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Influence of artificial disturbances on characteristics of the heated liquid film

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ABSTRACT

The characteristics of a water film flowing down a vertical plate with a heater at high Reynolds numbers (Re = 300 and 500) with and without artificial disturbances with the "most dangerous" wavelength have been studied experimentally. The field of film thickness at different values of heat flux has been measured using the fluorescent method. The temperature field on the liquid film surface was registered by the IR scanner.

Artificial disturbances with the "most dangerous" wavelength decrease a distance between the rivulets and transverse deformation of liquid film. The temperature gradients and shear thermocapillary stresses on the film surface become smaller. Artificial disturbances with the "most dangerous" wavelength at high heat fluxes cause an increase in amplitude, spectral energy and integral energy of temperature pulsations per a time unit as well as expansion of the frequency range of temperature pulsations in-between the rivulets at the bottom of the heater. An increase in wave amplitude and velocity is observed in the inter-rivulet areas. An increase in wave amplitudes, velocities, and average integral pulsations of temperature per a time unit and frequency range expansion in the bottom part of the heater under the action of disturbances can enhance heat transfer and improve film resistance to breakdown.

1. Introduction

The liquid films are used in various processes with heat and mass transfer. Currently, active investigation of these processes and search for the methods of heat and mass transfer enhancement are in progress. For example, it is experimentally determined in [1] that on a thin foil heater the propagating rewetting front was not flat and it was characterized by a cellular structure with regular boiling rivulets and interrivulet zones. In [2], it was shown theoretically that on the surface of condensate film the natural waves caused by flow instability are generated; they enhance heat transfer significantly. Heat transfer at the water film flow on a vertical surface of the heater was studied experimentally in [3] in the range of Reynolds numbers from 1 to 45. An increase in local heat transfer coefficient was detected at the heater bottom in-between the rivulets with an increase in the heat flux. Heat transfer enhancement was observed in [4] in a falling water film under the influence of artificial disturbances at Reynolds number of 250. It was shown in [5] that waves on the film surface had an impact on the heat transfer enhancement.

Two regimes of rivulet formation were distinguished in non-isothermal liquid films [6]. When the structures under regime "A" are formed, high temperature gradients of 10–15 K/mm are observed in the upper part of the heater. The boundary condition close to T = const was implemented on the heater surface. When the threshold heat flux was achieved at the heater top, significant deformations appeared on the film surface, and the flow was divided into vertical rivulets with certain wavelength Λ. At low Reynolds numbers high thermocapillary stresses, directed against the flow, led to film thickening in the form of a horizontal roll [7]. Theoretical studies are usually restricted by the analysis of the flow of non-isothermal waveless liquid films at low Reynolds numbers [8–10]. The existence of structures "A" at $Re \leq 2$ was confirmed. It was shown that at critical Marangoni number the perturbations with the "most dangerous" wavelength develop and lead to the formation of rivulets on the surface of the heated fluid film. The wavelength of the disturbances is equal to distance between rivulets.

In the case of regime "B", the rivulet flow was formed gradually with increasing heat flux and distance from the upper edge of the heater [6]. On the heater surface boundary condition q = const was

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implemented, and temperature gradients on the film surface did not exceed 1 K/mm. Under the influence of thermocapillary forces, directed from the hotter regions to the cold ones, film surface deformation occurred. Evolution of hydrodynamic disturbances into a thermocapillary-wavy form by heating the vertically falling liquid film was studied experimentally in [11,12]. Formation of temperature inhomogeneities before the 3D front of hydrodynamic wave was determined. These inhomogeneities lead to liquid film deformation and rivulet formation due to thermocapillary forces. The distances between the rivulets were also measured depending on the heat flux.

It is known that at a certain distance from the nozzle, the two-dimensional waves are formed on the surface of the isothermal liquid film. Hydrodynamic 2D waves in isothermal liquid films are unstable to three-dimensional disturbances. At decay of 2D waves into 3D ones, the synchronous waves without a shift in the transverse direction and subharmonic waves with phase shift were distinguished in [13,14]. Propagation of 2D and 3D waves on vertically falling isothermal water film under the effect of artificial disturbances was studied in [15] at $Re = 10–100$. It was shown that at $Re > 40$, the 3D synchronous waves propagate over the vertically falling water film, and horizontal distance between the crests of these waves does not depend on the Reynolds number.

Experimental results on transition from 2D to 3D wave motion on the vertically falling isothermal liquid films were presented in [16]. It was shown that this transition is accompanied by significant redistribution of liquid in the horizontal direction. Information about the characteristic shape of 3D structures, developed during transition, was presented.

Quasiregular metastable structures in the residual layer between the large waves of the laminar-wavy liquid film were investigated in [17]. To obtain the temperature field on the liquid film surface, an IR camera field was used in the experiment; to measure the thickness, the confocal method was applied. The assumption about the thermocapillary nature of regular structures in the residual layer of the film was confirmed experimentally. It was shown that an increase in the local surface temperature leads to a decrease in the local film thickness. The same result was presented in [5].

