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LONGITUDINAL CHARACTERISTICS OF WAVY FALLING FILMS

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Abstract—New data are presented on film thickness characteristics, over the Reynolds number range 370–11,020, and relatively long distances from liquid entry; i.e. 1.7–2.46 m. The mean film thickness δ_{mean} does not show a definite trend remaining roughly constant, while δ_{min} has a tendency to slightly increase. Other quantities such as the standard deviation s, δ_{max} and dominant wave velocity V_{wave} display a weak tendency to increase with longitudinal distance. This small variation of the aforementioned quantities suggests that the flow may not be fully developed, over the distances examined.

Key Words: liquid films, film thickness, waves, flow development, experimental data

INTRODUCTION

A falling film interface is usually covered with random waves of irregular shape, small and large, which interact in a complicated manner. Such a compliant surface tends to significantly influence heat and mass transfer rates to and from the liquid film. For low viscosity liquids, there is sufficient evidence in the literature that wave characteristics greatly depend on liquid flow rate (e.g. Telles & Dukler 1970; Chu & Dukler 1974, 1975; Wasden & Dukler 1989; Karapantsios *et al.* 1989; Karapantsios & Karabelas 1990), and on longitudinal distance from the film origin (e.g. Portalski & Clegg 1972; Takahama & Kato 1980). The latter dependence limits the applicability of all existing theoretical analyses which are based on two-dimensional permanent periodic waves of almost sinusoidal form. Such a regular wave regime is observed only at Re $\sim$ 5–20, *near* the wave inception line. At higher Re, the film waves are unsteady and irregular. Additionally, they seem to undergo a series of changes with distance up to a location where the flow reaches a fully developed (equilibrium) state. Upon inspection of available experimental evidence, one readily observes that there is an uncertainty regarding the required distance covered by the film to arrive at this asymptotic equilibrium state. Webb & Hewitt (1975), report a stabilization distance of about 6–10 m, while Takahama & Kato (1980) and Salazar & Marschall (1978) argue that their last downstream measuring station (1.7 and 1.3 m, respectively) may not be far from the point where waves attain fully developed conditions. Furthermore, the literature is poor on data concerning the longitudinal characteristics of wavy films at locations relatively *far* from the wave inception line, and this paucity of information does not permit reliable correlation of wave parameters with heat and mass transfer properties. To the best of the authors knowledge, only Zabaras (1985) has addressed the process of developing wavy falling films at locations far from the liquid feed, although not conclusively.

The purpose of this paper is to examine the dependence of local film characteristics on liquid Reynolds number ($\mathrm{Re} = 4\Gamma/\mu$) and on vertical pipe location, using new measurements of film thickness fluctuations. Re is varied in the range 370–11,020 and measuring stations are located between 1.7 and 2.46 m from liquid entry. Investigation of the developing nature of the flow at that particular length range is motivated by a parallel research program (Karapantsios 1994), concerning direct contact condensation of stream/air mixtures over wavy free falling films. The isothermal measurements presented here are considered essential information for fully interpreting the condensation experiments.

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EXPERIMENTAL APPARATUS

The basic features of the experimental setup are similar to those reported by Karapantsios *et al.* (1989). A vertical, transparent, Plexiglas pipe of 0.05 m I.D. and of 2.66 m total length is used, divided in three sections, i.e. inlet (0.3 m), intermediate (0.9 m) and measurement section (1.40 m). The latter is equipped with six pairs of (diametrically opposite) plugs mounted flush with the inner surface of the pipe. These pairs are aligned at the same azimuthal location at downstream distances of 1.72, 1.82, 1.89, 1.99, 2.19 and 2.46 m. The two plugs in each pair, located 180° apart in the circumferential direction, are used to ensure a symmetrical annular film flow and offer an additional means to check the alignment of the tube.

Filtered, deaerated tap water (stored in a large tank) is used in the tests flowing only once through the system. The water in the tank is kept at room temperature. A continuous uniform feed is obtained—the liquid freely flowing over a tapered feeding entry. Flow rates from 14 to 416 g/s are employed.

