Formation of thermocapillary structures in heated liquid film

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Abstract. Data on the formation of thermocapillary structures and breakdown of a heated liquid film flowing down a vertical surface with Reynolds number variation from 0.1 to 500 have been analyzed and generalized. Small-scale thermocapillary structures are distinguished. It is shown that the distances between temperatures heterogeneities (rivulets) of thermocapillary structures do not depend on the Reynolds number. It is determined that the interaction of waves with thermocapillary structures leads to an increase in the critical heat flux corresponding to the liquid film breakdown as compared with the data of publications.

1. Introduction
It is known that two-dimensional waves in isothermal liquid films are unstable to three-dimensional perturbations. When two-dimensional waves decay into three-dimensional ones, the synchronous waves without phase displacement of waves in the transverse direction and subharmonic waves with phase displacement are distinguished in [1, 2]. It is shown that the length of a wave unstable to transverse three-dimensional perturbations decreases with increasing Reynolds number. Propagation of two-dimensional and three-dimensional waves along a vertically flowing isothermal water film at Re = 10-100 and the effect of artificial perturbations are studied in [3]. It was experimentally shown that for Re > 40, two-dimensional waves are unstable to transverse perturbations with a wavelength of approximately 20 mm. They break up into three-dimensional waves that interact strongly and combine with each other. At Re < 20, the length of a wave unstable to transverse three-dimensional perturbations increases to 30 mm and more. It is determined that the transition from regular two-dimensional structures to a three-dimensional flow is accompanied by a significant redistribution of liquid in the longitudinal direction [4, 5]. The characteristic shapes of three-dimensional structures developing in the process of transition are described. It is found that the predominant structures on the film surface at Re > 50 are the short-lived rivulets, which are the chains of not less than 5-8 waves with close values of the transverse coordinate [6].

To date, various mechanisms of rivulet formation in the heated liquid films have been discovered, and two thermocapillary regimes have been identified: A and B [7]. The structures of two types A and B differ in the level of heat flux density, required for their formation, and size and nature of the dependence of interrivulet distance on the heat flux density and Reynolds number. Formation of regular structures in thermocapillary regime A on the surface of a smooth liquid film flowing over a vertical plane with small heaters of 6.5 × 13 mm at low Reynolds numbers was discovered and investigated in [8, 9]. Under the influence of thermocapillary forces directed against the flow, film thickening occurred. When the threshold heat flux density was achieved, the flow divided into vertical rivulets at a certain distance Λ with a thin film between them. Data on the formation of structures of
this type on the water film surface on extended heaters with the length of 60 mm are presented in [10]. This phenomenon at $0.1 \leq \text{Re} \leq 2$ was studied theoretically and analyzed in detail in [11]. It was determined that the distance between the rivulets is almost independent of Re, and for a fixed Marangoni number, it can even decrease with increasing Reynolds number.

In regime B, the rivulet flow is formed gradually with increasing heat flux density and distance from the upper edge of the heater. It is shown in [7, 10, 12] that in the region of sufficiently high heat fluxes with Re$> 15$, the distance between the rivulets depends weakly on the Reynolds number and film path length. Temperature fluctuations and wave characteristics of the water film flow over a vertical plate with a heater are studied in [13]. It is shown that two thermocapillary effects appear in-between the rivulets with increasing heat flux density. The transverse temperature gradients cause a significant decrease in the liquid film thickness, and the longitudinal gradients increase the relative wave amplitude as compared with the isothermal conditions. Formation of thermocapillary structures at small Reynolds numbers of up to Re $= 0.1$ is studied experimentally in [14]. It is shown that the transverse size of structures is determined by the capillary constant and does not depend on the viscosity of the liquid.

Breakdown dynamics is studied in [15] using a fiber-optic sensor. The influence of substrate wettability on thermocapillary breakdown of a liquid film is considered in [16]. In [17], the thermocapillary breakdown of a film is studied with a change in a wide range of Reynolds numbers and heater sizes.

The existence of thermocapillary structures in regime A at Re $= 150$ was detected in [18]. Formation of the smaller structures in the form of temperature heterogeneities across the flow with a distance between maxima of 2 ± 0.4 mm was registered there.

This work is aimed at analysis and generalization of data on the formation of various types of thermocapillary structures and breakdown of the heated liquid film with a variation of Reynolds number from 0.1 to 500.

2. Results and discussion

Based on the analysis of experimental data on the hydrodynamics of the flow of a heated liquid film, it has been established that the structures of type A are observed in the range of Reynolds numbers from 0.1 to 150. They appear on the liquid film surface when the threshold of heat flux density is reached. When structures of type A appear, high-temperature gradients of up to 10-15 K/mm are registered in the upper part of the heater. The boundary condition close to $T = \text{const}$ took place on the heater surface. Under the conditions of a developed wave flow, thermocapillary structures of type A were formed in the residual layer of the liquid film after propagation of the three-dimensional wavefront. The structures existed for a limited period of time and interacted with the front of the next wave transforming into rivulets that moved along the heater, changing their direction, Fig. 1a.

In regime B, a rivulet flow was formed gradually with increasing heat flux and distance from the upper edge of the heater, Fig. 1a. Structures of type B were registered in the range of Reynolds numbers from 0.1 to 500. Boundary condition $q = \text{const}$ was implemented on the heater surface, and temperature gradients on the film surface did not exceed 1 K/mm.

