Experimental study of the rivulet movement on the surface of the heated liquid film

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Abstract. Characteristics of the film flow were determined experimentally using simultaneous measurements of the thickness and temperature fields on the surface of the falling heated liquid film (LIF and IR scanner). Three different types of instability were registered on the surface of the heated liquid film: 3D hydrodynamic and two thermocapillary A and B instabilities. The development of thermocapillary structures of type A was considered in the residual layer behind the wave front. These structures caused a disturbance in the following wave front, leading to an increase in the amplitude of the waves. It was found that the amplitude of hydrodynamic waves in the upper part of the heater could be increased. The development of thermocapillary structures of type A at high heat flux initiated increasing of the rivulets deflection amplitudes.

1. Introduction

The liquid films flowing under the action of gravity along a flat surface are a well-known example of convective unstable flow with instabilities of various kinds, leading to formation and interaction of surface waves with a wide variety of characteristics.

The study of instability of the liquid film flow, development and formation of rivulet flows is of fundamental importance for understanding the patterns of heat transfer and occurrence of crisis phenomena at heat transfer to a film.

Three different types of instability were registered on the surface of the heated liquid film: 3D hydrodynamic and two thermocapillary A and B instabilities.

Experimental results on the transition from two-dimensional to three-dimensional wave motion on the vertically falling isothermal liquid films were presented in [1]. It was shown that this transition was accompanied by a significant redistribution of liquid in the horizontal direction [2].

When the structures were formed in regime A, high temperature gradients of up to 10-15 K/mm were observed on film surface at the top of the heater. The boundary condition close to T = const was implemented on the heater surface. The regular structures in the form of three-dimensional formations in a film of 25% alcohol solution flowing along the plane with small size heaters of 6.5 x 13 mm were firstly detected in [3, 4]. At heat flux density higher than the threshold value, a horizontal roller was formed on the heater, and this led to liquid movement in the form of vertical rivulets and a thin film between them. At that, resistance of the liquid film against breakdown increased sharply.
In regime B, the rivulet flow was formed gradually with an increase in the heat flux and distance from the upper edge of the heater [5]. Boundary condition \( q = \text{const} \) was implemented on the heater surface. Heterogeneities in the liquid film thickness across the flow led to temperature heterogeneities on the liquid film surface. A transverse temperature gradient (up to 1 K/mm) was formed, leading to an increase of deformation of the liquid film surface. Evolution of hydrodynamic waves to the thermocapillary-wave structures at heating of the vertically falling liquid film was studied experimentally in [6] for high Reynolds numbers.

The interaction of the thermocapillary structures with waves were registered in [7]. The influence of artificial disturbances on the waves and rivulets structures was described in [8].

2. Experimental setup

The setup was a closed circulation loop including a reservoir with a pump, test section, filter, rotameters, pipelines, and stop valve. The test section consisted of a textolite plate with film former, thermostabilizer and heater located on this plate. A flat copper heat exchanger of 150 mm width and 100 mm length was used as the heating element. Inside the heat exchanger the heated liquid was pumped through the rectangular channels. The average heat flux from the heater surface was calculated by the temperature difference of the pumped liquid at the heat exchanger inlet and outlet at a given mass flow rate. The temperature of the heater wall facing the film was measured by three thermocouples located on the vertical axis of symmetry. On the heating surface the boundary condition close to \( T = \text{const} \) was implemented, providing high temperature gradients near the upper edge of the heater. Distilled water with addition of a dye was used as the test liquid. The initial liquid temperature at the outlet of the film forming nozzle was 23 °C. The film Reynolds numbers was 33. The heat flux was varied within the range of 0.5-6 W/cm\(^2\). The vertical test section was opened to the atmosphere.

Characteristics of the film flow were determined experimentally using simultaneous measurements of the thickness and temperature fields on the surface of the falling heated liquid film (LIF and IR scanner). To excite the fluorophore, a laser with diode pumping was applied. The digital camera registered light, reradiated by fluorophore. The system provided spatial resolution of 0.1 mm. Temperature distribution on the water film surface was measured by the infrared scanner Titanium 570M, which allowed registration of the temperature field on the film surface with resolution of up to 640 x 512 pixels and sensitivity of 18 mK. Experimental setup and measurement procedure are described in detail in [7].

3. Discussion

The characteristic regime of water film flow over the heater with the heat flux density of 4.66 W/cm\(^2\) and \( \text{Re} = 33 \) is shown in figure 1. It can be seen that the two-dimensional waves move on the heater in the upper part, while a rivulet flow occurs in the lower part. It can be noted here that the transition from the wave flow to the rivulet flow is accompanied by zigzag motion (deflection) of rivulets in the transverse direction. To study the effect of the heat flux density on the motion of rivulets, the maximal amplitude of deflection was chosen as the criterion. This criterion was defined as the difference between the extreme right and extreme left positions of the rivulet crest during the time of registering across the flow.

The development of thermocapillary structures of type A was observed in the residual layer behind the wave front, figure 2 (\( X \) is coordinate along the flow, counted from the upper edge of the heater, \( Z \) is coordinate across the flow, counted from the right edge of the heater). These structures made a disturbance in the following wave front, leading to an increase in the amplitude of the waves. When reaching heat flux threshold value, the temperature gradients on the film surface near the upper edge of the heater increased to 10 K/mm, typical of forming the type A structures. Periodically, these structures were quite clearly visible, figure 2. They were formed in the residual layer in front of the oncoming wave near the upper edge of the heater. The distance between the thickness and temperature
heterogeneities could vary from 5 to 10 mm and corresponded to the mean length of instability wave in regime A at lower Reynolds number values.

Figure 3 presents data on wave amplitudes in rivulet (a) and interrivulet (b) areas for Re = 33 (A is wave amplitudes, X is coordinate along the heater). The amplitude of the waves at the top of the heater is higher than at the lower part, and increases with the heat flux. It was found that the amplitude of hydrodynamic waves in the upper part of the heater could be increased by interacting with the thermocapillary instability of type A.

We can distinguish two regimes of rivulets deflection. At low heat flux, where there is movement of the rivulets in a regime B, the amplitude of the rivulets deflection is a relatively low, figure 4. In this case, there is traditional thermocapillary - inertial mechanism of the rivulets deflection, which is described in [9]. Relatively weak thermocapillary forces (due to small temperature gradients on the film surface) are directed towards the center of the crest of a wave. Due to inertial forces wave passes the centerline. Thermocapillary forces begin to act in the opposite direction. At small heat flux, amplitudes of the rivulets deflection slightly rise by the middle of the heater, and then decrease, figure 4.

The development of thermocapillary structures of type A at high heat flux initiates increasing of the rivulets deflection amplitudes, figure 4. In this case, the higher temperature gradients are observed on film surface near the top edge of the heater. The waves were destroyed more intensively than in regime B.
4. Conclusions

Formation and movement of rivulets on the surface of a heated liquid film is studied. It is shown that for small heat fluxes the amplitude of rivulet deflection is slightly changed along the heater, and when the critical value of the heat flux is reached, its increase is observed. The development of thermocapillary structures of type A at high heat flux initiated increasing of the waves and rivulets deflection amplitudes. At high heat fluxes, the transverse movement of the rivulets prevents formation of dry spots on the heater surface.

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