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Statistical characteristics of a water film falling down a flat plate at different inclinations and temperatures

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Abstract

In this work, the statistical characteristics of the surface of a water film, freely falling down a vertical or inclined flat plate, have been investigated. The study was carried out in the frame of a research on passive cooling of heated surfaces by the evaporation of thin water films. The experiments, performed to confirm and extend previous results by the same authors, involved relatively cold water (ambient temperature or slightly warmer 20–30 °C) and warm water (50 and 70 °C). The range of Reynolds numbers includes the classical threshold for the transition between the laminar-wavy and the turbulent regimes. Two different plate inclinations with respect to the vertical position have been addressed (0° and 45°). Capacitance probes were adopted to collect discrete film thickness time series, which have been processed to extract relevant statistical data. A specific probe configuration including an electrical heating system has been developed in order to overcome the problem of vapour condensation onto the active surfaces of the electrodes in the presence of warm water. Data on mean, minimum and maximum film thickness as well as standard deviation and wave velocity are presented, discussing the trends observed as a function of film flow rate, plate inclination and film temperature, also considering the information coming from previous experimental campaigns.

1. Introduction

Researches on falling films have produced in the past a considerable amount of both theoretical and experimental information.

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The available literature on theoretical developments ranges from classical works dealing with the stability of the film surface (e.g., Kapitza, 1947; Benjamin, 1957; Yih, 1963; Bankoff, 1971; Spindler, 1981; Kokamustafaougullari, 1985) to reviews which provide an overall perspective of the knowledge obtained by the observation of physical phenomena characterising falling films and by the rigorous mathematical study of their behaviour (Alekseenko et al., 1994). Physical models have been also proposed on the basis of phenomenological observation of films, trying to more directly capture the relevant hydrodynamic mechanisms related to roll waves (see e.g., Brauner and Maron (1982) and subsequent works originated from their proposal).

Experimental works have been mainly focused on the study of statistical characteristics of the film surface in different conditions (Chu and Dukler, 1974; Takahama and Kato, 1980; Karapantsios et al., 1989; Karapantsios and Karabelas, 1990; Karapantsios and Karabelas, 1995; Karapantsios et al., 1996; Leuthner et al., 1998; Karimi and Kavaji, 1999). The basic idea of these researches is to analyse the wavy film surface by identifying statistically meaningful parameters capable to synthesize its complex behaviour. This line of research is still active, as testified by the number of works published in recent times, and new or improved measuring techniques are also proposed in order to provide more reliable information on statistical film parameters (Kang and Kim, 1992; Leuthner and Auracher, 1997; Kamei and Serizawa, 1998; Mori et al., 1998; Takamasa et al., 1998).

An obvious justification for such a long lasting (and continuing) effort in this field can be found in the well-known relevance that falling films have in several industrial applications, including heat and mass transfer devices. However, it is rather clear that falling films have also exerted an appeal on scientists and engineers as a consequence of the complexity of the behaviour of their surface, that shows a variety of non-linear wavy structures riding on a thin fluid substrate. This complexity, whose fascinating aspects are not made less interesting by everyday observation of falling films, whenever a viscous fluid flows over an incline, is shared with other fluid-dynamic instabilities and constitutes a remarkable challenge for any theoretical model. Undoubtedly, this has been one of the main reasons that stimulated the application to falling films of techniques developed for dealing with the dynamics of chaotic systems (Sheintuch and Dukler, 1989; Lacy et al., 1991), that represents a very suggestive development in this field.

Even in the present research, the starting motivation came from the proposed application of evaporating falling films in passive cooling of nuclear reactor containment (Ambrosini et al., 1995) and received further support by scientific interest. In particular, the measurement of film thickness was firstly considered as necessary for developing the research on passive cooling, in order to collect data of direct applicability to the specific conditions involved in the planned evaporation tests. Subsequently, it was considered worth to ascertain at what extent the available information about film behaviour, previously obtained by other researchers, could be considered applicable also in the case of the specific addressed system.

The non-intrusive nature of capacitance probes suggested to try their application in measuring water film thickness, thus exploring benefits and shortcomings of the related measuring technique in the addressed test conditions. The research was performed in steps (Ambrosini et al., 1996, 1997, 1998, 1999, 2001), improving and extending each time the measuring capabilities by appropriate changes in the probe configuration, thus taking profit of the experience gained during previous experimental campaigns. In this frame, the well-known problems encountered in using capacitance probes in the presence of vapour were also faced and solved.

The paper presents the latest results obtained by the research, trying to point out relevant conclusions from the overall activity performed so far. Statistical characteristics, including mean, maximum and minimum film thickness as well as standard deviation are considered; wave velocity data are also presented, obtained by cross-correlating signals from two different probes placed at a known distance along the film flowing direction.

The experimental data allow discussing the effect of film flow rate, temperature and surface inclination on statistical film characteristics, providing a perspective of the changes that the falling film undergoes in a range of flow rates including the classical threshold for the transition between laminar and turbulent flow.

2. Experimental apparatus

The experimental facility (Manfredini et al., 1993) has been conceived for performing falling film evaporation tests with countercurrent air flow, with main emphasis on heat and mass transfer phenomena. However, its characteristics turned out to be suitable also for studies of the surface behaviour of free falling films.

It mainly consists of a stainless steel flat plate (2 m long, 0.6 m wide, 0.022 m thick), mounted on a metallic frame allowing for plate inclination from the vertical up to the horizontal position and equipped with a spray system. The surface of the plate underwent a treatment by sandblasting and spray painting, in order to obtain conditions representative of the ones actually encountered in nuclear reactor containment shells. As the study of partial wetting of a sprayed surface was not within the objectives of the research, provisions have been taken in order to obtain a good wettability of the plate surface by the falling water film. Moreover, at the start of each test, mechanical means are used to obtain a satisfactory wetting of the plate surface.

An electrical heating system, consisting of 100 modular electric heaters, is located on the back side of the plate to simulate the power to be removed from the reactor containment after a postulated accident. The heaters are grouped into three heating sections, which are separately controlled by specific power-control systems.

The hydraulic circuit of the facility (Fig. 1) includes a main vessel (Mv) for water storage and preheating, a circulation pump (P1), a secondary heating vessel (Sv), a spraying system (Ss), consisting of a distributor pipe with four spray nozzles, two flowmeters (F1 at the inlet and F2 at the outlet), a semi-cylindrical container (Cc), a small phase separation barrel (B) and an open siphon-breaker vessel (Sb). A bypass line (permanently inactive in the present tests) allows to route water directly from the injection line to the separation barrel, by acting on two valves (V1 and V2), thus allowing for a check in the calibration of the two flowmeters before and/or after each evaporation test. Outlet water is then routed to the main vessel through a straight pipe.