Dynamics of temperature and thickness pulsations on the surface of the vertically falling heated water film at $Re = 150–500$ at propagation of developed 3D waves was analyzed in [18]. Some temperature disturbances are displaced to the area of rivulets due to transverse thermocapillary forces. At high heat fluxes only maximal temperature pulsations, caused by the largest waves, reach the lower edge of the heater. The maximal relative wave amplitude and temperature pulsations, characterized by the modified Marangoni number, increase with film heating in the inter-rivulet areas and do not change on the rivulet crests. This effect is enhanced with an increase in Reynolds number of liquid film.

Analysis of the effect of external forces on wave dynamics and temperature pulsations in the heated liquid films is important for understanding the mechanisms of heat transfer enhancement and film rupture. It was found out that when generating external artificial disturbances by using a system of cylinders of the same diameter, located in a horizontal line, immersed into the liquid film above the upper edge of the heater, there was a significant change in deformation on the heated film surface [6]. The "most dangerous" wavelength, when artificial disturbances significantly alter the distance between the rivulets in the falling non-isothermal liquid film, was determined in [19]. It was shown that for $Re < 40$, the "most dangerous" wavelength for a water film is 9.5–10 mm. This "most dangerous" wavelength corresponds to the distance between the rivulets in regime "A". Creation of high temperature gradients on the liquid film surface (critical number Marangoni) is necessary for the formation of rivulet flow in this regime. If the required temperature gradients on the film surface are not realized, we can produce artificial disturbances with the "most dangerous" wavelength for the purpose of forming and developing rivulets in regime "A".

Fig. 1 presents dimensionless spacing Λ/l_σ between rivulets on the liquid film surface in the heater region as a function of dimensionless spacing between disturbing cylinders l_w/l_σ (l_σ is the capillary constant equal to $[\sigma/(g\rho)]^{1/2}$, where σ is the surface tension coefficient, g is the acceleration of gravity, and ρ is the liquid density). One can see that a region, defined by the dashed lines, exists, where artificial disturbances can cause a significant reduction of spacing between rivulets. For disturbances with $l_w/l_\sigma < 2.8$ and $l_w/l_\sigma > 4.8$, the dimensionless spacing between rivulets is limited to the range $5 < \Lambda/l_\sigma < 7$ (continuous lines in Fig. 1), which corresponds to formation of rivulets in regime "B" without artificial disturbances. At $2.8 < l_w/l_\sigma < 4.8$, the dimensionless spacing between rivulets varies from 5 to 3.6. At $3.3 < l_w/l_\sigma \leq 3.6$ (dot-and-dash lines in Fig. 1), the rivulets with the minimal spacing between them ($\Lambda/l_\sigma = 3.6$) are formed on the film surface. The "most dangerous" disturbance wavelength is achieved. The regime of development of naturally forming instability ("B") existing on the film surface is fully suppressed.

It was found out in [20] that artificial disturbances with the same distance between the cylinders change the distance between rivulets up to $Re = 500$. It was determined that under the effect of external disturbances, the thermal entry length (the distance between the upper edge of the heater and the point, where the heated boundary layer reaches the surface of the film) increases in the interrivulet areas, formed between the crests of three dimensional synchronous waves, and decreases in rivulets.

The studies of hydrodynamics and heat transfer of flowing down liquid films are based on new experimental methods. This is largely due to the result of limited applicability of theoretical models (only for small Reynolds numbers). Thermography research methods were developed in the works [21–23]. The fluorescent method was applied to study of isothermal flowing down liquid films and film thickness measurements in [14]. The improvement of this method for investigation of heated liquid films was performed in [24,25]. The thickness of liquid films was also measured by using the optical-fiber [26], capacitive [11,27] and confocal [17] methods. A detailed methodological analysis of the liquid films thickness, measured by the capacitive and fluorescence methods, was carried out in [25]. The papers [5,28] describe the development of an experimental technique that combines simultaneous planar laser-induced fluorescence and infrared

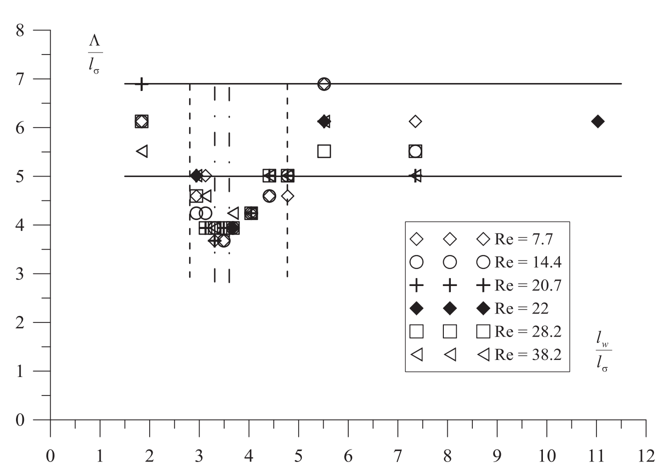

Fig. 1. The dimensionless spacing between rivulets on the surface of liquid film in the heater region as a function of dimensionless spacing between the cylinders [19]. The diameter of disturbing cylinders $d_w = 2$ mm.