Transform of the autocorrelation of the film thickness fluctuation with respect to the mean. This spectral distribution is then essentially a distribution of the film surface fluctuation (or ripple) energy.

Both static and dynamic calibrations of this measurement system were carried out. The static calibration consisted of inserting polyfoam cylinders of known diameters concentrically into the tubular test section (initially filled with water) and then measuring the corresponding changes in the detector output voltage (with reference to a dry test section). This was essentially equivalent to introducing concentric air cores of known diameters in the liquid-filled test section. The dynamic calibration consisted of establishing water film flows of various known mean thicknesses on the test section inner surface and measuring the corresponding changes in the detector output voltage.

In the presence of adjacent countercurrent gas flow, a falling liquid film (be it laminar or

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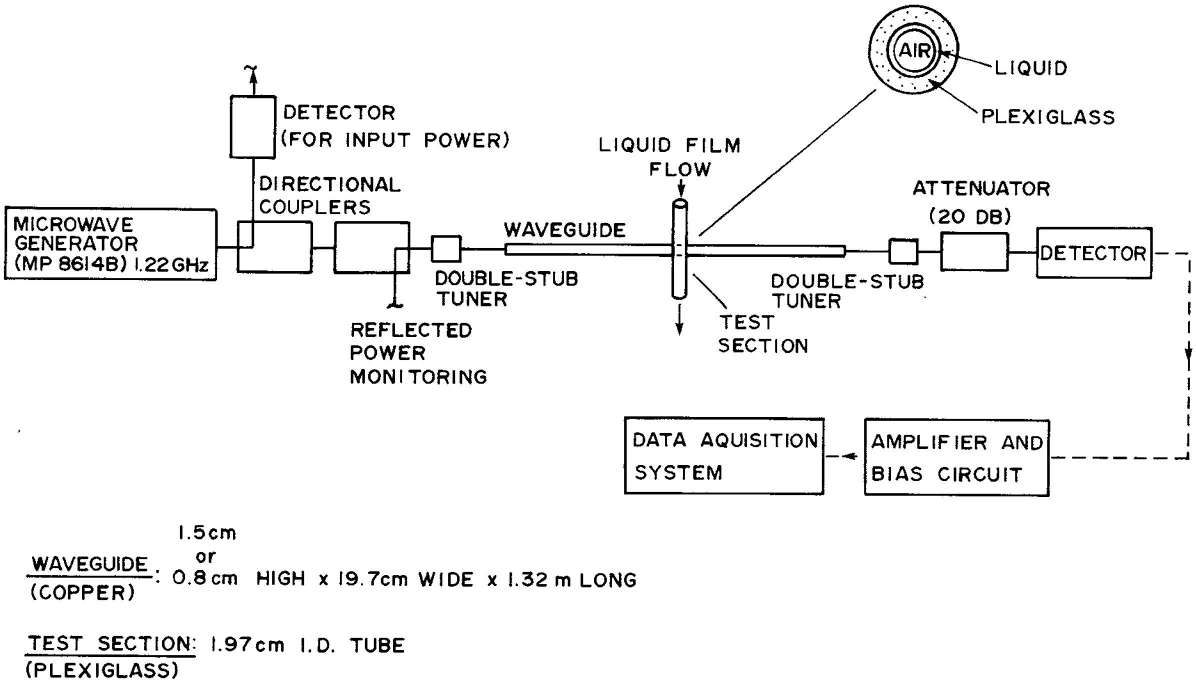

Fig. 1 Schematic diagram of microwave liquid film thickness measurement system

turbulent) generally exhibits the following characteristics:

(1) its mean downward velocity decreases somewhat and the mean film thickness increases accordingly because of the introduction of shear stress at the liquid-gas interface;
(2) the liquid film surface becomes covered with a complex pattern of waves. In the event of a reasonably large gas-liquid relative velocity, the dominant interfacial instability may be of the Kelvin-Helmholtz type (3). In such a case, the interfacial wavelengths are typically of the order of several centimeters and the wave frequencies are in the range 1 to 30 Hz.

The results of our tests follow the characteristics outlined above, as seen in Figures 2 and 3.

Figure 2 shows typical probability density functions obtained for the local water film thickness, both with and without countercurrent air flow through the tube core region. The aforementioned effect on the mean film thickness is clearly visible, as is the increase in thickness fluctuations with the introduction of air flow.

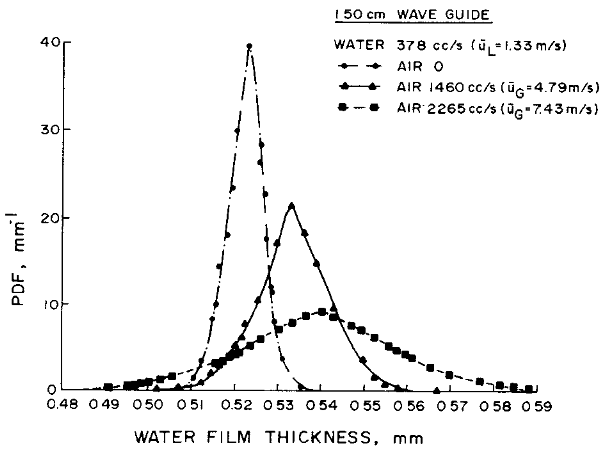

Fig. 2 Probability density function of water film thickness - with and without countercurrent air flow

Figure 3 shows a typical auto power spectral density function of the water film thickness fluctuation. Several (at least three) dominant interfacial wave frequencies can be observed (e.g., 22 Hz, 26 Hz, and 29 Hz, approximately).

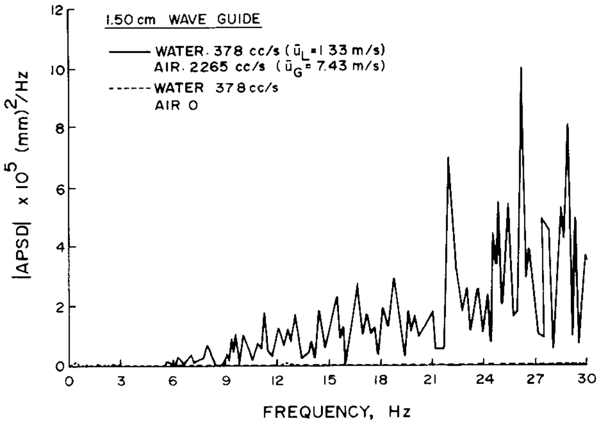

Fig. 3 Spectral distribution of water film thickness fluctuation energy - with and without countercurrent air flow

Discussion

While the work described above is related to that reported by Stuchly et al. (4), there are some important differences. The objective of Stuchly et al. was to measure gas volume fraction in a gas-liquid mixture flow. The mixture was considered to be homogeneous and the discrete gas phase to be spherical bubbles. This permitted estimation of the gas volume fraction by the use of mixture theory. The objective of our work, on the other hand, was to measure local liquid film thickness in an annular flow regime.

One other point is noteworthy. It was found during the course of these measurements that the reflected power exhibited virtually no change. This suggests that the observed changes in the output power were due to changes in absorption, rather than due to changes in the reactance loading the guide. In the case of lossless liquids, no such changes in absorbed power could, of course, be observed. This further suggests that such liquid-gas systems could also be measured by use of the technique of perturbation of a resonant system (5). We have initiated work to investigate this possibility.

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