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ROLE OF THERMOCAPILLARY CONVECTION IN RUPTURE OF A FALLING LIQUID FILM HEATED FROM BELOW

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ABSTRACT

The present work is aimed to describe and explain the physical mechanism of the rupture of a liquid film of moderate thickness falling down a heated substrate. Our investigations are based on the experimental data obtained using IR thermography, fiber optical technique as well as theoretical estimation of critical values. We show that thermocapillary convection may be responsible for critical film thickness. By investigating the instability of thermocapillary cells we demonstrate that thermocapillary forces play a dominant role in the first and the second stages of the dry patch formation process.

INTRODUCTION

Heated liquid films are used to ensure high heat and mass transfer rates and have important applications in engineering and microgravity. However, the free surface of the liquid film heated from below is susceptible to disruption by a number of phenomena such as thermocapillary instabilities, evaporation and boiling. In addition, the breakdown is followed by local film dry-out resulting in formation of apparent contact line. The actual physics that governs the phenomenon of the dry patches formation and the prediction of such processes in practice still remain unclear today. The goal of the present work is to attempt to describe and explain the possible physical mechanism of the rupture of a liquid film of moderate thickness falling down a heated substrate.

Experimental investigations by Kabov (1) discovered a spanwise regular structures formation for films falling down an inclined plate with a built-in rectangular heater and the increasing of the heat flux subsequently led to the formation of dry patches between rivulets. The slight influence of the plate inclination angle on the threshold heat flux required for film rupture was noticed. A nonuniformly heated liquid film may rupture either through the deformation touching the substrate, or through instability of the thinned region in accordance with long-wave theory (2, 3). The validity of the theory was confirmed by experiments with a heated 0.13-1.68 mm thick silicon-oil layer (4), where the predicted and measured minimum film thickness prior the rupture agreed to within 20 percent. The ‘dry patches’ reported in experiments were actually coated with a very thin adsorbed-layer of oil, the thickness of which was estimated to be less than 1 μm. In case of uniform heating long-wave theory predicts the film rupture through a spontaneous instability. And the point appears that the liquid film either resting on a horizontal substrate or falling down an inclined plate is not able to induce steady-state deformations of the interface (3). Experiments (5), which is not reasonable to explain in the context of long-wave theory, showed the development of a quasi-steady rivulet-like structures in a liquid film falling down a plate with a 150×150 mm heater for a wide range of the Reynolds number (Re=2.4–330). The effect of the heat flux on the film flow led to the formation of periodically flowing rivulets separated by thin film regions. It is found that upon reaching a certain critical thickness, the film between rivulets spontaneously ruptures (6) and it is subsequently showed that this critical thickness depends neither on the Reynolds number nor on the plate inclination angle (7).

Investigations by Kabov (8) showed that the appearance of dry spots is usually preceded by formation of regular structures and their evolution for the falling liquid film under local heating. The critical heat flux for the breakdown of the locally heated subcooled liquid film was found to be higher than for vertical tubes by one order.

The 0.85–1.3 mm thick layers of ethanol heated from below studied by Orell and Bankoff (9). They observed the appreciable thinning of the film prior to rupture with formation of Bénard–type flow cell pattern. At the threshold heat flux a dry patch quickly originates as a pinhole within the thinned region. VanHook et al. (10) performed experiments revealing that deformational instability leads to a drained region in an initially flat silicon oil layer heated uniformly from below. The initial thickness of the layer ranged between 50 μm and 250 μm and the temperature drop across the layer was between 0.05 ^{o}C and 5 ^{o}C as it was calculated assuming conductive heat transport. The long-wavelength instability is found to supplant hexagonal convection cells as the primary instability. The crucial role of the thermocapillary stresses in formation of nanopillar arrays in molten nanofilms was reported by authors of (11).

The long-wave analysis and the experimental works investigating the non-isothermal liquid film rupture (see review by Oron, Davis, Bankoff (3)) showed that dynamic Bond number can be a qualitative indicator of whether or not the film ruptures. This means that critical film thickness prior the rupture should depend on gravity and the plate inclination angle.

