Phase Velocities on Liquid Films Flowing on a Smooth Vertical Plate

S. PORTALSKI

Chemical Engineering Department
University of Surrey, Guildford, Surrey, England

A number of theories exist which predict the wave velocity on a falling liquid film. The results of these theories can be compared in terms of the ratio of the phase velocity of waves k to the average velocity in the liquid film v_{av}, giving

$$z = \frac{k}{v_{av}} \qquad (1)$$

According to Kapitsa's analysis (1948), the ratio 'z' should be 2.4 although his approximate solution gave the value of $z=3$. The author (1960), following a similar line to Kapitsa's, obtained a value for 'z' of nearly 2.5. The analysis of Brooke-Benjamin (1957) gave the value of $z=3$ and so did the theoretical work of Hanratty and Hershman (1955).

The experimental results on the phase velocity of waves on falling liquid films without air blow are few. Hewitt and Wallis (1963) reported a few observed wave velocities on water films for zero air flow conditions, but they made no attempt to correlate the results with the theoretical predictions quoted above since their measurements indicated that "several preferred wave velocities existed in the tube" at each of the six water rates for which they took high speed cine-photographs. They concluded that the wave velocities obtained by using a scanning device to pick out "synchronisms in the wave patterns" on the projected image of cine-films fell, in general, much below the theoretical predictions and that in every case several widely differing velocities could be obtained for each water rate studied.

Stainthorp and Allen (1965) used a light absorption technique to measure film thickness, velocity and frequency of the waves formed on the surface of water which contained nigrosine dye running down the inside of a vertical tube. They established mean wave velocities in the region of wave inception by measuring the mean time displacement of "corresponding waves on the photographic film" taken by an oscilloscope camera. They claim that at the higher values of Reynolds number small differences in each wave were "sufficient to establish the correspondence," but at low values "this method was not available." Therefore, readings were first taken at several positions lower down the tube where the waves were larger, and then "the correct wave velocity at initiation was established from the few possible alternatives." The correlation between the wave velocity at initiation and the film Reynolds number shows that their results also fall below the theoretical predictions quoted above except under the flow conditions where waves are first observed at a Reynolds number of about 20. They also reported that the average wave velocity depended very much upon the position at which it was measured below distributor, and they claimed that in all cases the average velocity continued to increase with distance below the distributor at constant flow rates but never reached a constant value although the measurements "appeared to be approaching some limiting value." Because they have not measured the ratio of the phase velocity to the average film velocity, it is difficult to say how much of the observed increase in wave velocity was in fact due to the film acceleration over the comparatively short section of the column over which they took the measurements. Their general conclusions were that the observed experimental values diverged considerably from those predicted by existing theories.

The author measured wave velocities on several liquid films and also on water films containing surface-active agents. Since the results have been evaluated in terms of the ratio of the phase velocity to the mean film velocity as in the theoretical analyses quoted above, a direct comparison with the theoretical predictions can be made.

APPARATUS

Since detailed description of the equipment has been given elsewhere (Portalski, 1963), this account will be confined only to some of the essential features of the apparatus shown diagrammatically in Figure 1. A long wetted wall with a

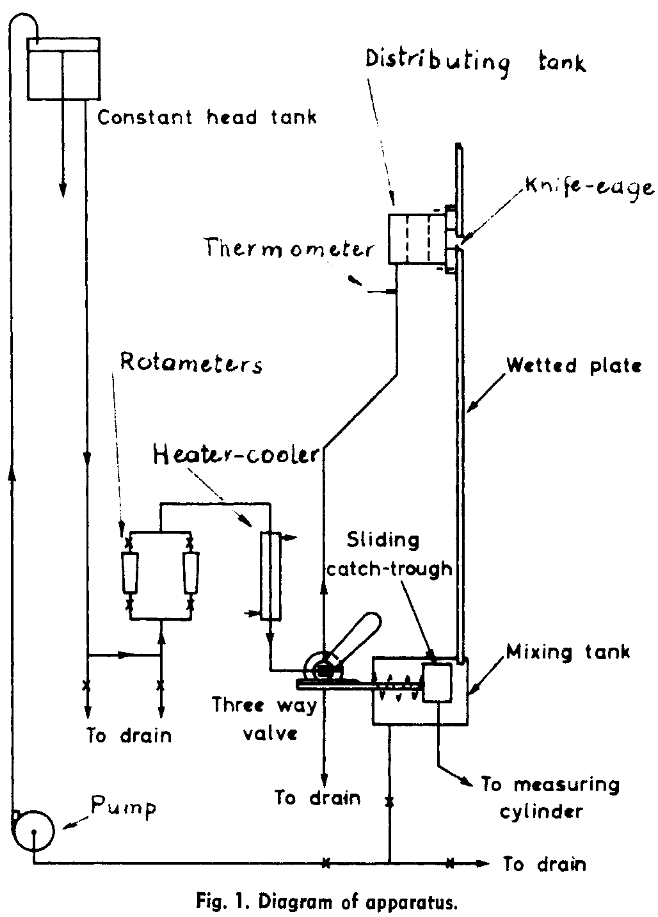

Fig. 1. Diagram of apparatus.

