Thermocapillary deformations of a spot-heated self-rewetting liquid layer

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Abstract. Thermocapillary deformations of horizontal self-rewetting layer of liquid (solution of 1-butanol of 5% concentration in water) when heated from a localized hot spot were studied experimentally. Measurements of the liquid layer deformations were performed using the confocal techniques with three-dimensional positioning system having high-speed linear actuator. Effect of equalizing the profile of the liquid surface over the heating area has been observed before the layer breakdown. The potential interest of the proposed studies induces by the large number of possible industrial applications, including space technologies and terrestrial applications, such as cooling of electronic components.

1. Introduction

Study of heat transfer from a spot heat source becomes one of the most important problems in thermophysics. The problem is directly related to the cooling of modern microelectronic systems [1]. It is known that on chip surface there is non-uniformity in heat flux distribution. Heat flux density in some zone 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. 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 the technology based on evaporation of a thin liquid layer. Dynamics of evaporation essentially depends on the conditions in the layer [3]. In particular, the breakdown of liquid layer leads to dramatic decreasing of heat transfer from a spotted heat source [4, 5]. Processes of liquid layer rupture and thermocapillary deformations are actively studied experimentally and theoretically in the present time [4-9]. Governing factor of liquid layer rupture is the thermocapillary effect. The rupture of the liquid layer takes place due to the interfacial temperature gradient that induces thermocapillary deformations and motion of the liquid from spot heated area to the periphery [4,5].

As discussed in papers [10, 11] dilute aqueous solutions of alcohols with a high number of carbon atoms (such as butanol, pentanol, exanol, heptanol or octanol) can be considered as “self-rewetting” fluids due to their properties associated with an anomalous dependency of the surface tension on temperature in some ranges of concentrations. This may open new horizons towards the development of more efficient heat transfer devices for different applications.
The present work is dedicated to study the thermocapillary deformations of horizontal layer of self-rewetting liquid (solution of 1-butanol of 5% concentration in water) when heated from a localized hot spot.

2. Experimental rig

Experimental studies were performed on the experimental setup shown in figure 1. Working fluid comes from the syringe on the substrate surface of the test cell, forming a horizontal liquid layer of 0.95 mm depth. The liquid layer is opened to the atmosphere. The test cell consists of a caprolon base, a metal substrate and a heater. There is a spot heating from the side of the substrate in the center of the horizontal liquid layer. Caprolon base has a special cutout in the upper part to mount the metal substrate and the through hole in the center with a diameter of 1.6 mm. The metal substrate is made of stainless steel with a diameter of 50 mm and a thickness of 1 mm. At the center of the substrate there is a closed hole with a diameter of 1.6 mm and a height of 0.8 mm. The heater was a brass core with 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. Temperature in the test cell is measured by thermocouples (type K) connected to the measuring system with an accuracy of 0.1°C. Relative humidity and atmosphere temperature are measured using the thermohygrometer Testo 645 with an accuracy of 2% and 0.1°C, respectively. Detailed description of the experimental setup is presented in [5].

The heat flux density is determined by measuring the temperature difference between two different sections along the heater tip. Confocal system Micro-epsilon is used for measuring the layer thickness over the heating area. The system consists of the controller and the sensor. Sensors have the spatial resolution of 36 nm, the accuracy of 0.5 μm, the spot diameter of 9 μm and the measuring range of 3 mm. The maximum temporal resolution is 100 μs. The sensor is fixed on the three-dimensional positioning system with high-speed linear actuator on one of the horizontal axes, figure 1. Linear actuator is connected to personal computer and controlled by special software. The sensor is moved with speed of 104 mm/s in range of ±5 mm from the centre of substrate. The maximum moving...
distance is 28 mm. Also the sensor can move along two other axes with the help of two hand-operated linear stages in range of 50 mm in order to adjust the sensor position for thickness measurements. The test cell is installed in a horizontal position with the help of two-axis goniometer.

