Thickness measurement in a horizontal liquid layer when heated from a localized hot-spot

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Abstract. Thermocapillary breakdown of thin (0.3 \textendash 0.7 mm) horizontal layers of liquid (ethanol) when heated from a localized hot spot was investigated experimentally. The effect of layer thickness on the breakdown dynamics was studied. Visualization and control of the liquid layer were carried out using schlieren and confocal techniques. Main steps of the breakdown process were determined with the help of both systems. Evolution of the layer thickness in the center of substrate was observed and the critical thickness of the layer was measured using confocal sensor.

1. Introduction

Investigation of heat transfer from a local heat source becomes one of the most important problems in thermophysics. The problem is closely connected to the cooling of microelectronic equipment [1]. Continuous development and complication of microchip structure in microelectronic devices produce nonuniform heat flux distribution on the chip surface and inevitably lead to degradation of its performance and reliability. Heat flux density in some regions is much higher than the chip average [2], of the order of 1 kW/cm\textsuperscript{2}. These specific regions called “hot spots” could have size from several hundred microns to 1-2 millimeters. However, using special localized cooling it is possible to produce large performance gains in microprocessors. Nowadays, there are several effective techniques for cooling of local hot spots such as spray cooling, boiling in microchannels, thermoelectric coolers. One of the promising methods for removing such high heat fluxes from a spotted heat source is technology based on evaporation of a thin liquid layer [3]. Dynamics of evaporation essentially depends on the conditions in the layer [4]. In particular, the breakdown of liquid layer leads to dramatic decreasing of heat transfer from a spotted heat source [5]. Processes of liquid layer rupture are actively studied experimentally [5-7] and theoretically in the present time [8-10]. The goal of the present work is to study the breakdown dynamics and measure the thickness of a horizontal evaporating liquid layer when heated from a localized hot spot.

2. Experimental setup

Experiments were conducted on the setup shown in Fig. 1. The working fluid is supplied to the test cell \textit{1} with the help of the syringe pump \textit{2} and a horizontal liquid layer \textit{3} is formed. The thickness of liquid layer is varied from 300 to 700 μm. The layer of liquid is opened to the atmosphere and maintained on the surface of the working area using sharp edge on the substrate perimeter. Spot heating of the horizontal liquid layer takes place in the center of the substrate. The test cell consists of
caprolon base 4, metallic substrate 5 and the heating element 6. The caprolon base has a special cut on the upper side for installation of the substrate and a central through hole with a diameter of 1.6 mm. The substrate is made of stainless steel and has a diameter of 50 mm and a thickness of 1 mm. In the center of the substrate is a closed hole with a diameter of 1.6 mm and a height of 0.8 mm. The heating element is made of brass and has a round tip with a diameter of 1.6 mm and a height of 3 mm. It is tightly inserted into the closed hole of the substrate through the caprolon base. Thermal paste is used for better thermal contact between the heater tip and the substrate. The distance between the tip and the upper side of substrate is 0.2 mm. The power of heating element is controlled by the power supply 7. Insulating material 8 is located on the underside of the heater to minimize heat losses. Temperature in the test cell is measured by thermocouples 9 (type K) connected to the measuring system 10 with an accuracy of 0.1°C. Location of the thermocouples is shown in Fig. 1. Relative humidity and atmosphere temperature are measured using the thermohygrometer Testo 645 11 with an accuracy of 2% and 0.1°C, respectively.

Figure 1. Scheme of the experimental setup

The heat flux density is determined by measuring the temperature difference between two different sections along the heater tip. The height of the horizontal liquid layer is maintained in constant position during all the experiment. Confocal system Micro-epsilon is used for measuring the layer thickness over the heating element. The system consists of the controller 12 and the sensor 13. Sensors have the spatial resolution from 10 to 60 nm, the accuracy 0.35 - 0.7 μm, the spot diameter 6 - 16 μm and the measuring range 0.3 - 10 mm. The maximum temporal resolution is 100 μs. The sensor is fixed on the three-dimensional positioning system with high-speed linear actuator 14 on one of the horizontal axes. Linear actuator is controlled from personal computer 15 and by special software. The maximum speed the axis moves at is 104 mm/s. The sensor moves in range of 50 mm by steps of 1 μm. Also it moves in two other axes with the help of two hand-operated linear stages in range of 50 mm. For visualizing the deformation of the surface and recording the layer breakdown dynamics schlieren technique 16 with Photron FASTCAM 675K-M3 high-speed camera was used (at 5000 fps, 640x640 pixels, 25 μm/pix). The test cell was installed in a horizontal position with the help of two-axis goniometer 17. Equilibrium contact angle of the substrate surface is defined by Young-Laplace equation [11] at room temperature of 25 ± 2 °C and is equal to θ = 8 ± 1 °. Profilometer “Micro Measure 3D station” was used for measuring the roughness of substrates. Average value of the substrate roughness is equal to $R_a = 0.037 \mu m$. 


3. Results and discussion

3.1. Experimental results
Experiments were conducted at atmospheric pressure, temperature and relative humidity of 28±2°C and 25±3%, respectively. Layer thickness was ranged from 300 to 700 μm. Ethanol (95%) was used as a working fluid. Heater temperature range was 20 - 105°C. The temperature values were measured at the moment of layer breakdown. Heat flux density was varied from 0 to 95.3 W/cm². Injection liquid flow rate was up to 200 μl/min. During the experiment heat flux is increased up to a critical value at which the liquid layer ruptures. At this moment heating process is stopped to prevent the failure of heating element.

