# FLOW AND HEAT TRANSFER IN COOLING MICROCHANNELS WITH PHASE-CHANGE

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**ABSTRACT**

The subject of the present work is the parametrical investigation of hydrodynamic and thermal characteristics of laminar flow with phase-change in a heating microchannels. The study is based on the quasi-one-dimensional model of non-isothermal capillary flow. This model takes into account the evolution of flow, heating and evaporation of the liquid, as well as the influence of capillary, inertia, friction and gravity forces. The effect of various parameters (sizes of microchannel, initial temperature of cooling liquid, wall heat flux etc.) on hydrodynamic and thermal structures of the flow, the length of heating, evaporation and superheat regions is studied. The specific features of the phenomena is discussed.

## 1. Introduction

Fluid flow in a heated capillary attract the attention of investigators in large measure because of their wide use in cooling systems of electronic devices. Beginning from the work of Tuckerman and Pease [1] attention has been paid mostly on single phase fluid flow in microchannel (Weisberg et al. [2]; Peng and Peterson [3]; Wu and Little [4]; Bailey et al. [5]). Although single phase flow in microchannels can effectively cool miniature devices, they present some inherit disadvantages, like large pressure drop and streamwise increases in the heat sink temperature. As opposed to that, two phase heat dissipation can achieve very high heat fluxes with low flow rate while maintaining a relatively constant surface temperature. The experiments of Bowers and Mudawar [6] conducted on boiling flow in mini and microchannels demonstrated that high value of heat flux can be achieved. Nowadays, there are a number of models of the evaporation liquid/ vapour meniscus in a capillary slot (Landerman [7], Khrustalev and Faghri [8]). An evaporation two phase flow model that takes into account the multistage character of the process as well as the effect of capillary, friction and gravity forces was proposed by Peles et al. [9] and Hetsroni et al. [10]. The aim of the present work is the analysis of the two-phase non-isothermal flow in a heated microchannel, which is based on the quasi-one-dimensional equations for capillary flow suggested by Peles et al. [9].

## 2. Governing equations

Figure 1 shows schematically the flow regions occurring in a capillary slot during phase change. The first region (heating region) is the region where the liquid temperature increases, beginning from the inlet up to the evaporation region. As the liquid temperature increases to its evaporation temperature, phase change begins, and halts at the superheating region inlet, where dry out occurs.

The quasi-one dimensional equations of the mass, thermal and momentum balance, describing the evaporation two phase flow and heat transfer in a heated capillary, were in troduced as eqs. [5 4] - [58] in Peles et al. [9]. The equations were then supplemented by equation [59] - [62] (Peles et al. [9]).

## 3. Numerical calculation

The subsequent calculations were performed for laminar flow of water ($\rho^{(2)} = 10^3 \mathrm{kg/m^3}, c_p = 4.19$ kJ/kg·K, $\beta =$ 0.059 N/m, $q_{ev} = 2256$ kJ/kg, $\theta = 0.67$ rad) in a vertical slot height 1.5 d mm. The inlet water temperature $T_{inl}^{(2)}$, gap-size d, heat flux q and gravitational acceleration g were varied within the limits; $273 < T_{inl}^{(2)} < 373$[K], $1 < d < 500$[μm], $10 < q < 600$ [W/cm²], $1 < g < 600$ [m/s²]. The following non dimensional parameters were chosen:

$$\overline{P} = P\beta^2/\rho^{(2)^3}\nu^{(2)^{(2)}}q_{ev}^2;\quad \overline{d} = \frac{d\cdot q_{ev}\rho^{(2)}}{\beta}$$

$$\overline{L} = Lq_{ev}\rho^{(2)}/\beta;\quad \overline{T} = \frac{TC_p^{(2)}}{q_{ev}};\quad \overline{g} = \frac{g\beta^3}{\nu^{(2)^3}q_{ev}^3\rho^{(2)^3}}$$

$$\overline{q} = \frac{q\beta}{\rho^{(2)^3}q_{ev}^2\nu^{(2)}};\quad \overline{u}^{(i)} = \frac{u^{(i)}\beta}{\nu^{(2)}q_{ev}\rho^{(2)}};$$

$$\overline{x}_j = x_j q_{ev}\rho^{(2)}/\beta \qquad [10]$$

The calculations show that $P_{inl}^{(2)}$, for a fixed vapor evaporation pressure, depends very weakly on $T_{inl}^{(2)}$, d and q at large Euler numbers. For example, the variation $0.52 \le \overline{T}_{inl}^{(2)} \le 0.68$, $4\times10^4 \le \overline{d} \le 2\times10^7$; $10^{-8} \le \overline{q} \le 2.5\times10^{-7}$ corresponds (at Eu > $10^8$) to less than 0.02% change in $P_{inl}^{(2)}$. The temperature in the meniscus symmetry point $T_{20}$ equals the saturation temperature $T_S$. Since the pressure drop in the liquid region of the capillary flow is small it is possible to assume that $T_S$ corresponds to $P_{out}^{(1)}$. The estimations show that such assumption does not effect practically, the results of the calculations.