large area is imperative for accurate determinations of both the mean film thickness (this gives v_{av}) and the phase velocity of the waves. The wetted wall section of the column consisted of a smooth stainless steel plate bolted to a steel framework so that a working section 21 in. wide and 7 ft. high was formed. The apparatus had a constant pressure tank, a heater/cooler to minimize the variations in temperature, and a knife-edge feed to eliminate any entry disturbances.

The flexible operation of the column under any conditions of flow was made possible by designing a special semiautomatic device that could be set to initiate any flow rate. A spring-loaded sliding catch-trough coupled to a three-way valve synchronized for stoppage of the feed and simultaneous fast discharge of weir-head liquid (at the knife-edge) ensured a very satisfactory collection of hold-up from the large wetted area for measurements of the film thickness and the average stream velocity.

Liquid was pumped to an overhead constant pressure tank and then it passed through a selected rotameter, a steam heater/water cooler, the special three-way valve mentioned above, and to the liquid distribution tank where the flow was calmed by means of screen baffles before flowing over the knife-edge (ground at 45°) on to the vertical plate. After flowing down, the liquid entered a mixing tank from which it was either recirculated or discharged down the drain in the case of mains water. Two rotameters were used for the water runs, a low-range and a high-range meter, and similarly two flow meters of a universal type were employed for the glycerol solutions and alcohols used in the experimental work.

EXPERIMENTAL TECHNIQUE

A direct simple method has been used. The procedure employed here was as follows:

The wetted plate was thoroughly cleaned (Tide and hot water) before every use. After cleaning, the column was flushed with water for about 20 min., when subsequently performing experiments with water films, or it was dried first and then flushed with liquid under examination, again for about 20 min., to ensure proper wetting of the plate.

During each experimental run, the flow rate was adjusted first to the required level, and when the conditions were steady, waves were triggered by tapping very gently with a finger on the rubber face of the supporting channel section of the column. A resulting orderly wave front, generated at the knife-edge of the plate, was timed with a fast stopwatch of 3 sec./rev., subdivided into 0.01 sec. The progress of this aligned wave motion could be followed without much difficulty right down the column. The fall of the waves was timed over the entire length of the plate (213 cm) and usually 12 direct timing measurements were taken for each flow rate of the various liquids used. The average time of flow of aligned waves t_{av} was subsequently found in each case.

The ratio of the experimental phase velocity k to the mean stream velocity v_{av} was then determined thus

$$v_{av} = \frac{Q}{A} \qquad (2)$$

where A is the cross-sectional area of the liquid film per unit wetted perimeter and is numerically equal to the mean film thickness, which was found experimentally by holdup measurements for each liquid rate used.

DISCUSSION OF RESULTS

The ratio of the experimental phase velocity to mean film velocity z is plotted against the film Reynolds number for individual liquids in Figs 2 to 5.

One may draw the following observations from the obtained results:

1. In true laminar flow, before the inception of wave motion, considerable attenuation of the induced waves was observed, and it may be seen from Figure 4 (experiments with 82% glycerine solution) that the value of 'z' with induced wave motion is about 1.5, that is, the same as the theoretical ratio of surface velocity to mean stream velocity in true viscous flow.
2. After wave inception the value of 'z' rises gradually with increasing flow rate towards the theoretically predicted value of $z=3$. This may be seen very clearly in the case of the two glycerine solutions in Figure 4.
3. In the range of well established wavy pseudolaminar mode of flow the value of 'z' stays at an approximately constant level and is very nearly equal to 3.
4. The value of 'z' in the pseudolaminar region of flow appears to be slightly smaller with the more viscous liquids than with the mobile ones.
5. In fully turbulent flow the value of 'z' is tending to a constant value of about 1.5.
6. In the transitional region between the pseudolaminar flow and fully turbulent flow 'z' decreases gradually from the value of approximately 3 to the level of about 1.5 when fully turbulent flow is established.
7. In the case when ripples are artificially suppressed by the addition of an optimum amount of a surface-active agent for this purpose (Tailby and Portalski, 1961), the quantity 'z' may reach a value even higher than 3, as seen in Figure 3. This may be due to a certain extent to the elimination of the hindrance effect of the otherwise existing ripples on the progress of the aligned wave front. But Whitaker (1964) has shown that the surface elasticity obtained from the presence of a monolayer would have an effect on the stability of the film and hence on surface waves and possibly on their propagation.
8. One may detect on the presented graph of 'z' vs. Re the existence of the various Reynolds numbers of transition, characteristic for the changing mode of film flow with increasing flow rates. The mode of film flow may be divided into the following regions:

