The effect of the heating rate on the rupture dynamics of the horizontal layer of silicone oil

D Y Kochkin¹,², D V Zaitsev¹ and O A Kabov¹,²

¹ Kutateladze Institute of Thermophysics, Russian Academy of Sciences,
   1 Lavrentyev Ave., Novosibirsk, 630090, Russia
² Novosibirsk State Technical University,
   20 Karl Marks Ave., Novosibirsk, 630073, Russia

E-mail: kochkin1995@mail.ru

Abstract. The experimental study of the rupture of a horizontal layer of silicone oil non-uniformly heated from below was conducted. The rupture occurred through the formation of a residual film on the heater. Residual film thickness was measured using a confocal sensor. It was found that with increasing heating rate, the thickness of the residual film increases.

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 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 the 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 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 [3-5] it was found that thermocapillary film rupture occurs through formation of a thin residual film and its subsequence disruption. 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]. Ajaev [9] reviewed theoretical and experimental studies of thin liquid film rupture due to different break-up mechanisms. Redon et al. [10] investigated the expansion of the dry spot in metastable liquid films on low-energy surfaces. Zaitsev et al. [11] investigated the influence of liquid viscosity on the thermocapillary rupture of a gravity-driven liquid film. In [12-15], a confocal sensor was used to measure the thickness of liquid films.
2. Experimental equipment and methods

The test section was a textolite plate with an embedded copper rod having the diameter of 12 mm (Fig. 1). The textolite plate had a cooling circuit over the perimeter with the temperature of the cooler (water) kept at 5˚C. A ceramic electrical heater was attached to the bottom edge of the copper rod. The temperature of the copper rod surface was measured with an embedded thermocouple and did not exceed 85˚C. In the experiments, two scenarios of heating the liquid layer were realized: in the first case the liquid film was heated rapidly (the heating power was 75 W), and in the second case the liquid film was heated slowly (the heating power increased stepwise in increments of not more than 10% of the threshold heating power at which a rupture occurs). With rapid and slow heating, the temperature of the copper rod surface increased by about 2.5 and 0.02 °C per second, respectively. A plexiglass cylinder was mounted on the test section to hold the liquid. The experiments were carried out at an ambient temperature of 23–25˚C. Test section is open to the atmosphere.

![Figure 1. Schematic of the experimental setup.](image)

Three different working liquids with viscosity changing 40 times were used: silicon oils PMS-5, PMS-100 and PMS-200. PMS silicone oils were 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 was fed to the substrate via a syringe 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 visualize the curvature of the liquid surface. The scheme of the schlieren system is shown in [16]. 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 sensor IFS2405-3 was used. The sensor was positioned on the free surface side of the film and oriented perpendicular to the substrate surface. Film thickness measurements were performed at a fixed point located above the heater center.
3. Experimental results and discussion
A horizontal liquid film was formed on the surface of the test section, after which the heater was turned on. Powering on the heater caused deformation of the liquid film and its rupture. Figure 2 shows the rupture process of a horizontal layer of silicone oil PMS-5 caused by rapid heating.

![Figure 2. Sequence of schlieren images showing dynamics of silicone oil (PMS-5) film rupture. Initial film thickness is 600 µm, and heating power is 75 W. A circle indicates position of the heated rod (with 12 mm diameter), and a cross indicates the point of film thickness measurement.](image)

The process of film rupture includes: deformation of the liquid layer, i.e. its thinning over the heater (images 1-3 in Fig. 2); formation and existence of the residual film (image 4 in Fig. 2); and rupture of the residual film (images 5, 6 in Fig. 2). Rupture of the residual film occurs around the perimeter of the heater. After rupture, the heater remains covered with liquid. 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. 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. This scenario is also observed both with sharp and with slow heating.

Figures 3 and 4 show changes in film thickness with time above the heater center for various working liquids during rapid and slow heating, respectively. Analysis of the data in Fig. 3, 4 shows that the liquid layer thins above the heater to a residual film.

![Figure 3. Changes in silicone oil layer thickness above the heater center with rapid heating (heating power is 75 W).](image)
It was found that the residual film thickness is practically independent of the initial layer thickness in the studied range (from 400 to 750 µm), but depends on the viscosity of the liquid (with increasing viscosity of the liquid, the thickness of the residual film increases). It was also found that with rapid heating (Fig. 3), the thickness of the residual film is approximately three times greater than with slow heating (Fig. 4) (the experimental time with rapid heating is more than 50 times less than with slow heating). Most likely the influence of the heating rate on the thickness of the residual film is explained by the fact that during slow heating, the liquid has more time to flow out of the heater region.

Conclusions
The rupture of the horizontal layer of silicone oil non-uniformly heated from bellow occurs through the formation of a residual film on the heater. Residual film was visualized using an optical schlieren system and measured using a confocal sensor. It has been found that the heating rate affects the residual film thickness (with a decrease in the heating rate from 2.5 to 0.02°C per second, the thickness of the residual film decreases about 3 times for all working liquids). The thickness of the residual film is also found to strongly depend on the liquid viscosity (with a 40 times increase in viscosity, the thickness of the residual film increased about 3 times).

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