K-type thermocouples are used to measure the heated surface temperature and both thermocouples and thermal resistances are provided to measure inlet and outlet film temperatures. In the experiments discussed in this work, the test facility was used without the transparent baffle plate (Pp), adopted to form a rectangular air channel during evaporation tests, and with the blower (Bl) switched off to obtain free falling film conditions. In these conditions, the evaporation rate is a small fraction of the film flow rate ($\approx$1.4 g/s in the worst case, to be compared film flow rates

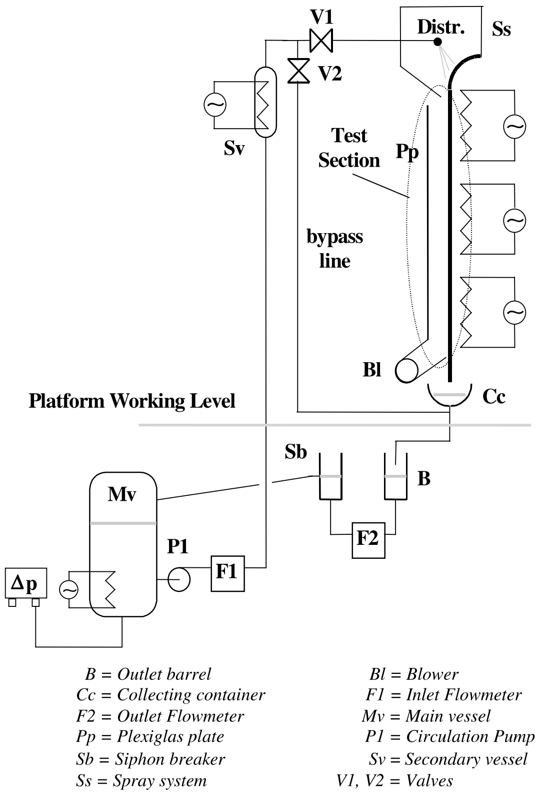

Fig. 1. Hydraulic circuit of the experimental apparatus.

ranging from 20 to 200 g/s). However, to compensate for its thermal effect, in tests with warm water it was needed to use the heating system, thus avoiding excessive film cooling along the plate.

The spray system creates a reasonably flat layer of water falling down the plate surface. Different arrangements were used for the spraying device in past experimental campaigns, trying to progressively improve film uniformity. A single spray nozzle was used in the first tests (Ambrosini et al., 1996, 1997), letting sprayed water to spontaneously generate the falling film after impacting over the receiving surface; subsequently, a four nozzle distributor pipe was introduced, thus allowing for a decrease in the length necessary for film formation (Ambrosini et al., 1998). Later on, in addition to the four nozzle distributor, a layer of filter material was added on the sprayed surface, thus obtaining a region of wave inception characterised by a rather smooth surface (Ambrosini et al., 1999). The latest measurements (Ambrosini et al., 2001) have been performed exactly reproducing the situation occurring in evaporation tests, i.e., making use of both the four nozzle distributor and of the layer of filter material, also including a fine mesh metallic net that was held down onto the plate surface just downstream the spray region. The latter provision had the result to introduce enough perturbation on the film surface as to suppress the smooth region of wave inception, possibly obtaining better developed conditions at the measuring location, placed roughly 1.7 m downstream the metallic net.

Whatever the adopted spraying device, it is understandable that on a relatively wide plate (0.6 m in width) local non-uniformity of film flow can be experienced. It was therefore considered advisable to perform film thickness measurements at three different transversal locations (left, centre and right) in order to get an idea of the effect of the obtained film distribution on the measured statistical parameters.

3. Measuring technique

Capacitance probes are used in different fields of engineering for measuring vibrations and displacements of bodies (see e.g., Baxter, 1997). Among the useful characteristics of these devices, the non-intrusive nature of the related measurements is probably the most important one. Another suitable characteristic is the flexibility allowed in the choice of the configuration of the measuring device, once a reasonable processing electronics is available: different shapes and sizes of the electrodes can be tested with the only need to adjust the amplification gain according to specified data acquisition input limits.

Alekseenko et al. (1994) present some of the possible capacitance probe configurations to be adopted for measuring film thickness and highlight the difficulties traditionally encountered in such an application. Early attempts made in the frame of the present research with a preliminary set up (Ambrosini et al., 1996, 1997) confirmed the existence of these practical problems, but also suggested the possibility to partly overcome them by appropriate provisions.

The probes recently adopted in this research have an inner electrode diameter of 2.5 mm, which can be considered a reasonable compromise between resolution and signal level (see Fig. 2). A larger outer electrode is also introduced, to which the biasing signal is fed. As the response to film thickness variation is non-linear, the decrease in sensitivity at small film thickness has been counteracted by a proper selection of signal amplification gain and offset, aiming at achieving an acceptable sensitivity to film thickness variations over the whole addressed range.

The calibration of the probes is made in static conditions, by recording the signal obtained at different values of the thickness of a smooth film of water created in a small basin. To get an idea of the smoothing obtained in representing wave details by this measuring technique, Fig. 3 presents the normalised signal from the adopted probes as a consequence of displacement over a

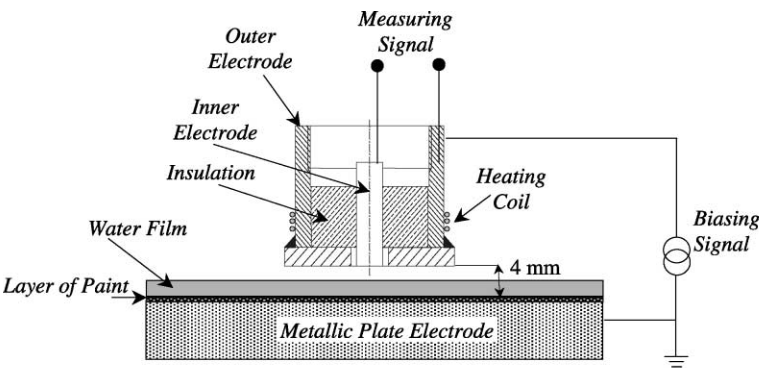

Fig. 2. Sketch of the measuring arrangement.

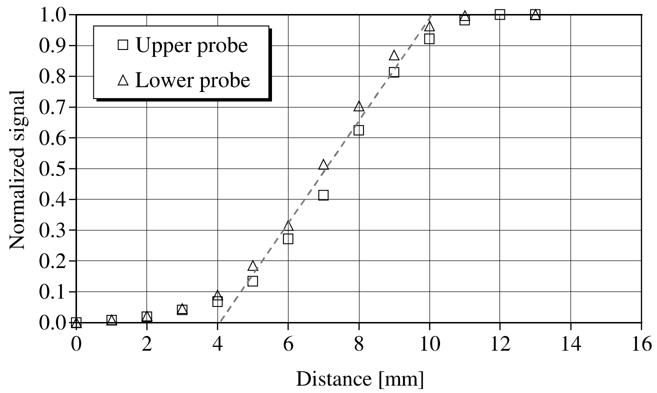

Fig. 3. Response of the probes to the displacement over a 1 mm metallic step.

