Int. J. Multiphase Flow, Vol. 4, pp. 405–412. Pergamon/Elsevier, 1978. Printed in Great Britain

TIME-AVERAGE LOCAL THICKNESS MEASUREMENT IN FALLING LIQUID FILM FLOW

RONALD P. SALAZAR† and EKKEHARD MARSCHALL

Mechanical and Environmental Engineering Department, University of California, Santa Barbara, CA 93106, U.S.A.

(*Received* 2 *December* 1976)

Abstract—A method for monitoring time-varying local film thickness variation through the detection of laser scattering from suspended latex particles is briefly described. This method was used in conjunction with the Jeffreys theory of drainage from a flat plate to determine time-average local film thickness.

Measurements were made at Reynolds numbers (equal to $(4Q/\nu)$) from 145 to 4030 at varying distances along the direction of flow. At the bottom of the flow, 134 cm from the top, average film thickness is given by the expression: $\bar{h} \approx a_1 Re^{n_i}$ where a_i and n_i are constants unique to each of the three Reynolds number regions, wavy laminar, transitional and turbulent.

INTRODUCTION

Decades of study of the characteristics of falling liquid film flow still leave many areas not satisfactorily explored. Theoretical approaches still depend on constraints which limit their usefulness, for example the assumption of periodic waves or the assumption of infinitesimally small wave amplitudes. These approaches were reviewed by Dukler (1972).

Experimental methods, reviewed in the extensive paper by Hewitt (1972), have been more successful but still the difficulties presented by random, three-dimensional surface waves have been formidable. The present study is part of a research program which has involved the design and application of new optical methods for the measurement of surface characteristics in liquid film flow, in particular, time varying local film thickness.

The philosophy adopted in this research program follows closely the one adopted by Telles & Dukler (1970) and Chu & Dukler (1974, 1975) who propose to investigate and describe the characteristics of the falling film flow by means of statistics. Within the framework of this philosophy, the time-average local thickness of a falling film is one of the statistical parameters describing the film flow.

In this paper the attempt has been made to demonstrate the dependence of local time-average film thickness not only on Reynolds number (equal to $(4Q/\nu)$ where Q is the volumetric flowrate per unit length across the flow and ν is the kinematic viscosity) as has been the general custom, but also on measurement location, that is, distance along the direction of the flow. Only a small number of studies have directed any attention toward the latter area, among them that of Portalski & Clegg (1972).

EXPERIMENTAL APPARATUS

The liquid used in these experiments was distilled water at 24°C. It was distributed evenly across a small reservoir from which it flowed over a machined knife edge and down a vertical Plexiglas plate, 35.67 cm wide and 155 cm in length. The sides of the plate were bordered by very smooth 1.27 cm thick Plexiglas sledges. The flowrate could be adjusted to provide Reynolds numbers from 145 to 4030.

Time varying local film thickness was measured by detecting changes in the length of a column of scattered light produced by a laser beam directed normally to the Plexiglas plate and falling film as shown in figure 1. The light scattered from suspended latex particles to a photodetection apparatus is proportional to liquid film thickness. The unique advantages of this method include the following: (a) the voltage to film thickness relationship is linear, unlike capacitance and resistance methods, (b) the film thickness is instantaneously monitored over a

†Present address: Jet Propulsion Laboratory, Pasadena, CA 91103, U.S.A.

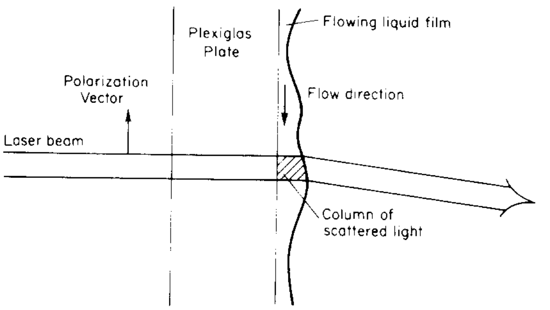

Figure 1. Laser scattering with a falling liquid film.

very small circular area determined by the diameter of the laser beam, in this case 1.6 mm. The size of the measurement area is not well defined for the two other methods mentioned above. Thus, the present method allows the detection of very short high frequency waves. This method was described in detail by Salazar & Marschall (1975) and by Salazar (1976).

Film thickness measurements were taken at four locations and eight Reynolds numbers as shown below.