## 4. Results and discussion

The effect of the inlet liquid temperature, the size of the capillary gap, the wall heat flux and gravity on the hydrodynamic and the thermal characteristics of the flow in microchannel were studied. These data show that the preliminary heating of the liquid (increase of $T_{inl}^{(2)}$) is accompanied by displacement of the meniscus toward the inlet of capillary. In accordance with that the length of the liquid region of the flow ($x_*$) decrease whereas the length of vapour region increase. Noteworthy that the length of the evaporation region (as well as the shape of interface surface) does not depend on $T_{inl}^{(2)}$.

Increasing the inlet liquid temperature causes the expansion of the vapour region, leading to a vapour temperature and velocity growth at the outlet. The latter is accompanied by a significant change of the microchannel drag. The calculation has shown that the decrease in the liquid region drag is smaller than the growth of the hydraulic drag at the vapour region. As a consequence the total pressure drop between the inlet and outlet cross

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Increasing the inlet liquid temperature causes the expansion of the vapour region, leading to a vapour temperature and velocity growth at the outlet. The latter is accompanied by a significant change of the microchannel drag. The calculation has shown that the decrease in the liquid region drag is smaller than the growth of the hydraulic drag at the vapour region. As a consequence the total pressure drop between the inlet and outlet cross sections of the microchannel increase as the liquid preliminary heating increases.

The effect of capillary gap-size on the interface surface, vapor velocity and the difference of pressure and temperature between inlet and outlet cross sections of the microchannel was studied. Increasing the capillary gap size (d) leads to the expansion of the liquid region. This effect is explained as follows: at the fixed values of the other parameters an increase of d leads to a growth in the total mass flux of the liquid through the capillary. Since the area of heat transfer surface and wall heat flux are invariable, the energy per unit mass of liquid decrease. Accordingly the heating rate of the liquid decreases too. The latter is accompanied by a displacement of the meniscus toward the outlet cross section and therefore $x_*$ increases. The length of the evaporation region increases proportionally to the size of the gap, whereas the $(X_{**} - x_*)/d$ ratio does not depend on d. The latter shows that the shape of the interface surfaces are similar for various d. The decrease of the superheat region length with gap-size growth leads to a decrease in the outlet vapor velocity and temperature.

The effect of gravity on the liquid and vapor parameters in the inlet and outlet cross section is also studied. It is seen that an increase in the gravity is accompanied by a significant growth of the liquid pressure $P_{inl}^{(2)}$. At the same time an increase of the vapor pressure in the outlet cross section is observed. However, the rate of liquid and vapor pressure growth are very different. This causes an increase of the difference $\Delta p = p_{inl}^{(2)} - p_{out}^{(1)}$ as gravity increase as well as the sign change at some value of $\bar{g}$. The temperature difference $\Delta T = T_{inl}^{(2)} - T_{out}^{(1)}$ and vapor velocity in the outlet cross section of the microchannels practically do not depend on gravitational acceleration.

The effect of wall heat flux on the length of the heating and evaporation regions, vapor velocity, temperature and pressure in the outlet cross section is shown in Fig. 2 - 3. These data illustrate some important features of capillary flow at large Euler numbers.

As was shown in Peles et al. [9] at $Eu > 10^8$ the mass flux through the microchannel is directly proportional to the wall heat flux. In this case the energy per unit mass of liquid absorbed from the wall does not depend on the value of the heat flux. As a consequence the length of the heating and evaporation regions as well as the liquid and vapor temperatures are invariable on q. This phenomenon which may be called "The effect of self-regulation" has an important meaning to estimate the limiting permissible thermal states of the system with phase change of a cooling liquid.

**5. Conclusion**

A quasi-one-dimensional equation of non-isothermal capillary flow is applied to study parametrically the thermohydrodynamic characteristics of two-phase flow in a heated microchannel. It is shown that a self-regulated regime of flows may be realized at large Euler number. It is significant to note that at these flows the liquid mass flux through the capillary is directly proportional to the heat flux on the wall. Under this condition the length of the heating, evaporation and superheating regions as well as the temperature distribution, practically, do not depend on the wall heat flux.

