Rivulet structures formation, rupture and heat transfer in the falling liquid films

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Abstract. The evolution of three-dimensional waves into thermocapillary-wave structures, rivulets deflection, heat transfer enhancement and rupture vertically falling water film at heating were studied. Characteristics of the film flow were determined experimentally using simultaneous measurements of thickness and temperature fields on the falling heated liquid film surface (LIF and IR scanner). The amplitudes and velocities of waves, amplitudes of rivulet deflection, temperature fluctuations on the film surface, frequency spectra and pulsation energies were determined. Several different types of instability were registered on the surface of the heated fluid film: 3D hydrodynamic and thermocapillary A, B and C instabilities. The thermocapillary structures of type A arise in the residual layer behind the front of the wave, leading to an increase in the amplitude of the waves and rivulets deflection amplitudes. It is shown that the heat flux of rupture increases and intensity of heat transfer enhances due to an increase in the surface waves and rivulet deflection amplitudes.

1. Introduction
The fluid films falling under the gravity action along a flat surface are a well-known example of convective unstable flow with instabilities of various types, leading to formation and interaction of surface waves with a wide variety of characteristics. The study of the liquid film flow instability and 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.

Two-dimensional waves in isothermal fluid films are unstable at three-dimensional perturbations. The synchronous waves without waves phase displacement in the transverse direction were discovered theoretically in [1], when the two-dimensional waves decay into three-dimensional ones. Park and Nosoko [2] registered experimentally that a wave unstable length to transverse three-dimensional perturbations decreases with increasing Reynolds number. Alekseenko and colleges demonstrated that this transition was accompanied by a significant redistribution of liquid in the transverse direction [3]. The detailed experimental study of transition from the 2D wave regime to the 3D one was presented in [4, 5]. The experiments were carried out on water and glycerin solutions. The waves moved along the vertical lines one after another, forming the rivulet-like structures with a higher film thickness in the residual layer behind the wave crest as compared to the film between the lines.

The surface tension dependence on temperature leads to the shear stress formation on the film surface. As a result, hydrodynamics and heat transfer are the interrelated processes, and this complicates the problem significantly. To date, various mechanisms of rivulet formation in the heated liquid films have been investigated, and the thermocapillary structures of different type have been registered [6].
The structures of A and B types differ in the level of heat flux density, required for their formation, as well as in size and nature of distance between rivulets dependence on the heat flux and density Reynolds number. High value of the temperature gradient up to 10-15 K/mm was registered on the film surface at the top of the heater, when the structure of type A was formed. The boundary condition close to $T = \text{const}$ 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 [7, 8]. At heat flux higher than the threshold value, a horizontal roller was formed on the heater, and this led to liquid movement in the form of rivulets and a thin film between them.

In regime B, the rivulets flows were formed gradually with an increase in the heat flux and distance from upper edge of the heater [6]. Boundary condition $q = \text{const}$ was registered on the heater surface. Heterogeneities in the thickness of the fluid film across the flow led to temperature heterogeneities on the film surface. A temperature gradient up to 1 K/mm was formed on the fluid film, leading to an increase of surface deformation.

Evolution of hydrodynamic waves to thermocapillary-wave structures at heating of the vertically falling liquid film was studied experimentally in [9] for high Reynolds numbers.

The interaction of the thermocapillary structures with waves were registered in [10]. The influence of artificial disturbances on the waves and rivulet structures was described in [11].

Breakdown dynamics was studied in [12] using a fiber-optic sensor. The influence of substrate wettability on thermocapillary breakdown of a liquid film was considered in [13]. In [14], the thermocapillary breakdown of a film was studied with a change in a wide range of heater sizes and Reynolds numbers.

This work focuses on the generalization and analysis of data on various types of thermocapillary structures formation, film breakdown and heat transfer enhancement on the liquid film with variation of Reynolds number from 0.1 to 500.

2. Experimental setup
The setup was a circulation loop including a pump, working section, rotameters, filter, pipelines, and stop valve. The working section consisted of a plate with thermostabilizer, film former and heater located on this plate. A copper heat exchanger of 150 mm width and 100 mm length was used as the heating element. A heated liquid was pumped through the rectangular channels inside the heat exchanger. The average heat flux was calculated by the temperature difference of the pumped liquid at the heat exchanger inlet and outlet at a given mass flow rate. The heater wall temperatures were measured by the three thermocouples located on vertical axis of symmetry. On the heated surface the boundary condition close to $T = \text{const}$ was implemented, providing high value of temperature gradients near the heater upper edge. The heat flux density was varied in the range of 0.5-10 W/cm². Reynolds numbers were varied from 0.1 to 500, where $Re = \Gamma / \mu$, $\mu$ is the fluid dynamic viscosity and $\Gamma$ is the liquid specific mass flow rate. The working section was open to the atmosphere.

