The thermocapillary deformations in the locally heated shear-driven liquid film flowing in minichannel

V V Cheverda \textsuperscript{1,2}

\textsuperscript{1} Kutateladze Institute of Thermophysics SB RAS, Novosibirsk 630090, Russia
\textsuperscript{2} Novosibirsk National Research State University, Novosibirsk 630090, Russia

E-mail: slava.cheverda@gmail.com

Abstract. Using phase schlieren system we have measured the shape of thermocapillary bump in the gas-driven (nitrogen) locally heated water film flowing in the minichannel. The measurements were conducted for liquid and gas flow rates corresponding to Re\textsubscript{L}=5.6 and Re\textsubscript{G}=73.5, respectively, and heat flux of 2 W/cm\textsuperscript{2}. The paper shows a qualitative coincidence of the experimental results obtained for the locally heated flowing liquid film and the numerical results on the deformation in a locally heated shear-driven water film flowing in the minichannel.

1. Introduction.
Film flow is widely used in the food industry and when cooling of the heating elements of a nuclear reactor, as well as in other devices with a high heat generation. Cooling of microelectronic equipment in space flight conditions is especially acute problem. Two-phase flows are a promising cooling solution. The review on the regimes of two-phase flows in the channels of different geometries under different conditions is presented in [1]. The experimental investigations of two-phase flows in rectangular channels are given in [2, 3]. A stratified flow with shear-driven liquid film is a sub regime of two-phase flow. In [4, 5] it is revealed that the critical heat flux in a shear-driven liquid film is 10 times greater than that in the gravitationally flowing liquid film at the same liquid flow rate.

At a local heating of the flowing liquid film, a thermocapillary bump arises due to thermocapillary effects [6]. In [7], thermocapillary bump was measured in flowing film of 25\% solution of ethyl alcohol in water, using schlieren method. Similar experiments were carried out on measuring the thermocapillary bump in a flowing film of a 10\% solution of ethyl alcohol in water using an optical fiber sensor [8].

Numerical simulation of thermocapillary bump formation in the falling liquid film of 25\% ethyl alcohol in water was carried out in [9], as well as compared with experimental data. The authors' studies in [10, 11] were focused on thermocapillary structures formation in underheated thin fluid films flowing down through a locally heated plate. Numerical simulation of thermocapillary bump formation in the gas driven liquid film flowing in the minichannel was carried out in [12, 13]. The analysis of deformation calculated numerically under local heating of a liquid film of 25\% ethanol solution in water, flowing down (the liquid Reynolds was equal to 1) a vertical plate with local heating (heat flux of 0.57 W/cm\textsuperscript{2}) has shown that relative deformation (absolute value of deformation divided by the initial thickness of the liquid film) was about 1.02 [14]. The analysis of numerically calculated
deformation of locally heated FC-72 film flowing under a constant shear stress that simulates the gas driven flow of a liquid film, revealed that shear stress influences the magnitude of deformation [15]. For example, at FC-72 liquid flow rate corresponding to Re=1, the tangential tension of 0.012 kg/s m, heat transfer coefficient of 20 W/m K, and heat flux of 0.1 W/cm^2, the relative deformation (absolute deformation divided by the initial thickness of the liquid film) was about 1.2, which is comparable with the deformation in a locally heated falling down liquid film [14]. The difference can be explained by the fact that liquids vary in physical properties, as well as due to difference in heat fluxes. The authors have also shown that with increasing shear stress, the magnitude of the deformation increases. This is due to the fact that with increasing shear stress, the film thickness is reduced, and consequently the shear stress on the film surface caused by thermocapillary forces is growing, and thus, the magnitude of the deformation increases.

The calculation of heat transfer and thermocapillary deformations in a nitrogen gas driven water film in the microchannel (height of 250 micron) was carried out in [16, 17]. The authors of [16] investigated the effect of acceleration on heat transfer and deformation of the water film, and showed that with increasing acceleration from 0 to 20g deformation decreases. At a fixed heat flux on the heating element, with increasing gas flow rate, the flow rate of the evaporated liquid is reduced, and at a fixed temperature of the heating element, increase of gas flow rate leads to the growth of the amount of evaporated liquid. In [17] it is shown that the thermocapillary bump is formed near the upper edge of the heater, while the minimum thickness of the liquid film is achieved near the lower edge of the heater (along the flow). Besides, the deformation in the form of jets occurs on both sides of the channel due to evaporation and thermocapillary forces. Described deformations occur because of evaporation and thermocapillary forces.