1 mm thick step of metallic material placed on the plate surface, thus simulating an idealised sharp square wave. As it can be noted, the edge of the step is represented by a curve showing that the effective area of the inner electrode has approximately an equivalent diameter of 6 mm, which can be considered still acceptable to the present purposes.

The results of different series of calibration tests are reported in Fig. 4, where it can be noted that very small differences appear between the data taken in cold (20–30 °C) and warm (60–70 °C) water, possibly due to the large dielectric constant of water and to its limited change in the range considered for temperature; this justified the adoption of a single calibration line for both water temperatures. As a preliminary calibration of both probes did not show remarkable differences in their behaviour, the best fit line obtained with the first probe was adopted also for the second probe, whose signal is used only for providing information related to the transit time of the waves between the two measuring locations.

The presence of a slightly variable thickness of paint on the surface could pose a problem for repeatability of results at different locations if the probes were placed at a fixed distance from the

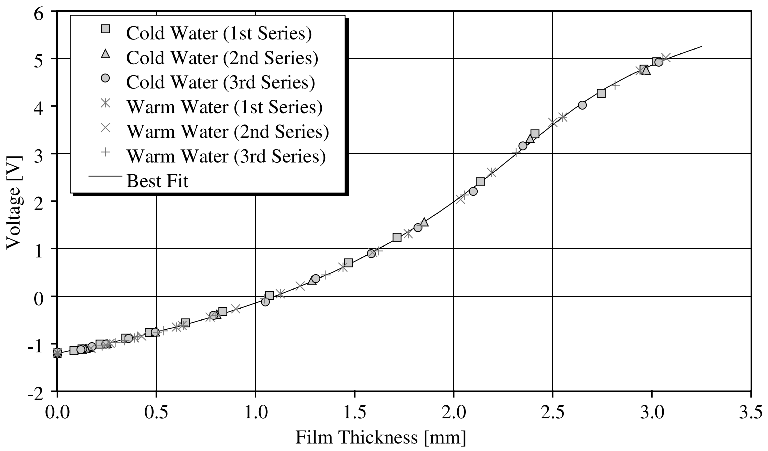

Fig. 4. Calibration data points and best fit line.

plate surface. However, this difficulty was easily overcome providing that a same signal (i.e., a same capacitance) was obtained in the zero film thickness condition (i.e., dry surface) before each measurement. In such a way, any drift in the signal due to thermal expansion or any other reason was also easily detected and compensated by the zeroing procedure.

The difficulty of operating with capacitance probes in humid air was also found to be not a very limiting one as far as relatively cold water was used; in this case, the periodical drying of the probe by a compressed air jet during zeroing turned out to be sufficient to obtain a stable performance. On the other hand, with warm water, i.e., in the presence of high vapour mass fraction, the problem of condensation onto the active probe surfaces required a specific solution, resulting in the introduction of an insulated electrical heating wire, that was wound around the lateral surface of the probe (Fig. 2). The wire was supplied with dc current at low voltage (≅2 V) and a thermocouples was held on the lateral surface of the probe to monitor the obtained temperature, which was conveniently kept slightly higher than film temperature. A stable signal was obtained by this means, allowing a meaningful calibration and a successful application of the probe.

The measuring chain and the overall measuring arrangement includes two probes (named "upper" and "lower", in the following) at a longitudinal distance of 70 mm mounted on a system of sleds allowing for their easy positioning with respect to the plate; in particular, a sled is used to displace the probes horizontally and two independent sleds allow motion in the direction normal to the plate surface. The probes are biased with a 20 V_{pp}, 10 kHz sinusoidal carrier and produce an amplitude modulated signal having the same frequency. The signal is firstly preamplified and then amplified and rectified; use of an active electronic filter (with a cut frequency of 800 Hz), finally, provides the required demodulation, resulting in a time varying signal related to the instantaneous value of film thickness through the calibration curve. This signal is received by the data acquisition system and sampled with a scan rate of 14,000 Hz, averaging each group of 7 data; the resulting effective frequency of data acquisition is therefore 2000 Hz, a value large enough to capture all the interesting details of the film surface. Film thickness time histories are recorded for periods of 8.192 s, corresponding to 16,384 values for each considered test conditions at the mentioned effective sampling frequency of 2000 Hz. A similar duration of data acquisition was used, for instance, by Karapantsios et al. (1989) and Karapantsios and Karabelas (1995).

4. Experimental results

Previous steps of the research (Ambrosini et al., 1997, 1998, 1999), performed with similar measuring techniques, but different probes, provided information about the statistical behaviour of cold water films that have been substantially confirmed and extended by the latest achievements. A summary of the main conclusions obtained in these previous steps is reported hereafter.

- The mean film thickness was reasonably represented by classical expressions for laminar flow (e.g., Nusselt theory) up to a threshold value of the Reynolds number at which larger deviations appeared, possibly due to the transition to turbulent flow.
- The maximum film thickness data (evaluated as the maximum in each measured time series) were found to experience a sharp increase at Reynolds numbers between 400 and 1200 and then leveled out at 2–2.5 mm; the comparison with previous data from other researches on free

falling films (Karapantsios and Karabelas, 1995) for similar distances from the film inlet section, showed a reasonable agreement.
- The minimum film thickness data (evaluated as the minimum in each measured time series) showed a very weak dependence on film flow rate in the addressed range and were in good agreement with literature results (Karapantsios and Karabelas, 1995).
- Coherently with what observed for the maximum film thickness, also the standard deviation showed a sharp increase for Reynolds numbers greater than about 400; moreover, the comparison with previous data (Karapantsios and Karabelas, 1995) provided again a reasonable agreement.
- Wave velocity, evaluated by the use of the cross-covariance function applied to the signals coming from two probes at a known distance from each other (Ambrosini et al., 1999), compared well with literature data, notwithstanding the different measuring and processing techniques adopted by the other researchers.
- The estimated wave velocity appeared rather independent from inclination at low Reynolds number, becoming increasingly affected by this parameter at large flow. Normalisation of the wave velocity using the mean film velocity for a laminar smooth film from the Nusselt theory allowed making the data clouds obtained at three different inclinations (0°, 45° and 60°) to approximately merge together for sufficiently high Reynolds number.

