COMPARISON OF METHODS OF MEASURING THE THICKNESS OF A LIQUID FILM

B. Ya. Karastelev, V. V. Permyakov,
A. M. Podsushnyi, V. F. Yukhimenko,
and Yu. V. Yakubovskii

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Measurements of local thicknesses and the maximum repetition frequency of waves in a liquid film running off a vertical tube have been made by needle, electrical-conductivity, and high-speed photographic methods.

The solution of many hydrodynamics and heat-transfer problems in two-phase flows requires a knowledge of the local thickness of a film moving in a tube. At the present time several methods are used to measure film thicknesses. A review and appraisal of these methods [1] shows that the electrical conductivity, capacitance, and needle methods are the most appropriate for determining the characteristics of the wave motion of a film of liquid in a tube. We compare the results obtained by the electrical-conductivity, needle, and high-speed photographic methods.

The characteristics of film motion were determined for the gravitational motion of a liquid film on the outside surface of a vertical tube 20 mm in diameter [2]. The technique of measuring the thickness of a film by the needle method using a quick-response electron pulse counter is described in [3]. It should be noted that when the needle leaves the wave it attracts liquid to itself. The time of attraction of liquid filaments and their separation from the point of the needle can be determined by high-speed photography. A filament exists for 1-2 μsec, while the point of the needle is immersed in the crest of a wave for 6–10 μsec. Since the liquid bridge exists for such a short time, its effect on the measurement can be neglected.

An examination of the photographs permits an estimate of the perturbation caused by the entrance of the needle into the liquid film. The contact of the needle with the surface of the liquid film forms waves in front of the needle. For a needle 0.2 mm in diameter these waves have a wavelength and amplitude very much smaller than those of the very small scale waves of liquid films, and therefore it can be assumed that the needle does not introduce a significant error into the results of the measurements.

The high-speed photographs do not show a clear boundary between the film and the tube over which the liquid flows. To determine the flow parameters a thin gauge plate 3 mm in diameter was placed at the tip of the needle. The distance from the end of the needle to the plate was measured under a microscope. Before taking photographs the needle was separated from the wall of the tube by this distance, as determined with a micrometer. The photographs of the liquid film were taken in the part of the tube where the transducer for measuring the film thickness by the electrical conductivity was set up.

To determine the characteristics of the wave motion of the film by the electrical conductivity method a three-channel low-frequency amplifier was built using a curcuit given earlier [4]. The output of the amplifier was fed into an N-700 loop oscillograph. To the input of the amplifier were connected coaxial transducers made of brass tubes of inside diameter 3 mm in which a brass electrode 0.8 mm in diameter was inserted. The electrode was insulated from the tube by silk thread impregnated with epoxy resin.

The transducers were calibrated in an arrangement similar to that described in [4] consisting of two plates 80 mm in diameter separated by a distance which could be varied by a micrometer. The lower plate was made of brass and the upper of a material having a high resistivity and a small dielectric constant. A transducer was inserted into the brass plate in such a way that its upper end was exactly in the

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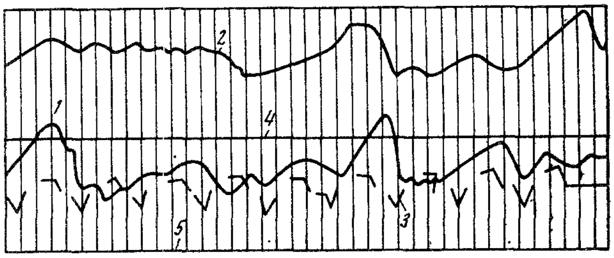

Fig. 1

plane of the plate. Water from a thermostat was admitted into the gap between the plates. The electrical conductivity of the water was monitored continually.

The transducers were calibrated for carrier frequencies from 3000 to 8000 Hz and input voltages from 0.1 to 1 V. Transducers with a carrier frequency of 5000 Hz and an input voltage of 0.8 V were the most acceptable. The accuracy of measuring the thickness of thin (0-200 μ) films increased with an increase in frequency and input voltage, but the largest film thickness which could be measured decreased appreciably. For frequencies below 3000 Hz the output signal was distorted. It was noted also that the initial current increased with an increase infrequency and input voltage since for dry plates and zero gap a current passed through the transducer due to its capacitance. In the experiments the initial current for zero gap and dry plates was 4.5 mA for an input voltage of 0.8 V and a frequency of 5000 Hz.

In the calibration special attention was paid to the choice of material for the upper plate. The most suitable material from the point of view of dielectric constant and resistivity is micarta, but in the calibration it was found that the surface layer of the micarta became saturated with liquid which led to a large error in calibration. For this reason the upperplate was made of plastic which is less hygroscopic than micarta.

As an example curves 1 and 2 of Fig. 1 show oscillograms of the measurements of the thickness of the film above transducers located 1200 and 1400 mm from the entrance of the liquid into the tube.

To synchronize the high-speed photography and the recording of the film thickness of the oscillograph one of the galvanometers of the oscillograph was connected in series with the neon lamp which serves as the time marker for the high-speed camera. The current through the lamp while it was glowing was recorded by the oscillograph (curve 3). From the time marks of the N-700 oscillograph the values of the film thickness can be determined eveyr 5 μsec. Before the beginning of the experiment with the tube dry the light spot from the galvanometer connected to the transducer coincided with the light spot from the free galvanometer. Thus the positions of the transducers were fixed on the dry tube. In processing the oscillogram the film thickness was counted from the "zero" lines 4 and 5.

