

Characteristics of film flow during transition to three-dimensional wave regimes

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Abstract. Results of experimental study of transition processes from two-dimensional to three-dimensional wave regimes for the case of isothermal falling liquid film are presented. Experiments were carried out using liquids with various physical properties in the range of Reynolds numbers $5 < Re < 100$. It is shown that the process of transition to the three-dimensional wave motion is accompanied by formation of rivulets and that the downflow evolution of the rivulets usually has non-monotonic character. The statistical analysis of the 3D wave's characteristics allowed us to characterize in detail different scenarios of downflow evolution of 3D waves and to determine the regimes of fully developed steady-state 3D wave flow. Noticeable differences between natural and forced wave evolution have been observed for the relatively small Reynolds numbers whereas for the higher Reynolds numbers fast evolution of all investigated statistical characteristics with achievement of the steady-state 3D wave regimes of film flow occurs.

1. Introduction

Three-dimensional wave regimes are considered to be the last stage of film flow evolution at moderate Reynolds numbers. In such regimes the film surface is covered by the numerous 3D waves chaotically interacting with each other. Usually 3D waves arise due to transverse instability of nonlinear 2D waves which in turn can be formed during the process of natural wave evolution or generated by artificial modulation of liquid flow rate. The case of transition to three-dimensional wave regimes for excited 2D waves is more investigated by now. Recent experimental ([1], [2], [3]) and theoretical ([4], [5], [6]) investigations show good agreement in characteristic dimensions of 3D waves despite some differences in their shape. Using modern experimental techniques, in the first place Laser Induced Fluorescence (LIF) technique, allow us to reveal sufficient redistribution of liquid in transverse direction in the processes of 2D – 3D transition ([2], [3]) for the case of isothermal film flow, which leads to the formation of well pronounced rivulets on the time-averaged fields of film thickness. Such behavior is unexpected for isothermal film flow and previously was not observed in experiments basically because of using local probes or shadowgraph technique adjusted for registration of the waves' parts which have high curvature of free boundary. Main aim of this work is to investigate experimentally general dependencies of process of transition from two-dimensional to three-dimensional wave motion and associated formation of rivulets on the vertically falling liquid film surface in the range of $5 < Re < 100$ for the downstream distances up to 140 cm. The main consideration was given to the analysis of statistical characteristics of the waves at different



distances from the film inlet and make up accurate classification of wave regimes in the specified range of flow rates.

2. Experimental techniques and operating conditions

The liquid film was formed on the vertical transparent glass plate with width of 50 cm and length of 140 cm by adjustable slot distributor. The film freely flows down onto one side of the plate by the action of gravity. Three types of working fluids were used in experiments: water ($\nu = 0.99 \cdot 10^{-6} \text{ m}^2/\text{s}$, $\rho = 998 \text{ kg/m}^3$, $\sigma = 0.072 \text{ kg/s}^2$), water-glycerol solution WGS1 ($\nu = 1.6 \cdot 10^{-6} \text{ m}^2/\text{s}$, $\rho = 1050 \text{ kg/m}^3$, $\sigma = 0.072 \text{ kg/s}^2$), and water-glycerol solution WGS2 ($\nu = 2.2 \cdot 10^{-6} \text{ m}^2/\text{s}$, $\rho = 1070 \text{ kg/m}^3$, $\sigma = 0.072 \text{ kg/s}^2$) where ν – kinematic viscosity, ρ – density and σ – surface tension of liquid. That allowed us to cover range of Kapitza numbers $\gamma = \sigma \rho^{-1} \nu^{-4/3} g^{-1/3}$, where g is gravity acceleration, from $\gamma \approx 1100$ for more viscous WGS2 up to $\gamma \approx 3700$ for water. The range of investigated Reynolds numbers $5 < \text{Re} = q/\nu < 100$, where q – volumetric flow rate per unit width. The 2D – 3D transition processes in the case of the natural wave evolution as well as for the case of initially regular excited 2D waves were investigated. For the last case the regular two-dimensional waves were forced by the periodic flow rate modulation with prescribed frequency F . With help of regular 2D waves the uniformity of local flow rate distribution over the plate's surface was controlled. In the case of uniform distribution of liquid the wave's front in the upper part of the flow is a straight line perpendicular to the flow direction. The procedure of control and adjustment of uniformity of liquid distribution was performed obligatory before each experiment.