![Figure 2. Visualization of breakdown dynamics and formation of the dry spots](image)

It was found that breakdown process consists of several steps. At the beginning, thinning of the liquid layer over the heating area (Fig. 2a) due to the effect of thermocapillary forces [12, 13] and evaporation is observed. Further thinning leads to the formation of residual liquid layer in the area of the local heating, Fig. 2b. Then the residual layer evaporates until its thickness reaches the critical and breakdown of the liquid layer occurs, Fig. 2c, [5, 6]. After the breakdown the whole area of the local heating rapidly dries and quite symmetrical circular dry spot is formed, Fig. 2d.

![Figure 3. Dependence of the layer thickness over the heating area on time (initial layer depth 500 μm)](image)

Evolution of the layer thickness in the center of substrate is observed with the help of the confocal system. All detected steps of the breakdown process observed by the schlieren technique were also
confirmed using the confocal method. Dependence of the layer thickness over the heating area on time is shown in Fig. 3.

Evolution of the layer thickness before the breakdown was measured for different initial layer depth in range from 300 to 700 μm (Fig. 4). Pulsations of the layer thickness before formation of the residual layer have been observed. It is found that critical thickness of residual layer and thickness of residual film have no dependence on the initial layer depth and its values are 35 ± 2 μm and 10 ± 1 μm, respectively. It is assumed that critical thickness of the residual layer for present substrate mostly depends on the properties of working liquid. The time of dry spot formation is decreased when the layer thickness and, accordingly, the local heating intensity is increased. The time varies from 6 to 0.67 seconds. Temperature in the center of substrate increases and more intense evaporation of residual layer takes place. Thus, one of the main factors influencing the residual layer breakdown and the heating region draining is evaporation.

**Figure 4.** Dependence of the layer thickness over the heating area on time for different initial layer depth

3.2. Numerical modelling

The problem of thermocapillary deformations and breakdown of the locally heated horizontal liquid layer has been solved numerically in axisymmetric statement. The thin layer approximation model is used [12, 13]. Capillary pressure, viscosity and gravity are taken into account. Evaporating rate is supposed to be proportional to the temperature difference between temperatures of the liquid surface and ambient. Heat transfer in the substrate is also simulated. The deformation of the free surface has been calculated for the corresponding experimental conditions. The model predicts the formation of the thin residual layer of the liquid and film breakdown at sufficiently intensive heating.

**Figure 5.** Calculated film thickness and surface velocity over the center of the heater (See parameters in Fig. 4)
Calculated film thickness dynamics over the heater center is shown in Fig. 5. After a period of rapid decrease in the thickness of the film a time of a slow decrease in the thickness of the film follows down to zero, Fig. 5a. The main mechanism of the outflow of the liquid from the heating zone in the first case is the thermocapillary shear stress, and in the second case this is the evaporation. One can see that points on curves in Fig 5a with maximal curvature divide the curves into two quasilinear parts. The film thickness for these points has quite the same value about 10 µm. One may conclude that at thickness less than 10 µm the main drainage mechanism is evaporation. At small liquid thickness the viscosity suppresses thermocapillary flows. Liquid surface velocity over the heater center is shown in Fig. 5b. Maximum in the curves correspond to the start of the decrease in the velocity. The film thickness for these points has quite the same value about 40 µm. Maximum of the slowdown acceleration of the liquid surface takes place at values of the film thickness about 20 µm.

4. Conclusions
Influence of the layer thickness on the breakdown dynamics of liquid layer was studied. The existence of residual liquid layer over the heating area before the breakdown has been proved. Pulsations of layer thickness over the heating area before the formation of residual layer have been found. Critical thickness of residual layer and thickness of residual film have no dependence on the initial layer depth. The main drainage mechanism for the residual layer is evaporation.

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References
[1] Bar-Cohen A, Wang P 2012 J. Heat Transfer 134 5
[2] Mahajan R, Chiu C, Chrysler G 2006 Proceedings of the IEEE 94 8
[3] Gatapova E Ya, Kabov O A, Marchuk I V 2004 Technical Physics Letters 30 5
[4] Fedorets A A, Marchuk I V, Kabov O A 2013 Interfacial Phenomena and Heat Transfer 1 1
[5] Lyulin Yu V, Spesivtsev S E, Marchuk I V, Kabov O A 2015 Technical Physics Letters 41 11
[6] Zaitsev D V, Rodionov D A, Kabov O A 2007 Microgravity Science and Technology 19 pp 100-103
[7] Zaitsev D V, Kabov O A 2007 Microgravity Science and Technology 19 174-177
[8] Ajaev V S 2013 Interfacial Phenomena and Heat Transfer 1 1
[9] Williams M B, Davis S H 1982 J. Colloid Interface Sci. 90 pp 220-228
[10] Burelbach J P, Bankoff S G and Davis S H 1990 Phys. Fluids A 2 pp 322–333
[11] Marchuk I V, Cheverda V V, Strizhak P A and Kabov O A 2015 Thermophysics and Aeromechanics 22 3
[12] Marchuk I V 2009 Journal Engineering of Thermophysics 18 3
[13] Marchuk I V 2015 Journal Engineering of Thermophysics 24 4