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Thermocapillary rupture of a horizontal liquid layer on a silicon substrate

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Abstract. This paper is an experimental study of thermocapillary breakdown phenomenon in a horizontal film of liquid placed on a silicon nonisothermal substrate. With the help of a high-speed video camera the speed of the three-phase contact line was measured during the growth of a dry spot.

1 Introduction

The modern industry often uses apparatus with liquid film flow. Thin liquid film is a promising approach for developing of cooling of devices with high local heat release, in particular, for high-end electronic chips [1,2]. The industry creates a need for cooling of high local heat fluxes from electronics components like computer chips, and power electronics (transistors and thyristors).

Film-based cooling systems are highly efficient since they provide a high rate of heat transfer at moderate flow rates of the coolant. The reduction in the film thickness enhances heat transfer; however, thin films are prone to film breaking and this increases drastically the temperature of the cooled element and may cause failure.

The effect of substrate wetting and liquid properties on the thermocapillary breakdown of a falling liquid film was studied in [3-5]. The paper [6] studied the effect of substrate structuring on phenomenon of falling liquid film breakdown. The papers [7, 8] deal with the effect of inclination angle and heater size on the heat flux at which the falling film breaks down. The paper [9] was pioneering in study of thermocapillary breakdown of a steady horizontal liquid layer. The papers [4, 10] demonstrated that the critical heat flux for the case of horizontal liquid films is by several times higher than the critical level for gravity-driven liquid films. This explains the relevance of the present study.

The key objective of this paper is to study the dynamics of liquid film breakdown using a high-speed camera.

2 Methods

Experiments were conducted with locally heated substrates made of silicon with the diameter of 50.8 mm and thickness of 0.4 mm. The substrate was mounted on a textolite

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basement with an embedded copper rod with the diameter of 12.7 mm (Fig. 1), and thermal paste was applied for improvement of heat contact between the substrate and basement. The copper rod has a thermal contact with a ceramic heater. The heat flux was calculated from the temperature drop over the copper rod for the situation of steady process. It was also controlled by the known electric power consumed by the heater. The working liquid was distilled super-pure Milli-Q water with the initial temperature of 25°C. The proper volume of water was fed to the substrate via a syringe pump. The substrate perimeter has cooling arrangement. The water temperature in the cooling circuit was sustained at 5°C.

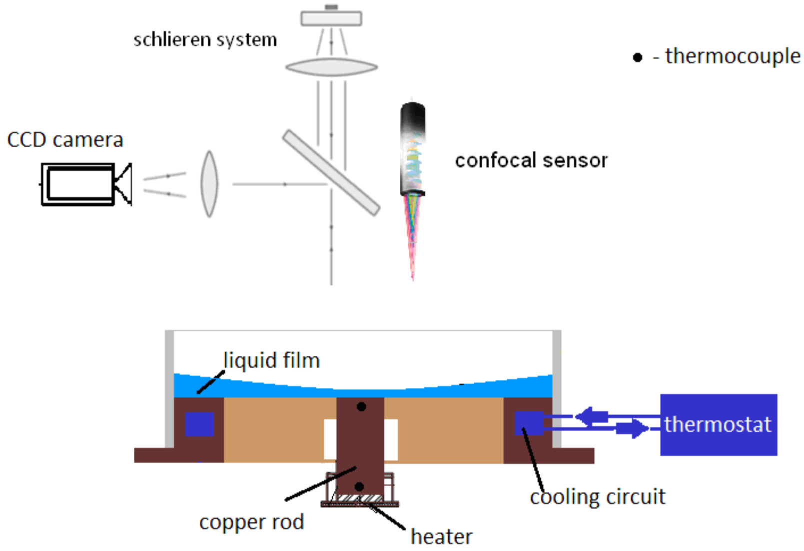

Fig. 1. Diagram of the experimental setup.

Experiments were carried out for films with the initial thickness 400-600 μm. The heat flux was incremented with small steps up to the threshold flux (which ensures film breakdown). The steadiness of process was controlled using thermocouples installed in the working section and heater. The film breakdown initiates a sharp growth of heater temperature.

To visualize the liquid surface deformations and disruption of the film, we used a Photron FASTCAM high-speed camera (shot at 2000 fps) coupled with an optical schlieren system. In order to measure the instantaneous film thickness, we used the confocal Micro-Epsilon chromatic sensor. For a flat film the method provides an accuracy in thickness measurement of about 1 μm. The spatial and temporal resolution of the method is about 0.5 mm and 1 ms, respectively. The total film thickness was controlled by he known volume of liquid fed using the syringe pump.

3 Results

Under the action of heating, a dry spot forms above the heater and spreads over the substrate (Fig. 2).

