The effect of viscosity on rupture dynamics in the non-uniformly heated horizontal liquid film

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Abstract. In the present work, we study the rupture dynamics of a horizontal liquid film non-uniformly heated from below in a wide range of liquid viscosity. To visualize the liquid surface deformations and disruption of the film, we use a Nikon digital camera (shot at 60 fps) coupled with an optical schlieren system. In order to measure the instantaneous film thickness, we use the confocal Micro-Epsilon chromatic sensor. It was found that the process of film rupture can be divided into three stages: 1) film thinning down to a residual film on the heater; 2) existence of a stable residual film for some time; 3) rupture and dryout of the residual film. The thickness of the residual film was found to strongly depend on the liquid viscosity: for water, it is about 10 µm, whereas for PMS-200 it is about 275 µm.

1. Introduction

Thin liquid films are widely used in different branches of industry and may provide very high heat transfer intensities at comparatively low flow rates. Also, liquid films can be used for cooling of high-power computer chips of electronics devices whose power dissipation has been increasingly growing in recent years.

A subcooled liquid film heated from the substrate is susceptible to thermocapillary instabilities arising from the temperature dependence of the surface tension (the so-called Marangoni effect), which may lead to film rupture. To avoid the loss of systems performance by film rupture, it is of paramount importance to understand when, why and how the film rupture occurs. Liquid films can be of different configurations: films flowing under the action of gravity, films flowing under the action of hydrostatic pressure, shear-driven films, but the simplest case is a still horizontal layer.

Papers [1, 2] were pioneering in studying of thermocapillary rupture of a horizontal liquid film non-uniformly heated from below. In 0.85–1.3 mm thick layers of ethanol [1] the appearance of a dry patch is preceded by the formation of a thinned region in the film with convective cells pattern. At the threshold heat flux, a dry patch quickly originates as a pinhole within the thinned region. In 0.13–1.68 mm thick silicon-oil layers [2] the heating causes a steady state thermocapillary dimple above the heater, gradually deepening with the heat flux, until finally the edge of the dimple touches the substrate, with formation of a nearly dry patch, remaining covered with a thin layer of oil less than 1 µm thick. In [3, 4] it was found that thermocapillary film rupture occurs through the formation of a thin residual film and its subsequence disruption. In [5] the authors used a confocal method trying to
measure the thickness of the residual film, but they failed due to the reflection of the probing light from the substrate.

In experiments with liquid films, it is important to measure the instantaneous liquid film thickness. Film thickness measurement methods are divided into intrusive and non-intrusive. In turn, non-intrusive methods are divided into the field (schlieren method [6], fluorescence method [7, 8]) and local (electric conduction method, capacitance method [8], fiber-optical method [4, 9-11], and confocal method [12-13]). The schlieren method is suitable for measuring film surface deformations with a tilt angle of no more than 3-5° and requires a reference point for measuring the absolute film thickness. The fluorescent method implies the use of a dye and is not suitable for measuring the thickness of evaporating liquid films (the concentration of the dye changes). Capacitance method and electric conduction method have low spatial resolution and require installation in the substrate. The fiber-optical method has bad angular characteristic and is appropriate for measuring the thickness of nearly flat films (with an inclination angle less than 1-2°). Against the background of the shortcomings of the methods described above, the confocal method seems to be most suitable for measuring thin liquid films since it has a high spatial and temporal resolution, high accuracy and good angular characteristic. In the present work, we use the confocal method for measuring rupture of heated liquid films in a wide range of liquid viscosity. In order to eliminate the reflection from the substrate, we applied a special black coating. The use of the thus improved confocal method has allowed us for the first time to measure the thickness of the residual film for water.

2. Experimental equipment and methods
The test section is a textolite plate with an embedded copper rod having a diameter of 12 mm (Fig. 1). The substrate has a cooling circuit over the perimeter with the temperature of the cooler (water) kept at 5°C. A ceramic electrical heater is attached to the bottom edge of the copper rod. In the experiments, the electrical power on the ceramic heater was 75 W. At that, the temperature of the surface of the copper rod, measured with the thermocouple, did not exceed 85°C. A plexiglass cylinder is mounted on the test section. To reduce the reflection coefficient, the substrate is coated with a special black paste. The experiments are carried out at an ambient temperature of 23–25°C. The test section is open to the atmosphere.

![Fig. 1. Schematic diagram of the experimental setup.](image-url)
Four different working liquids with the viscosity changing 200 times were used: ultrapure water (Milli-Q), silicon oils PMS-5, PMS-100, and PMS-200. PMS silicone oils are chosen as working liquids since they have practically the same basic thermophysical properties with a large variation of viscosity. A predetermined volume of the working liquid with the initial temperature of 25°C is fed to the substrate via a syringe pump to form a liquid film with the initial thickness varied from 400 to 700 µm.

