Cooling of a microchannel with thin evaporating liquid film sheared by dry gas flow

Yu O Kabova¹,² and V V Kuznetsov³,⁴

¹Kutateladze Institute of Thermophysics, SB RAS, 630090, 1 Lavrentiev prosp., Novosibirsk, Russia
²Novosibirsk State University of Architecture and Civil Engineering, 630008, 113 Leningradskaya Str., Novosibirsk, Russia
³Lavrentyev Institute of Hydrodynamics, SB RAS, 630090, 15 Lavrentiev prosp., Novosibirsk, Russia
⁴Novosibirsk State University, 630090, 2 Pirogov str, Novosibirsk, Russia

E-mail: kabova@itp.nsc.ru

Abstract. A joint motion of thin liquid film and dry gas in a microchannel is investigated numerically at different values of initial concentration of the liquid vapor in the gas phase, taking into account the evaporation process. Major factors affecting the temperature distribution in the liquid and the gas phases are as follows: transfer of heat by liquid and gas flows, heat loses due to evaporation, diffusion heat exchange. Comparisons of the numerical results for the case of the dry gas and for the case of equilibrium concentration of vapor in the gas have been carried out. It is shown that use of dry gas enhances the heat dissipation from the heater. It is found out that not only intense evaporation occurs near the heating areas, but also in both cases vapor condensation takes place below the heater in streamwise direction.

1. Introduction

Investigation of dynamics and evaporation of locally heated thin liquid films sheared by gas flow becomes one of the most important and most complicated problems in thermal physics, since it is concerned with the problem of cooling of microelectronic equipment [1, 2, 3]. Modern microprocessor represents a flat surface consisting of zones with an inhomogeneous heat release [4]. The shape of these zones is often close to rectangular one [5], and the size can range from a few hundreds of microns to several millimeters. The thermal-power density in hot zones ("hot spots") can reach 1 kW / cm² and differs from the average thermal-power density on the chip by 5-10 times. Such "hot spots" as well as the chip itself might be considered as a local heat sources. Spray cooling, boiling in microchannels, thermoelectric modules are just some examples of methods using to solve the problem of heat removal from small size hot zones. One of the promising solution allowing to remove high heat fluxes is technology using processes with phase change, for example evaporation of a thin liquid film moving in a flat microchannel under the action of a gas flow [5, 6], but thin films are subjected to rupture, which drastically reduces the efficiency of the apparatus and can lead to their breakdown [7, 8, 9]. In addition to the thermocapillary effect one of the most important factors affecting the dynamics of the liquid film rupture and the formation of a dry spot in the region of local heating is evaporation [6, 10]. It is worth noting that, as a rule, liquid film is supposed to be sheared by the dry gas flow [7].
2. Mathematical model

In the present work a joint motion of thin film of incompressible viscous liquid and gas in a horizontal microchannel is considered, taking into account the evaporation process at different values of initial concentration of the liquid vapor in the gas phase. The microchannel is assumed to be unbounded in streamwise and spanwise directions. A part of wall at the side of liquid film is heated; temperature at the heater is prescribed. Coupled two-phase problem is simulated using a 3D nonstationary model; the model is based on the previously developed mathematical model [9]. The transport processes in the liquid and in the gas phases are described by the Navier-Stokes, continuity and energy equations and diffusion equation in the gas phase. For the deformable gas-liquid interface the following boundary conditions are posed: the condition of continuity of the temperature (it is equivalent to the fact that we remain in equilibrium thermodynamics) and the tangential components of the liquid and gas velocity vectors, the mass conservation condition, the dynamic condition with the term expressing the mechanical effect of the evaporated matter on the liquid, the thermal boundary condition and condition of local thermodynamic equilibrium. This means that near the liquid surface the partial vapor pressure is equal to the equilibrium pressure corresponding to the local temperature. The upper wall is adiabatic and impermeable. The dynamic viscosity and surface tension are assumed to depend on temperature. The problem is transformed to specially developed new variables, so that continuity equations in the liquid and in the gas retain their form in new variables but kinematic condition at the free interface simplifies and become linear. We employ the lubrication theory to derive reduced set of equations, so we assume that the characteristic film thickness and the characteristic film thickness variation are much smaller than the characteristic length scale of the film in streamwise and spanwise directions, thereby the film aspect ratio is taken asymptotically small \( \varepsilon = H_0/l \ll 1 \). Considering inertial terms to be negligible, the system of equations with boundary conditions is rewritten in dimensionless form.