	Distance from leading edge
Station 1	8.26 cm
Station 2	27.31 cm
Station 3	65.41 cm
Station 4	133.99 cm
Reynolds numbers	145, 217, 362, 600, 1000, 1955, 3050, 4030

This provided at least two measurements within the wavy region for each Reynolds number. The range of flow rates includes all the different flow regions which have been identified for water (Tailby & Portalski 1962) from wavy laminar to fully turbulent.

ABSOLUTE FILM THICKNESS

One of the difficult aspects of this method is that of determining absolute film thickness. As with some other methods, all we see in the output of the measurement system is a constantly varying voltage and there is no simple way of determining V_o, the voltage that represents zero film thickness. We see a manifestation of this problem when there is a large d.c. level shift between measurements at the same Reynolds number or between two calibration lines.†

On the calibration curve, V_o is easily determined by extending the straight calibration line down to zero liquid thickness. It was originally thought that the zero thickness intercept, V_o, would always be the same percentage of the voltage output with a dry plate, V_{oa}, before any water is added.

If this were true, we could simply record the voltage for a dry plate on the measurement apparatus, and V_o would be a known percentage of this voltage.

However, after many calibration lines were found it became apparent that although the slope remained unchanged, V_o is not always the same percentage of V_{oa}. In fact this percentage might vary by a factor of two or more between one calibration curve and another. This result is most likely due to the fact that every time a calibration is made the laser has been moved very slightly, resulting in a different intensity pattern of diffuse reflection from the Plexiglas surface.‡

†Calibration of the thickness measurement system is performed by placing a duplicate of the photodetection apparatus over a static horizontal water film of known thickness. Thickness is increased by a known amount and the voltage output from the system is recorded. A plot is then made of voltage output vs film thickness. This gives us the slope of the straight calibration line in V/mm but not its absolute level.

‡The intensity distribution is not hemispherical but is irregular due to slight irregularities in the surface.

When water is added, the angle of observation of the spot of laser light on the Plexiglas surface changes due to refraction of the scattered light with a resulting change in observed intensity. The amount of this change is different for every separate measurement.

V_o had to be determined indirectly. Some way of providing a reference voltage for each measurement of average film thickness was needed. If the reference voltage always represented the same film thickness, then any reading of average voltage at any Reynolds number and position could, by comparing it with the local reference, be converted to absolute film thickness. Once average film thickness was known for all locations and Reynolds numbers, then V_o could be determined for each recording of time varying local thickness.

The reference used here was the lowest voltage output produced by a draining film after the flowmeter has been turned down to zero. This was decided upon after observing that a non-wavy film covered the measurement point for some time after the water was turned off and before the film drained away.

The following was done at each location and Reynolds number: average voltage was recorded over 20 s on an integrating digital voltmeter, then the flowmeter was turned to zero, the voltmeter integration time to 1 s and the voltage output was observed until the film broke up and the measurement point was left dry. When this happened, the voltage rose very sharply. The lowest voltage observed over this time was recorded. This process was repeated at least three times for each measurement and the average of all three was taken.

This led us to the obvious questions: (1) how do we determine what film thickness the reference voltage represents, and (2) does the reference voltage always represent the same film thickness?

The second question has two parts: (a) is the reference film thickness different at different measurement positions, and (b) is the reference film thickness the same for different measurements at the same position? As to the latter, we note that the physical process of film drainage proceeds very nearly the same way every time it is observed, and there is good uniformity between the three draining film voltage readings. Also, as mentioned before, we take the average of several readings so this is not a source of any difficulty.

In contrast, the reference film thickness, no doubt, changes significantly between different measurement stations. We deduce this from the fact that the drainage time t_D† is a function of position. Physically what occurs is this: when the flow is stopped the film begins to drain away, the thickness decreasing at each station and the amount of drainage, hence the decrease in film thickness is a direct function of drainage time. The lower stations have longer drainage times before the film breaks up, hence smaller reference film thickness, than do the upper stations.

This brings us to question 1—what is the reference film thickness at each measurement position?

To answer this we need another reference of known film thickness to which the draining film reference can be compared. Such a reference was found by the following means: the difficulty in film thickness measurements occurs because of the presence of waves. Therefore, if the film is not wavy its thickness can be easily measured by mechanical means, using a micrometer for example. But part of every falling film is flat, in the region near the entrance before waves appear.

Micrometer measurements were taken and film thickness voltage recorded in this flat area just below the knife-edge. Once the absolute film thickness and the film thickness output voltage were found at this point, the calibration curve (V/mm) could be used to find the thickness difference between the flat flowing film and the draining film.