The parallel-wire electrical conductance probe is used for measuring instantaneous local film thickness. The technique is quite sensitive and accurate for this type of measurement; e.g. Karapantsios *et al.* (1989). Probes are fabricated for all six measuring stations along the test tube. Each probe consists of a pair of chromel parallel wires glued in a plug. The wires have a diameter of ~0.5 mm, a length of ~2 cm and are spaced 2 mm apart. The use of thinner wires (<0.1 mm) mounted with a shorter spacing (<1 mm), as Koskie *et al.* (1989) suggest for improving spatial resolution, is avoided due to the required excessive signal amplification and the ensuing electronic noise interference (Karapantsios *et al.* 1989). The measurement is based on the inverse proportionality between electrical resistance and liquid layer thickness covering the wires. Individual probe calibration is carried out outside the measurement tube. The plug with the parallel wires is fixed on a precision micrometer. By precisely measuring (within ±0.01 mm) the changes in the depth of immersion of the wires in water and the corresponding changes of output voltage, a unique relationship is obtained. Calibration procedures and electrical signal conversion to film thickness are described in detail elsewhere (Karapantsios 1994). Probe calibration outside the one-piece test tube permits the use of such a long measurement section (1.4 m), avoiding the usual alignment problems and possible imperfections due to flanged sections which may introduce errors in the development of an axisymmetric flow. The conductivity of the test water is frequently measured during the experiments to insure proper signal reduction.

To permit simultaneous film thickness measurements at different locations, each conductance probe is connected to a separate electronic analyzer. Testing and calibration of the analyzers' circuits is done before and after each set of experiments.

Data are collected over a 10 s period with a 400 Hz sampling frequency. Exploratory runs with sampling frequencies 1, 5 and 10 kHz, at various liquid flow rates, did not alter the picture of the measured voltage traces. This indicates that for the particular probe geometry, a 400 Hz sampling frequency provides an adequate temporal resolution, much higher than typical maximum dominant frequencies of film records (Karapantsios *et al.* 1989). Three records (scans) are acquired at each flow rate, and at all locations, to check for repeatability and further increase the confidence of the calculated statistics. The estimated overall error in film thickness measurements—including calibration, measurement, digitization and data handling—is always less than 7%. The uncertainty in calculating the average wave velocity by the cross correlation of two simultaneous film thickness records sampled at different stations, depends on the particular probes' spacing at this given sampling resolution (400 Hz). Worst-case estimates of the calculated wave velocities are within 18% of the reported value.

RESULTS

Variation of the time-averaged film thickness, δ_{mean}, against Reynolds number is plotted in figure 1. All δ_{mean} values collected at different locations are shown as cross symbols (+) without specific designation. The data by Karapantsios *et al.* (1989), taken with a tube of the

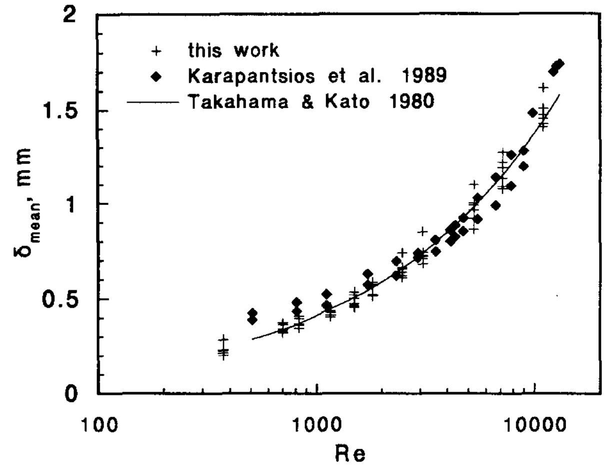

Figure 1. Variation of the mean film thickness, σ_{mean}, with Reynolds number.

same diameter (at $x = 2.5$ m) and the empirical formula proposed by Takahama & Kato (1980)

$$\delta_{\text{mean}} = 0.473\left(\frac{\nu^2}{g}\right)^{1/3}\left(\frac{\Gamma}{\mu}\right)^{0.526} \qquad [1]$$

are also plotted. Here Γ is the mass flow rate per unit width and ν,μ the kinematic and dynamic viscosity, respectively. The best fit for our data, taken at all measuring stations, is obtained by ordinary least squares and is given as:

$$\langle\delta_{\text{mean}}\rangle = 0.451\left(\frac{\nu^2}{g}\right)^{1/3}\left(\frac{\Gamma}{\mu}\right)^{0.538} \qquad [2]$$

$\langle\,\rangle$ denotes averaging over all measuring stations. Interestingly, [2] agrees very well with the correlation of Takahama & Kato (1980), although these authors obtained data for a different distance from the origin (1.7 m). The largest deviations are observed at the highest Reynolds numbers, which is not very surprising considering that experiments by those workers were limited to Re < ~8000.

