Experimental investigation of heat transfer in a rivulet driven by gas flow in a minichannel

V V Cheverda$^{1,2}$ and O V Svetlichnaya$^{1,2}$

1 Kutateladze Institute of Thermophysics SB RAS, 630090, Russia, Novosibirsk, 1 Lavrentev Av.
2 Novosibirsk State University, 630090, Russia, Novosibirsk, 2 Pirogov St.

E–mail: slava.cheverda@gmail.com

Abstract. The heat transfer in a shear driven rivulet flow at isothermal conditions in a minichannel has been studied. The experiments were conducted using the setup, specially designed for the shear driven rivulet flow. The effect of liquid flow rate and substrate temperature on the width of the rivulet was studied experimentally using Laser induced fluorescence technique (LIF). The temperature distribution for different time moments of the rivulet surface was measured by the FLIR infrared (IR) camera. IR-measurements served to demonstrate that rivulet surface temperature is lower than substrate one due to liquid evaporation from the rivulet surface.

1. Introduction

Two-phase flows in mini- and microchannels are widely investigated in scientific groups around the world because of their wide application in modern and advanced science and technologies (electronic cooling, chemical process engineering, medical and genetic engineering, bioengineering and etc). Two-phase flow patterns in mini- and microchannels, including channels with diameters close to 1 mm, have been recently studied by several investigators [1].

The liquid-film flow in a minichannel is a separate flow with fluid wetting the entire substrate surface. In papers [2 - 4] it was found out that in the microchannels (0.1 – 0.5 mm height) there is the area of the stable stratified flow with a thin liquid film.

The flow of a liquid film driven by gas flow in a minichannel offers an effective technical means to cool microelectronic equipment under both terrestrial gravity and microgravity conditions. Previously, the operating principle of such system was described in [5]. In the use of microsystems with extended flat micro- and minichannels there is a problem of large pressure difference. It is necessary to provide a flow of large amounts of liquid and gas sufficient for effective cooling of electronic devices, which is energy-consuming. In the case of a rivulet flow, only part of the substrate is wetted. The use of rivulet flows in cooling systems is a promising solution for heat-exchange intensification because of an anomalously large heat-transfer coefficient in contact wetting line [6]. The viscosity of a liquid is greater than that of a gas, which ensures a decrease in the resistance to flow and the axial pressure drop and reduces the energy required for driving a two-phase fluid mixture along a minichannel.

A map of wave regimes for the rivulet flow of aqueous solutions of alcohol and glycerol was plotted with help of LIF optical method in [7, 8]. Stability of rivulet flows and hydrodynamic waves
on the surface for a falling down rivulet was investigated in [9, 10]. The mathematical model describing the rivulet flow of a low-boiling fluid (FC-72) shear-driven by gas flow in micro- and minichannels was proposed in [11] and experiments with rivulet flows of FC-72 fluid under variable gravity (parabolic flight) conditions were carried out in [12]. The experiments with water rivulet flows under variable gravity conditions were described in [13]. Stability of water rivulet was described and the rivulet flow was found to be less stable during microgravity.

In paper [14] it is shown that for a falling liquid rivulet on thin heated constantan foil the average heat flux density in the zone wetted by the rivulet is by the factor of 2.5 higher than the average density of the heat flux from the entire foil surface, and the heat flux density in the region of the contact line of wetting is higher by the factor of 2.8 than the total heat flux from the entire foil surface. So, the flow with evaporation in a contact line is a promising solution for microelectronic cooling.

In this paper we have experimentally demonstrated decreasing the rivulet width due to the liquid evaporation.

2. Experimental setup and technique of measurement

The experiments are conducted using the setup, specially designed for the shear driven rivulet flow (figure 1). The setup includes: the test cell, the working liquid supply system, the measuring system (sensors) and optical (LIF - Laser induced fluorescence technique and IR-scanner) systems, working fluids circuits, data acquisition and remote control systems. Water and dry nitrogen from a gas bottle are used as the working liquid and gas. Gas flow rate is varied from 0.5 l/m to 100 l/m. Pressure value inside the channel is set at fixed value of 1 ± 0.03 bar. Thoroughly degassed water is supplied to the test cell by the syringe pump from a flexible liquid container. The flexible container is used to provide working liquid supply without any bubbles. The liquid flow rate is regulated in the range between 1 ml/m and 100 ml/m. Three temperature stabilization systems based on the use of thermo-electrical modules (Peltier elements) are used to stabilize the liquid and gas temperatures at the inlet to the test cell. All thermo-modules are cooled by water circuit. All temperatures are maintained between 10 and 60°C. After the test cell the mixture of vapor, gas and liquid is evacuated to the atmosphere. All parameters are controlled remotely by means of the control and data acquisition system designed on the LabView software platform. For more details about the test cell (figure 2a) please see [12].

![Figure 1](image_url)

**Figure 1.** Scheme of the experimental setup for the study of heat transfer and dynamics of liquid rivulet shear driven by gas flow.
The optical system consists of IR scanner Titanium 570M (resolution 640x512 pixels with frequency 115 Hz, for wavelength 3.7 - 4.8 microns and photo camera Nikon D-7000 to observe processes inside the minichannel. For IR measurements a special window transparent for this IR-scanner is used.

The wetting contact angle of the minichannel substrate is measured by drop method with help of our DSA-100 system (goniometer). This angle is about 114.4±3° (figure 2b).

3. Experimental results

Photo images of the rivulets have been obtained from top view at different gas and liquid flow rates, temperature. One can notice from the picture that the rivulet width slightly increases with the liquid flow rate (figure 3). IR-pictures are demonstrated in figure 4. One can see that the rivulet temperature is lower than the substrate one due to evaporation effect.

![Figure 2](image2.png)

**Figure 2.** Scheme of the experimental test cell (a) and photo (b) of the sessile water drop on the minichannel substrate (average contact angle is about 114.4±3°), where 1 – optical window, 2 - thermocouples, 3 – stainless steel substrate, 4 – textolite cover with optical window, 5 – textolite frame, 6 – mixture outlet, 7 – Peltier element; 8 – water heat exchanger; 9 – liquid nozzle; 10 – liquid inlet; 11 – gas inlet; 12 – textolite base plate.

![Figure 3](image3.png)

**Figure 3.** Rivulet width versus liquid flow rate and substrate temperature for fixed gas flow rate of 70 l/min.
Figure 4. Photo and IR image of shear driven liquid rivulet inside minichannel with gas flow on a heated substrate (liquid flow rate – 10 ml/min, gas flow rate – 30 l/min, $T_{\text{substrate}} = 50^\circ$C), 1 – plastic window, 2 – transparent window for IR camera, 3 – water rivulet.

4. Conclusion
In the present paper a shear driven rivulet flow in the minichannel with gas flow has been studied experimentally. The effect of gas flow rate and substrate temperature on the rivulet width has been demonstrated. IR-measurements serve to demonstrate that the rivulet surface temperature is lower than the substrate one due to liquid evaporation from the rivulet surface.

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