Dry spots dynamics in shear-driven thin liquid films under intensive local heating

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Abstract. Development of the modern microelectronic equipment requires the effective cooling solutions because it is necessary to remove high heat fluxes of up to 1 kW/cm\textsuperscript{2} and higher from the local hot spots of the processor. Thin and ultra-thin (less than 10 µm in thickness) liquid films, moving under the action of a forced gas flow in a mini-channel, are promising for the use in the temperature control systems of the modern semiconductor devices. Here we report results of systematic experimental studies of the flow and rupture of a water film, shear-driven in the channel, under intense heating from a local heat source with size of 1x1 cm\textsuperscript{2}. To carry out high-speed visualization of the process, the FASTCAM SA1.1 CCD camera is used (with the speed of up to 100 000 frames per second). The camera is equipped with an optical system of high spatial resolution (2.5 µm per 1 pixel of the camera sensor). With the help of high-speed imaging, it was found that the maximum intensity of heat removal from the heater is achieved in the mode, when the film flow continuity is broken. The heater is covered with dry spots having typical size on the order of 10-100 µm and typical lifetime on the order of 0.1-1 ms. At that, the number of dry spots that exist simultaneously on 1 cm\textsuperscript{2} of the heater surface can reach several hundred. During 1 s up to 1 million dry spots appear and disappear at the area of the heater.

1. Introduction

One of the most important problems of thermal physics today is cooling of microelectronic equipment. Currently, the production of processors changes from the 14 nm manufacturing process technology to the 7 nm technology. New IBM processors use 7 nm transistors. This has been made possible through the use of a silicon-germanium alloy in the transistor design instead of pure silicon, the traditional material for the manufacture of microchips [1]. A normal-size processor can accommodate more than 20 billion transistors having size of 7 nm. In addition to reducing the size of the microprocessor unit, the use of the silicon-germanium alloy has improved the switching speed of transistors and lowered the power consumption. The average heat flux density on the chips of commercially available computers and other electronic devices is up to 200-300 W/cm\textsuperscript{2}. In local areas of 100 µm\textsuperscript{2} to a few square millimeters, the heat flux density reaches values of 1 kW/cm\textsuperscript{2} or more (IBM). Devices of the next generation may have even higher heat fluxes and pulsed loads [2], which requires a new thermal management level.

There are three “classical” methods of heat removal from localized heat sources of high intensity: 1) boiling in microchannels [3], 2) spray cooling [4], and 3) micro-jet cooling [5]. In [6,7] the fourth
method of effective cooling was proposed, in which heat removal is due to intensive evaporation of a thin liquid film, moving in a flat micro-/minichannel under the action of gas flow. Recent experimental investigations conducted in [8] proved possible removal of heat fluxes with density of up to 1200 W/cm² from the heating area of 1x1 cm² using this method. In [9,10] it was showed that such a system can operate stably in a wide range of the channel heights (0.17-2 mm) and angles of the channel inclination to the horizon (0-360°). In [11] a 3D non-stationary mathematical model of joint motion of evaporating liquid film and co-current gas flow in a microchannel with local heating has been developed, taking into account a deformable gas-liquid interface, convective heat transfer in the liquid and gas phases as well as temperature dependence of surface tension and liquid viscosity. The aim of the current paper is to experimentally study the dynamics of the flow and destruction of the liquid film in such a system, in order to explain the mechanisms responsible for high heat transfer rates achieved in the previous experiments. Unlike our previous studies, her we use an advanced imaging system with high spatial and temporal resolution.

2. Experimental setup

Figure 1 shows the design of the test section that is basically a sealed channel with openings for the entry and exit of liquid and gas. The lower part of the channel is a plate made of stainless steel. In the steel plate, a copper cylinder is flush-mounted, serving as a heater. The cylinder is heated using a nichrome coil, wound around its lower part. The surface of the copper heater is a square area of 10x10 mm². This design of the heater provides constant temperature on the surface of the cylinder, \( T_w = \text{const} \) (as confirmed by thermocouple measurements). The working surface (stainless steel plate together with the copper heater) was rough polished. The morphology of the working surface was analyzed using an atomic force microscope. The root mean square (RMS) surface roughness was found to be 0.8 µm. The working area is covered with a transparent cover of optical glass, thus forming a flat channel. The channel height in the experiments was 2 mm, while the channel width was 40 mm. The working gas – atmospheric air – with the relative humidity of 20-40% and initial temperature of 25 °C is used, which is supplied to the working area by means of an air compressor. As the working fluid in the experiment, ultra-pure distilled Milli-Q water is used with the initial temperature of 25 °C. The liquid is supplied to the working area by means of a gear pump.