We investigate a gravity-driven subcooled liquid film practically uniformly heated from the substrate. The test section is opened into the atmosphere and the liquid film is in contact with the ambient air. As the heat flux grows the longitudinal periodically flowing rivulets forms and stable thin film forms between the rivulets. It was found that upon reaching a certain critical thickness (~60 μm), the film between rivulets spontaneously ruptures (6) and it was subsequently showed that this critical thickness depends neither on the Reynolds number nor on the plate inclination angle (7). The experiments were performed for water-air system. In the present work we give a hypothesis describing the physical scenario of such kind of the film disruption and confirm it by the preliminary experiments.

NOMENCLATURE

a	thermal diffusivity coefficient, m^2/s
Bo	Bond number
Bo^*	Dynamic Bond number
c_p	specific heat capacity, J/kgK
k	liquid thermal conductivity, W/mK
k_g	gas thermal conductivity, W/mK
g	gravity acceleration, m/s^2
Re	Reynolds number
Ra	Rayleigh number
Q	volumetric flow rate, m^3/s
h_0	initial film thickness, m
h_{cr}	critical film thickness, m
Ma	Marangoni number
T	temperature, K, ^{o}C
T_{cr}	critical temperature, K, ^{o}C
T_g	gas temperature, K, ^{o}C
T_w	temperature of the heated plate, K, ^{o}C
W	width, m
ΔT	temperature difference, K, ^{o}C
α	wavenumber, m
β	coefficient of thermal expansion, 1/K
λ	wavelength, m
ν	kinematic viscosity, m^2/s
σ_0	liquid surface tension, N/m
σ_T	surface tension temperature dependence coefficient, N/mK
Θ	inclination angle, degree

EXPERIMENTAL RESULTS

The experiments are performed on a closed-type flow loop (Fig.1, (7)). Distilled water as a working liquid is supplied from a thermostat into a film distributor with a calibrated 285 μm flat nozzle slot, to form a film flow of width W=150 mm (initial temperature of liquid is 24°C; the range of Reynolds number is Re=$Q/W\nu$=3.2–30.2, where Q is the volumetric liquid flow rate, ν is the kinematic viscosity; initial film thickness, calculated using the Nusselt equation, h_0=$(3\mathrm{Re}\,\nu^2/g\sin\Theta)^{1/3}$, ranges from 93 to 368 μm).

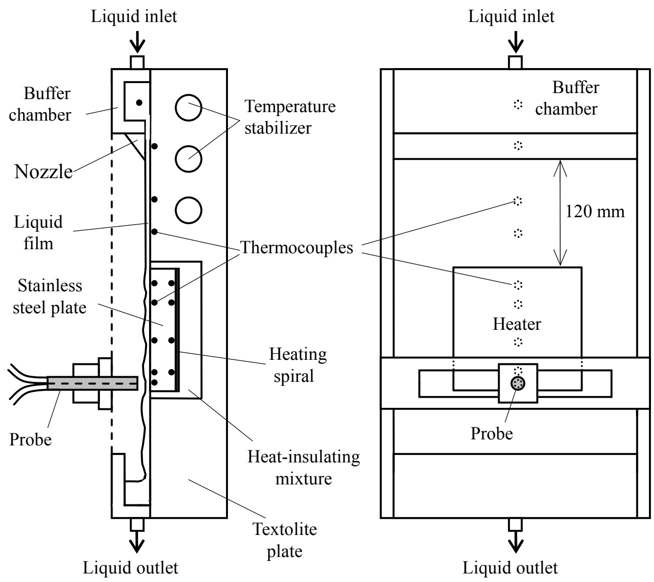

Figure 1: Cross-section (a) and front view (b) of the test section.