Figure 2 shows the longitudinal change of δ_{mean} with Reynolds number as a parameter. The data exhibit a peculiar variation with distance, similar for neighbouring Reynolds numbers. For Re < ~3000 the variation is moderate while for Re > 5000 it is more pronounced. Experimental error (<7%) does not seem to be responsible for such differences and the statistically estimated

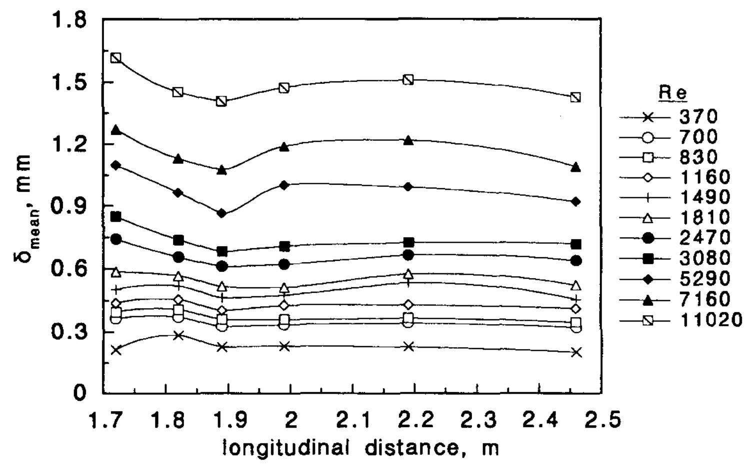

Figure 2. Longitudinal variation of the mean film thickness, δ_{mean}.

error (standard error from repeated runs at a significant level of 95%) is always less than 5% of the reported value. If the flow is still developing at that distance (> 1.7 m) a tendency for lower δ_{mean} values along the test section is expected, e.g. Kapitsa (1964). This is due to evolving large waves, which move on the thin substrate layer. Wave coalescence occurs creating larger lumps of liquid; consequently, wave frequency decreases and wave length, amplitude and streamwise velocity increase. Thus, application of mass conservation arguments along the liquid film points to decreasing mean thickness values with distance. However, from an inspection of figure 2, such a variation of δ_{mean} with longitudinal distance cannot be clearly discerned.

Portalski & Clegg (1972) and Salazar & Marschall (1978) reported a similar peculiar behavior for shorter distances from liquid entry and for Reynolds numbers less than 4000. Takahama & Kato (1980) found also an axial variation in their experimental values and attributed it to flow instability which caused drastic longitudinal changes in the flow characteristics. It is recalled that their measuring stations extend down to 1.7 m. Zabaras (1985) measured film thickness at three locations (1.7, 1.94 and 4 m) from the liquid feed. Curiously, his time-averaged film thickness data are considerably lower than the data of this work and of other similar studies; i.e. that of Takahama & Kato (1980). For the stations at 1.7 and 1.94 m and for $310 < Re < 3100$ Zabaras noticed a small overall decrease in δ_{mean} with distance, varying in the limits ~3% to ~17%. Surprisingly, by comparing data from the two stations, at 4 and 1.94 m from origin, he noticed that for $Re = 768$, δ_{mean} *decreased* by ~6% while for $Re = 1830$ and 2600 it *increased* by ~10%. Such a peculiar behavior, if not just a subtle feature of the developing flow, might be partly attributed to the different working fluids used in different runs of that study.

The standard deviation of the recorded time series is plotted against distance in figure 3. Total statistical error is up to 11%. It is seen that for $Re = 370$, s is practically constant while for $Re < 3000$ there is an overall tendency for increasing s with longitudinal distance. For $Re > 5000$ the situation is not as clear. Takahama, & Kato's data (1980) for thickness variance, and for distances up to 1.7 m, display an increasing trend up to $Re \sim 8000$. Zabaras (1985) also shows, that for $Re < \sim 3000$, s increases with distance. Arguments similar to those advanced in connection with figure 2, hold for the length effects on the "coefficient of variation" s/δ_{mean}—a very common indicator or wave growth. The respective graph is omitted due to space limitations. In particular, s/δ_{mean} exhibits a broad peak region in the range $\sim 1500 < Re < \sim 7000$ for almost all stations. Values between ~0.3 and 0.7 are observed, in general agreement with data presented by Takahama & Kato (1980), and Karapantsios *et al.* (1989).