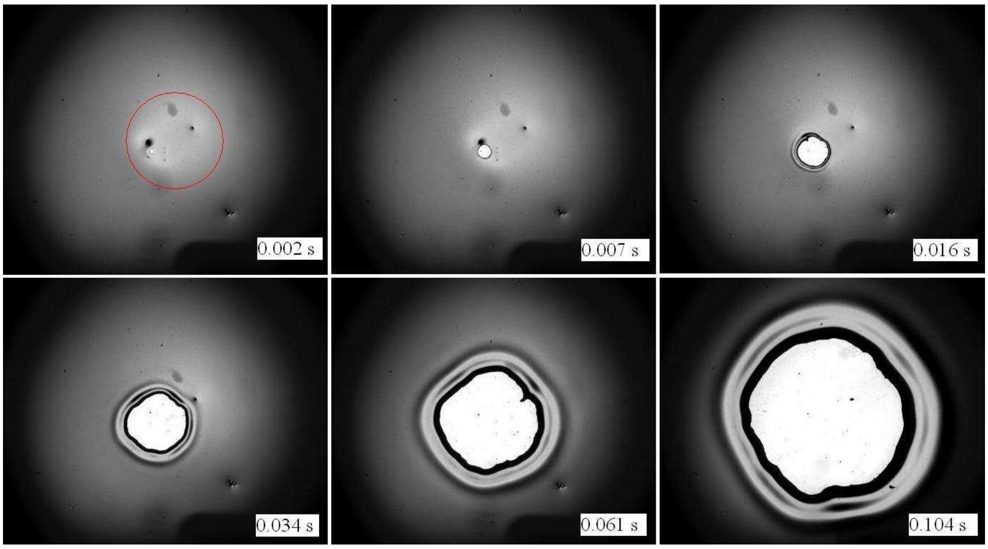

Fig. 2. The dynamics for dry spot expansion on the silicon substrate (for initial film thickness 600 μm, critical heat flux 11.2 W/cm^2). The time is measured since the breakdown startup.

To measure the contact line velocity we used the ImageJ software. The program automatically calculates the area of dry spots on the downloaded photos which are obtained at a shooting speed of 2000 frames per second (Fig. 3). Considering that the dry spot has a circular shape knowing its area and the time between frames, we calculate the contact line speed.

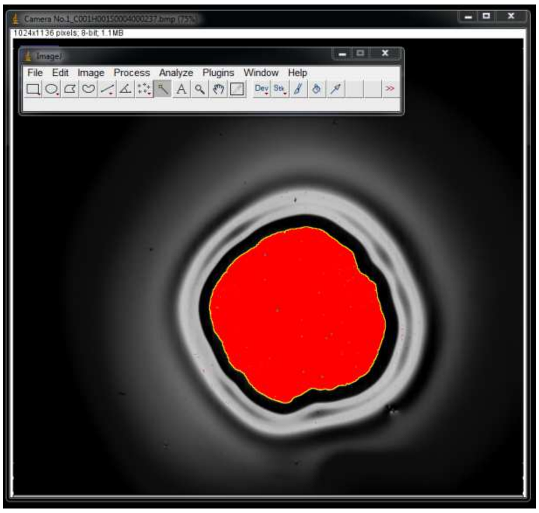

Fig. 3. ImageJ interface for calculating the dry spot area.

The initial thickness of the liquid layer was 400-600 μm and the critical heat flux was 8 -12 W/cm^2. At the initial moment of the rupture, the speed of the contact line was 0.06-0.1 m/s, then the speed of the contact line decreased as shown in Fig. 4.

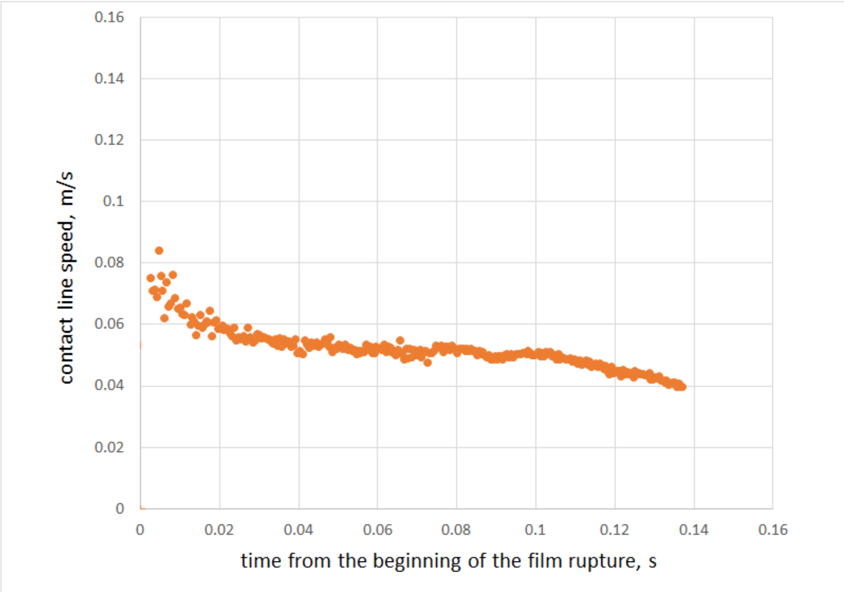

Fig. 4. Contact line velocity vs. time.

4 Conclusion

In the work we studied the process of rupture of a horizontal layer of liquid under the action of thermocapillary forces. As a result of heating, a dry spot forms above the heater and propagates along the substrate, and its propagation velocity is maximum at the initial moment of rupture, reaching approximately 8 cm/s.

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