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Experimental study of the effect of the substrate roughness on the thermocapillary breakdown of a horizontal liquid film

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Abstract. The paper describes experiments on study of influence of the substrate roughness on the phenomenon of thermocapillary breakdown in a horizontal nonisothermal film of liuqid placed upon a stainless steel substrates. The critical heat flux for fim breakdown is almost independent of roughness. However, the substrate roughness is signifcant for dynamics of film breakdown. The velocity of contact line propagation decreases with the roughness growth. The final size of a dry spot decreases for higher roughness.

1 Introduction

The modern industry often uses apparatus with liquid film flow. Thin liquid film is a promising approach for developing of cooling of devices with high local heat release, in particular, for high-end electronic chips [1,2]. The industry creates a need for cooling of high local heat fluxes from electronics components like computer chips, and power electronics (transistors and thyristors).

Film-based cooling systems are highly efficient since they provide a high rate of heat transfer at moderate flow rates of the coolant. The reduction in the film thickness enhances heat transfer; however, thin films are prone to film breaking and this increases drastically the temperature of the cooled element and may cause failure.

The effect of substrate wetting and liquid properties on the thermocapillary breakdown of a flowing film was studied in [3-5]. The paper [6] studied the effect of substrate structuring on phenomenon of liquid film breakdown. The paper [7] deals with the effect of inclination angle of the working section. The papers [8, 9] were pioneering in study of thermocapillary breakdown of a steady horizontal liquid layer. The papers [4, 10] demonstrated that the critical heat flux for the case of horizontal liquid films is by several times higher than the critical level for gravity-driven liquid films. This explains the relevance of presented study.

The key object of this study is the effect of substrate roughness on the threshold heat flux which causes film breakdown and also the dynamics of this breakdown.

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2 Methods

Experiments were conducted with locally heated substrates with different size of roughness made of stainless steel with the diameter of 50.8 mm and thickness of 1 mm. The substrate was mounted on a textolite basement with an embedded copper rod with the diameter of 12.7 mm (Fig. 1), and thermal paste was applied for improvement of heat contact between the substrate and basement. The copper rod has a thermal contact with a ceramic heater. The heat flux was calculated from the temperature drop over the copper rod for the situation of steady process. It was also controlled by the known electric power consumed by the heater. The working liquid was distilled super-pure Milli-Q water with the initial temperature of 25°C. The proper volume of water was fed to the substrate via a syringe pump. The substrate perimeter has cooling arrangement. The water temperature in the cooling circuit was sustained at 5°C.

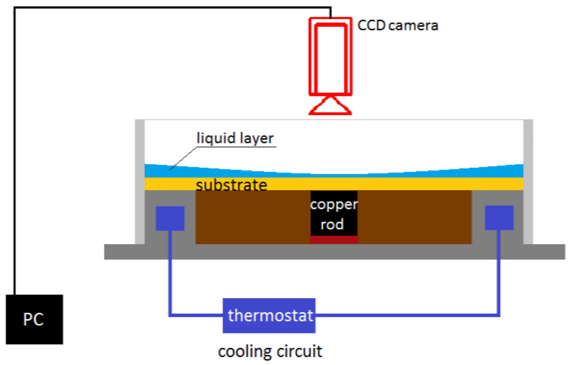

Fig. 1. Diagram of the experimental setup (the heater's power source is not shown).

The using of removable substrate in this setup ensures study of breaking a horizontal liquid layer on substrates with different roughness. The different scale of roughness was achieved by surface polishing. The morphology of the surface was analyzed using a scanning electron microscope (HITACHI S3400N) and an atomic force microscope (Solver Pro NT MDT).

The liquid film thickness was measured with a probe moved with a motor-driven microdisplacement tool. As the film surface is toughed by the probe tip, this creates a liquid meniscus recorded with a CCD camera. The total film thickness was controlled by he known volume of liquid fed using the syringe pump. Experiments were carried out for films with the initial thickness 350 μm (+/- 5 μm). The heat flux was incremented with small steps up to the threshold flux (which ensures film breakdown). The steadiness of process was controlled using thermocouples installed in the working section and heater. The film breakdown initiates a drastic growth of heater temperature.

The film breakdown was recorded with the CCD camera DMK 23GP031 placed above the working section.

3 Results

Experiments were conducted for stainless steel substrates with different levels of roughness (Ra = 0.05 μm, Ra = 1.30 μm, Ra = 2.5 μm). It was found that the threshold heat flux (initiating the film breakdown) is almost independent of roughness and it was about 10-11 W/cm^2. Experiments were carried out for the initial film thickness 350 μm (+/-5 μm), and this thickness is dictated by the fact that a moderate heat flux is required to break down this

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film. In the process of heating, the contribution from water evaporation was low and the final film thickness was also about 330 μm.