The latest step in the research has been devoted to consolidating and extending the conclusions obtained in previous phases, using improved instrumentation, and to a systematic analysis of the effect of film temperature on the statistical characteristics of film surface. The latter aspect is more interesting because of the changes in water properties due to temperature increase rather than for the effect of evaporation, which is relatively weak in the addressed conditions.

Measurements of film thickness were carried out with relatively cold water (at about 20–30 °C) and with warm water at about 50 and 70 °C. The flow rate ranged from 20 to about 200 g/s and was varied is steps of 10 g/s. Only two plate inclinations were considered (0° and 45° from the vertical position). As usual, three measurement locations across the plate width (left, centre and right) were adopted, at a longitudinal distance of about 1.7 m from film injection.

Fig. 5a and b show typical time series of film thickness as measured by the two probes for cold water at the maximum available flow rate ($\sim$200 g/s) for the two different inclinations. It is clear in the figures that, though the longitudinal distance of the probes is only 70 mm, some waves find enough space to strongly change their shape, possibly due also to the developing nature of the flow. The effect of inclination on the film structure also appears, showing an overall thickening of the film and an increase in the number of large waves observed within the considered time window.

Observation of several similar time series (not reported here for space limitations) at different flow rates, temperatures and inclinations leads to the following considerations:

- with increasing the film flow rate, the presence of large waves is observed, departing from a relatively smooth surface towards the chaotic pattern observed in Fig. 5;
- the film generally thickens with increasing flow rate and inclination, but a weak thinning is observed as the temperature increases;

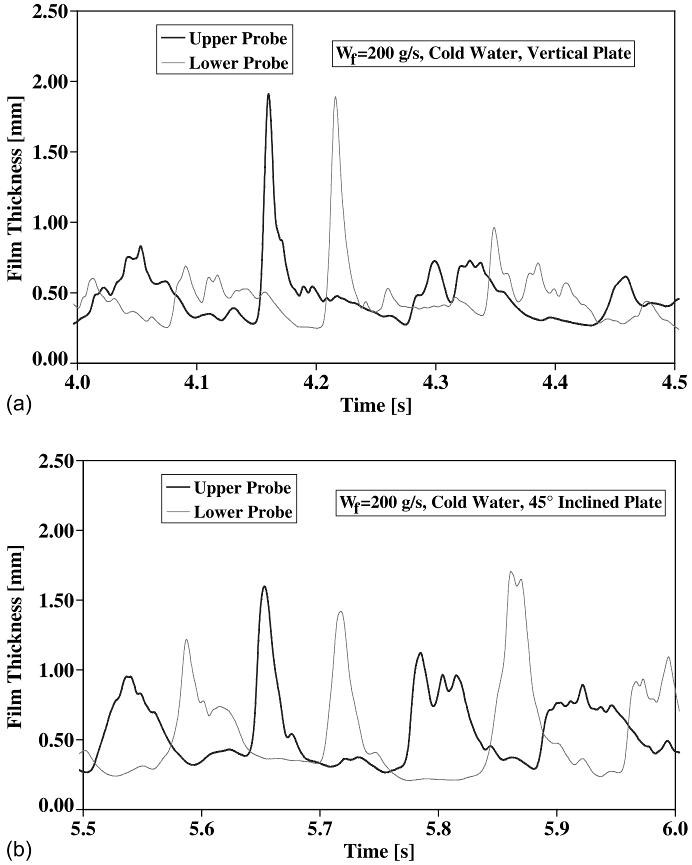

Fig. 5. Samples of film thickness time series.

- with inclined plate, waves appear to experience a transition which is not observed with vertical plate, occurring at large flow rates (150–200 g/s); this involves a sensible decrease in the height of waves and was observed preferably with warm water.

The above observations find confirmation in the analysis of statistical characteristics of the film. Fig. 6 summarises the data obtained for the minimum, the maximum and the mean film thickness at the three different temperatures and the two inclinations. The independent variable chosen for these plots is the Reynolds number. It can be seen that:

- the minimum film thickness weakly increases with increasing the Reynolds number; a closer look to the data suggests that the substrate is progressively thinning with increasing temperature, while it tends to be thickened by increasing the plate inclination;
- the mean film thickness shows a smoothly increasing trend with Reynolds number; for the other parametric trends considerations similar to those made above for the minimum film thickness apply;

