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Breakdown dynamics of a horizontal evaporating liquid layer when heated locally

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Abstract. Breakdown of liquid layer when heated from a localized hot spot was investigated experimentally. Water and ethanol were used as working liquids with a layer thickness of 300 μm. Basic steps of the breakdown process were found and mean velocities of the dry spot formation were determined. The formation of residual layer over the hot-spot before the breakdown has been found for both liquids. The creation of a droplet cluster near the heating region is observed when using water as a working fluid. It was shown that evaporation is one of the general factors influencing the process of layer breakdown and dry spot formation as well as thermocapillary effect.

1 Introduction

Study of heat transfer from a local heat source becomes one of the most important and complicated problems in modern thermophysics. The problem is closely connected to the problem of microelectronic equipment cooling [1]. Permanent consumption of electricity by the device inevitably leads to increasing the microprocessor temperature and degradation of its performance and reliability. The average heat flux density on the surface of chips of commercially available computers and other electronic devices is currently known to reach 100 W/cm^2. Continuous development and complication of microchip structure produce nonuniform heat flux distribution on the chip surface. This effect takes place due to the design features of computer chips, where the processor cores cause the formation of "hot" spots. Heat flux density in some regions is much higher than the chip average [2], of the order of 1 kW/cm^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 [3], boiling in microchannels [4], thermoelectric coolers [5]. 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. Dynamics of evaporation essentially depend on the conditions in the layer [6]. In particular, the breakdown of liquid layer leads to dramatic decreasing of heat transfer from a spotted heat source [7]. Processes of liquid layer rupture are actively studied experimentally [7-9] and

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theoretically [10-12] in the present time. The goal of the present work is to study using schlieren technique the breakdown dynamics of a horizontal evaporating liquid layer when heated from a localized hot spot.

2 Experimental rig

Experiments were conducted on the rig shown in fig. 1. The working area consists of a caprolon base, a metal substrate and a heating element. Fluid from the syringe pump enters the work area, forming a horizontal liquid layer opened to the atmosphere. Spot heating of the horizontal liquid layer takes place in the center of the substrate. The test cell consists of caprolon base, metallic substrate and the heating element. 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 heat source of the heater is a nichrome wire wound on the core rod. Heating is controlled by the power source. The heater core was placed in the cutout of the base on its lower side, and between the heater and the base there was an air gap of 2 mm. From the bottom of the heater there was an insulating material to minimize heat loss. Temperature in the test cell is measured by thermocouples (type K) 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 with an accuracy of 2% and 0.1°C, respectively.

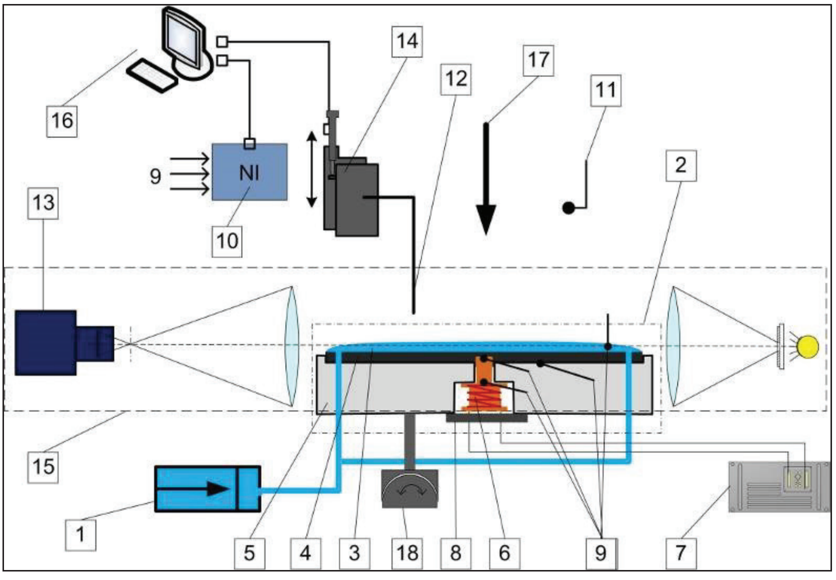

Fig. 1. Scheme of the experimental rig. 1 – syringe pump; 2 – test cell; 3 – liquid layer; 4 – substrate; 5 – base; 6 – heating element; 7 – power source; 8 – insulating material; 9 – thermocouples; 10 – measuring system; 11 – thermohygrometer; 12 – probe; 13 – camera; 14 – linear actuator; 15 – shadowgraphy technique; 16 – PC; 17 – schlieren technique; 18 – goniometer.