Characteristics of the film flow were determined experimentally using simultaneous measurements of the thickness and temperature field on 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 registering the field of temperature on the film surface with resolution of up to 640 x 512 pixels and sensitivity of 18 mK. Measurement procedure and experimental setup were described in detail in [15].
3. Discussion
The thickness and temperature fields of the film surface were measured synchronously, and interaction of waves with thermocapillary instability was studied.

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

![Figure 1](image)

**Figure 1.** Three-dimensional distribution of film thicknesses over the water surface, Re=50, q= 6 W/cm². Bending lines visualize the approximate contours of rivulets. Dashed line indicates maximal deviation of rivulet from the middle position. Fronts of incoming 3D waves are shown in the upper edge of the heater.
In regime B, rivulets were formed gradually with increasing density of heat flux and distance from the heater upper edge. The type B structure was registered at Reynolds numbers from 0.1 to 500. Boundary condition \( q = \text{const} \) was realized on the heater surface, and the gradient of the temperature on film surface did not exceed 1 K/mm, Fig. 1c.

Formation of the smaller structure in the form of temperature heterogeneities across the film flow has been found. This structure, designated as type C, was observed in the residual layer of liquid after propagation of a large wave before formation of type A structure, Fig. 1b.

Figure 2 presents the currently available experimental and theoretical data generalization on the dimensionless distance between rivulets in structures on various fluid films. The thermocapillary structures of types A, B and C are indicated. As can be seen, the dimensionless distances between liquid rivulets in these cases are independent on the Reynolds number.

**Figure 2.** Generalization of data on dimensionless distance between the rivulets of wave and thermocapillary structures. 1 – type B structure, water [16]; 2 – type B structure, FC-72 [6]; 3 – type A structure, water, [17]; 4 – structure of type A, data of [18]; 5 – structure of type A, FC-72, [6]; 6 – the dependence of the distance between three-dimensional waves on Reynolds number [2]; 7 – type B structure, water solution of glycerin [16]; 8 – type A structure, water; 9 – type C structure, water.

Under action of the thermocapillary stresses directed from the hotter to the colder regions, an increase in the film surface deformation occurred. As a result, when the heat flux became higher, the fluid film breakdown took place. When forming the type A structure, the fluid film breakdown occurred in the heater upper part, where maximum deformation of the fluid film surface was registered, and during type B structure formation, it occurred in the heater lower part.

Generalization of experimental data on the density of heat flux, corresponding to formation of type A structures is fulfilled in the form of dependence between criterion \( K_{mA}^* \) and \( \text{Re} \).

\[
K_{mA}^* = -q_\lambda (\sigma T/(c \rho g v^2/3v^5))L/l_c,
\]

(1)
where $q_A$ is the heat flux density at which type A structures are formed, $v$ is the liquid kinematic viscosity, $c$ is the heat capacity of fluid, $g$ is the gravity acceleration, $L$ is the heater length, $l$ is the scale of viscous-gravitational interaction, $(v^2/g)^{1/3}$, $\rho$ is the liquid density, and $\sigma_T$ is the temperature derivative of surface tension coefficient equal to $\partial \sigma/\partial T$. The parameter $Km$ is an analogue of the Marangoni number and can also be considered as the ratio of the thermocapilalry tangential stress scale on the film to the scale of the tangential stress on the wall with a purely gravitational flow.

If only structures B were formed on the fluid film surface, breakdown always occurred between the formed rivulets in the heater lower part. With increase in the heat flux in the heater lower part, there was a increase deformation on the liquid film surface, which led to its breakdown. Data for the breakdown in regime B are summarized by dependence from [20]

$$Km_{crB}^* = 165Re.$$  \hspace{1cm} (3)

During formation of structures in regime A on the liquid film surface, the heat flux corresponding to breakdown, increased significantly, 1.76 times

$$Km_{crA}^* = 290Re.$$  \hspace{1cm} (4)

The nature of liquid film breakdown changed, which is explained by a change in film deformation and an increase in the wave amplitudes and rivulets deflection amplitudes.