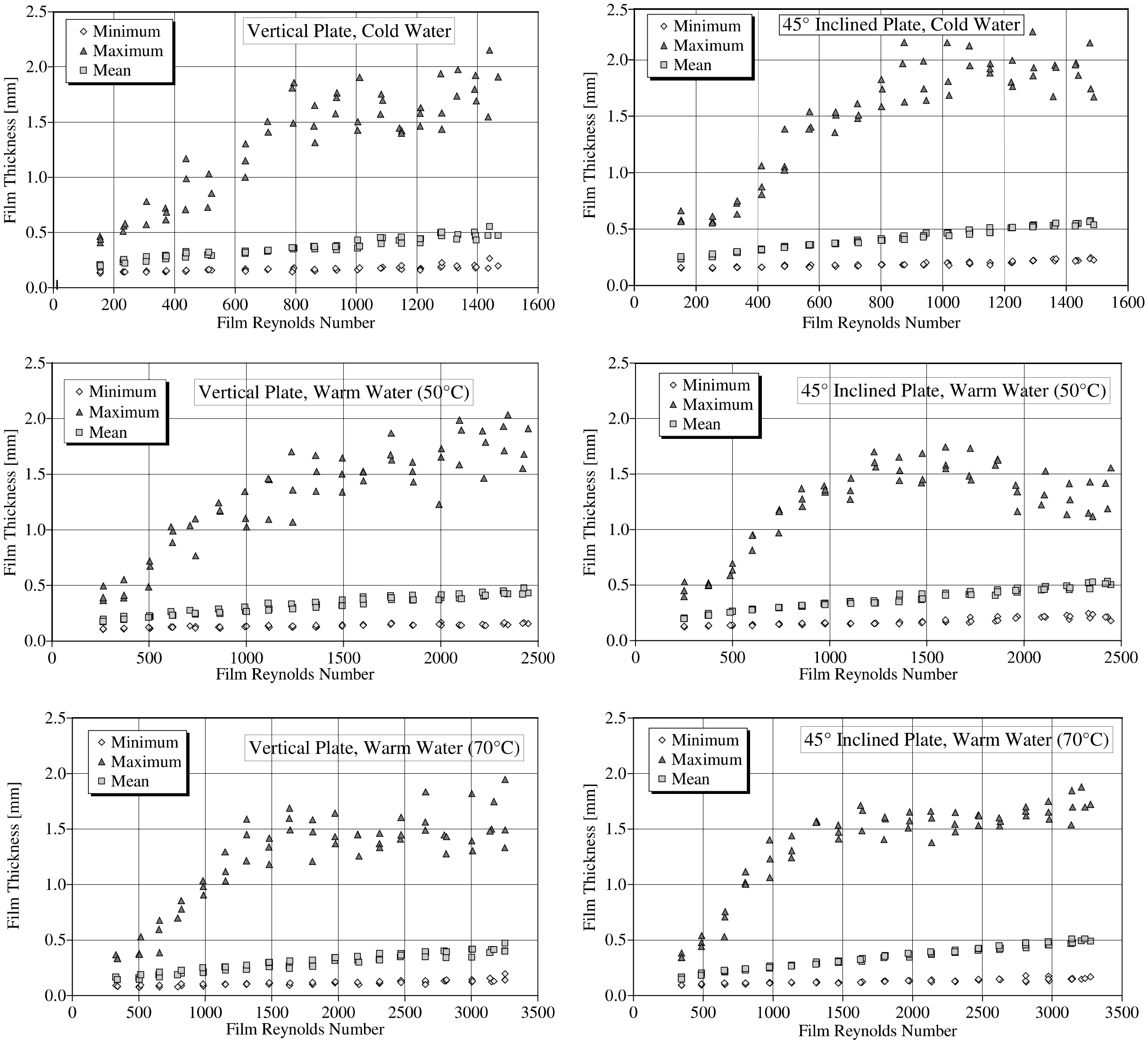

Fig. 6. Minimum, maximum and mean film thickness as a function of the film Reynolds number.

- the maximum film thickness, on the other hand, shows a more varied behaviour:
  - with vertical plate, it shows the previously noted sharply increasing trend at relatively low Reynolds number, followed by a region of lower increasing rate, exhibiting a relatively weak dependence on temperature;
  - with inclined plate, a trend similar to the one observed for vertical plate is found only with cold water, while with warm water, after the first increase, a sort of decreasing and then increasing trend is observed for this variable.

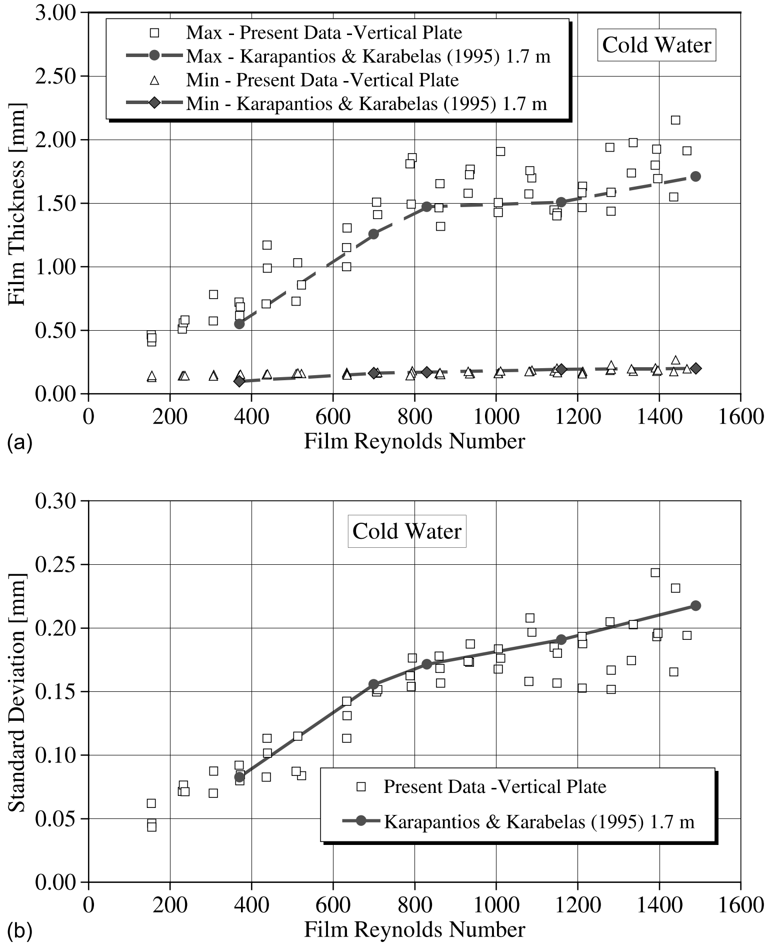

Fig. 7. Comparison of minimum and maximum film thickness and standard deviation for cold water and vertical plate with data from Karapantsios and Karabelas (1995) at a comparable distance from injection (1.7 m).

In order to partly assess the adequacy of the obtained measurements in front of previous experience, Fig. 7 compares the data of minimum and maximum film thickness and standard deviation obtained with cold water and vertical plate with information coming from Karapantsios and Karabelas (1995), who used the outer surface of a vertical tube as test section. As it can be noted, the agreement is good in the considered range of Reynolds number, though a considerable spread is observed in the present data for both maximum film thickness and standard deviation. This is a consequence of both repeating the measurements at different locations in the plate width at a same flow rate and of the chaotic nature of the superficial waves that causes the measured values to vary in a nearly stochastic way in different 8 s long recordings.

Mean film thickness data have been made dimensionless by the relationships (see Henstock and Hanratty, 1976)

$$\delta^+ = \frac{\delta w^*}{\nu_l}, \quad w^* = \sqrt{\frac{\tau_c}{\rho_l}}, \quad \tau_c = \frac{2}{3}\tau_w + \frac{1}{3}\tau_i$$

where ν_l and ρ_l are the liquid kinematic viscosity and density and τ_c is a characteristic shear stress depending on the wall shear stress, τ_w, and on the interfacial shear stress, τ_i. In the case of a free falling film it is $\tau_i = 0$ and τ_w is calculated by a force balance including gravity. It can be noted that such a dimensionless formulation is often used for gas sheared films in annular flow (see e.g., Asali et al., 1985; Ambrosini et al., 1991) and it has been applied in the present study in the purpose to compare the obtained data with correlations devised for such a case. In fact, by this choice, film thickness data can be compared with both the correlation obtained from the classical Nusselt theory for a laminar smooth film (Nusselt, 1916)

$$\bar{\delta}^+_{Nu} = \frac{\sqrt{2}}{2} Re_l^{0.5} \tag{1}$$

and the correlation by Asali et al. (1985) obtained on the basis of data related to annular flow

$$\bar{\delta}^+_{As} = 0.34 Re_l^{0.6} \tag{2}$$

In the above relationships, the film Reynolds number is defined as

$$Re_l = \frac{4\Gamma_l}{\mu_l} \tag{3}$$

where Γ_l is the liquid mass flow rate per unit perimeter and μ_l is the dynamic viscosity of liquid water.