In the course of preparation for experiments aboard the International Space Station (ISS) it is scheduled to carry out an analysis and select the optical system to measure thermocapillary deformations at local heating of a gas driven liquid film flowing in the minichannel under zero gravity conditions. The obtained results will be used for verification of existing numerical models.

2. Experimental setup.
Installation for carrying out laboratory experiments is open loop (Fig. 1). In the experiments, the liquid and gas are transferred from the tanks. Set gas flow rate and pressure in the test section are maintained automatically through Bronkhorst regulators. The degassed liquid is fed into the test section by means of the syringe pump (Cole-Parmer EW-74905-54) through the thermal stabilization system. Thermal stabilizing systems based on Peltier elements are used to maintain the desired temperature of the liquid and gas at the inlet of the test section. These systems are cooled by means of a water system including pump, radiator, and safety valves.

![Figure 1. Schematic diagram of the experimental setup](image-url)
In the course of experiment, a two-phase mixture is evacuated into the atmosphere through the separation system employing a membrane pump (KNF N0150 AN.12E VP). The separation system is used to separate used water from the gas phase. All experimental parameters are monitored and recorded using software developed in LabView.

The test section (Fig. 2) consists of a textolite plate with mounted stainless steel plate serving a substrate. A frame, which is covered on top by optical glass, thus forming a minichannel with a height of 5 mm and a width of 30 mm, is attached to the textolite plate. Liquid film flow is created by means of the liquid nozzle with a height of 150 µm and a width of 30 mm. Gas flow enters the minichannel and flows over the liquid knife (42 mm wide), after which affects the fluid. The stainless steel substrate with copper bar (10 x 10 mm²) pressed into the substrate at a distance of 29 mm from the liquid nozzle is polished to a mirror-quality surface. The temperature of the substrate is measured by 10 K-type thermocouples. Two-phase mixture is evacuated from the test section through the orifice.

3. Experimental results.

The liquid film profile was measured using a phase-schlieren system (NIMO). The operating principle of this system is based on a combination of the schlieren method and the principles of interferometry. Using a special transparent liquid-crystal filter with variable transmittance, a schlieren image with a specific phase shift first is created horizontally (Fig. 3a) and then vertically (Fig. 3b). A series of obtained images are processed using the principles of interferometry, and then a three-dimensional profile of the resulting deformation is constructed. The measurement area is a circle with a diameter of 30 mm. The system’s sensitivity is 50 nm, while the error is 1 µm. A detailed description and operating principle is given in [18].

Based on obtained experimental results we have measured deformation profiles of the locally heated shear-driven water film. The heat flux was supplied to the copper rod by means of a ceramic electric heater. Part of this heat is removed by the film, while the other part is distributed over a substrate of stainless steel, and the remaining small portion is lost in heating the air surrounding the copper rod with attached ceramic heater.

Profile measurements were carried out first without heating under isothermal conditions of water film flow. Then the power of the heater was slowly increased to the specified value. The measurements were taken after reaching constant temperature not changing over five minutes. We
have obtained three-dimensional measurements of deformation profile (Fig. 3). Figure 3c presents the deformation of the thermocapillary bump across the flow (along line A passing through the center of the heater). Figure 3d presents the deformation profile of the film along the flow (along the line B passing through the middle of the heater).

Figure 3c shows considerable thinning of the film near the side walls of the heater. This thinning is caused by two factors: 1) the shear stress from the gas is not high enough and as a result the film is slightly convex in the center, and 2) there is an additional convexity due to thermocapillary bump in the center of the liquid film. At that, thermocapillary deformations are formed near the edges of the heater [16, 17]. However, they are not visible in Fig. 3, because they are located outside the field of view of the optical system.

It is seen that deformation in this region reaches 200 µm and even more. According to the research presented in [19], the film located at the edges of the heating element is the most likely to rupture and form dry spots, that is confirmed by conducted measurements of surface deformation.