To visualize the liquid surface deformations and disruption of the film, we used a Nikon camera (shot at 60 fps) coupled with an optical schlieren system. The main purpose of the schlieren system is to determine the curvature of the liquid surface. The schematic diagram of the system is shown in Fig. 1. The Lens 1 is placed in front of an incoherent Light source at the focus distance. Collimated light generated by a collimating Lens 1 passes through 50% Beam splitter towards the liquid layer. Then part of the light reflects from the surface of the liquid. The reflected light goes again through the beam splitter and then focuses by the Lens 2 in its focal plane. Finally, the intensity of the images obtained is related to the inclination angle of the film surface. In our work, the schlieren method was used only for visualization without measuring surface deformation. The field of view of the camera is 32×18 mm. Resolution of the image is 1920×1080 pixels.

To measure the instantaneous local film thickness, Micro-Epsilon controller IFC2451 with confocal chromatic sensors IFS2405-0.3 and IFS2405-3 were used. The sensor is positioned on the free surface side of the film and oriented perpendicularly to the substrate surface. Film thickness measurements are performed at a fixed point located above the heater.

To determine the instantaneous local film thickness during the rupture, we measure the distance to the film surface during the film rupture and the distance to the substrate surface after the rupture. To minimize reflection of the incident light at the substrate, the heater is covered with a thin layer of special black paste and is carefully polished. The reflection from the heater surface without black coating is an order of magnitude larger than the useful reflection from the surface of the film. Using black coating it is possible to reduce the reflection from the substrate by almost two orders of magnitude. An estimated thickness of the coating is 50 µm. The method of treatment of the coating provides the surface roughness of the order of 1 µm. The wettability of the working surface was measured at different points using a drop shape analysis system (DSA100 by Krüss GmbH). At room temperature, the static advancing contact angle was 85±5°, whereas the static receding contact angle was 13±4°.

3. Experimental results and discussion
Powering on the heater causes thinning of the liquid film and formation of a dry patch in the film within a period of several tens of second (depending on liquid). Figure 2 shows the typical change of the film thickness with time for water.

It was found that the process of film rupture can be divided into three stages: 1) film thinning down to a residual film on the heater (period of 0-12 s in Fig. 2); 2) existence of a stable residual film (period of 12-16 s in Fig. 2); 3) rupture and dryout of the residual film (period of 16-19 s in Fig.2). Rupture of the residual film usually begins at the heater edge and is accompanied by the formation of a drop in the heater center. Measuring the water film thickness (Fig. 2) was performed using an IFS2405-0.3 sensor at a point where no drops were formed. 10 runs were carried out and the measured residual film thickness for water was found to be 9.5 ± 3 µm. Schlieren images of the residual film allow us to state that it is flat and its thickness is approximately the same all over its area.
Fig. 2. Change of water film thickness in time, measuring rate is 0.3 kHz, the initial film thickness is 400 mm, heating power is 75 W.

Figure 3 shows the rupture process of a horizontal layer of silicone oil PMS-5, which also includes the same three stages as in the case of water. However, the residual film of silicone oil exists for a much longer time.

![Sequence of schlieren images showing the dynamics of silicone oil (PMS-5) film rupture. Initial film thickness is 600 µm, the heating power is 75 W. A circle indicates the position of the heated rod (of diameter 12 mm).](image)

It is interesting to note that the residual film thickness is virtually not dependent on the initial film thickness in the range studied (from 400 to 750 µm). The rupture of PMS-100 and PMS-200 silicone oil films proceeds in accordance with the same scenario as the case of PMS-5 film rupture. The thickness of the residual film was found to strongly depend on the liquid viscosity: for water, it is about 10 µm, whereas for PMS-200 it is about 275 µm (Fig. 4).
Fig. 4. Residual film thickness vs. kinematic viscosity for different working liquids. Initial film thickness varies from 400 to 750 μm, the heating power is 75 W.

4. Conclusion

It was found that the process of rupture of a horizontal liquid layer, non-uniformly heated from the substrate, is accompanied by the formation of a residual film on the heater. Schlieren images of the residual film allow us to state that the residual film is rather flat. Residual film thickness was measured using a confocal sensor. To minimize reflection of the incident light from the substrate, the heater was covered with a thin layer of special black paste. The thickness of the residual film was found to strongly depend on the liquid viscosity: for water, it was about 10 μm, whereas for PMS-200 oil it was about 275 μm.

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