Varieties of the gas driven water rivulet flow regimes in the minichannels

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Abstract. This paper reports on an experimental study of the gas (nitrogen) driven water rivulet flow regimes in the minichannel. The width of the liquid nozzle is 10 mm, the height and width of minichannel are 1.61 ±0.02 mm and 30 mm correspondently. The new flow regime has been found by authors. Its occurrence is connected with influence of relatively large static wetting angle of water on the flow and comparably small height of the channel. It was named “rivulet bridge”. The paper presents a map of the various rivulet flow regimes, characterized by different geometry and different kinds of surface deformations at temperature 40°C.

1. Introduction
Solving of complex computing tasks requires the use of powerful electronics. Due to the large number of transistors on a limited surface, such electronic devices have a high heat dissipation, that should be compensated by cooling systems of high efficiency. Thus, it is possible to prevent the transistors from burning out and, consequently, it will help to protect electronic devices from breakdown.

Two-phase systems have a great potential for use in cooling systems. The first studies, dedicated to the development of a compact, advanced cooling technology based on two-phase flows can be found here [1]. The macroscopic interface shape is shown to be sensitive for slip length comparable with the initial film thickness. The slip is found to increase evaporative mass flux with the maximum velocity value in the micro-region. The review on the regimes of two-phase flows in the channels of different geometries under different conditions is presented in [2]. The experimental investigations of two-phase flows in rectangular channels are given in [3, 4]. In particular, the rivulet flow, a kind of film flow, has a number of advantages useful for cooling. The main advantage of rivulet flow is the presence of two contact lines, in the area of which the heat transfer coefficient is several times greater than the average [5]. Cheverda et al in [6] also showed, that the maximum heat flux density takes place in the area of the contact line and exceeds the average heat flux density from the entire. The lower energy consumption for pumping the gas-liquid mixture through the channel is also an important advantage of the rivulet flow in comparison with the film flow.

A liquid film flow refers to a separate flow in which the fluid flows over the entire surface of the substrate. At a rivulet flow only a portion of the substrate is wetted by liquid, while the other part remains dry. Due to abnormally high heat transfer coefficient in the area of three phase contact line [7, 8], a rivulet flow is perspective solution for cooling purposes. The fluid viscosity is significantly
higher than the gas viscosity. Because of it rivulet flow has lower energy consumption comparing with film flow. Despite the increased interest to this kind of problems, a number of available experimental [9, 10] and theoretical works [11] is quite small and extremely insufficient for comprehension of the physics of the processes associated with the heat transfer in gas driven rivulet flow of water in the minichannel.

Studies related to rivulet flows can also be useful for studying the film flow. For example, a flowing down film can split into several rivulets due to the influence of temperature, external disturbances, periodic artificial perturbations, etc [12, 13].

To create an effective cooling system, a research of water rivulet flow regimes in minichannels at different temperatures is required. It is also important to obtain the geometric parameters of the rivulet flow and to measure the evaporation of water under different conditions.

2. Experimental setup

Experimental setup is presented in Fig.1. The following are the main elements of the working setup: gas supply system; fluid delivery system; the system for maintaining a predetermined pressure in the test section and a regenerative system; the power supply system (not shown); the water thermostabilization system; the data collecting system; the optical system; the replaceable test section with the temperature-controlled substrate of the minichannel (from 10 to 100°C).

![Figure 1. The sketch of experimental setup for studying the nitrogen driven isothermal rivulet flow regimes of the working fluid (water) in a horizontal minichannel](image)

The basis of the test section (Figure 2) is the frame (5) and cover (4) made of textolite. With the help of previously calibrated thermistors, initial temperature of the liquid (10) and gas (11) at the inlet of minichannel, as well as temperature of the substrate (3) are maintained at the value of 40°C with an accuracy of 0.2°C using Peltier elements (7) which are cooled by water heat exchanger (8). The inlet temperatures of the gas and liquid as well as outlet temperature of the mixture, the temperature of the substrate (2) and the ambient temperature are measured by thermal sensors.

The top wall of the channel should be transparent for visualization of the process and because of it test cell is covered by optical glass (1). Geometrical parameters of the channel are the following: the
width is 30 mm and a height is 1.61±0.02 mm. Liquid from the inlet gets to the liquid nozzle (9) and after that gets into the minichannel. The nozzle width for rivulet flow is equal to 10 mm. Gas (nitrogen) is fed into the test section under pressure through the nozzle (11) and drives the fluid rivulet along a rough substrate made of stainless steel (3). The surface was processed with abrasive M-40. Further, mixture of water and nitrogen is released through the orifice (6).

**Figure 2. Sketch of the test section**

Employing DSA-100 system and using sessile drop method (see Fig. 3) we measured the advancing wetting contact angle 140° (Figure 3) and receding wetting contact angle 10° (Figure 4). Hysteresis amounted to 130°.

**Figure 3. Advancing contact angle**

**Figure 4. Receding contact angle**

Also, we measured surface roughness for a better understanding of the interaction between the substrate and the liquid. The arithmetic average of the absolute values of the profile deviations within the basic length (Ra) was 0.458 µm.

### 3. Results and Discussion

We obtained regime map for various gas driven water rivulet flow regimes in the minichannel. For convenience geometrical and surface deformations are presented on different Figures (Figure 5 and Figure 6). Maps were obtained at a temperature of 40°C. We observed a new form of geometric deformations, which has not previously been detected for the FC-72 fluid flow. We called it “rivulet
bridge” (Figure 6(1),6(2),6(3)). In this regime, the rivulet does not have a contact with the side walls of the channel, however, it touches the upper and lower walls of the channel.

These kinds of geometric deformations were revealed: divergent (Figures 6(2), 6(5)), in which the flow width increases by more than 10% compared to the initial width; straight (Figures 6(3), 6(6)), the width of which remains within 10% compared to the initial one; pulsating rivulet bridge (Figure 6(1)), in which the appearance of the drop completely filling the channel alternates with the drainage of the channel; and unstable flow regime (Figure 6(4)), which represents two or more narrow rivulets.

**Figure 5.** Flow regime map representing varieties of the geometry of the nitrogen driven rivulet flow of water in the minichannel at 40°C. 1 – divergent rivulet bridge, 2 – straight rivulet bridge, 3 – pulsating rivulet bridge, 4 – divergent flow regime, 5 – straight flow regime, 6 – unstable flow regime

For better visualization we have also constructed a map representing various surface deformation regimes (Figure 7). We observed both the regimes already observed earlier for the flow of a shear-driven rivulet flow of FC-72 in minichannel (2D waves and 3D waves), and a new type of surface deformation braiding regime [14] that is caused by a larger surface tension coefficient.
Figure 7. Flow regime map representing varieties of the surface deformations of the nitrogen driven rivulet flow of water in the minichannel at 40°C. 1 – 2D waves, 2 – braiding, 3 – 3D waves

In conclusion it should be noted, the emergence of a new flow regime we associated with the fact that the static wetting angle of water is much higher than that in the fluorinert fluid FC-72. It means that the height of the water rivulet when driven by the gas in the minichannel is much greater than that of FC-72 fluid. Hence, we can conclude that the static wetting angle significantly affects the rivulet flow regimes.

Acknowledgments
The work was financially supported by the Ministry of Education and Science of the Russian Federation (Agreement 14.613.21.0067, project identifier RFMEFI61317X0067).

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