The shadowgraph imaging was used for registration of the wave patterns over whole area of the plate. The white matt screen placed behind the glass plate on the variable distance was used for the technique realization. The halogen light source and registering camera were placed from the film side. Varying the distance between the screen and the plate allows obtaining shadow images for parts of liquid surface with different curvature. When the screen is placed close to the glass plate, shadow images represent the areas with high curvature and are similar to those obtained in other works (e.g. [1]). If the screen is placed at the distances of a few centimeters from the plate, the film areas with much lower curvature form evident shadows on the screen. The distance between the screen and the glass plate was selected before each experiment in order to register capillary ripples having high curvature as well as the rivulets having lower curvature of film surface (figure 1).

The Laser-Induced Fluorescence (LIF) technique was used for measurement of instant film thickness distribution with high time and spatial resolutions. High-speed camera registers LIF images with frequency of 1 kHz on the measurement areas with sizes from $13 \times 13 \text{ cm}^2$ up to $19 \times 19 \text{ cm}^2$ dependently on flow conditions; this leads to spatial resolution from 0.13 mm/pix to 0.19 mm/pix accordingly. Record length of each set of LIF images was 2 seconds. For each investigated regime the records were obtained independently at the different distances from film inlet. Various statistical characteristics were obtained for each record. As it turned out, the most informative for evaluating the downstream wave evolution were such statistical characteristics as the film thickness probability density function (PDF), dispersion D and spectral power density $Y(f)$ of film thickness temporal variation.

3. Experimental results

For all investigated liquids three typical scenarios of wave evolution depending on Reynolds number can be singled out in the range of $5 < \text{Re} < 100$. Major difference between liquids consists in different values of boundary Reynolds numbers which exact definition is the complex problem and lies beyond the scope of this work.

First scenario of wave evolution is observed for low $\text{Re} < \text{Re}_1$ when transition to three-dimensional wave regimes does not occur even in the bottom part of the test section. The waves have a shape close to two-dimensional up to the end of test section and time-average film thickness distributions over the plate are flat. Re_1 is different for the different liquids and lies in the range from 5 to 15. Over this value ($\text{Re} > \text{Re}_1$) transition from two-dimensional to three-dimensional wave regimes occurs which is

characterized by fast degradation of transverse size of the waves. In the upper part of the flow initially 2D waves, no matter natural or excited, are breaking down into numerous 3D waves with characteristic dimension of 1 – 2 cm in transverse and longitudinal directions.

For $Re_1 < Re < Re_2$ (where $40 < Re_2 < 60$) the second scenario of wave evolution with well pronounced rivulets is observed. In this case evolution of natural and excited waves is different and rivulets are observed up to the end of the test section (figure 1). Forming 3D waves move mainly upon the rivulets and form chains. At the same time wave motion between rivulets looks depressed. Despite some differences in the regimes of natural and excited wave evolution the shapes of 3D waves in bottom part of the test section have similar characteristics.

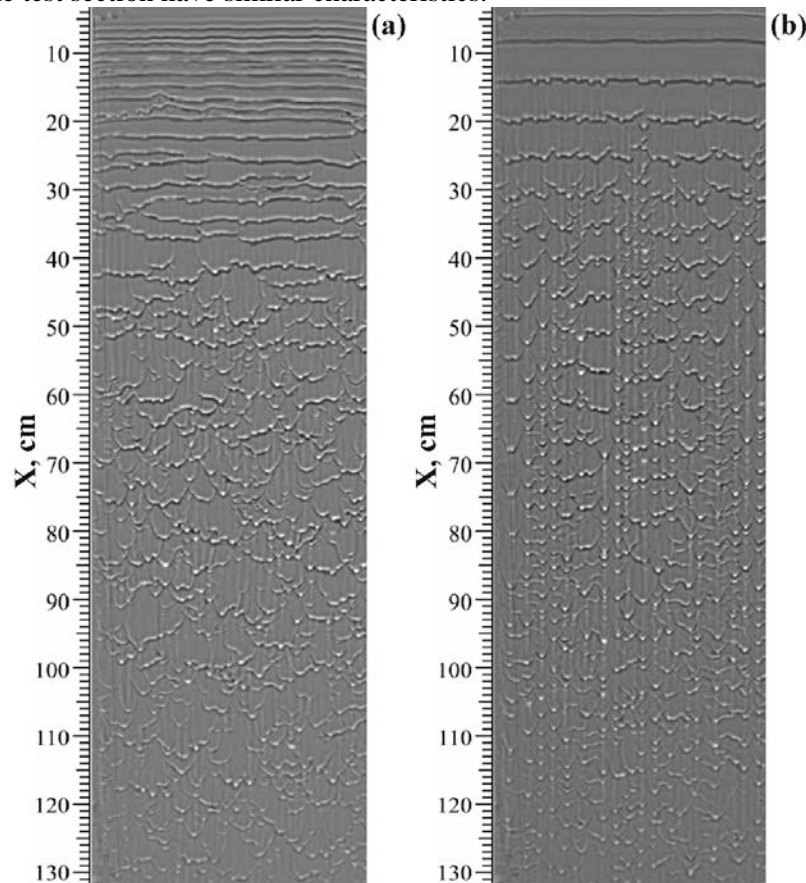


Figure 1. Shadowgraph images of water film at $Re = 25$. a) natural wave evolution, b) evolution of excited waves, $F = 8\text{Hz}$. X – downstream distance from the film inlet.