Figures 4 and 5 show the longitudinal variation of the maximum and the minimum film thickness, δ_{max} and δ_{min}, respectively. It is found that in general δ_{max} increases while δ_{min} decreases gradually with distance. Only for $Re = 370$, δ_{max} is fairly constant. Data by Portalski & Clegg (1972) for shorter distances (< 1.7 m) show that both δ_{max} and δ_{min} remain almost constant, for a fixed flow rate. The same observation is also made by Takahama & Kato (1980) for δ_{min} only. Contrary

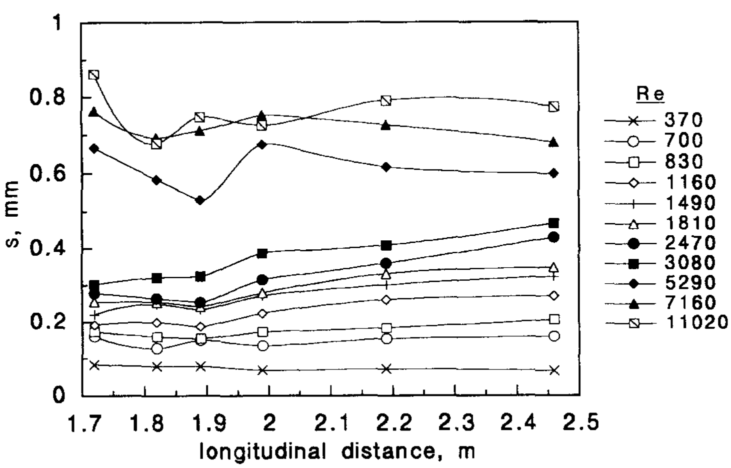

Figure 3. Longitudinal variation of the standard deviation, s.

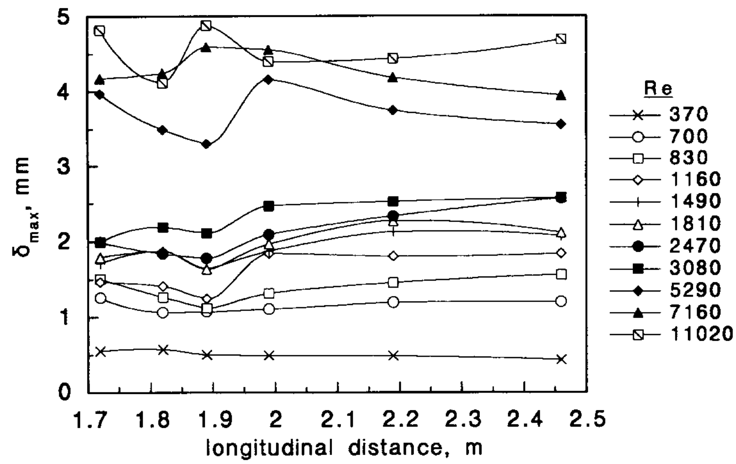

Figure 4. Longitudinal variation of the maximum film thickness, δ_{max}.

to those results, both δ_{max} and δ_{min} of this work exhibit small changes even at the most distant station employed here.

Recently, a novel approach to describe surface waves, quite different than conventional methods, was presented by Karapantsios & Karabelas (1990). Two new quantities were proposed, the first and the second time derivative of the film thickness records, given as:

$$\frac{d\delta}{dt} \cong \frac{\Delta\delta}{\Delta t} = \frac{1}{\Delta t}\left[\delta\left(t + \frac{\Delta t}{2}\right) - \delta\left(t - \frac{\Delta t}{2}\right)\right] \quad [3]$$

and

$$\frac{d^2\delta}{dt^2} \cong \frac{1}{\Delta t}\left[\left(\frac{\Delta\delta}{\Delta t}\right)_{(t+(\Delta t/2))} - \left(\frac{\Delta\delta}{\Delta t}\right)_{(t-(\Delta t/2))}\right] = \frac{1}{\Delta t^2}[\delta(t+\Delta t) - 2\delta + \delta(t - \Delta t)], \quad [4]$$

respectively. "Spatial evolution portraits" were obtained at various Reynolds numbers by plotting the rate of surface displacement, $d\delta/dt$, versus local film thickness, δ; Eulerian surface accelerations, $d^2\delta/dt^2$, were also calculated. It was suggested that both the first and the second time derivative of the film thickness contain useful information concerning the mechanisms by which waves grow and vanish (Karapantsios & Karabelas 1990). Therefore, the longitudinal distribution of these quantities may prove to be a significant piece of evidence.