The film distributor is situated at the top of the main plate made of textolite. A 150×150 mm electrical heater is embedded in the plate at a distance of 60 mm from the nozzle slot. The base of the heater is a stainless steel plate 6 mm in thickness, to the inner surface of which a flat heating spiral is attached. The average heat flux on the heater, q, determined by the electric power dissipated on the heating spiral, varies from 0 to 1.53 W/cm^2. Several thermocouples are embedded in the steel plate to measure its surface temperature. In order to minimize heat losses from the heater into the textolite plate, a 2 mm gap around the heater is filled with a mixture of epoxy resin and charcoal, having thermal conductivity of 0.15 W/mK. The experiments are carried out under quasi-stationary conditions.

The test section is opened into the atmosphere. Plate inclination angle with respect to the horizon, Θ, is varied from 3 to 90 deg.

To measure the instantaneous local film thickness we use a non-contact fiber optical probe. The probe is positioned on the free surface side of the film at a specified distance from the substrate, 600 μm in the present study. For a smooth film the method provides an accuracy of about 5 μm. The sensitivity, spatial and temporal resolution of the technique is about 1 μm, 0.5 mm and 10^{-4} s, respectively. The method is described in detail in (12).

We present in Figure 2 obtained by Zaitsev et al. (7) data on critical film thickness h_{cr} in coordinates (Re; $h_{cr}(\sin\Theta)^{0.006}$). Exponent at $\sin\Theta$ is obtained from minimum scatter of points. Let us briefly outline the conclusions obtained in (7). Rupture of a subcooled flowing liquid film heated from substrate is preceded by the formation of steady state longitudinal film surface deformations. It is found that the film spontaneously ruptures at the moment when the film thickness in the thinned region reaches a certain critical minimum and the substrate temperature reaches a certain critical maximum. Both critical values depend neither on the Reynolds number nor on the plate inclination angle, and for water with initial temperature of 24°C are about 60 μm and 45°C, respectively.

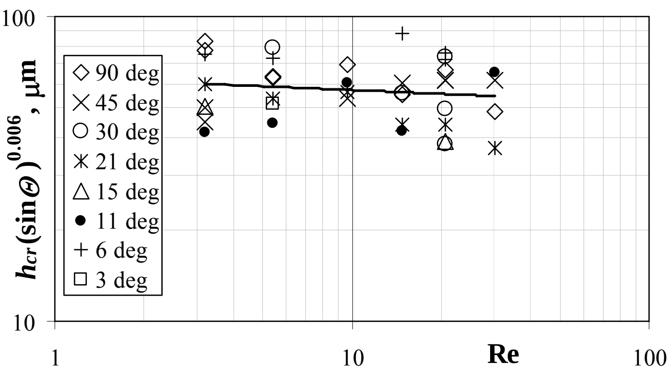

Figure 2: Critical film thickness for different Re and Θ. Line – generalization of data, (7).

ESTIMATIONS OF THE CRITICAL VALUES

We propose the occurrence of small-scale longitudinal jet-like film deformations initiated by thermocapillary convection (Fig. 3) at the moment when stable thin film forms between the rivulets. The wavelength of this thermocapillary structures is much smaller than typical length of thermocapillary instability, leading to film rupture. The structures cause small-scale variations in the film thickness and thus in the film surface temperature, smoothing large-scale temperature variations. Thus, these structures due to small-scale thermocapillary convection can stabilize the film against thermocapillary rupture. We give an estimation of the critical values in the context of Pearson's theory. As the heat flux grows the film thickness between rivulets gradually decreases and upon reaching a certain critical thickness the thermocapillary flow becomes unstable and the film spontaneously ruptures. This closed hypothesis is capable to explain the independence of the critical film thickness prior the rupture on Reynolds number and the plate inclination angle. To certainly prove the theory more detailed experimental data are needed. We also perceive that the presence of ambient air (14) can be important for the occurrence of Marangoni convection.

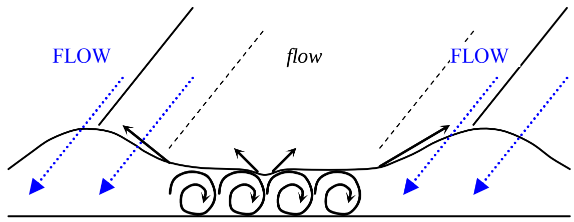

Figure 3: Sketch of the flow.

