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Wave – Thermocapillary effects in heated liquid films at high Reynolds numbers

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ABSTRACT

The temperature distributions and wave characteristics of the water film flowing down a vertical plate with a heater of 100 × 150 mm at Re = 150, 300, 500 are studied. The field of film thicknesses at different heat flux values was measured using the fluorescence method. The temperature field on the film surface was measured by an infrared scanner. The experimental data were obtained for variations in temperature over the liquid film surface with time during the propagation of waves. Thermocapillary forces that arise on heating lead to the formation of rivulets separated by thin layer troughs, with three-dimensional (3D) waves propagating over the crests of rivulets. Averaging of measurements allowed the values of the transverse film deformation and distance between the rivulets to be determined. In the interrivulet zone Marangoni number increases with a rise of the heat flux. The amplitudes of 3D waves in a water film flowing down a vertical heated plate have been measured. The film thickness and 3D wave amplitudes on the heater grow with increasing heat flux and distance downstream the flow, but the relative wave amplitude remains unchanged. In the heated regions between rivulets, the relative amplitude of waves increases with decreasing average thickness (or local Reynolds number). Analysis of results obtained for large Reynolds numbers showed that the relative amplitudes of waves in the regions between rivulets at high heat fluxes are much greater than those for small Reynolds numbers and in isothermal falling films. Two mechanisms of thermocapillary forces influence on the motion of the wavy liquid film are marked. For the first time, the exhibition of such a strong thermocapillary effects is revealed in the heated liquid film at high Reynolds numbers.

1. Introduction

The heat transfer processes in liquid films are widely used in industrial technologies. Investigation of the three-dimensional (3D) wave dynamics during the formation of rivulet flows in nonisothermal liquid films is necessary for better understanding of the mechanisms of heat transfer and crisis phenomena in heated films. Besides the fundamental science interest, this knowledge is important for increasing the efficiency of modern heat and mass transfer apparatuses.

Due to the danger of rupture, film processes are implemented in practice, as a rule, at high Reynolds numbers (Re = 50–1000). It was believed earlier that thermocapillary phenomena under these conditions had no appreciable effect on hydrodynamics and heat transfer in the falling liquid films. The appropriate engineering calculation formulas were created without consideration of the influence of thermocapillary forces [1,2].

Various regimes of the structures formation in a heated falling liquid film were discovered in [3–6]. The structures in regimes A and B differ by the level of heat flux necessary for their formation and by the character of the wavelength dependence on the heat flux and the Reynolds number. The appearance of flow structure in regime A is accompanied by the development of high temperature gradients (up to 10 K/mm) in the upper part of the heater [4]. Under the action of thermocapillary forces directed against the flow (from heated to cold regions), the film exhibited thickening and, in the case of a threshold heat flux, the flow disintegrated into vertical rivulets separated by thin film. Previously, the formation of regular structure in a thermocapillary regime A on the surface of a smooth liquid film flowing down a vertical wall containing small size (6.5 × 13 mm) heaters was discovered and studied at small Reynolds numbers. Recently, data on the formation of flow structure of this type on the wave surface of water films flowing down extended heaters with lengths of 100 mm at Re = 150 were reported in [7]. The results of theoretical investigations, which were usually restricted to analysis of the flow of a nonisothermal film at small Reynolds numbers [8–12], confirmed the existence of this structure.

The rivulet flow structure in regime B gradually develops with growing heat flux and increasing distance from the upper edge of

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Nomenclature

$A = H_{max}$ wave amplitude (mm)
$A_{max} = (H_{max} - H_{min})/H_{av}$ relative (dimensionless) amplitude, the ratio of the difference between the largest maximum and smallest minimum for large waves to the average film thickness in the region of measurements
g gravity acceleration (m/s^2)
$Def = (H_{riv} - H_{val})/H_0$ ratio of the difference between mean film thicknesses on the rivulet crest and in the valley between rivulets to the initial film thickness
H thickness of the heated liquid film (mm)
H_0 initial film thickness averaged by time and heater width (mm)
H_{av} average film thickness in the region of measurements (mm)
H_{max} largest maximum of wave (mm)
H_{min} smallest minimum of wave (mm)
H_{riv} average film thicknesses on the rivulet crest (mm)
H_{val} average film thicknesses in the valley between rivulets (mm)
$Ka_{loc} = \sigma^3_{loc}/(g\nu^4_{loc}\rho^3)$ local Kapitza number
L heater length (mm)
$l\sigma = (\sigma/\rho g)^{0.5}$ capillary constant (mm)
$Ma = -\sigma_T\Delta_T/(\rho\nu^{4/3}g^{1/3})$ Marangoni number
$Mn^* = \frac{\tau_{sur}}{\tau_w} = \frac{\partial\sigma}{\partial T}\frac{\partial T}{\partial x}\frac{1}{\rho g H}$ modified Marangoni number
q heat flux (W/cm^2)
q_b heat flux of film rupture (W/cm^2)
$Re = \Gamma/(\rho\nu)$ Reynolds number at inlet film temperature
Re_{loc} local Reynolds number of the film
T_0 inlet film temperature (°C)
T, T_{sur} temperature of film surface (°C)
T_{max} the mean maximum temperature (°C)
T_{min} the mean minimum temperature (°C)
T_F mass average temperature (°C)
t time (s)
X coordinate along the flow from the upper edge of the heater (mm)
X_n distance from the lower edge of film-former nozzle to the upper edge of the heater (mm)
$X_p = X_n + X$ distance from the lower edge of film-former nozzle to the point of measurement (mm)
Z coordinate from the left edge of the heater (mm)