From each original film thickness time record of this work, new time records are created by computing the above derivatives. Their values are almost evenly distributed above and below zero,

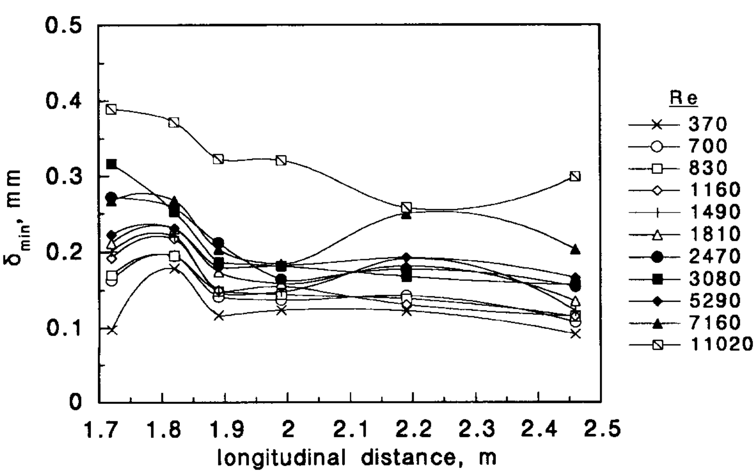

Figure 5. Longitudinal variation of the minimum film thickness, δ_{min}.

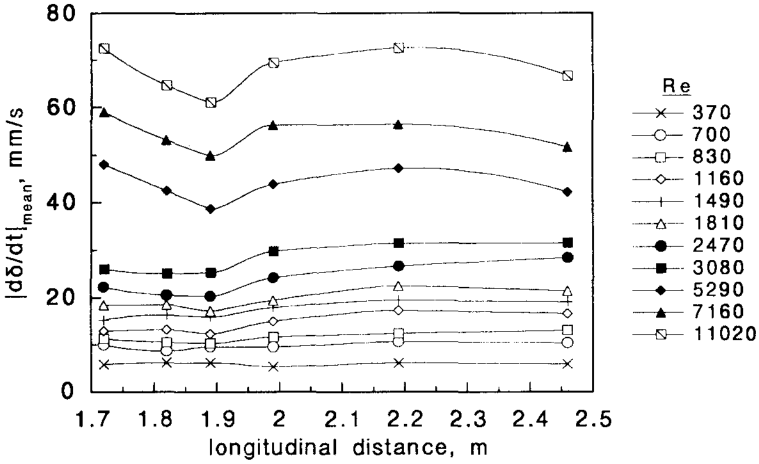

Figure 6. Longitudinal variation of the rate of surface displacement, $|d\delta/dt|_{mean}$.

in accord with calculations by Karapantsios and Karabelas (1990). By taking the absolute values of these time series and then averaging, new quantities result; i.e. $|d\delta/dt|_{mean}$ and $|d^2\delta/dt^2|_{mean}$. The latter represent the mean *absolute* rate of surface displacement and surface acceleration despite the fact that, overall, there is no net movement of the surface normal to the flow direction. These newly defined quantities may be viewed as alternative indicators of large wave amplitude since they essentially describe the development and growth of large roll waves (Karapantsios & Karabelas 1990).

