The effect of evaporation on a horizontal liquid film rupture

D Y Kochkin
Kutateladze Institute of Thermophysics SB RAS, Novosibirsk, 630090, Russia
Novosibirsk State Technical University, Novosibirsk, 630073, Russia
E-mail: kochkin1995@mail.ru

Abstract. This work is devoted to the experimental study of the rupture of a horizontal liquid layer placed on a stainless steel substrate non-uniformly heated from below. The goal of this work is to study the dynamics of film deformation and to determine the effect of evaporation and film thickness on the rupture. The film thickness and the deformation profiles were measured using the confocal Micro-Epsilon system with a positioning system. Liquid film initial thickness varied from 300 to 850 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. 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 the thermocapillary rupture of a horizontal liquid film non-uniformly heated from below. In [3-5] it was found that thermocapillary film rupture occurs through formation of a thin residual film and its subsequence disruption. The paper [6] investigated the influence of liquid viscosity on the thermocapillary rupture of a gravity-driven liquid film. The influence of heater size and inclination angle on the heat flux at which the gravity-driven films rupture was investigated in [7, 8].

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 field (schlieren method [9], fluorescence method [10, 11]) and local (electric conduction method, capacitance method [10], fiber-optical method [4, 12-14], and confocal method [15, 16]) ones. The schlieren method is suitable for measuring film surface deformations with a tilt angle to horizon of no more than 3-5° and it 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 (concentration of the dye changes). Capacitance method and electric conduction method have low spatial resolution and require installation in the substrate. Fiber-optical method has bad angular characteristic and is appropriate for measuring the thickness of nearly flat films (with 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 high spatial and temporal resolution, high accuracy and good angular characteristic. In the present work, we use the confocal method for measuring deformation of heated liquid films.

2. Experimental equipment and methods
The test section base is a textolite plate with an embedded copper rod having the diameter of 12 mm (Fig. 1). The base has a cooling circuit over the perimeter with the temperature of the cooler (water) kept at 23°C. A ceramic electrical heater is attached to the bottom edge of the copper rod. Experiments were carried out with non-uniformly liquid layer, heated from below, placed on a substrate made of stainless steel measuring 51 mm in diameter and 1 mm thick. The method of treatment of the substrate provides the surface roughness of the order of 0.05 µm. The substrate was fixed on a textolite base (Fig. 1), thermal resistance between the substrate and the base is reduced by using thermal paste. The temperature of the surface of the copper rod, measured with the thermocouple, did not exceed 55°C. The surface temperature of the stainless steel substrate above the heater is not measured, but is estimated to be no more than 3°C lower than the temperature of the copper rod surface. The substrate has a cooling circuit over the perimeter connected to the thermostat with the temperature of the cooler (water) of 23°C. The experiments are carried out at an ambient temperature of 23–25°C and atmospheric pressure. Milli-Q water with the ambient temperature was used as a working liquid. A predetermined volume of the Milli-Q water is pumped to the substrate using a syringe to form a liquid layer with the initial thickness varied from 300 to 850 µm. The power supply has been programmed to control the heating. The heating power increased automatically in small steps (0.15 W for every 18 s) up to the film rupture.

![Figure 1. Schematic of the experimental setup (a), photo of the test section (b).](image)

Photron Fastcam high-speed camera with an optical schlieren system was employed to visualize film deformations and disruption. The intensity of the schlieren 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 shooting speed was 3000 frames per second. The field of view of the camera is 23×23 mm. Resolution of the image is 1024×1024 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 confocal sensor is mounted on the platform of the positioning system and is oriented perpendicular to the substrate surface. The positional device is adjusted in two axes manually and in one axis by an actuator that is controlled...
from the PC. The actuator is able to move at a given speed (up to 100 mm/s) and in 1 μm increments over a distance of 50 mm. Thickness measurements of the liquid layer can be carried out both at a fixed point and by moving the sensor along the surface of the substrate.

3. Experimental results and discussion

Figure 2 shows schlieren images of the process of rupture of a horizontal liquid film. Under the action of heating, deformations are formed on the surface of the film. When the critical deformation is reached, a residual film is formed above the heater (Fig. 2, image 5), in which a rupture occurs (a dry spot appears).

![Figure 2](image)

Figure 2. Sequence of schlieren images showing dynamics of water film rupture. Initial film thickness is 850 µm. A circle indicates position of the heating rod (of diameter 12 mm). Upper row - deformations of the film surface (the time from the start of heating is shown), the lower row - formation and growth of the dry spot (the time from the nucleation of the dry spot is shown).