The dependence of the average heat transfer coefficient on the density of heat flux is presented in Fig. 3. The average heat transfer coefficient is calculated by dependences $\alpha = q/(Tw - T_0)$. The calculations made using the Nusselt model [20] for a smooth film show good consistency with the experimental data for a small heat flux (Fig. 3a). Heat transfer enhancement during heat exposure has been detected. The convective heat transfer coefficient increases with heat flux increase.

![Figure 3](image_url)

**Figure 3.** Dependence of the average heat transfer coefficient on heat flux at Re = 33 and $T_0 = 23^\circ C$. 1 – experimental data; 2 – calculated for a smooth film using the Nusselt model [20] $T_0 = 23^\circ C$ (a); $T_0 = 15^\circ C$ (1), $23^\circ C$ (2), $30^\circ C$ (3), $40^\circ C$ (4) (b).
The area of most intensive growth coincides with the density of heat flux corresponding to the formation type A thermocapillary structure. After this structure formation in the heater upper part, the value of heat transfer coefficient growth with increasing density of heat flux does not stop but becomes smoother. This interesting result agrees with the data for the surface wave amplitudes and rivulet deflection. It can be argued that the obtained data indicate a significant intensification of heat transfer with increasing wave amplitudes and rivulets deflection. The maximum intensification of heat transfer for Re = 33 reaches 60% at T₀ = 30°C.

Conclusion
The data on formation of thermocapillary structures and breakdown of a heated fluid film flowing down a vertical surface with Reynolds number variation from 0.1 to 500 have been analyzed. It is shown that the distances between rivulets of thermocapillary structures do not depend on Reynolds number. It has been established that formation type A metastable thermocapillary structure in upper part of the heater affects the critical heat flux corresponding to fluid film breakdown. It is shown that the critical heat flux increases with increasing film Reynolds number; it exceeds significantly the data on breakdown in the absence of thermocapillary structures of type A. The development of type A thermocapillary structures at high heat flux density causes an increase in the wave and rivulet deflection amplitudes. It has been established that heat transfer coefficient enhances due to development of the thermocapillary instability in the heater upper part, which leads to an increase in surface waves amplitudes and rivulets deflection amplitudes.

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References
[1] Joo S W and Davis S H 1992 J. Fluid Mech. 242 529547
[2] Park C D and Nosoko T 2003 AIChE Journal 49(11) 2715
[3] Alekseenko S V, Guzanov V V, Markovich D M and Kharlamov S M 2012 Tech. Phys. Lett. 38(8) 739
[4] Kharlamov S M, Guzanov V V, Bobylev A V, Alekseenko S V 2015 Phys. Fluids 27(11) 114106
[5] Guzanov V V, Bobylev A V, Heinz O M, Kharlamov S M, Kvon A Z, Markovich D M 2017 International Journal of Multiphase Flow 99 474
[6] Chinnov E A and Kabov O A 2003 J. Appl. Mech. Tech. Phys. 44 708
[7] Kabov O A 1996 Heat Transfer Research 27(1) 221
[8] Kabov O A, Diatlov A V, Marchuk I V 1995 G P ed Celata and R K Shah 9–11 October Rome Italy I 203–10
[9] Chinnov E A 2014 Int. J. Heat Mass Transfer 71 106
[10] Chinnov E A 2017 Int. J. Heat Mass Transfer 108 2053
[11] Chinnov E A, Abdurakipov S S 2017 Int. J. Heat Mass Transfer 113 129
[12] Zaitsev D V, Rodionov D A, Kabov O A 2007 Micrograv. sci. technol. 19 100
[13] Zaitsev D V, Kirichenko D P, Kabov O A 2015 Technical Physics Letters 41 551
[14] Zaitsev D V, Semenov A A, Kabov O A 2016 Thermophysics and Aeromechanics 23 625
[15] Chinnov E A, Abdurakipov S S 2020 Int. J. Heat Mass Transfer 156 119822
[16] Shatskii E N, Chinnov E A et al. 2017 Technical Physics Letters 43 1080
[17] Chinnov E A, 2009 Thermophysics and Aeromechanics 16 69
[18] Franks A M, Kabov O A 2006 Phys. Fluids. 18 032107-1
[19] Chinnov E A, Sharina I A 2008 Thermophys. Aeromech. 15(1) 121
[20] Nusselt W 1923 Zeitschrift der VDI Bl 67(H9) 206