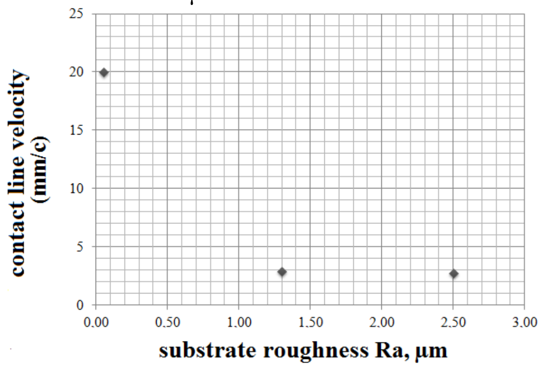

Fig. 2. Graphs of contact line velocity vs. substrate roughness.

Our study demonstrated that the speed of dry spot expansion (Fig. 2,3.) and the final dry spot size (Fig. 4.) depend significantly on the surface roughness. For example, for a surface with roughness Ra = 0.05 μm the velocity of contact line is by order higher than for the same kind of substrate with the roughness of Ra = 1.30 μm. But in experiments with a substrate with a higher roughness (Ra = 2.5 μm) the further increase in line velocity is insignificant. The experimental data are explained by a concept that the contact line after film breakdown is caught by the substrate roughness and this reduces the breakdown velocity.

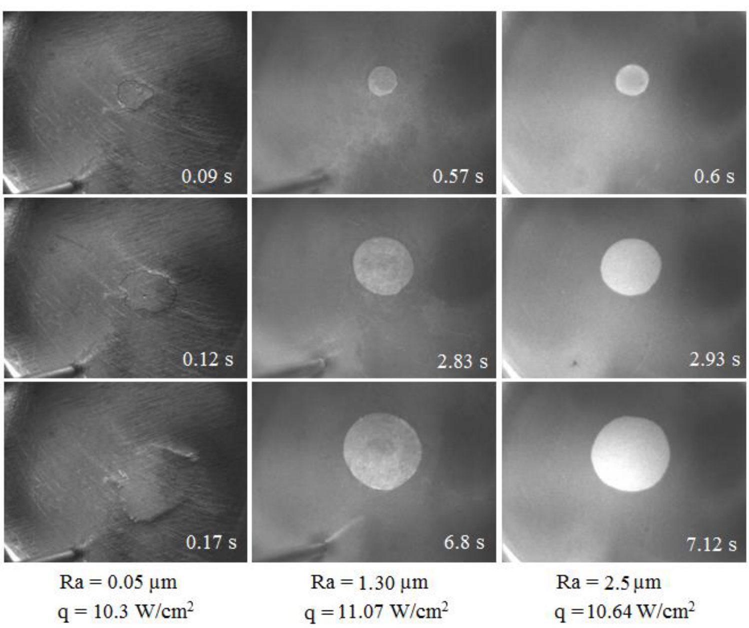

Fig. 3. The dynamics for dry spot expansion on the stainless steel substrate with the thickness of 1 mm at different scales of roughness (for initial film thickness 350 μm). The time is measured since the breakdown startup.

The smaller final size of dry spot at higher roughness is explained by counteraction of roughness to dry spot expansion.

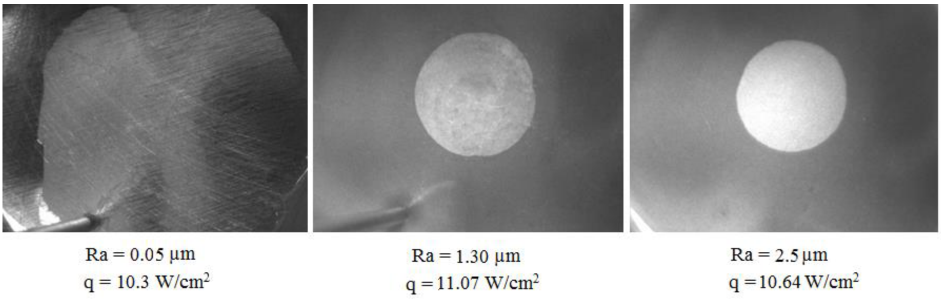

Fig. 4. Picture of the final size of a dry spot for substrates with different roughness.

4 Conclusion

The tests demonstrated that the substrate roughness has almost no impact on the critical heat flux needed for breakdown of a locally heated liquid film. However, roughness is significant for breakdown dynamics and the final size of the dry spot. For a higher roughness of substrate, the contact line velocity and the final size of dry spot become lower.

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