3. Results and discussion
The study was carried out at atmospheric pressure, temperature of 25±1°C and relative humidity of 25±2%. A self-rewetting fluid (i.e., liquids with a surface tension increasing with temperature) is used as working liquid in the experiments. Figure 2a shows the particular behaviour of surface tension versus temperature for ordinary liquids and self-rewetting fluids. For ordinary liquids the surface tension is a decreasing function of the temperature, i.e. the surface tension derivative with temperature \( \sigma_T < 0 \). For dilute aqueous solutions of these alcohols, the surface tension as a function of the temperature goes through a minimum and there is a range of temperature above which \( \sigma_T (T, c) > 0 \). Therefore, as illustrated in figure 2b, in presence of self-rewetting liquids, when liquid–vapour interfaces and temperature gradients are present, it is expected to observe surface flows directed from the cold to the hot regions, for temperatures higher than that of the minimum of the surface tension. The self-rewetting fluid was a solution prepared by simple mixing of deionized ultrapure water and n-butanol with concentrations at 5%. The depth of the liquid layer was 950 µm. For working fluid the critical heat flux density when the breakdown of the liquid layer occurs is measured. The value of the critical heat flux equals 3 W.

The results of profile measuring of the liquid layer thickness are shown in figure 3. During the first 20 seconds after the start of heating, the development of deformations proceeds according to the classical scenario for normal liquids (surface tension decreases with temperature growth). As the temperature rises, the surface tension decreases. In the heating region, thinning-down of the liquid layer takes place due to the thermocapillary effect. Further, when temperature of liquid over heating area reaches a point where the surface tension increases with increasing temperature (above 50°C), the reverse effect occurs. Thermocapillary stresses on the layer surface begin acting at the center of the heating region. The fluid is strongly flowing from the periphery towards the heater (from the cold to the hot region) due to the inversed Marangoni effect. The thinning-down of the liquid stops, and then the thickness of layer rises slowly. Finally the surface of the liquid layer becomes closer to its original position without heating. After equalizing the interface, the temperature gradually reaches a critical value, and a layer is ruptured. Thus, it was first found that when the layer of a given solution is heated from spot source, the effect of equalizing the gas-liquid interface profile takes place immediately before the rupture of the layer.
4. Conclusions
New experimental studies and measurements of surface deformations of spot-heated layer of self-rewetting liquids (aqueous solution of 5% of 1-butanol in water) in an axisymmetric configuration have been performed. Thickness profiles of the liquid have been measured using the confocal method and three-dimensional positioning system having high-speed linear actuator. It was found that continuous spot heating of self-wetting liquid layer leads to thinning-down first and than to reverse thickening-up of the liquid surface over the heating area. Just before the layer breakdown the thickness was close to initial thickness (without heating) of the liquid layer. The reverse thickening-up of the layer was caused by the anomalous dependence of the surface tension on the temperature, were surface tension increases with growth of temperature in a certain range.

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References
[1] Bar-Cohen A, Wang P 2012 J. Heat Transfer 134 5
[2] Mahajan R, Chiu C and Chrysler G 2006 Proceedings of the IEEE 94 8
[3] Fedorets A A, Marchuk I V and Kabov O A 2013 Interfacial Phenomena and Heat Transfer 1(1) 51
[4] Lyulin Yu V, Spesivtsev S E, Marchuk I V and Kabov O A 2015 Technical Physics Letters 41(11) 1034
[5] Lyulin Yu V, Spesivtsev S E, Marchuk I V and Kabov O A 2017 Thermophysics and Aeromechanics 24 949
[6] Zaitsev D V, Rodionov D A and Kabov O A 2007 Microgravity Science and Technology 19 100
[7] Marchuk I V, Cheverda V V, Strizhak P A and Kabov O A 2015 Thermophysics and Aeromechanics 22 297
[8] Marchuk I V 2009 Journal Engineering of Thermophysics 18 227
[9] Marchuk I V 2015 Journal Engineering of Thermophysics 24 381
[10] Savino R, Cecere A and Di Paola R 2009 International Journal of Heat and Fluid Flow 30 380–8
[11] Abe Y 2006 Ann. N.Y. Acad. Sci. 1077 650–67

Figure 3. Thickness profile of the self-rewetting liquid layer over the heating area. Initial layer thickness: 950 μm. Liquid: solution of 1-butanol of 5% concentration in water. Heat flux: 3 W.