Dimensionless mean film thickness data as a function of film Reynolds number are shown in Fig. 8, where only the data concerning inclined plate have been reported for the sake of clarity, as they show a lower spread due to a more uniform distribution of the film flow across the plate width. The change in the slope of the correlating line, already noted in previous data, occurs at a value of the Reynolds number that, in the limits of the observed data spread, seems to progressively increase with water temperature.

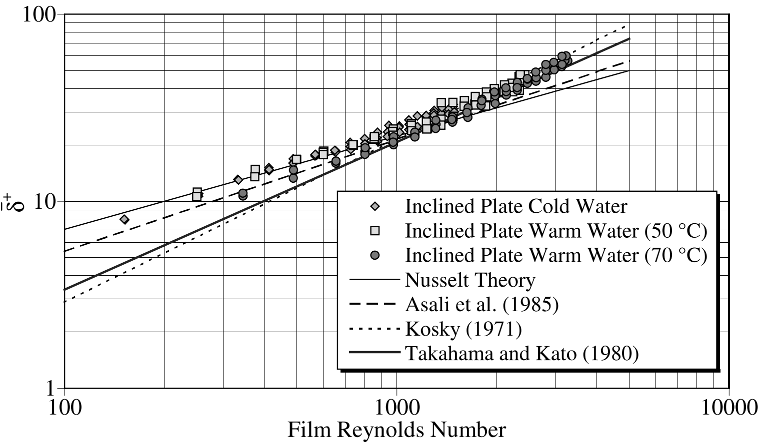

Fig. 8. Dimensionless film thickness as a function of the film Reynolds number for inclined plate.

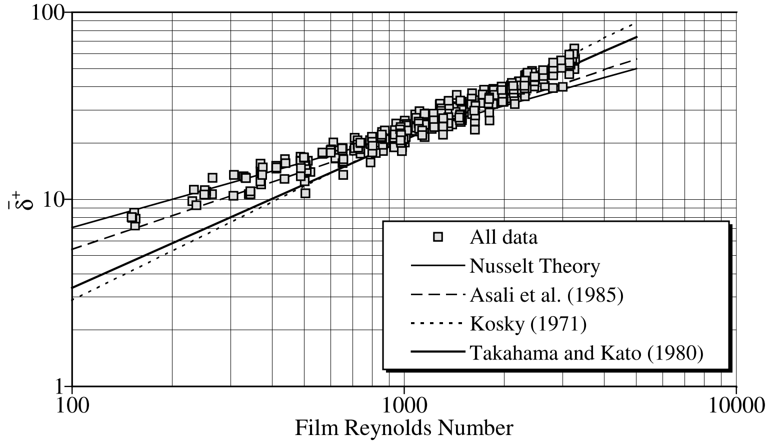

Fig. 9. Dimensionless film thickness as a function of the film Reynolds number (vertical and 45° inclined data).

As shown in Fig. 9, where all the mean film thickness data have been reported (for both vertical and inclined plate), it is interesting to note that at low Reynolds number (i.e., possibly before the transition to turbulent flow) the Nusselt theory (or the correlation by Asali et al. (1985) for gas sheared flows) approximately represents the observed trend; on the other hand, at larger flow rates, the exponent of the power law in the correlating line must be increased as noted in previous works (e.g., Takahama and Kato, 1980, and Ambrosini et al., 1991). It is worth noting that the same expression based on a "one-seventh power law" velocity distribution within the film (Kosky, 1971)

$$\bar{\delta}^{+} = 0.0512 Re_{1}^{0.875} \tag{4}$$

that was found suitable for gas sheared annular flow data (Ambrosini et al., 1991), is reasonably successful in correlating the thickness of a free falling water film at sufficiently high Reynolds number. On the other hand, it can be also found that the data are not far from the Takahama and Kato (1980) correlation

$$\bar{\delta} = 0.473 \left(\frac{v_{1}^{2}}{g \cos \theta} \right)^{1/3} \left(\frac{\Gamma_{1}}{\mu_{1}} \right)^{0.526} \tag{5}$$

where θ is the inclination of the plate with respect to the vertical. In the adopted dimensionless form, this correlation turns out to be

$$\bar{\delta}^{+} = 0.0890 Re_{1}^{0.789} \tag{6}$$

It is worth recalling that the correlation by Takahama and Kato (1980) has been successfully applied by Karapantsios and Karabelas (1995) for cold water over a wide range of Reynolds numbers involving turbulent flow (up to $Re_{1} = 11020$).

Power spectra have been obtained from the recorded film thickness time histories (Fig. 10) following a procedure similar to the one applied by Karapantsios et al. (1989) and described in detail in a previous paper (Ambrosini et al., 1998). Warm water data with vertical plate have been addressed. As it can be observed, the modal frequency of the waves increases with increasing the

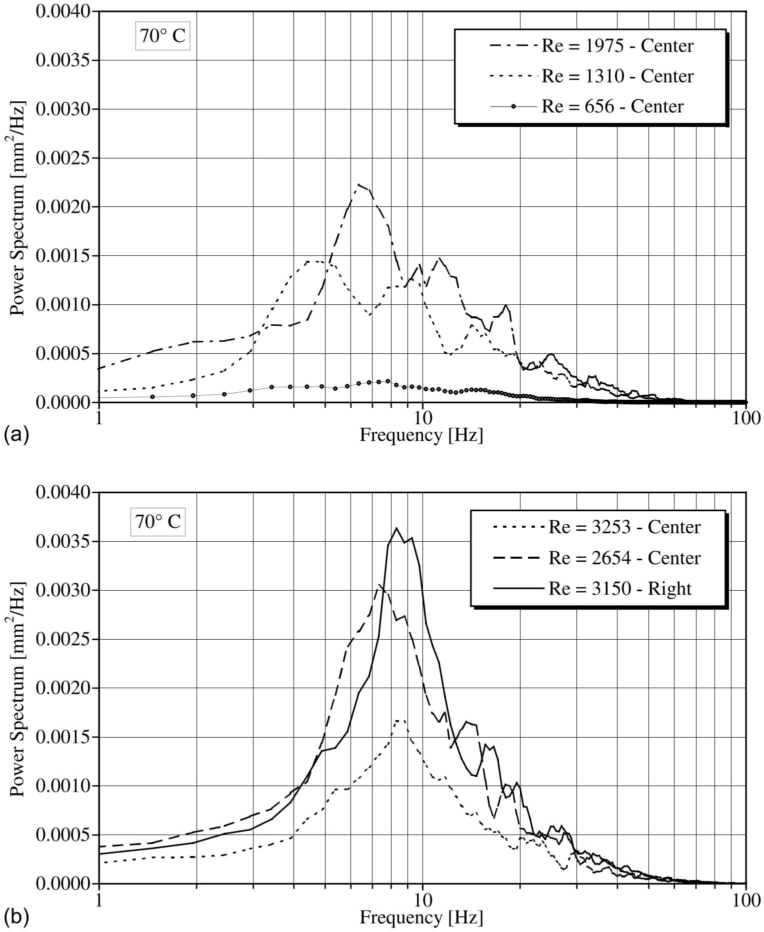

Fig. 10. Power spectra of waves at different values of the Reynolds number for vertical plate and film temperature of 70 °C.