To put it more simply, we have at the measurement point: V_{ff}, voltage output for a flat flowing film; V_{df}, minimum voltage output for a draining film; h_{ff}, measured thickness of a flat flowing film; M, slope of the calibration curve (V/mm). h_{df}, the height of the draining film, is

†$t_D \equiv$ time required for the film to recede from the measurement point.

found in the following manner: first we use the known quantities to find V_o, the voltage representing zero film thickness

$$V_{ff} - h_{ff}(M) = V_o \quad ,$$

then the following expression to find h_{df}

$$M(h_{df}) = V_{df} - V_o \quad ,$$

$$h_{df} = \frac{(V_{df} - V_o)}{M}.$$

h_{df} was determined for the lowest possible flat film Reynolds number at measurement station 1, $Re = 600$. Under these conditions, the surface is free of waves and inlet disturbances are very small.

We now have h_{df} at station 1, but what about the lower stations, where the flow is wavy at most or all Reynolds numbers? To find h_{df} at these stations, we employ the theory of drainage of a Newtonian liquid on a flat plate. For the geometry shown in figure 2, Jeffreys (1930) found the expression for film thickness, $h = (\nu x/gt_D)^{1/2}$, where t_D = drainage time.

This formula has been shown by different authors (Denson 1970, Lang & Talmadge 1971) to be true for long drainage times. That is, the Jeffreys formula is approached when the initial film profile, $h(x, 0)$ can be neglected.

Can the initial profile be neglected here? Two factors indicate that is should be neglected and Jeffreys' formula used: (1) $h(x, 0)$ is the instantaneous profile of the film when the flow is stopped and this would obviously be too complicated a function to account for due to the wavy film surface; (2) Denson gave a value of critical time beyond which Jeffreys' formula applies. For the case he studied, that of a large sessile drop on a horizontal surface suddenly turned vertical, the critical time at a distance L from the film edge was given by

$$\tau = \frac{\nu L}{gh^2} \quad ,$$

where h is at $t = 0$, $x = L$.

Using typical values for a water film at station 1, i.e. $\nu = 1 \times 10^{-2}\,\mathrm{cm^2/s}$, $h = 0.3$ mm, $L = 8.26$ cm we find $\tau = 9.4 \times 10^{-2}$ s.

The drainage time before the film breaks up is much greater than τ for every measurement station so the Jeffreys formula is assumed to apply for the present case.

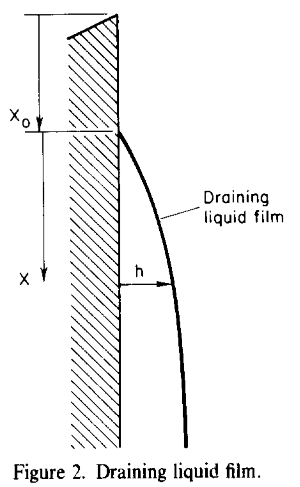

Figure 2. Draining liquid film.

To apply this to our own situation where x_o, the position of the film edge is changing as a function of time, we make the assumption that the minimum voltage output, V_{df}, always occurs at approximately the same distance, x, from the film edge. Therefore, x has the same value in the Jeffreys formula for all 4 stations and we can say that

$$h_{df} = \frac{k}{t_D^{1/2}}$$

where k is a constant to be determined.

For t_D we use the time required for x_o, shown in figure 2, to reach the measurement point after drainage begins. These have been measured for stations 1–4:

Measurement station	$\bar{t}_D$ (average of 6 readings)
1	10.7 s
2	14.2 s
3	38.2 s
4	70.6 s

The measured value of h_{df} at station 1 is used to find k, then the drainage times are inserted in the preceding equation to find the following values of h_{df}:

Measurement station	h_{df}
1	0.221 mm
2	0.192 mm
3	0.117 mm
4	0.086 mm

Now that we have a known reference film thickness at each measurement location, available by turning the flowmeter to zero, we can establish the absolute film thickness at each station and Reynolds number.

RESULTS

The results of the average film thickness measurements are shown in figure 3. They compare well with data of Portalski & Clegg (1972) who used a light absorption technique. As might be expected, the agreement is best near the top of the plate where the surface is mostly flat and decreases farther down the plate where the surface becomes rougher.

