Experimental study of the thermocapillary rupture dynamics of water and ethanol layers

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Abstract. Rupture dynamics of thin (500 µm) horizontal liquid films of water and ethanol was experimentally investigated during non-uniform heating from the side of smooth substrate. On the same substrate under similar heating conditions, the propagation rate of a dry spot in a horizontal water film was found to be several orders of magnitude higher than the rate of propagation of a dry spot in an ethanol layer.

1. Introduction

Many technological processes are based on liquid film flow. To ensure the stability of these processes, it is necessary to provide a continuous film flow without dry spots. In addition, thin liquid films are a promising candidate for cooling local heat sources such as computer chips. Non-uniformly heating of thin liquid layers leads to free surface deformations caused by the thermocapillary effect producing surface shear stresses arising due to surface tension temperature dependence. With an increase in the temperature gradient along the liquid layer, the deformations of the free surface increase and can reach the substrate with the formation of a dry spot. To avoid loss of system performance due to film breakdown, it is extremely important to understand the film breakdown mechanism.

The study of thermocapillary rupture of a nonisothermal horizontal liquid film heated from the substrate side began with the works [1, 2]. In [3-5] it was found that thermocapillary film rupture includes the stage of a thin residual film formation. The influence of heater size and inclination angle on the heat flux corresponding to the rupture of the gravity-driven film was investigated in [6-8]. Paper [9] reviewed theoretical and experimental studies of liquid film breakdown due to different mechanisms. Redon et al. [10] investigated the expansion of the dry spot in metastable liquid films on low-energy surfaces. In [11], the breakdown of thin liquid films sprayed on substrates with different wettability was studied. The effect of the wetting angle on the dry spot dynamics and on the critical heat flux upon the rupture of a horizontal liquid layer that is heated locally from the substrate side is studied experimentally in [12]. In [13] different working liquids and coatings are used to investigate the effect of the substrate wettability on the rupture of the nonisothermal falling liquid film. In [14-17], a confocal method was used to measure the thickness of liquid films.

In the present work, to study the process of thermocapillary rupture, a still horizontal liquid layer was chosen, since this is the simplest configuration of the film.
2. Experimental equipment and methods

Experimental investigations are conducted using the experimental setup shown in Figure 1. The test section consists of a textolite plate, a copper rod (12 mm in diameter) with an electrical heater, and a cooling circuit connected to the thermostat. The water temperature in the thermostat is 23°C. The test section is open to the atmosphere. A more detailed description of the experimental setup and methods is presented in [18].

A stainless-steel disk with a diameter of 51 mm and a thickness of 1 mm, on which a layer of working liquid is formed was used as a test substrate. The substrate was treated by polishing the disk to a flat mirror surface. The method of substrate treatment provided the surface roughness of the order of 0.05 µm. Power supply was programmed to control the heater power. The heating power automatically increased stepwise (0.15 W for every 18 s). Heating stopped immediately after the appearance of a dry spot on the substrate surface. Ultrapure Milli-Q water and ethanol (95 wt %) with the initial temperature equal to ambient temperature were used as working liquids. The experiments were carried out at an ambient temperature of 23–25°C and relative air humidity of 28–30%.

Figure 1. Schematic of the experimental setup.

Photron Fastcam high-speed camera with an optical schlieren-system was employed to visualize film disruption. The shooting speed was 50 and 3000 frames per second. The field of view of the camera was 23×23 mm. The resolution of the image was 1024×1024 pixels. To measure the instantaneous local film thickness, Micro-Epsilon controller IFC2451 with confocal chromatic sensor IFS2405-3 was used. ImageJ software was used to automatically process schlieren-images to calculate the dry spot area.

3. Experimental results and discussion

A horizontal liquid film forms on the substrate, after which the heater was turned on. Powering on the heater causes the liquid film thinning above the heater due to shear stress caused by the temperature dependence of surface tension. Figure 2 shows changes in film thickness above the heater center after heating starts. The figure also shows the surface temperature of a copper rod. The maximum shown temperature is the temperature at which the film rupture occurred. The evolution of the liquid film thickness and the rupture temperature are close for water and ethanol films. Unfortunately, it is not possible to measure the film thickness of less than 80 µm by confocal chromatic sensor IFS2405-3.
Figure 2. Change in film thickness above the heater center after heating starts.

Figure 3. The sequence of schlieren-images showing the dynamics of liquid film rupture. Upper row – water and lower row – ethanol. The time from the dry spot nucleation is shown. A circle indicates the heating rod position (diameter 12 mm).

Figure 3 shows the dry spot dynamics in horizontal layers of water and ethanol. In a water film, the dry spot originates as a pinhole in the residual film and then quickly spreads along the substrate surface. The rupture of the ethanol layer begins at the edge of the residual layer, and as a result the ring shape dry spot is formed. In comparison with the rupture of the horizontal water layer, the growth rate of the dry spot during the ethanol film rupture is several orders of magnitude lower (figure 4).
Apparently, slow growth of the dry spot in the horizontal ethanol layer is associated with good wettability of the substrate with ethanol [12]. The maximum dry spot area in the water film is found to be several times larger than the maximum spot area in the ethanol film.

![Graph showing dry spot area over time](image)

**Figure 4.** Dry-spot diameter depending on time. Water (top image), ethanol (bottom image).

It should be noted that the dry spot in a water film remains at its maximum size even after the temperature gradient in the substrate disappears, while the dry spot in the ethanol film collapses once the heating stops due to the small advancing contact angle.
Conclusions
Before the stage of formation of a dry spot, the process of thermocapillary rupture of horizontal films proceeds according to a similar scenario in water and ethanol. However, after the nucleation of a dry spot, its dynamics for these working liquids is significantly different. A dry spot in a horizontal layer of water spreads several orders of magnitude faster than that in ethanol. In addition, a dry spot in the layer of water has a larger maximum size than that in a layer of ethanol and does not disappear even after the substrate cooling.

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