Major factors affecting the temperature distribution in the liquid and the gas phases are as follows: transfer of heat by liquid and gas flows, heat loses due to evaporation, diffusion heat exchange. These factors significantly affect each other and, by turn, are heavily dependent on the resulting temperature distribution. Previous investigations [9, 11] have shown that the heat removal from hot spots is mainly determined by evaporation. Therefore, the intensification of the heat dissipation may be achieved by intensifying the evaporation.

An important difference from the previous works is a specification that incoming gas does not contain liquid vapor. Namely, previously [9, 11] it was posed, so as for many problems with the diffusion evaporation, that the vapor concentration must be equal to the saturated concentration on the free interface (vapor concentration corresponding to the pressure of the saturated vapor).

Since a non-stationary problem is solved, for the case of the dry gas, it would be more convenient to calculate the process where, at the beginning of the calculation, the input gas has equilibrium moisture, but for some small time interval the vapor concentration in the input gas flow decreases to zero and remains so (dry gas). Then after a while the heater is turned on, and the heat and mass transfer processes gradually stabilize.

Numerical solution of the problem is implemented by the finite difference method. The alternating directions implicit (ADI) method is used to solve the system of grid equations with boundary conditions. To solve the problem on each fractional grid step the Thomas algorithm is used. For more details refer to [9, 11].

3. Numerical results

Calculations have been performed for the constant channel height equal to 250 mkm. In all calculations the liquid is water and the gas is air. Gas is moving in x-direction and the heater upper edge is located at the origin of coordinate system. The heater size is constant in all calculations and equal to 3 x 6, 4 mm² (length x width). Channel has been supposed to be horizontal, so that inclination angle is equal to 0. The gas and the liquid Reynolds numbers have been kept constant in all calculations and equal to Reₕ=20 and Reₙ=8, 5 correspondingly (the initial film thickness \( H_0=92 \), 2 mkm). The initial temperature is equal to 20°C. All quantities shown in figures are presented in a
In the dimensionless form, here the time and the temperature are set as \( t = \frac{lt}{U} \) and \( \theta = \frac{T - T_0}{T} \).

Calculations of the total evaporation rate, \( J_n \), have been performed using the following formula

\[
J_{\text{total}} = \oint \frac{k_3(w_g - w)}{1 - k_3} \, dx \, dy,
\]

here \( n \) is the area of calculations. This follows from mass conservation law at the free boundary.

Figure 1 shows the total heat transfer from the heater for the cases of dry gas (black lines) and for the case when the vapor concentration in the gas phase at the microchannel inlet is equal to the saturated concentration on the free interface (red lines). It can be seen that the use of the dry gas significantly increases the heat transfer from the heater both at high temperature on the heater and at low temperature prescribed on the heater.

![Figure 1](image1.png)

**Figure 1.** The total heat transfer from the heater vs time. Black lines - dry gas, red lines - equilibrium concentration of vapor in the gas. Lines 1 and 3 correspond to the temperature on the heater equal to 22.5\(^\circ\)C, lines 2 and 4 correspond to the temperature on the heater equal to 30\(^\circ\)C. All quantities shown on figure are presented in a dimensionless form.

Figure 2 shows the distribution of the evaporation intensity over the gas-liquid interface (or vapor condensation). In the case (a) the gas flow entering the channel does not contain liquid vapor, in the case (b) their concentration is equal to equilibrium for the average temperature. It can be seen that the vaporization rate in case (a) is much higher. In addition, it can be seen that in both cases vapor condensation takes place after the heater in streamwise direction and the process of condensation plays an important role in the redistribution of the heat.

![Figure 2](image2.png)

**Figure 2.** Distribution of the evaporation intensity over the gas-liquid interface (or vapor condensation). (a): dry gas, (b): equilibrium concentration of vapor in the gas. Prescribed temperature on the heater is 30\(^\circ\)C.
Figure 3 shows the gas-liquid interface position along the channel at $y = 0$ for the dry gas when the gas flow entering the channel does not contain liquid vapor, and for the case when liquid vapor concentration is equal to equilibrium for the average temperature. Deformation of the film as a bump at the front edge of the heater exists for both cases. The top of the bump is located near the front edge of the heater. The governing factor in this phenomenon is the thermocapillary effect due to the intensive heating and strong temperature gradient along the liquid film near the front edge of the heater. But for dry gas significant film thinning occurs in the area of gas stream entrance to the channel and this overall thinning gradually decreases downstream. This takes place because the incoming dry gas causes evaporation of a liquid that absorbs heat and therefore a longitudinal temperature gradient appears, the value of which decreases downstream. And the resulting Marangoni force causes the film thin. This should be taken into account since significant film thinning may lead to a film rupture.