Because the formation of rivulets in the film flow is usually connected with non-isothermal effects, direct measurements of film surface temperature were performed with help of Titanium ATR-570M infrared scanner. Measured with total error not exceeded 0.05K temperature fields of the film surface have shown that the film is isothermal on the whole flow area.

In third scenario of wave evolution which is observed for Reynolds number $Re > Re_2$ the 2D-3D transition occurs in the upper part of the flow over a few wavelengths of 2D waves. Rivulets formation in such regimes is not monotonic. Till 40 – 50 cm amplitude of rivulets can increase and further downstream they begin to decay up to full disappearance at the lower part of the test section. Difference between cases of natural and forced wave evolution is observed only in the upper part of the plate at the distances up to a few wavelengths from the film inlet, after that the wave patterns for both cases become similar and appeared to be steady state 3D wave flow regime.

Detailed analysis of time-averaged film thickness distributions in dependence on different time-averaging intervals allows us to reveal formation of short-living rivulets shifting at random in transverse direction. Chaotic behavior of such rivulets leads to their disappearance or sufficient decrease of their amplitude on time-averaged film thickness distribution for large values of averaging time. As it turned out such short-living rivulet is the chain consisting of at least 5 – 8 3D waves. And such chains look like the main structures of regimes with high $Re > Re_2$.

Differences between scenarios and the direction of wave evolution can also be observed through analysis of statistical characteristics. As an example, probability density functions (PDF) of the liquid film thickness (h) at different distances from the film inlet are shown in figure 2. Distributions have characteristic asymmetric right-tailed shape. For the high Reynolds numbers (the case of $Re > Re_2$) the film thickness PDFs almost don't change with downstream distance (figure 2(a)) and are identical for the cases of natural and forced wave evolution. However transform of the PDFs with shifting of the most probable film thickness value with downstream distance is observed for the lower Re (case of $Re_1 < Re < Re_2$) (figure 2(b)). In this case the difference between the cases of natural and forced wave evolution can be observed up to the end of test section (lines 4 and 5 in figure 2(b)).