Formation of the smaller structures in the form of temperature heterogeneities across the flow has been found. These structures, designated as type C, were observed, as a rule, in the residual layer of liquid after propagation of a large wave before the formation of structures of type A. Temperature gradients on the liquid film surface at different points of time are shown in Fig. 1b. At zero time, we can see only gradients from the fronts of passing waves. With a decrease in the film thickness behind the wavefront and its heating, temperature heterogeneities appear on the surface with an average distance between them of 1.5 mm ($t = 20$ ms). Then, they are enlarged and transformed into thermocapillary structures of type A. At lower Reynolds numbers, the stationary structures of type C are registered, Fig. 2. Three maxima appeared on the left side of the heater. The maximal temperature of liquid on the film surface increased to 68°C. The difference between the maximal and initial temperature was 44°C. The distance between small-scale heterogeneities was 2.5–3 mm.
Fig. 1. Three-dimensional distribution of thicknesses, temperatures, and gradients over the water film surface, $Re=50$, $q=6 \text{ W/cm}^2$, the heater of 150x100 mm. a - Three-dimensional distribution of thickness and temperature over the liquid film surface. b – Distribution of temperature gradients over the liquid film surface.

Fig. 2. Thermogram and temperature distribution over the water film surface, $Re=11.8$, $q=9.9 \text{ W/cm}^2$, the heater of 6.55 x 22 mm.
Generalization of available experimental and theoretical data on the dimensionless distance between the rivulets of the observed structures is presented in Fig. 3. The characteristic regions of thermocapillary structures A, B, and C are identified. It can be seen that the dimensionless distances between the rivulets in all three cases are self-similar relative to the Reynolds number. Dependence of the distance between the crests of three-dimensional hydrodynamic waves (3D) on Reynolds number, derived from the data of [3], is given. At low Reynolds numbers, the distance between the crests of three-dimensional waves decreases sharply with increasing Re. For Re > 30, it does not depend on Reynolds number and is close to the distance between the rivulets in regime B.

Under the action of thermocapillary forces directed from the hotter to the colder areas, an increase in deformation of the film surface occurred. As a result, when the heat flux density became higher, the liquid film breakdown took place. When forming the structures of type A, the liquid film breakdown occurred in the upper part of the heater, where maximum deformations of the film surface were registered, and during the formation of structures of type B, it occurred in the lower part of the heater. Generalization of experimental data on the heat flux, corresponding to the formation of structures of type A is fulfilled in the form of dependence between criterion $K_{mA}^*$ and Re, Fig. 4. Criterion $K_{mA}^*$ characterizes specific thermal power $W_{mA}/B$, released on the heater for heating the film

$$K_{mA}^* = -q_A(\sigma \gamma/(c \rho g^{2/3} \nu^{5/3}))L/\nu = -W_{mA}\sigma \gamma/(Bc \rho g^{2/3} \nu^{4}),$$

where $B$ is heater width, $c$ is heat capacity of liquid, $g$ is acceleration of gravity, $L$ is heater length, $\nu$ is scale of viscous-gravitational interaction equal to $(\nu^2/g)^{1/3}$, $q_A$ is heat flux density, corresponding to

![Fig. 3. Generalization of experimental data on dimensionless distance between the rivulets of thermocapillary and wave structures. 1 - structures B, water [14]; 2 - structures B, FC-72 [7]; 3-structures A, water, [10]; 4 - structures A, data of [11]; 5 - structures A, FC-72, [7]; 6 – dependence of wavelength of unstable formation of three-dimensional waves on Reynolds number according to [3]; 7 - structures B, water solution of glycerin [14]; 8 - structures A, water; 9 - structures C, water. $l_\sigma$ - capillary constant.](image)
formation of structures in regime A, $\nu$ is kinematic viscosity of liquid, $\sigma_T$ is temperature derivative of surface tension coefficient equal to $\frac{\partial \sigma}{\partial T}$, $\rho$ is liquid density.

The condition for structure formation in regime A on the liquid film surface is described by the following relation

$$Km_A^* = 113\text{Re}^{1.08}. \quad (2)$$

Data on the liquid film breakdown during the formation of A and B structures are presented in Fig. 4. If only structures B were formed on the liquid film surface, breakdown always occurred in the lower part of the heater between the formed rivulets. With an increase in the heat flux density in the lower part of the heater, there was a sharp increase in liquid film deformation, which led to its breakdown. A summary of data for different types of liquid is presented in Fig. 2b. Data for the breakdown in regime B are summarized by dependence from [19]

$$Km_{cri B}^* = 165\text{Re}. \quad (3)$$

During the formation of structures in regime A on the liquid film surface, the heat flux densities corresponding to breakdown increased significantly. The nature of liquid film breakdown changed, which is explained by a change in film deformation

$$Km_{cri A}^* = 290\text{Re}. \quad (4)$$

Fig. 4. Generalization of experimental data on the formation of thermocapillary structures and liquid film breakdown. 1 – experimental data on water film breakdown after formation of structures A, 2 – dependence (2), 3 – dependence (3), 4 – dependence (4), 5 – line, above which structures B become perceptible, 6 – experimental data on formation of structures A on the water film surface.
Thus, the data on the formation of thermocapillary structures and breakdown of a heated liquid film flowing down a vertical surface with Reynolds number variation from 0.1 to 500 have been analyzed and summarized. Thermocapillary structures of a small scale were distinguished. It is shown that the distances between the rivulets of thermocapillary structures for these regimes do not depend on the Reynolds number. It has been established that the formation of metastable thermocapillary structures of type A in the upper part of the heater affects the value of the critical heat flux corresponding to liquid film breakdown. It is shown that the critical heat flux increases with increasing film Reynolds number and at high Re numbers, it exceeds significantly the data on a breakdown in the absence of thermocapillary structures of type A.

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