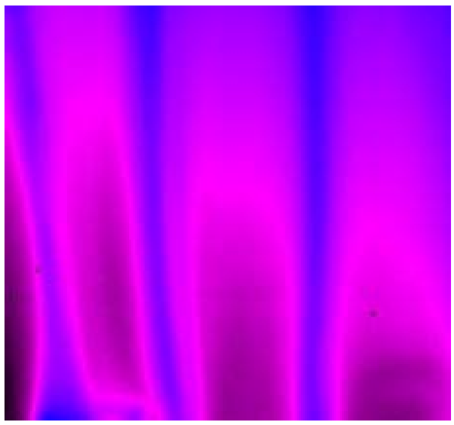

Figure 4: IR image of rivulets for water, g=90 degree, Re=15, q=0.8 W/cm^2.

Let us define the Marangoni, Rayleigh, Bond and dynamic Bond numbers:

$$Ma = \frac{\sigma_T \left(c_p \Delta T\right) h}{\nu k},$$

$$Ra = \frac{g\beta\nabla T h_0^3}{\nu a},$$

$$Bo = \frac{\rho g h_0 \cos\Theta}{\sigma_0 / h_0},$$

$$Bo^* = \rho g h_0^2 \big/ \sigma_T \Delta T .$$

The buoyancy-driven convection is negligibly small since *Ma/Ra*>110 for all considered regimes. The maximal Bond number is $Bo_{\max}\underset{h_{0\max}=400\mu m}{\approx} 0.02 \ll 1$. It is meant that gravity effect is negligible.

In order to estimate the value of the temperature difference across the film thickness we use the two-sided problem for heat transfer analogously to (10, Fig. 5). In that case from the boundary condition for flat conducting layers:

$$k\frac{dT}{dy} = k_g \frac{dT_g}{dy} \qquad (1)$$

we find the uniform temperature difference across the liquid layer ΔT, which is calculated knowing the top and bottom temperatures:

$$\Delta T = \frac{(T_w - T_g)H}{1+H}, \text{ where } H = \frac{k_g}{k} \qquad (2)$$

Substituting the experimental values $T_w = 45\ ^oC$, $T_g = 24\ ^oC$, $H = \frac{k_g}{k} = 0.039$, we obtain the temperature difference ΔT=0.824 K.

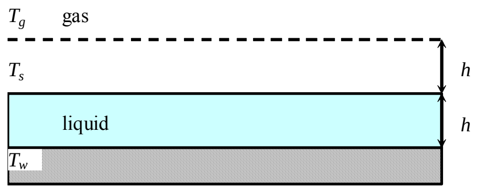

Figure 5: Sketch of the two-layer problem.

We determine the dynamic Bond number and Marangoni number in the region of the stable thin liquid film between the rivulets: $Bo^*\underset{h=60\mu m}{\approx} 0.2$ and *Ma*=103, respectively.

The long-wave analysis and the experimental works investigating the non-isothermal liquid film rupture (see review 3) showed that dynamic Bond number can be a qualitative indicator of whether or not the film ruptures. By this it is meant that critical film thickness prior the rupture should depend on gravity and the plate inclination angle. The recent our investigations of a gravity-driven subcooled liquid film practically uniformly heated from the substrate showed that upon reaching a certain critical thickness (~60 μm), the film between rivulets spontaneously ruptures (6) and it was subsequently showed that this critical thickness depends neither on the Reynolds number nor on the plate inclination angle (7).

We have found that the Marangoni instability is responsible for the value of the critical film thickness just upon the liquid film rupture. We propose the occurrence of small-scale longitudinal jet-like film deformations initiated by thermocapillary convection at the moment when stable thin film forms between the rivulets. These small-scale deformations can be seen on Fig.6 in the middle of the upper side of the image (green-blue colors). The convection tends to smooth large-scale film surface deformations, and, thus, stabilizes the film against thermocapillary rupture.

We give an estimation of the critical values in the context of Pearson's theory. As the heat flux grows the film thickness between rivulets gradually decreases and upon reaching a certain critical thickness the thermocapillary flow becomes unstable and the film spontaneously ruptures.