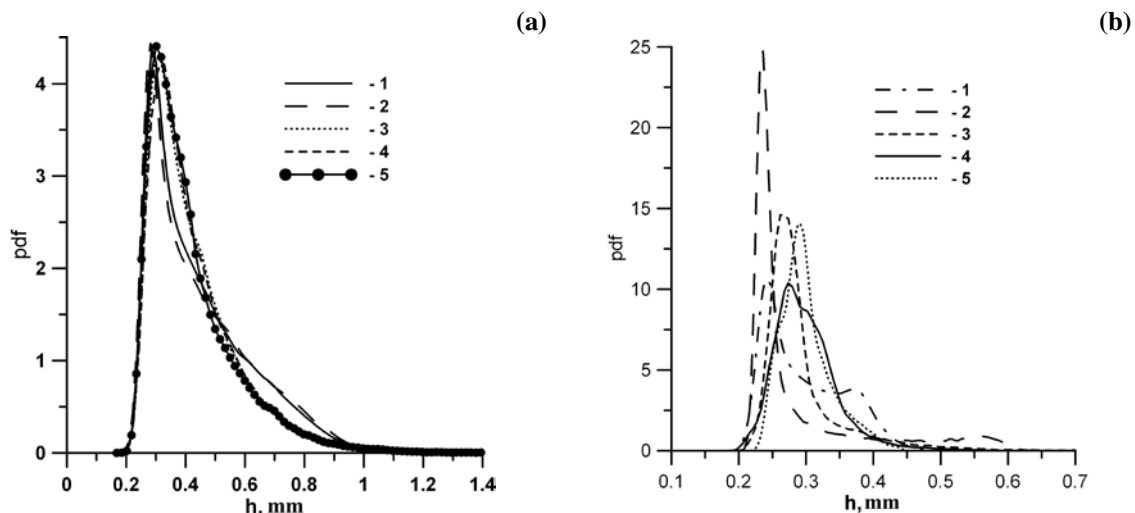


Figure 2. Film thickness PDFs, working liquid - WGS2. a) $Re = 54$, distance X from the film inlet: 1 – $X = 26$ cm; 2 – $X = 26$ cm, $F = 7$ Hz; 3 – $X = 92$ cm; 4 – $X = 133$ cm, $F = 7$ Hz; 5 – $X = 133$ cm. b) $Re = 19$, 1 – $X = 26$ cm; 2 – $X = 26$ cm, $F = 7$ Hz; 3 – $X = 92$ cm; 4 – $X = 133$ cm; 5 – $X = 133$ cm, $F = 7$ Hz.

Values of the dispersion D were obtained by averaging of the calculated local D values over the each transverse section of the measurement area. Some examples of characteristic downstream evolution of D are shown in figure 3. Initial growth of D with downstream distance in the upper part of flow is attributed to the initial developing and growth of 2D waves in this region. Farther downstream, in the region of flow where 2D waves are decayed into 3D waves significant diminishing of D is observed for all investigated regimes. But if for the high Reynolds number (case of $Re > Re_2$) after fast evolution in the upper part of flow D reaches steady-state value for the both, natural and forced 2D waves (lines 3 and 4 in figure 3), in the case of lower Reynolds number (case of $Re_1 < Re < Re_2$) downstream evolution of D is different: the gradual decreasing of D is observed up to the end of the plate (lines 1 and 2 in figure 3). It should be underlined that in the flow regimes for the case of $Re_1 < Re < Re_2$ transition from 2D to 3D waves is accompanied with formation of well pronounced rivulets observed not only on the time-averaged but also on instant film thickness distribution.

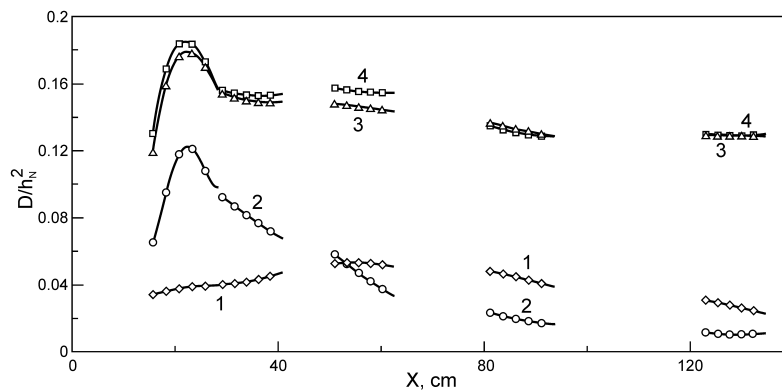


Figure 3. Film thickness dispersion D normalized to the squared undisturbed film thickness (h_N^2). Working liquid – WGS2. 1 – $Re = 19$, natural waves; 2 – $Re = 19$, forced waves $F = 7$ Hz; 3 – $Re = 54$, forced waves $F = 7$ Hz; 4 – $Re = 54$, natural waves.

Fast forming of the steady-state three-dimensional wave motion for the case of large $Re > Re_2$ is also observed while analyzing spectral power density (figure 4(a)). Also the difference in spectral characteristics between the cases of natural and excited waves is revealed only on short distances in the upper part of the flow and farther downstream the spectral characteristic for the both cases become identical. It is interestingly that for the steady-state flow regimes in the area of the high frequencies the spectral power decays by law of $Y \sim f^\alpha$, with index of power $\alpha = -2.8$. This index is close to that obtained in the work [7] and as it turned out it doesn't depend on the liquid properties.