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**Figure Captions**

Fig. 1 Flow scheme

Fig. 2 The effect of wall heat flux on the meniscus position
a) the dependence of $x^*(q)$
b) the dependence of $x^{***}(q)$
c) the dependence of $\Delta x(q)$

Fig. 3 The dependencies of vapor temperature, pressure on a velocity in outlet cross section of capillary on heat flux on the wall
a) the dependence $\Delta T(q)$
b) the dependence $u^{(1)}(q)$
c) the dependence $\Delta p(q)$

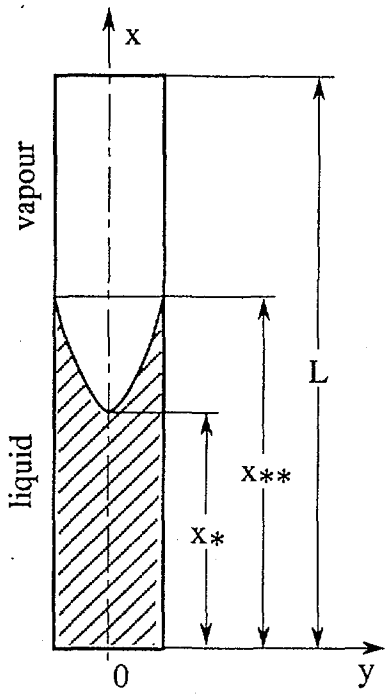


Fig. 1

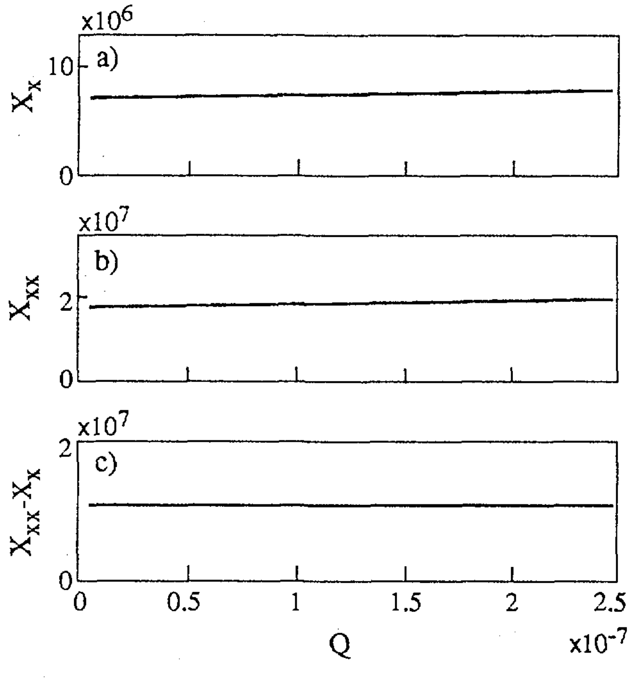


Fig. 2

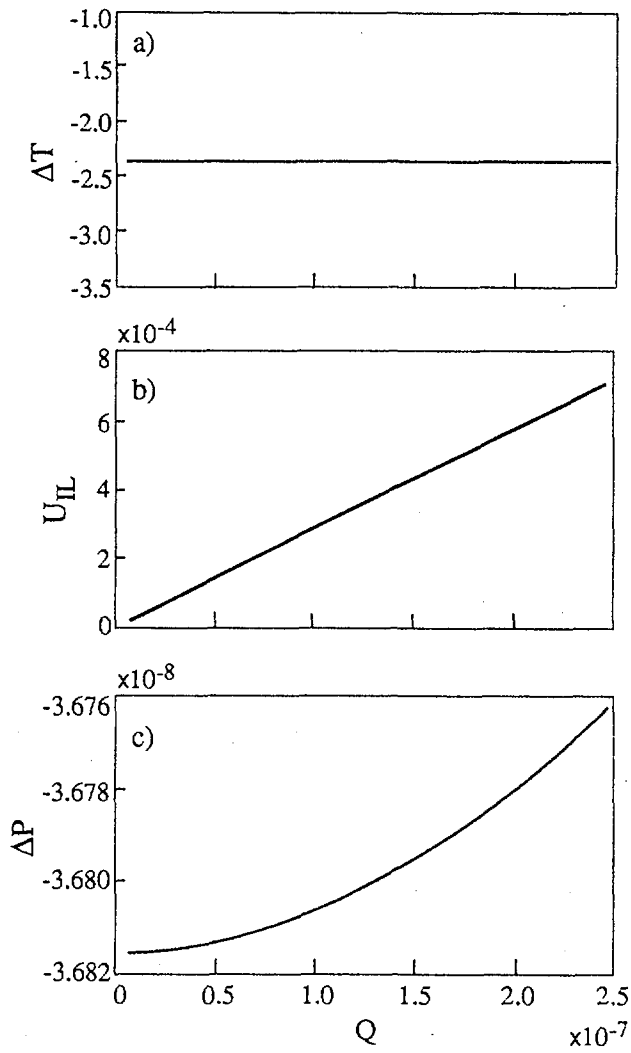


Fig. 3