Thermocouples built into the stainless-steel plate and into the copper cylinder allow to determine the temperature of the working surface. The heat flux is determined by the electrical power released on the heating coil. The thermal conductivity of copper is 400 W/mK, which is more than an order of magnitude higher than the thermal conductivity of stainless steel (15 W/mK). This provides moderate heat spreading from the heater to the steel plate. According to estimates, using the measurements of thermocouples embedded in the steel plate, the heat spreading is about 15% at \( q > 200 \text{ W/cm}^2 \). To reduce heat losses to the atmosphere, the heater was wrapped with a layer of heat-insulating material (figure 1). According to estimates using thermocouple measurements embedded in the heater, the thermal losses to the atmosphere do not exceed 10% at \( q > 400 \text{ W/cm}^2 \). Thus, the heat loses into the atmosphere and heat spreading into the steel plate in total do not exceed 25% at heat fluxes higher than

![Figure 1. Design of the test section. 1 – gas inlet; 2 – liquid inlet; 3 – thermocouples; 4 – nichrome coil; 5 – copper cylinder; 6 – thermal insulation; 7 – steel plate; 8 – glass plate; 9 – outlet of liquid and gas.](Image)
To carry out high-speed visualization of small-scale dry spots that occur on the heater under intense heating, the FASTCAM SA1.1 camera is used (5400 frames per second at a resolution of 1024x1024 pixels and up to 675000 frames per second at lower resolutions). The camera is equipped with an optical system of high spatial resolution (2.5 µm per 1 pixel of the camera sensor), figure 2. Images from the camera were processed using ImageJ software.

3. Results

It was found that the maximum intensity of heat removal from the heater is achieved in the pre-crisis regime, when the film flow continuity is broken (for more details, see [8]). The heater is covered with small dry spots (typical size on the order of 10-100 microns) with the lifetime on the order of 1/10000-1/1000 s. The number of spots that exist simultaneously on one square cm of the surface can reach several hundred. The dynamics of formation and disappearance of a typical dry spot is presented in figure 3 (shooting frequency of 100 000 frames per second). At the initial moment, we can observe a continuous film of liquid (figure 3-1), then a microscale bubble arises in the film (figure 3-2), then film rupture occurs very rapidly, which leads to the formation of a dry spot (figure 3-3). Then further development of the spot is observed (figure 3-4), after that the spot is washed out (figures 3-5, 3-6). It was estimated that at the heat flux of 450 W/cm², during 1 s up to 1 million dry spots appear and disappear at the area of 1 cm² (the surface of the heater). With increasing heat flux, the number of dry spots and the frequency of their formation increase.

Figure 4 shows the time dependence of the average diameter of 10 dry spots at the same parameters of the experiment. Totally we analysed 158 consecutive dry spots from one video. It was found that about 50% of them have lifetime less than 0.5 ms. From figures 3 and 4 it is seen that the process of the dry spots formation is extremely fast (the speed of the contact line is estimated to be on the order of 10 m/s). The growth of the microscale bubble in the film and the formation of a dry spot occur so rapidly (the timescale is ~10 µs) that the shooting frequency of 100 000 frames per second is not enough to study this process in detail. In future experiments, it is planned to increase the shooting frequency up to 500 000 frames per second. During dry spot expanding and shrinking the speed of the contact line is much less (10-100 cm/s).
Figure 3. Formation and dynamics of a dry spot. The shooting frequency is 100 000 frames per second. Field of view is 0.75 x 0.33 mm$^2$. The liquid Reynolds number $Re_l = 40$, superficial gas velocity $U_{sg} = 19.5$ m/s, heat flux $q = 450$ W/cm$^2$, the heater surface temperature $T_w = 130°C$. Flow is directed from right to left.

Figure 4. Time dependence of the average diameter of 10 different dry spots. The same parameters of the experiment as indicated in caption of figure 3.
Figure 5. Dependence of the total length of contact line on the heat flux. Run 1: \( \text{Re}_1 = 45; \ U_\text{sg} = 7.4 \text{ m/s}; \ \text{CHF} = 200 \text{ W/cm}^2 \). Run 2 (figures 3-4): \( \text{Re}_1 = 40; \ U_\text{sg} = 19.5 \text{ m/s}; \ \text{CHF} = 470 \text{ W/cm}^2 \).

Also, there is another interesting phenomenon connected with the total area of dry spots on the heater surface. With an increase of the heat flux the total area of dry spots increases, but when the heater reaches a certain temperature (\( \approx 100^\circ\text{C} \)), the total area of dry spots starts to decrease. Very close to the crisis the total area of dry spots on the heater attains minimum (nearly all the heater area is covered with liquid). In contrast to the area of dry spots, the total length of contact line on the heater increases with increasing heat flux and reaches a maximum in the pre-crisis regime. The dependence of the total length of the contact line on the heat flux is shown in figure 5 for two different runs. It is seen that for Run 2 in pre-crisis regime the total area of the contact line on the heater reaches 30 cm.

Intensive evaporation in the region of the contact line [12] may explain the achievement of high heat transfer rates in shear-driven liquid films (in [8] the critical heat flux (CHF) as high as 1200 W/cm\(^2\) was achieved).

4. Conclusion
With the help of high-speed imaging technique, it was found that in the pre-crisis regime the heater is covered with a great number of dry spots having typical size on the order of 10-100 \( \mu \text{m} \) and typical lifetime on the order of 0.1-1 ms. During 1 s up to 1 million dry spots appear and disappear at the area of the heater at the heat flux of 450 W/cm\(^2\). The total length of the contact line on the heater increases with increasing heat flux and reaches a maximum in the pre-crisis regime. Intensive evaporation in the region of the contact line may explain high heat fluxes achieved in the experiment.

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