![Figure 3. Gas-liquid interface position along the channel at $y = 0$. Black line - dry gas, red line - equilibrium concentration of vapor in the gas. Prescribed temperature on the heater is 30ºC](image)

The minimum film thickness takes place near the heater side downstream. The main reasons are evaporation taking place due to significant increase of temperature on the gas-liquid interface, and thermocapillary effect. Calculations of the minimum values of the film thickness vs time are shown in figure 4. It is seen that the film thinning in the case of dry gas is more significant than in the case of the equilibrium concentration of vapor in the gas. And with increasing the heater temperature, this difference increases.

![Figure 4. Minimum film thickness vs time. Black lines - dry gas, red lines - equilibrium concentration of vapor in the gas. Lines 1 and 2 correspond to the temperature on the heater equal to 30ºC, lines 3 and 4 correspond to the temperature on the heater equal to 22.5ºC](image)
Figure 5 shows the velocity fields along the channel at \( y=0 \) and at the free interface for the case of the dry gas. Deformations of the gas-liquid interface cause distortion of the velocity fields. Calculations show that near the channel entrance, as well as near the heating area, the velocity field differs significantly from the case of co-current flow in a channel with straight streamlines. Therefore the widespread assumption that the dynamic effect of a gas flow on a liquid could be replaced by the action of a certain average shear stress may lead to significant errors while investigating the co-current gas and liquid flow in a channel. In addition, one can see some destabilization of the flow near the heating area and formation of an array of rolls or rivulets descending downstream.

4. Conclusions
The systematic numerical investigations of temperature and concentration profiles evolution in gas and liquid phases were performed. In addition velocity fields in the liquid and gas phases as well as evolution of free interface deformations and film thickness at constant liquid flow rate and different values of the temperature at the heating element were calculated for the case of the dry gas. Comparisons of the numerical results for the case of the dry gas and for the case of equilibrium concentration of vapor in the gas have been carried out.

It is shown that use of dry gas enhances the heat dissipation from the heater both at high and low temperatures prescribed on the heater but the film thinning in the case of dry gas is more significant. It is found out that not only intense evaporation occurs near the heating areas, but also condensation of vapor.

Acknowledgments
The work was supported by the Russian Science Foundation, Agreement no. 14_19_01755.

References
[1] Hirokawa T, Murozono M, Kabov O and Ohta H 2014 *Frontiers in Heat and Mass Transfer* 5 1-8
[2] Nasr M H, Green C E, Kottke P A, Zhang X, Sarvey T E, Joshi Yo K, Bakir M S and Fedorov A G 2017 *Int. Journal of Heat and Mass Transfer* **108** 1702–13

[3] Nasr M H, Green C E, Kottke P A, Zhang X, Sarvey T E, Joshi Yo K, Bakir M S and Fedorov A G 2017 *Journal of Electronic Packaging* **139** 011006

[4] Mahajan R, Chin C and Chrysler G 2006 *Proceedings of the IEEE* **94** 1476-85

[5] Sri-Jayantha S M, McVicker G, Bernstein K and Knickerbocker J U 2008 *IBM Journal, Res. & Dev.* **52** 623–634

[6] Lyulin Yu V, Spesivtsev S E, Marchuk I V and Kabov O A 2015 *Technical Physics Letters* **41** 1034–37

[7] Houshmand F and Peles Y 2013 *Int. Journal of Heat and Mass Transfer* **64** 42-52

[8] Kabova Yu O, Kuznetsov V V, Kabov O A 2008 *Microgravity sci. technol.* **20** 187-192

[9] Kabova Yu, Kuznetsov V, Kabov O, Gambaryan-Roisman T and Stephan P 2014 *Int. J. Heat and Mass Transf.* **68** 527-541

[10] Liu R and Kabov O A 2012 *Physical Review E-Statistical, Nonlinear, and Soft Matter Physics* **85** 066305

[11] Kabova Yu, Kuznetsov V V and Kabov O 2014 *Interfacial Phenomena and Heat Transfer* **2** 185-102