Figures 6 and 7 show the variation of the above quantities with streamwise distance. There is a remarkable similarity between the trends observed in these figures and those outlined for the axial variation of s, discussed earlier in connection with figure 3. Both $|d\delta/dt|_{mean}$ and $|d^2\delta/dt^2|_{mean}$, appear to increase with distance and with Reynolds number. The situation again is not so clear at high Reynolds numbers. Quite substantial mean absolute rates of displacement (up to $\sim$70 mm/s) and mean absolute surface accelerations (up to 25 m/s^2) are estimated. Results reported by Karapantsios & Karabelas (1990), agree well with data of this work. From these results, it becomes rather obvious that a highly disturbed interface covers the falling liquid layer and future studies must account for this effect. Of course more experimental evidence is needed regarding the spatial and temporal resolution of measurements before conclusive statements can be made. Limiting rates of surface displacement, $(d\delta/dt)_{max}$ and $(d\delta/dt)_{min}$, (not presented here) are also calculated for various Reynolds numbers and at different measuring stations. As with δ_{max} and δ_{min}, there is a tendency for $(d\delta/dt)_{max}$ to increase and for $(d\delta/dt)_{min}$ to decrease with distance. Regardless of location, both

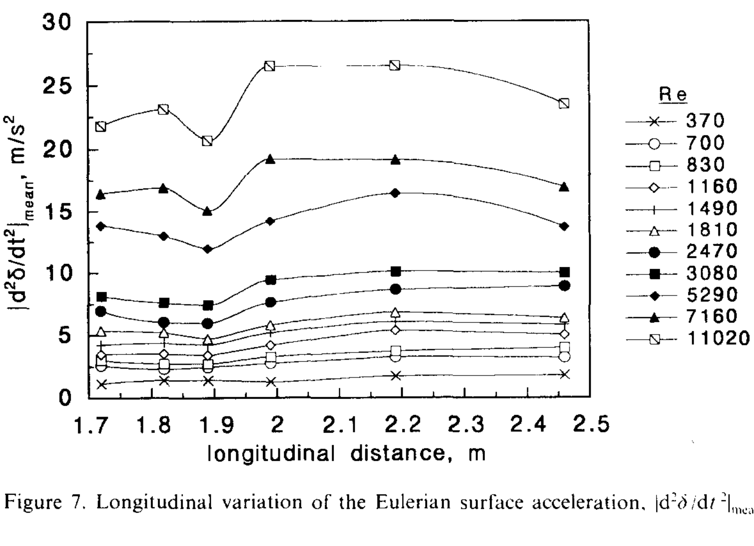

Figure 7. Longitudinal variation of the Eulerian surface acceleration, $|d^2\delta/dt^2|_{mean}$.

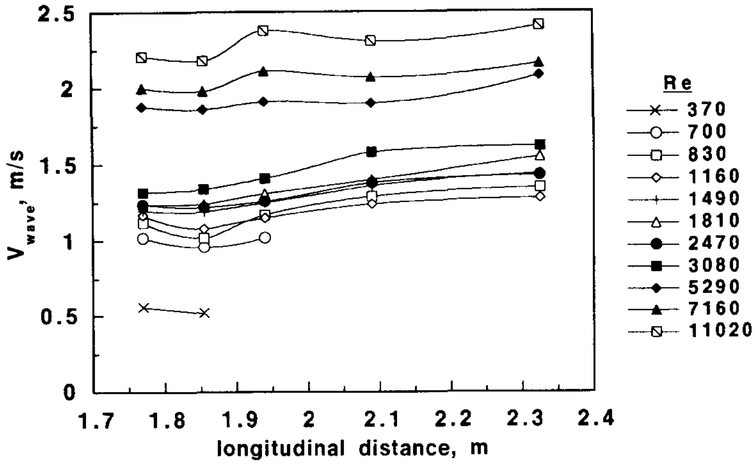

Figure 8. Longitudinal variation of the average wave velocity, V_{wave}.

these limiting rates vary monotonically with Reynolds number. Moreover, they appear to agree quite well with the values communicated by Karapantsios & Karabelas (1990), lying between ~50 and ~800 mm/s for the maximum rates and approximately −20 and −550 mm/s for the minimum rates.

By simultaneously measuring the film thickness at all stations along the flow and crosscorrelating the time records, the average streamwise wave velocity, V_{wave}, is estimated. Computation is based on the time delay between the upstream and the downstream signals assuming they are stationary and ergodic. The results are plotted in figure 8 as V_{wave} against longitudinal distance. It is clearly seen that V_{wave} tends to increase with axial distance, a situation more evident at low Reynolds numbers. Wave velocities measured by Zabaras (1985) at 1.7, 1.94 and 2.30 m from liquid entry agree reasonably well with the new data. For Re = 374 only two data points are included in the graph because the reliability of determining such low velocities with a relatively large probe spacing (7 cm) is reduced. Indeed, the correlation coefficient computed in this case by the crosscorrelation function is very low (20–30%).