Steady laminar — pseudolaminar — transitional — pseudoturbulent — turbulent

$\uparrow Re_1 = Re_i$ $\quad\uparrow Re_2$ $\quad\uparrow Re_3$ $\quad\uparrow Re_4$

Appropriate Reynolds numbers of transition (as above) may be easily found on the relevant phase velocity vs Reynolds number graphs. Steady laminar flow terminates at the point of inception of wave motion and the critical Reynolds number for the change Re_1 is therefore the same as the Reynolds number of wave inception Re_i described

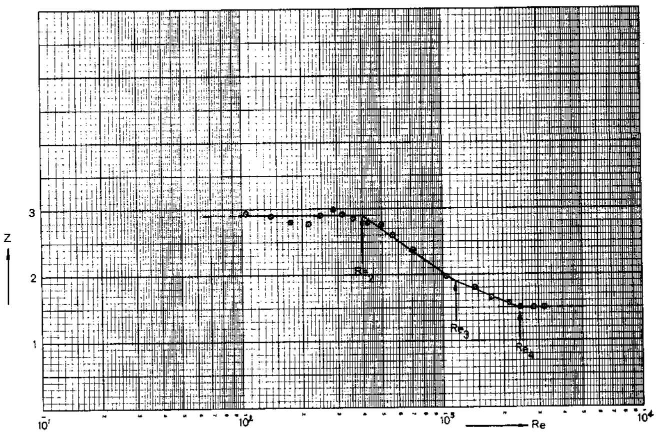

Fig. 2. Phase velocity of wave motion for water.

earlier in connection with film thickness studies by Brauer (1956) and also by the author (1963). One can see from Figure 2 that for water the transitional region finishes at $Re \simeq 1160$ ($Re_3 = Re_t$) which agrees very well with the previous study (Portalski, 1963) on the film thickness and the mode of flow on a smooth vertical plate.

CONCLUSIONS

It has been shown that it is possible with the type of apparatus used in this work to trigger off an orderly wave motion right at the knife-edge of the liquid distributor and watch its progress down over a considerable length of the wetted plate of the column.

This alignment of the wave motion at the distributor will preserve the identity of the wave front for a distance of over 200 cm and its time of travel may be measured directly with accuracy.

This eliminates the ambiguity of wave identification, which is no doubt present, when measuring the phase velocity by either (1) using a mechanical scanning device to pick out synchronisms in the wave patterns (Hewitt and Wallis, 1963) or (2) by measuring the mean time displacement of corresponding waves—over a very short distance commensurate with the wavelength—on the photographic film of an oscilloscope camera (Stainthorp and Allen, 1965). The values of the ratio of phase velocity to the mean stream velocity z obtained in this work show very little scatter for individual liquids and they agree reasonably well with those predicted by the existing theories for the wavy pseudolaminar mode of film flow, that is, up to a Reynolds number of about 400 for water films. At the higher Reynolds numbers the value of 'z' decreases until in full turbulent flow it reaches the level of approximately 1.5.

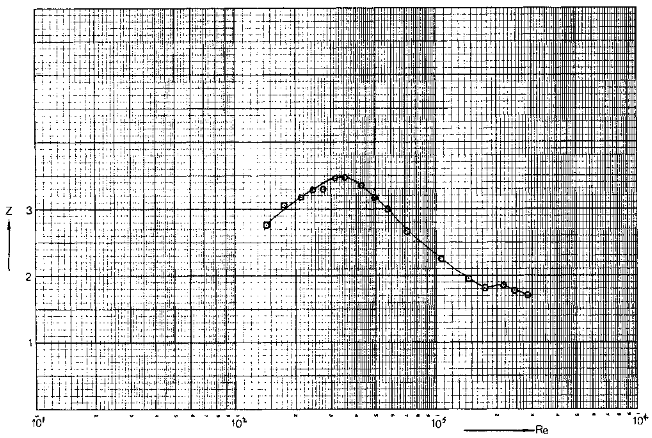

Fig. 3. Phase velocity of wave motion for water containing 0.20% Tide to suppress rippling