The flat region before the appearance of waves is characterized by a steady decrease in film thickness as the flow is accelerated by gravity. When waves begin to form the average thickness first increases (or the rate of decrease lessens), then apparently decreases to a steady value and changes little thereafter.

The Reynolds numbers 145–600 exhibit slightly different behavior between stations 3 and 4, actually appearing to increase in film thickness. One possible explanation for this is the following: as the film flows down the plate "streaming" motion becomes more and more apparent. When viewed normal to the flow direction, a cross section might appear as in figure 4 near the bottom of the plate. It is possible that the film thickness is consistently higher at some positions across the plate than at others and that the measurement location coincided with one of these areas.

Also of interest is the curve for a Reynolds number of 1000, which is in the transitional region between laminar and turbulent flow (see Tailby & Portalski 1962). The film thickness behaves very much like that for laminar flow at stations 1 and 2 but between 2 and 3 it changes

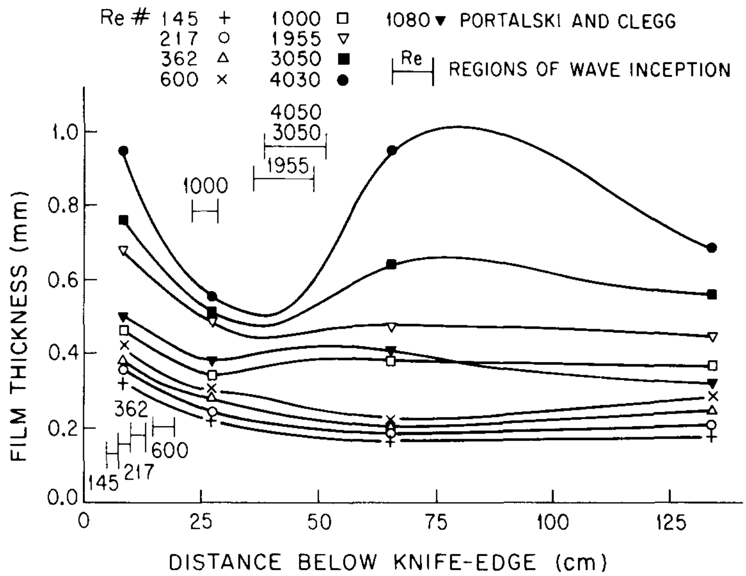

Figure 3. Time-average film thickness vs measurement position.

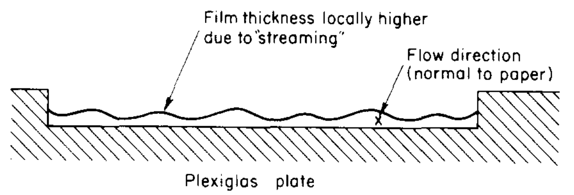

Figure 4. Variation of film thickness in crosswise direction.

very drastically, moving closer to the curves for turbulent flow. Apparently, the flow begins "pseudo-laminar" then later becomes turbulent, the transition taking place in the region of onset of surface waves.

Figure 5 shows the variation of thickness with Reynolds number at each measurement location. Here we can see indications of the changes in film behavior as we pass from one Reynolds number region to another. The regions shown on the graph are those proposed by Tailby & Portalski (1962).

At station 4 where the thickness has reached a fairly steady value for most Reynolds numbers and the wave motion is fully developed, the film thickness can be expressed as a simple function of Reynolds number for each of the wavy laminar, transitional and turbulent regions. One finds in the region below $Re = 600$: $\bar{h} \approx a_1 Re^{n_1}$; between 600 and 1955: $\bar{h} \approx a_2 Re^{n_2}$; and in the fully turbulent region above 1955: $\bar{h} \approx a_3 Re^{n_3}$, with the following values for a_i and n_i:

$$a_1 = 0.0362\ \text{mm}, \qquad n_1 = 0.3252$$

$$a_2 = 0.0247\ \text{mm}, \qquad n_2 = 0.3741$$

$$a_3 = 0.006792\ \text{mm}, \qquad n_3 = 0.5536.$$

Thus, only two measurements of local average film thickness in each of the three identified Reynolds number regions are necessary to predict local average film thickness for other Reynolds numbers.

Referring again to figure 3 we note that for the highest Reynolds number the film thickness may not have reached a steady value even at station 4 (134 cm for the entrance). Because of this it is possible that n_3 should be somewhat lower and the true curve might be closer to that in region 2 or even region 1.