Reynolds number. The height of the spectrum at the modal frequency also tends to increase with the Reynolds number, but in similarity with the observed spread in standard deviation and maximum film thickness, exceptions can be found in processing time series. As an example, the comparison of the values obtained for $Re_l = 3150$ in the right measuring position and for $Re_l = 3253$ in the centre of the plate points out this aspect.

Concerning wave velocity, V_w, the present experimental data for cold water films confirm the trends observed in a previous experimental campaign (Ambrosini et al., 1999). Both, the old and the latest data related to cold water are reported in Figs. 11 and 12; as it can be noted, the effect of inclination on wave velocity comes into play at sufficiently high Reynolds number, whilst at low flow rate wave velocity appears almost independent from it. The dependence on inclination at large Reynolds number is the same as for the average velocity of a smooth laminar film calculated by the Nusselt theory, V_{Nu}, causing the ratio V_w/V_{Nu} to become rather independent from inclination for sufficiently high Re_l. Coherently with the approximate independence on inclination of

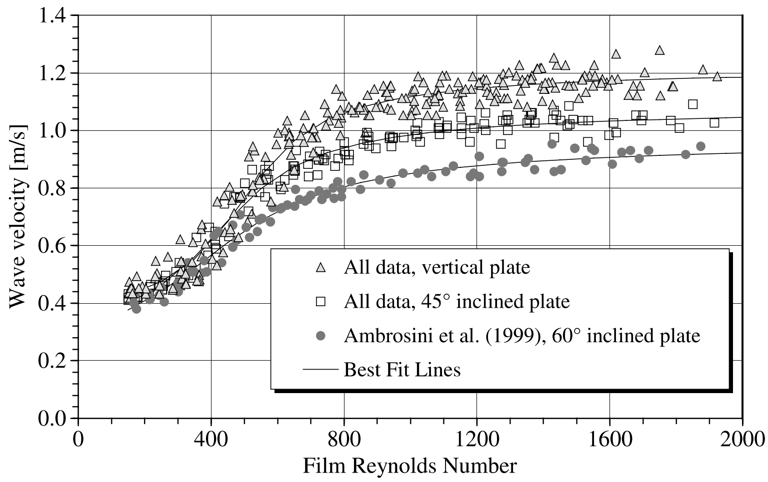

Fig. 11. Wave velocity from previous (Ambrosini et al., 1999) and present data for cold water at different plate inclinations.

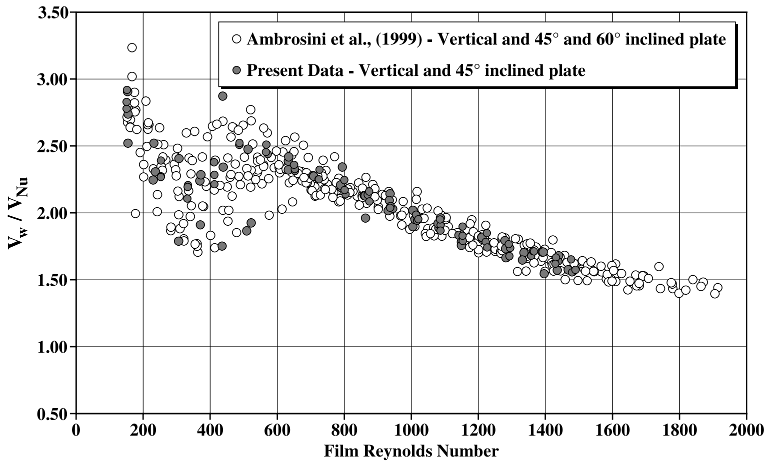

Fig. 12. Ratio of the wave velocity to the laminar smooth film average velocity for both previous (Ambrosini et al., 1999) and present data, cold water and different plate inclinations.

the estimated wave velocity at low flow rate, the ratio V_w/V_{Nu} exhibits a large spread at small Reynolds numbers. Fig. 13 compares a best fit line obtained from present cold water data for vertical plate with the data from other works showing very good agreement. It must be remarked that the data adopted for comparison have been obtained by very different experimental facilities, including vertical tubes as operating surfaces, and different measuring and data processing techniques (see the related references for details).

The additional information coming in relation to wave velocity from warm water measurements is summarised in Fig. 14, where the ratio of the measured wave velocity to the average velocity of a smooth laminar film is again reported as a function of the film Reynolds number. As

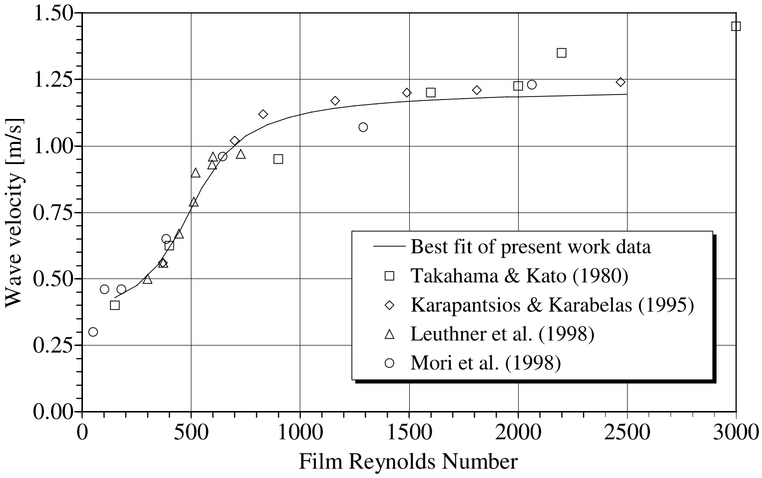

Fig. 13. Comparison of the best fit line of wave velocity data from present work for cold water and vertical plate with results from other works.