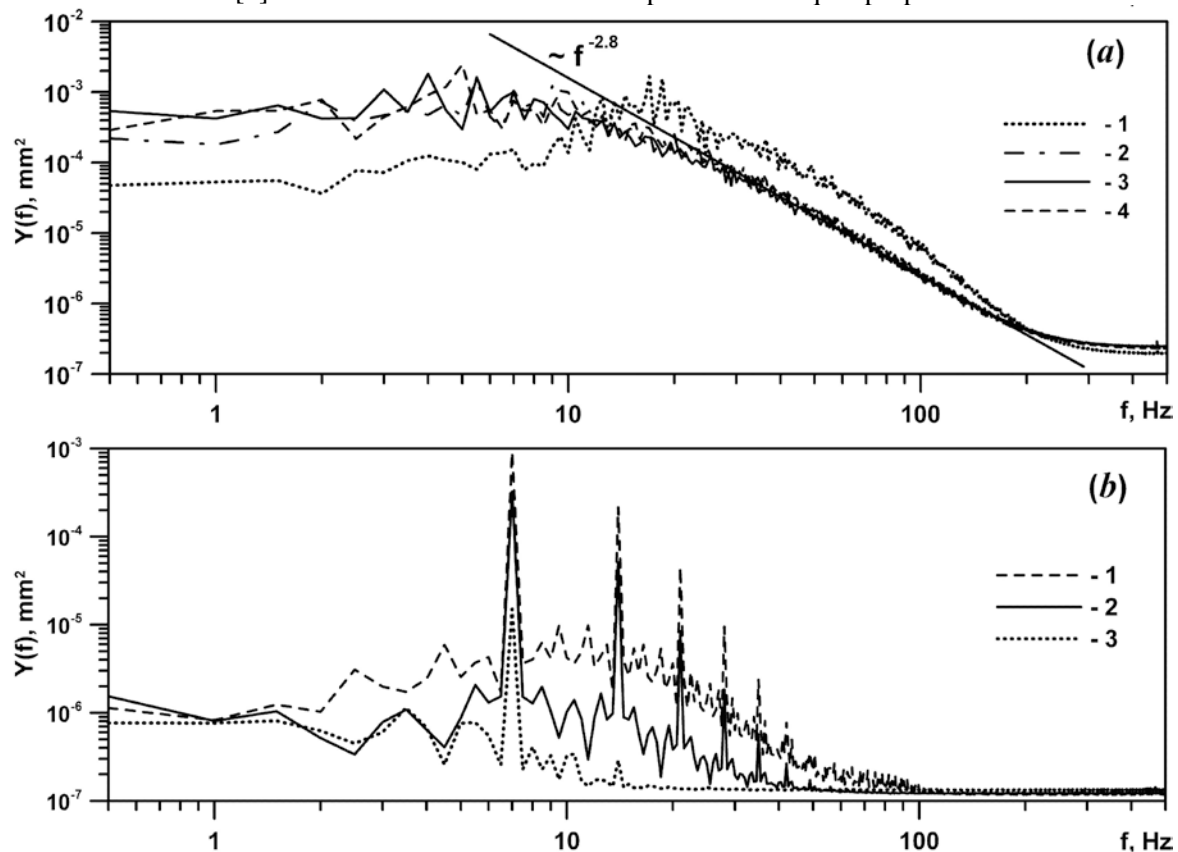


Figure 4. Spectral power density $Y(f)$ at various distances from the distributor. Working liquid – WGS2 a) $Re = 54$, natural waves, 1 – $X = 21$ cm, 2 – $X = 87$ cm, 3 – $X = 128$ cm; 4 – forced $F = 7$ Hz, $X = 128$ cm. b) $Re = 13.5$, forced waves $F = 7$ Hz. 1 – $X = 21$ cm, 2 – $X = 56$ cm, 3 – $X = 128$ cm.

For the cases of $Re_1 < Re < Re_2$ spectral power density shows significant difference between the regimes of forced and natural waves on all distances downstream the film inlet. Also spectra revealed downstream decay of wave motion (figure 4(b)) with gradual downstream decrease of spectral power especially in the range of high frequencies.

4. Conclusions

Performed experimental study of wave evolution on isothermal film flowing down a big plate reveals three typical scenarios of wave evolution depending on the Reynolds number in the range of $5 < Re < 100$.

For low $Re < Re_1$, where Re_1 is different for the different working liquids and lies in the range from 5 to 15, no transition to three-dimensional wave is observed and the waves have a shape close to two-dimensional up to the end of test section. In this case time-averaged film thickness distributions over the plate are flat.

For $Re_1 < Re < Re_2$, where $40 < Re_2 < 60$, the second scenario of wave evolution with well pronounced rivulets forming in the process of 2D - 3D wave transition is observed. For this range of Reynolds numbers no steady-state 3D wave regimes of film flow have been observed. All considered statistical characteristics of the waves show gradual downstream decaying of 3D waves at all distances from the film inlet.

For $Re > Re_2$ fast evolution of the film flow toward steady state 3D wave regimes is observed. Rivulets formation in such regimes is not monotonic. The amplitudes of rivulets are increased in the upper part of the flow and further downstream the rivulets begin to decay up to full disappearance at the lower part of the test section. Stabilizing of the dispersion value as well as of the PDFs and spectral power densities of film thickness fluctuations for such regimes apparently indicates that at these regimes stabilization of 3D wave motion occurs.

Acknowledgments

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