The results of measuring the thickness of the liquid film by the needle, electrical conductivity, and high-speed photographic methods are presented in Fig. 2, where points 1-4 show the minimum film thickness (δ_{min}) measured by the needle, transducers 1 and 3, and high-speed photography respectively; points 5-8 give the film thickness at the rest of the wave (δ_{max}) measured respectively by the needle, transducers 1 and 3, and high-speed photograph; points 9-11 show the maximum frequency of repetition of the waves measured respectively by the needle and transducers 1 and 3. The values of the minimum film thickness obtained by these methods agree and remain constant and equal to 180-200 μ for Reynolds numbers Re-13-200. The values of the maximum thickness obtained by all three methods agree up to Re = 20. Units on the axis of ordinates are 10^{-3} m.

With an increase in the flow rate of the liquid (Re > 20) the values of the maximum thickness measured by the electrical conductivity and high-speed photographic methods agreed to Re-45, while the values obtained by the needle method increased sharply, and those by the transducer slightly. This is a result of the fact that the wave character of the film was not taken into account in the calibration. High-speed photography gave a value of δ_{max} somewhat lower than the value obtained by the needle method. This can be accounted for by the fact that it is difficult to obtain a clear photograph of the film profile for larger Reynolds numbers. The somewhat larger value of the film thickness at the crest of the wave measured by the needle method can be accounted for by the presence near the surface of the film of a layer of air saturated with water vapor through which the measuring circuit is closed.

Figure 2 compares the changes in the maximum repetition frequency of the waves for a change in Re. The data presented show that in all cases examined the frequencies obtained by these methods agree. For all flow rates studied the film surface was not smooth. The repetition frequency of the waves increased with increasing Re.

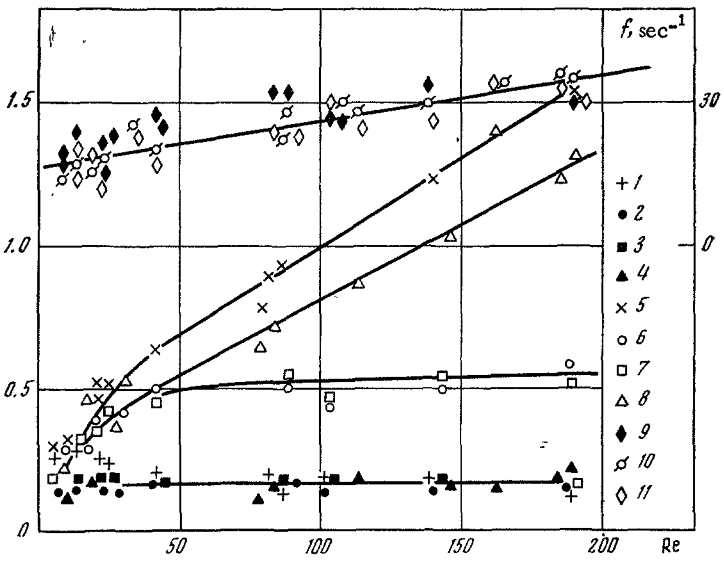

Fig. 2

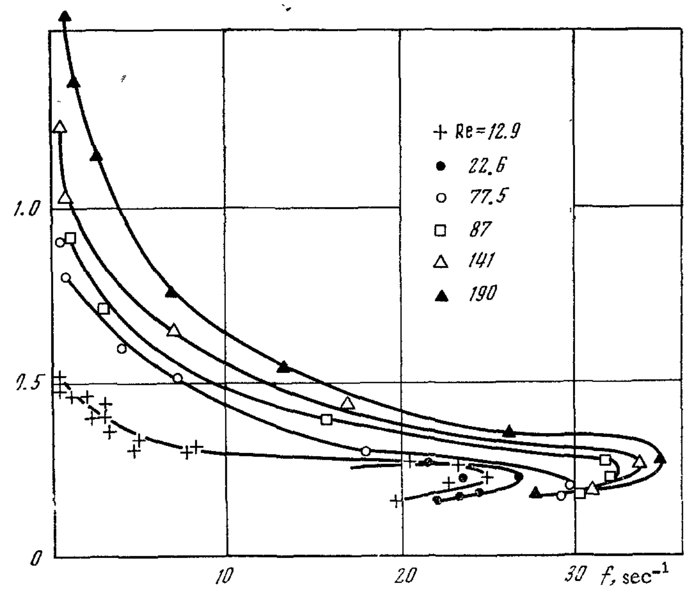

Fig. 3

The frequency of the waves as a function of the position of the end of the needle above the film for various flow rates of the liquid is shown in Fig. 3. Calculation of the frequency of the waves from the oscillogram and a comparison of points with the same frequency in the height of the oscillograms with the reference curves permits a comparison of film thickness measured by the needle and electrical conductivity methods.

The film thicknesses up to 0.5 mm can be measured with sufficient accuracy by the electrical conductivity method with transducers of the indicated dimensions. For thicker films the needle method and high-speed photography give better results.

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