The heat flux density is determined by measuring the temperature difference between two different sections along the heater tip.:

$$q = \lambda \, \Delta T / l, \quad (1)$$

where λ is the thermal conductivity of the heater material, W/cm·K; l is the distance between the two sections of the heater tip, cm; and ΔT is the temperature difference in two cross sections along the length of the heater tip, K.

The height of the horizontal liquid layer is maintained in constant position during the all experiment. The probe with a diameter of 100 μm is installed at a required distance from the substrate surface. Precise linear actuator and shadowgraphy technique are used in order to determine the position of the probe. The probe moves in range of 5 mm by steps of 1 μm. With the help of high-precision syringe pump the flow rate is chosen for providing a constant layer thickness, taking into account the evaporation. The horizontal layer surface and the probe are observed using video camera Imaging Source DFK 23GP031 with a resolution of 2592x1944 pixels. To visualize surface deformations and register the breakdown an optical schlieren system is used with high-speed video camera Photron FASTCAM 675K-M3 (speed of 5000 fps at a resolution of 640x640 pixels and a scale of 25 μm/pix). The test section is mounted in horizontal position using a goniometer. The surface roughness of the substrate was determined by profilometer "Micro Measure 3D station" and the average roughness value is equal to R_a=0.327 μm. The contact angle on the working surface in the heating area was determined by the sessile drop method (Young-Laplace) [13] at a room temperature of 25±2°C and equals to θ_1=6±1° for ethanol and θ_2=76±1° for water.

3 Results and discussion

Experiments were conducted at atmospheric pressure, temperature and relative humidity of 28±2°C and 25±3%, respectively. The used working liquids were ethanol (95% (mass.), GOST R 51723-2001) and ultrapure water. For water purification the system Merck Millipore Direct-Q 3 UV is used which allows providing the water of type I (ultrapure water). The height of the liquid layer was 300 μm. 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. For both working fluids the critical heat flux density when the breakdown of the liquid layer occurs is measured. The value of the critical heat flux density for ethanol equals to 12.6 W/cm^2 at the substrate temperature in the heating area of 37.1°C, for water it is 117 W/cm^2 at the substrate temperature of 133°C, respectively.

It was found out that for both working liquids the layer breakdown occurs according to one scenario [7, 14, 15]. First, a thermocapillary deformation of the layer above the point heating area appears (Fig. 2a, b). Further thinning leads to the formation of a residual liquid layer in the area of the point heating, Fig. 2c [8]. Then, the residual liquid layer evaporates to a critical thickness, at which the layer breakdown takes place, Fig. 2d. After the breakdown the entire heating area is intensely dried, and the round dry spot is formed, Fig. 2e. It should be noted that local heating of the water layer is followed by the formation of a droplet cluster [6, 14, 16] above the heating area and the breakdown takes place at a distance of about 1 mm from the substrate center. When using ethanol as a working liquid residual layer formation and rupture occur directly above the heating element in the center of the substrate.

The average rate of dry spot formation was measured for two working fluids and was determined as the ratio of the characteristic radius of the resulting dry spot to the time of its formation in the heating area. The time of dry spot formation is counted from the moment of the residual layer breakdown to its complete evaporation. The average velocity of dry

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spot formation for ethanol is 0.06 mm/s, and for water it is 5.15 mm/s, respectively. The time of dry spot formation for ethanol as a working fluid is 7.85 seconds, and for water - 0.13 seconds. First of all the difference in the velocity of dry spot formation is connected with different evaporation rate of the residual layer. The evaporation rate directly depends on the heat flux density and the substrate temperature. In addition, it is influenced by the difference in properties and hydrodynamic parameters of working fluids: contact angles and surface tension.