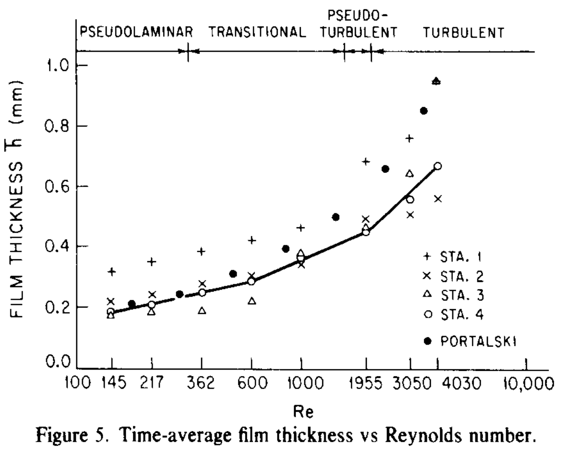

Figure 5. Time-average film thickness vs Reynolds number.

Also shown in figure 5 is average film thickness data obtained by Portalski (1963). These measurements represent average film thickness over a whole plate (53.34 cm wide and 213.36 cm long), found by stopping the flow and measuring the amount of liquid which drains away. The most that could be expected here is general agreement between data obtained by such different methods and, in fact, that is what we see. The agreement appears best in the Reynolds number region below 1500.†

CONCLUSIONS

We have presented the results of local average film thickness measurements obtained by the laser-scattering method. They illustrate very clearly the importance of measurement location on liquid film properties. This dependence is quite dramatic over the 134 cm distance from the entrance for the measurements made here. It appears that for this range of Reynolds numbers (145–4030) the measurement location dependence may lessen somewhat beyond 134 cm from the entrance.

For the measurements at station 4 (134 cm from the entrance) three distinct Reynolds number regions were found which agreed approximately with those found by Tailby & Portalski (1962). Within each of these regions the average film thickness was given by a function of the following form: $\bar{h} \approx a_i Re^{n_i}$ (a_i and n_i constants unique to each region).

Acknowledgement—This work was supported by National Science Foundation Grant GK-35797.

REFERENCES

Chu, K. J. & Dukler, A. E. 1974 Statistical characteristics of thin, wavy films, part II—studies of the substrate and its wave structure. *A.I.Ch.E. Jl* **20**, 695–706.

Chu, K. J. & Dukler, A. E. 1975 Statistical characteristics of thin, wavy films, part III—structure of the large waves and their resistance to gas flow. *A.I.Ch.E. Jl* **21**, 583–593.

Denson, C. D. 1970 The drainage of Newtonian liquids entrained on a vertical surface. *I/EC Fundamentals* **9**, 443–448.

Dukler, A. E. 1972 Characterization effects and modeling of the wavy gas–liquid interface. *Progress in Heat and Mass Transfer*, Vol. 6. Pergamon Press, New York.

Hewitt, G. F. 1972 The role of experiments in two-phase systems with particular reference to measurent techniques. *Progress in Heat and Mass Transfer*, Vol. 6. Pergamon Press, New York.

Jeffreys, H. 1930 The draining of a vertical plate. *Proc. Camb. Phil. Soc.* **26**, 204–205.

†If the curves of figure 3 were to be graphically integrated to estimate average film thickness over the whole plate the agreement would no doubt be much better.

LANG, K. C. & TALMADGE, J. A. 1971 A postwithdrawal expression for drainage on flat plates. *I/EC Fundamentals* **10**, 648–650.

PORTALSKI, S. 1963 Studies of falling liquid film flow: film thickness on a smooth vertical plate. *Chem. Engr Sci.* **18**, 787–804.

PORTALSKI, S. & CLEGG, A. J. 1972 An experimental study of wave inception on falling liquid films. *Chem. Engr Sci.* **27**, 1257–1265.

SALAZAR, R. P. & MARSCHALL, E. 1975 Thickness measurement in liquid film flow by laser scattering. *Rev. Scient. Instrum.* **46**, 1539–1541.

SALAZAR, R. P. 1976 Statistical characteristics of a falling liquid film. Ph.D. dissertation, University of Calif., Santa Barbara.

TAILBY, S. R. & PORTALSKI, S. 1962 Wave inception on a liquid film flowing down a hydrodynamically smooth plate. *Chem. Engr Sci.* **17**, 283–290.

TELLES, A. S. & DUKLER, A. E. 1970 Statistical characteristics of thin, vertical, wavy, liquid films. *I/EC Fundamentals* **9**, 412–421.