An attempt was made in several previous investigations, e.g. Zabaras (1985), to relate the amplitude of individual large waves to their streamwise average velocity. Such a relationship would be extremely useful for the development of generalized analytical expressions for describing roll waves. Poor correlation was obtained between these two quantities (Zabaras 1985) although on physical grounds it was expected to hold. It is noted here that reservation may be expressed about Zabaras' definition of the amplitude of large waves which seems to be somewhat arbitrary. In figure 9, the standard deviation of film thickness, s, a reasonable indicator of large wave average

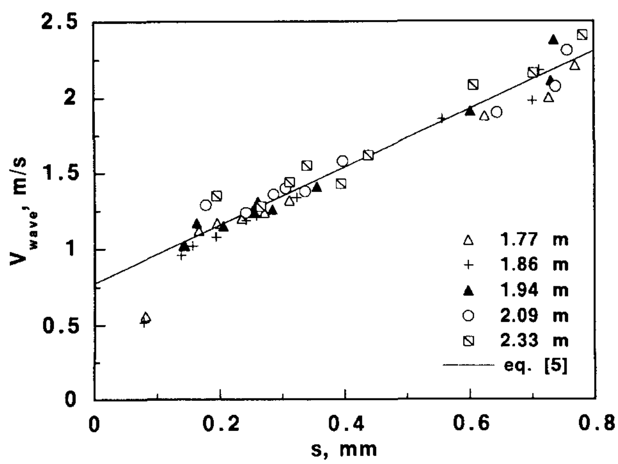

Figure 9. Variation of average wave velocity, V_{wave}, with standard deviation, s of film thickness fluctuations.

amplitude, is plotted against average wave velocity. A striking linear variation of s with V_{wave} is observed. The data seem to have no significant dependence on downstream location. Least squares fitting is employed only in the region 1 m/s $< V_{wave} <$ 2.5 m/s, since no adequate data points are available for $V_{wave} <$ 1 m/s. The best line fit is also included in the graph, given by

$$\langle V_{wave} \rangle = 0.774 + 1.916 \langle s \rangle \qquad [5]$$

$$(R = 0.99)$$

where s is in mm and V_{wave} is in m/s. A possible correlation between V_{wave} and δ_{mean} and δ_{min}, was also explored in this work with unsatisfactory results.

The spectral density functions for the range of Reynolds number encountered in this study, were calculated for the data taken at all six stations according to the procedure discussed by Karapantsios *et al.* (1989). They all display a peak, either broad or sharp, at a frequency between 5 and 10 Hz which agree with data by Karapantsios *et al.* (1989) and Takahama & Kato (1980). No appreciable dependence on downstream location is noticed, in line with the data presented by Takahama & Kato (1980) for their most distant downstream location (> 1.3 m).

CONCLUDING REMARKS

The new experimental data suggest that the wavy surface of *turbulent* free falling film undergoes relatively small changes with distance even at downstream locations far from the origin (> 1.7 m). For laminar films it is known that there is an equilibrium state whereby the mean film thickness attains a constant value corresponding to an equilibrium wave velocity (Kapitsa 1964). However, δ_{mean} may not be a sufficiently stringent criterion for characterizing the equilibrium state of turbulent films. Indeed, in this work δ_{mean} is approximately constant but δ_{min} has the tendency to slightly decrease; s, δ_{max}, $|d\delta/dt|_{mean}$, $|d^2\delta/dt^2|_{mean}$ and V_{wave} display a weak tendency to increase with longitudinal distance. This variation of the aforementioned statistical quantities (for the distances examined here) indicates that the wavy flow may not be fully developed, although the respective changes are not as large as reported for smaller downstream distances (< 1.7 m) by other researchers, e.g. Portalski & Clegg (1972) and Takahama & Kato (1980). Our observations are in line with the experimental evidence presented by Zabaras (1985) for large distances in the flow direction (up to 4 m).

Some peculiar nonuniformities are observed at distances x smaller than 2 m for most of the quantities calculated here, for which no satisfactory explanation can be offered at present. However, the possibility cannot be excluded that these nonuniformities, as well as similar variations observed in the data of Takahama & Kato (1980) for $x <$ 1.7 m, may be due to very minor geometrical imperfections. The latter may have a greater effect at high Reynolds numbers.

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