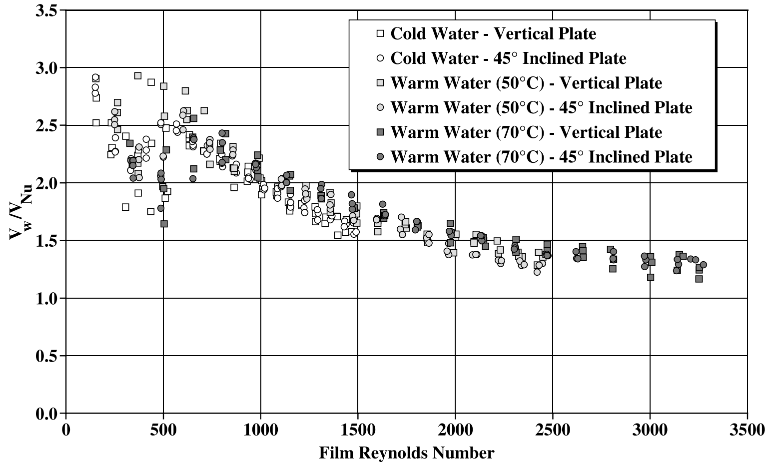

Fig. 14. Ratio of the wave velocity to the laminar smooth film average velocity as a function of the Reynolds number.

it can be noted, this representation is again effective in making data at relatively large Reynolds number to collapse into single clouds regardless of plate inclination, but still differences related to the different water temperatures are visible. An improvement in data correlation was found by using as independent variable the group $Re_1/\mathrm{Fi}_\theta^{1/11}$, where it is

$$\mathrm{Fi}_\theta = \frac{\sigma^3}{\rho_1^3 g \cos\theta \nu_1^4} \tag{7}$$

and σ is surface tension. Examples of use of this group in correlating wave parameters can be found, e.g., in Alekseenko et al. (1994). In the present work, the film number Fi_θ is defined as a

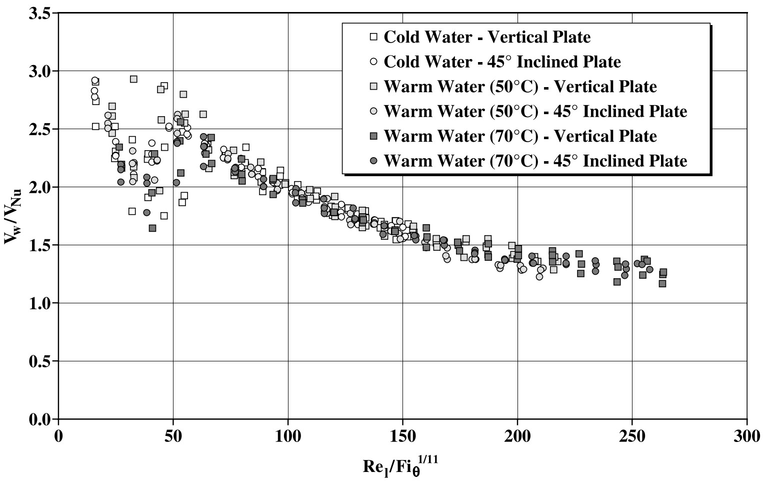

Fig. 15. Ratio of the wave velocity to the laminar smooth film average velocity as a function of $Re_l/\mathrm{Fi}_\theta^{1/11}$.

property group also depending on plate inclination. Though the generality of this approach should be proven over a wider range of fluid properties, Fig. 15 shows that in the present case it turns out successful in making the different data clouds at sufficiently high Reynolds number to merge into a single one regardless of water temperature. In particular, the obtained asymptotic decreasing trend seems to settle down to a constant value slightly larger than unity, but this observation should be supported by data at higher flow rates to be relied upon.

5. Conclusions

Experimental data collected in the present research allow pointing out some interesting features of the behaviour of falling films in a range of Reynolds numbers including the classical threshold for the transition between the wavy-laminar and the turbulent regimes.

The presence of two different transitions clearly appears from the data:

- a first transition occurs at a flow rate close to the lower boundary of the presently investigated range and involves the appearance of larger waves on the film surface; this is pointed out by the sharp increase in both the maximum film thickness and the standard deviation of recorded time series and by the rise in wave velocity from values of about 0.5 m/s or less to the range of 1–1.2 m/s;
- a second transition is found at flow rates where a lower rate of increase in maximum film thickness and standard deviation is observed; this transition seems to occur approximately in the same range of Reynolds numbers in which a change in the slope of the film thickness correlating line is observed, suggesting a possible relation to the transition to turbulence.

Considering the second transition, an effect of water temperature on the value of the Reynolds number at which it occurs appears from the data. In particular, present data seem to suggest that the critical Reynolds number for such a transition tends to slightly increase with increasing temperature.

As far as wave velocity is concerned, two main parametric effects have been pointed out: namely, the effect of plate inclination and the effect of film temperature. Considering the first aspect, representing the data in the form of the ratio of wave velocity to the average velocity of a laminar smooth film obtained by the Nusselt theory was found effective in collapsing into a single trend data at large enough Reynolds number obtained with different plate inclinations. In other words, while at low flow rate the evaluated wave velocity seems to be rather independent of inclination, the asymptotic trend at large Reynolds number is found to depend on inclination in similarity with the dependence on inclination of the mean velocity in a laminar smooth film.

On the other hand, the effect of temperature on wave velocity was better represented by a tentative choice for the independent variable other than the Reynolds number, involving the property group Fi_θ; it must be recognised that, though Fi_θ also includes the effect of inclination (as $\cos\theta$ appears at the denominator), the gross effect of inclination is anyway accounted for by the ratio $V_\mathrm{w}/V_\mathrm{Nu}$.

Furthermore, it has been interesting to find out that, making use of a particular definition of the dimensionless film thickness, it is possible to observe a qualitative similarity between the trends of mean film thickness in free falling films and in gas sheared annular flow films (see, e.g., Ambrosini et al., 1991).

It must be finally recognised that the presented results pertain to the particular investigated conditions, concerning a flat plate with some specific film-feeding system and distance of the measuring station (1.7 m). Therefore, their application to other conditions and systems must be made with the same due caution that in this work stimulated to check the applicability of previous data to the present conditions.

In this regard, the spread observed in some of the data (namely, maximum film thickness and standard deviation) must be clearly pointed out as a feature coming directly from the adopted experimental apparatus and measuring procedure. In particular, as above explained, the main effects contributing to this spread are:

- the use of three different measuring locations (centre, left and right), having slightly different specific flow rates as a consequence of imperfect uniformity in flow distribution across the plate width;
- the data acquisition period of 8 s, which turned out to be a prudent time span to avoid possible signal drifting during the measuring period, while capturing, at the same time, all the relevant features of the flow;
- the chaotic nature of the flow, which causes waves of different maximum height being recorded in the 8 s time span at each data acquisition, leading to a spread in some of the measured parameters;
- the number of data presented for the same nominal conditions, which provides a clear idea of repeatability in the measurements of each relevant quantity.

Nevertheless, the agreement found in many cases with experiments from previous researches, often carried out in very different experimental test rigs, with different measuring and data processing techniques, allows to propose these data as having enough significance and applicability.

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