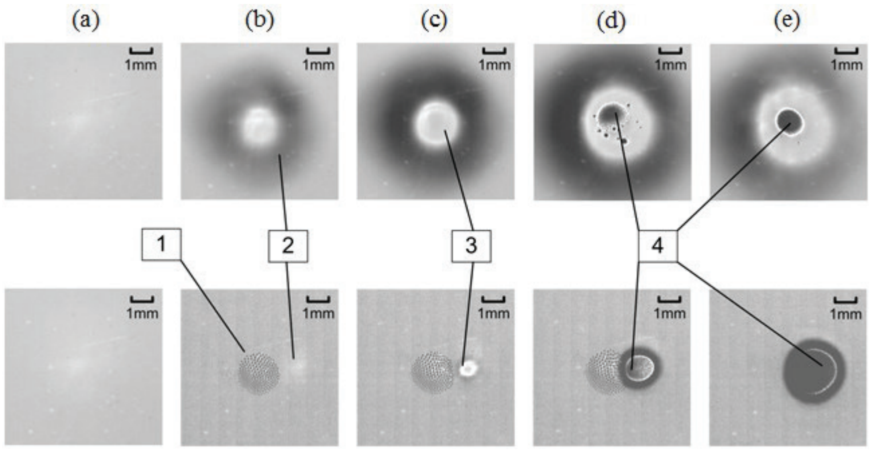

Fig. 2. The dynamics of the liquid layer breakdown in case of point heating. Liquids are ethanol and water, the layer depth is 300 μm. 1 – droplet cluster; 2 – thermocapillary deformation; 3 – residual layer; 4 – dry spots.

In the study of thermocapillary breakdown of the water layer with local heating the existence of the droplet cluster was found (Fig. 3), followed by its falling and formation of capillary waves [16]. Droplets in a cluster are held above the layer surface due to intensive evaporation in the heating area and falling of individual droplets begins after breakdown of residual layer (Fig. 3 c, d). The phenomenon of droplet cluster was investigated in detail in [16-18].

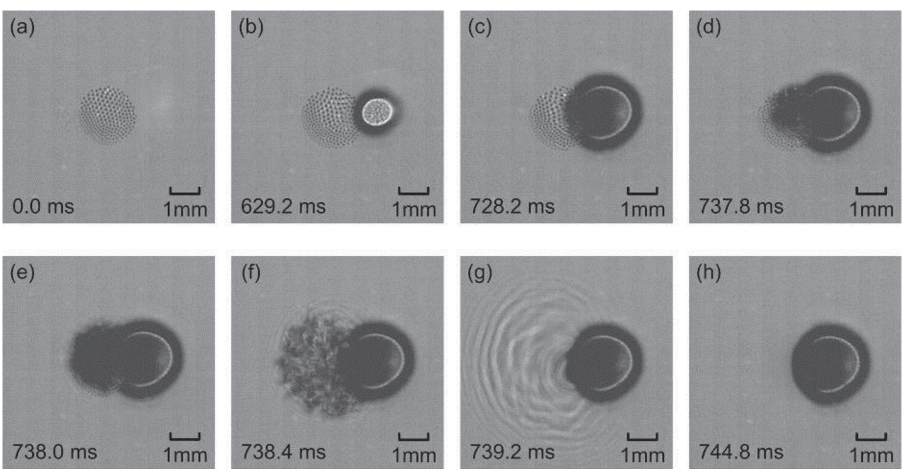

Fig.3. Visualization of the droplet cluster and the breakdown dynamics. The liquid is water and the layer depth is 300 μm.

4 Conclusions

Influence of the working liquid on the breakdown dynamics was studied. Visualization of the breakdown dynamics has been performed for thin layers of ethanol and water using schlieren technique. It is found that for rupture of the water layer the density of heat flux required to be by an order of magnitude higher than the critical heat flux density for ethanol layer at the same thickness. At the same time typical velocities of breakdown of water and ethanol differ by two orders of magnitude. This fact is directly related to the difference in the critical heat fluxes and intensity of evaporation. It is proved that before the breakdown the residual layer appears in the area of local heating. When using water as the working liquid the formation of a droplet cluster may be observed near of the heating area. Along with the thermocapillary effect, evaporation is one of the main factors that influence the breakdown of residual liquid layer and dry spot formation in the heating area.

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