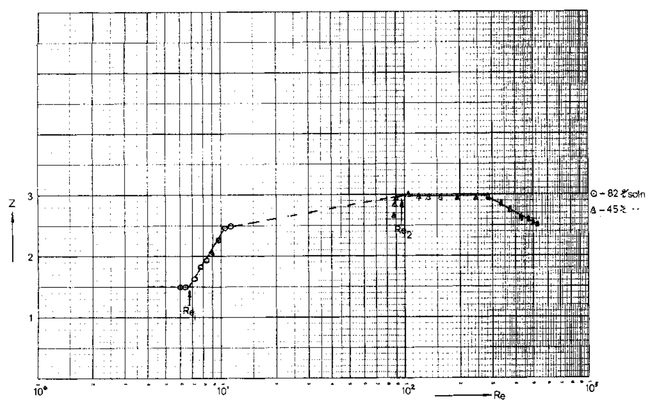

Fig. 4. Z vs. Re for two glycerine solutions.

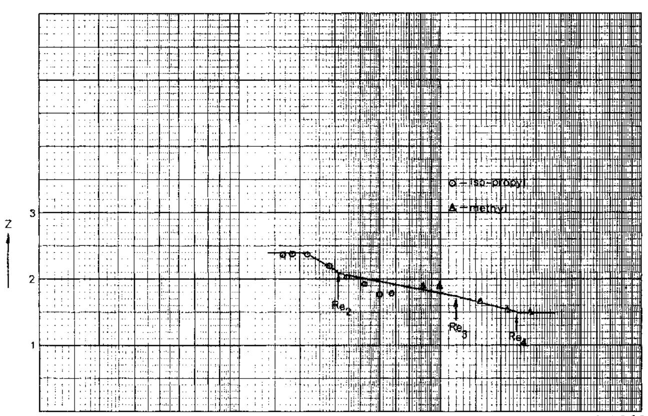

Fig. 5. Z vs. Re for methyl and iso-propyl alcohols.

NOTATION

- A = cross-sectional area of the liquid film per unit wetted perimeter, cm^2/cm
- k = phase velocity of wave motion, cm/s
- Q = liquid flow rate per unit length of wetted perimeter, cm^3/s cm
- v_{av} = mean film velocity, cm/s
- z = k/v_{av}
- ν = kinematic viscosity of liquid, Stokes
- Re = film Reynolds number = $4Q/\nu$, dimensionless

Subscripts

- 1, i = value at the inception
- 2 = value at the point of change from pseudolaminar to transitional flow
- 3 = value at the point of change from transitional to pseudoturbulent flow
- 4 = value at the point of change from pseudoturbulent to turbulent flow

LITERATURE CITED

Brauer, H., "Strömung und Wärmeübergang bei Rieselfilmen," VDI-Forschungsheft 457, VDI-Verlag, Düsseldorf (1956).

Brooke-Benjamin, T., "Wave Formation in Laminar Flow Down an Inclined Plane," *J. Fluid Mech.* **2**, 554 (1957).

Hanratty, T.J., and A. Hershman, "Initiation of Roll Waves," *AIChE J.*, **7**, 488 (1961).

Hewitt, G.F., and G.B. Wallis, "Flooding and Associated Phenomena in Falling Film Flow in a Tube," United Kingdom Atomic Energy Authority, Research Group Report, A.E.R.E.R. 4022 (1963).

Kapitsa, P.L. "Wavy Flow of Thin Films of Viscous Liquids," *Z. Eksper. Teoret. Fiz. SSSR.*, **18**, 3 (1948).

Portalski, S., "The Mechanism of Flow in Wetted Wall Columns," Ph.D. thesis, London University (1960)

———., "Studies of Falling Liquid Films," *Chem. Eng. Sci.*, **18**, 787 (1963)

Stainthorp. F.P., and J.M. Allen, "The Development of Ripples on the Surface of a Liquid Film Flowing Inside a Vertical Tube," *Trans. Inst. Chem. Engrs.* T85 (1965)

Tailby, S.R., and S. Portalski, "The Optimum Concentration of Surface Active Agents for the Suppression of Ripples," *ibid.*, **39**, 328 (1961)

Whitaker S., "Effect of Surface Active Agents on the Stability of Falling Liquid Films," *Ind. Eng. Chem. Fundamentals*, **3**, 133 (1964)

Manuscript received March 20, 1973; revision received and accepted June 11, 1973.