To measure the deformations of the liquid layer, a confocal sensor mounted on the positional system and moved by an actuator along the substrate surface at a speed of 20 mm/s (measurement frequency 0.3 kHz) was used. Figure 3 presents the deformation profiles evolution of the liquid layer with increasing temperature of the copper rod surface.

![Figure 3](image)

Figure 3. Deformation profiles evolution.
Figures 4, 5 show the graphs of dependences of the critical temperature of the copper rod surface and the threshold heating power (at which the liquid layer breaks) on the initial thickness of the liquid layer, measured before the experiment by the confocal sensor in the center of the cuvette. It can be seen from the graphs that with an increase in the initial thickness of the liquid layer, the rupture temperature and, accordingly, the threshold heating power increase.

![Graph of critical temperature vs. liquid layer thickness](image1.png)

**Figure 4.** The dependence of the critical temperature of the rupture on the liquid layer thickness.

![Graph of heating power vs. liquid layer thickness](image2.png)

**Figure 5.** The dependence of the threshold heating power on the liquid layer thickness.

It should be noted that with an increase in the rupture temperature and the time of the experiment, the fraction of evaporated liquid increases. Therefore, fig. 4, 5 also present the dependences of the critical temperature and the threshold heating power on the average thickness of the liquid layer before the rupture. The average thickness of the liquid layer before the rupture was calculated, knowing the geometrical dimensions of the cuvette and the volume of liquid in it. The liquid volume before the rupture, in turn, was determined by the profile of the deformation measured by the confocal sensor (as the volume of a solid of revolution is limited by the deformation profile). Analysis of the graphs (Fig.
4. 5) shows that at small values of the initial thickness of the liquid layer (h₀ = 300 μm) evaporation is insignificant, however, with an increase in the initial thickness, the fraction of the evaporated liquid increases, because the critical temperature and the experiment time increase. For the initial film thickness h₀ = 850 μm, evaporation is already about 15%.

Conclusion
It was found that with an increase in the liquid layer thickness, the rupture temperature and the threshold heating power increase. At small values of the initial thickness of the liquid layer, evaporation is insignificant, however, with an increase in the initial thickness, the fraction of the evaporated liquid increases.

Acknowledgments
This work was supported by the Russian Science Foundation (Project No. 19-19-00695).

References
[1] Orell A, Bankoff S G 1971 Int. J. Heat and Mass Transfer 14 (11) 1835–42
[2] Burelbach J P, Bankoff S G, Davis S H 1990 Physics of Fluids A: Fluid Dynamics 2 (3) 321
[3] Zaitsev D V, Kabov O A 2007 Microgravity Science and Technology 19 (3–4) 174–7
[4] Zaitsev D V, Rodionov D A, Kabov O A 2007 Microgravity science and technology 19 (3–4) 100–3
[5] Lyulin Y V, Spesivtsev S E, Marchuk I V, Kabov O A 2015 Tech. Phys. Lett. 41 (11) 1034–7
[6] Zaitsev D V, Semenov A A, Kabov O A 2016 Thermophysics and Aeromechanics 23 625
[7] Chinnov E A, Kabov O A, Muzykantov A V, Zaitsev D V 2001 International Journal of Heat and Technology 19 31
[8] Chinnov E A, Kabov O A, Marchuk I V, Zaitsev D V 2002 International Journal of Heat and Technology 20 69
[9] Settles G S 2001 Schlieren and Shadowgraph Techniques: Visualizing Phenomena in Transparent Media (Berlin: Springer-Verlag)
[10] Chinnov E A, Kharlamov S M, Nazarov A D, Sokolov E E, Markovich D M, Serov A F, Kabov O A 2008 High Temperature 46 (5) 647–53
[11] Hewitt G F, Lovegrove P C and Nicholls B 1964 AERE-R 4478
[12] Zaitsev D V, Kabov O A and Evseev A R 2003 Experiments in Fluids 34 (6) 748
[13] Zaitsev D V and Kabov O A 2005 Experiments in Fluids 39 (4) 712
[14] Zaitsev D V, Chinnov E A, Kabov O A, Marchuk I V 2004 Technical Physics Letters 30 (3) 231–3
[15] Zhou D W, Gambaryan-Roisman T, Stephan P 2009 Experimental Thermal and Fluid Science 33 (2) 273–83
[16] Gong S, Ma W, Wang C, Mei Y, Gu H 2015 Int. J. Heat Mass Transfer 90 636–44