![Image](a)

**Figure 3.** Change in deformation profile of the locally heated shear-driven water film flow in the minichannel: a, b – phase patterns at horizontal and vertical arrangement of the phase schlieren system filter (Re<sub>e</sub>=5.6, Re<sub>g</sub>=73.5, q=2 W/cm<sup>2</sup>, T<sub>o</sub>=25.5°C), c – water film deformation profile along the line A; d – water film deformation profile along the line B, where 1 – is the measured profile, 2 – is heater’s position.

The measurement of deformation along the flow shown in Figs. 3d confirm the presence of thermocapillary thickening, which is predicted by theoretical works [16, 17]. The maximum of this thickening in line B is observed near the front edge of the heater, where apparently there is a
maximum temperature gradient. For the above parameters, the maximum deformation along the line B was 77 μm.

It should be noted that the lateral deformation profile qualitatively agrees well with the calculation presented in [17]. At the same time, the longitudinal deformation profile along the line B is somewhat different from that obtained in [17]. In the calculations [17], the maximum in the region of the heater’s front edge is much more pronounced. Perhaps this is due to different boundary conditions. In [17] calculations were made for the conditions q=const, while in this paper, the condition T = const is satisfied at the heater.

The conducted measurements confirm an important conclusion that has been derived theoretically in [17]. These calculations have shown for the first time that for locally heated shear-driven liquid film, transverse deformations significantly exceed the longitudinal ones. In [17], this difference was almost two times. In the present experimental work, the difference is 2.5 times. It is known that in locally heated flowing liquid film, the longitudinal and transverse deformations are of the same order [17].

4. Conclusions
Finely, we can conclude that the measurements of deformations in a locally heated nitrogen gas driven water film flow in minichannel were carried out for the first time and the data obtained well agree with the numerical simulation of such liquid film flow in minichannel, conducted in [9, 12, 14]. Obtained data partially coincide with the results of works [15-17]. The difference in the results is due to the fact that numerical simulations were carried out for film flow in microchannel rather than minichannel.

In conclusion, we recommend using this optical technique when designing experiments aboard the ISS to study the heat transfer in the locally heated liquid film driven by gas in a microchannel.

Acknowledgments
The work was funded by RFBR and Novosibirsk region (research project № 17-48-540124).

References:
[1] Chinnov E A, Ronshin F V, Kabov O A 2015 Thermophysics and Aeromechanics 22 265-284
[2] Chinnov E A, Ronshin F V, Guzanov V V, Markovich D M, Kabov O A 2014 High Temperature 52 681-687
[3] Chinnov E A, Ron’shin F V, Kabov O A 2014 Thermophysics and Aeromechanics 21 759-762
[4] Zaitsev D V, Rodionov D A and Kabov O A 2009 Technical Physics Letters 35 88-94
[5] Kabov O A, Zaitsev D V, Cheverda V V, Bar-Cohen A 2011 Experimental Thermal and Fluid Science 35 825
[6] Kabov O A 1998 Thermophysics and Aeromechanics 5 597-602
[7] Kabov O, Scheid B, Sharina I and Legros J 2002 Int. J. Therm. Sci. 41 664
[8] Zaitsev D V, Kabov O A, and Evseev A R 2003 Exp. Fluids 34 748–754
[9] Frank A M and Kabov O A 2006 Phys. Fluids 18 032107
[10] Chinnov E A, Shatskii E N 2014 High temperature 52 461-464
[11] Chinnov E A, Shatskiy E N 2014 Technical physics letter 40 7-9
[12] Kabova Yu O, Kuznetsov V V, Kabov O A 2008 Microgravity Sci. Technol. 20 187–192
[13] Gatapova E Ya and Kabov O A 2008 Int. Journal of Heat and Mass Transfer 51 4797–4810
[14] Kabov O A, Legros J-C, Marchuk I V and Scheid B 2001 Fluid Dynamics 36 521–528
[15] Gatapova E Ya, Kabov O A and Marchuk I V 2004 Technical Physics Letters 30 46-52
[16] Kabova Yu O, Kuznetsov V V, Kabov O A 2014 Interfacial Phenomena and Heat Transfer 2 85-102
[17] Kabova Yu, Kuznetsov V, Kabov O, Gambaryan-Roisman T, Stephan P 2014 Int. Journal of Heat and Mass Transfer 68 527–541
[18] Joannes L, Dubois F and Legros J C 2003 Applied Optics 42 5046-5053