Greek symbols
Γ specific mass flow rate of liquid (kg/m s)
Λ averaged transverse distance between the rivulets (mm)
ν coefficient of kinematic viscosity (m^2/s)
λ length of hydrodynamic waves (mm)
μ coefficient of dynamic viscosity of liquid (Pa s)
ρ liquid density (kg/m^3)
σ coefficient of surface tension (N/m)
σ_T temperature derivative of surface tension coefficient (N/mK)
$\tau_{sur} = \sigma_T \mathrm{grad}T$ thermocapillary shear stress on the liquid film surface (Pa)

the heater [13,14]. The presence of transversal nonuniformity in the film leads to inhomogeneity of the temperature field on the film surface. The resulting temperature gradient (up to 1–2 K/mm) gives rise to increasing deformation of the liquid film surface [15]. It was established [16–18] that, for sufficiently high heat fluxes at 6 < Re < 250, the distance between rivulets weakly depends on the Reynolds number, slope of the plate, and path length traveled by the flow. The existence of the two types of structures on the surface of a nonisothermal flowing liquid film was confirmed theoretically in [19]. It was shown that a thermocapillary regime leads to a decrease in the wave flow, while a thermocapillary-wave regime admits wave propagation only along calculations were restricted to a region of Re < 5–8 and did not describe the transition from a hydrodynamic instability in a wavy liquid film to 3D perturbations.

An experimental investigation of artificial disturbances influence on the formation of structures was performed under conditions of flow of water film on a vertical plate with a heater [20,21]. It is found that artificial disturbances on the surface of liquid film may cause a significant variation of the spacing between rivulets, and the scenario of evolution of wave pattern depends on their intensity. Artificial disturbances on the film surface cause the transverse distance between rivulets to decrease from values corresponding to the thermocapillary-wave regime B of formation of rivulets to values close to those of transverse distance typical of the thermocapillary regime A. It is demonstrated that it is possible to control the formation of structures on the surface of a heated film of liquid, and the conditions of maximal effect of artificial disturbances are determined.

The main part of investigations of the thermocapillary force effect on hydrodynamics and heat transfer in falling liquid films was performed at small and moderate Reynolds numbers (Re < 50). In [22] the formation of rivulets in the falling liquid film was investigated at Re = 33. Measurements of the local thickness of the film were taken using the fluorescence method. In [23] the wave characteristics of the falling liquid film were investigated using the capacitive and fluorescence methods. The film Reynolds number varied from 22 to 33. The influence of the transverse and longitudinal thermocapillary effects on formation of rivulets and creation of waves was studied. In [6], the formation of regular rivulets under the condition of liquid film flow in the area of 2D and 3D waves on the vertical heater with a size of 150 × 150 mm was investigated in experiments with water and with the FC-72 liquid. Two regimes of rivulet formation are described. It is found that within the thermocapillary-wave mechanism, vertical rivulets form on the inhomogeneities in the film thickness along the crests of two-dimensional waves (during their breakup into three-dimensional waves) or on the developed synchronous 3D waves.

In [24] experimental studies of regular rivulet flows in cryogenic liquid films flowing down the heated surfaces were conducted. The influence of evaporation intensity on the dynamics of wave characteristics variation along cryogenic liquid film flowing at non-adiabatic conditions was presented in [25]. The growth of wave amplitude and heat transfer were discovered.

The experimental data about the influence of thermocapillary forces on the dynamics of wave structure development at flowing over the heated surface of subcooled oils in the wide range of Prandtl number first were obtained in [26,27] with the use of high-speed thermography and confocal method for local film thickness measurements. The existence of thermocapillary structures in the residual layer of liquid between the large wave fronts to be established.

The three-dimensional waves are most wide-spread in nature and technology provokes particular interest. In the case of breakup