The wavelength of small size rivulet-like convective structures between the larger rivulets can be estimated using IR scanner or from the instability analysis.

We use the simple linear stability analysis of the thermocapillary convection and find the critical values from the Pearson's problem (13). For flat liquid layer the height of the Marangoni cell coincides with the layer thickness *h*, whereas the transverse size of the cell is determined by the characteristic instability wavelength λ. If the Marangoni number well exceeds the critical value, then (13)

$$\lambda = \frac{2\pi h}{\alpha}, \text{ where } \alpha = \sqrt{Ma/8} \qquad (3)$$

Knowing the critical substrate temperature we can find the critical Marangoni number $Ma_{cr} = \frac{\sigma_T (c_p \Delta T) h}{\nu k}$, where ΔT is the temperature difference across the film thickness.

Hence, we find the critical wavelength:

$$\lambda_{cr} = 4\pi\sqrt{\frac{2\nu k h_{cr}}{\sigma_T c_p \Delta T_{cr}}} \qquad (4)$$

For critical values of film thickness *h*=60 μm and temperature difference ΔT=0.82 K we obtain critical wavelength $\lambda_{cr} \approx 0.1$ mm.

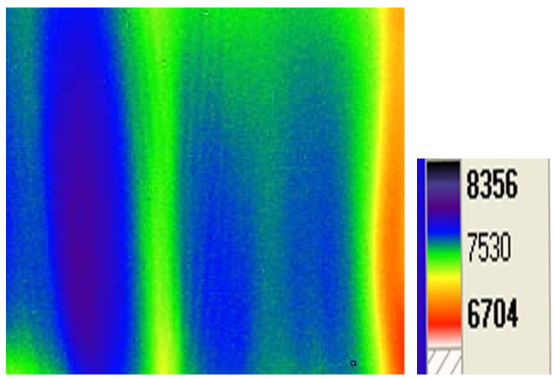

Figure 6: IR image for water, g=90 degree, Re=10, q=1 W/cm^2.

The infrared measurements of the film surface temperature are performed with high speed IR-camera TITANIUM 570M. It is seen the small size rivulet-like convective structures with the wavelength of approximately 0.5 mm (Fig.6) exist prior the rupture. These small-scale deformations can be seen in Fig.6 in the middle of the upper side of the image (green-blue colors). Having the discrepancy of the experimental wavelength and the theoretical estimation by the Pearson's theory we plan to give a more detailed analysis of the instability and perform more precise experiments.

Also we have performed preliminary IR investigation of flowing down liquid film. The forming rivulets clearly detected by IR-camera and the temperature gradient along the film surface can be found from the measurements (Fig. 4).

CONCLUSIONS

We investigate a gravity-driven subcooled liquid film practically uniformly heated from the substrate. The test section is opened into the atmosphere and the liquid film is in contact with the ambient air. As the heat flux grows longitudinal, periodically flowing rivulets form with regions of thin film between them. It was found that upon reaching a certain critical thickness (~60 μm), the film between rivulets spontaneously ruptures and it was subsequently showed that this critical thickness depends neither on the Reynolds number nor on the plate inclination angle. In the present work we give a hypothesis qualitatively describing the physical scenario of such kind of the film disruption and confirm it by the preliminary experiments.

We propose the occurrence of small-scale longitudinal jet-like film cells initiated by thermocapillary convection on thin film between the rivulets. The convection tends to smooth large-scale film surface deformations, and, thus, stabilizes the film against thermocapillary rupture. We give an estimation of the critical values in the context of Pearson's theory. As the heat flux grows the film thickness between rivulets gradually decreases and upon reaching a certain critical thickness the thermocapillary flow becomes unstable and the film spontaneously ruptures. This closed hypothesis is capable to explain the independence of the critical film thickness prior the rupture on Reynolds number and the plate inclination angle. To certainly prove the theory more detailed experimental data are needed. We also perceive that the presence of ambient air can be important for the occurrence of Marangoni convection.

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