Numerical study of flow condensation of dielectric liquid in microchannel

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Abstract. This paper presents a numerical analysis of flow condensation of dielectric liquid perfluorohexane in a rectangular microchannel using the annular flow model. It is shown that accumulation of liquid near the channel corners causes the heat transfer enhancement due to liquid film thinning. The numerical method is validated against experiments and predicts well the average heat transfer coefficients during flow condensation in a rectangular microchannel for vapor quality higher than 0.5.

1. Introduction
Due to the rapid growth of applications that require the transfer of a large amount of heat from small areas, the attention has recently been paid to design of the microchannel cooling systems. While microchannel heat sink was successfully used as a compact boiler, packaging design is constrained by the size of the loop-s condenser. Therefore, implementation of two-phase flow boiling in these systems requires the development of compact condensers based on microchannel technology [1]. Compact condensers have microchannels with different cross-sections of the rectangular, square and circular shape. The experiments with horizontal rectangular and square channels are reported in [2, 3] for condensation of refrigerants R134a, R32, R1234ze, and R410A. The correlations are proposed in [2] to predict the heat transfer coefficients for uniform film thickness in an annular flow. A heat transfer model for condensation heat transfer in rectangular minichannels was developed in [3] considering the effects of vapor shear stress and surface tension. The condensation flow of the refrigerant FC-72 in a rectangular microchannel with a 1-mm hydraulic diameter was numerically studied using the volume of fluid model in [4]. Nevertheless, the effect of capillary forces in microchannels requires more detailed consideration, since they can cause the significant redistribution of the liquid flow and the heat transfer enhancement. The aim of this study is a numerical investigation of the characteristics of liquid distribution and local heat transfer during flow condensation of dielectric liquid perfluorohexane in a rectangular microchannel using the model of annular flow proposed in [5]. This liquid is the main component of FC-72 and has well determined thermophysical properties.

2. The model formulation
The numerical study of the heat transfer during condensation of perfluorohexane at small reduced pressure was performed for rectangular microchannel with a cross-section of 335x930 μm. The calculations were made on the basis of the Navier-Stokes equations averaged over the thickness of the liquid film accounting presence of the meniscus near a channel corner caused by the capillary forces action. It happens because the liquid pressure in the meniscus is reduced in comparison with that for
the liquid film area. Typically, the condensation in microchannel starts from the high vapor quality and the main flow pattern is the annular flow. The model of evaporation in a vertical rectangular microchannel for the annular flow was proposed in [5]. This model can be used also for prediction of heat transfer during condensation in horizontal microchannel if the interfacial waves are absent. It is based on the allocation of liquid flow in two zones consisting of the flow in a corner of the channel bounded by meniscus and liquid film flow on the channel walls. To obtain the total interface shape, these solutions match together with an account of the conjugation conditions. For thin-film area, the small parameter exists that is \( \varepsilon = \delta_0/a << 1 \), where \( \delta_0 \) is the initial liquid film thickness and \( a \) is the half-width of the long side of the channel. Using this small parameter and neglecting the gravity term for the flow in a microchannel, the Navier-Stokes equations and interface boundary conditions can be reduced for film flow area to the equation for prediction of the evolution of interface shape during condensation as follows

\[
\left( m^3 + 1.5 \frac{K}{\varepsilon} m^3 \right)_x + \left( m^3 m_{yy} \right)_y = \frac{3}{\varepsilon^3} \left( \frac{Ga}{m \gamma} \right)_x - \frac{G_i \Theta_{w,i}}{m \varepsilon}. \tag{1}
\]

Here \( \gamma = 1 - \frac{\rho_{\text{liq}} g \rho_{\text{gas}}}{\rho_{\text{liq}} g a} \), \( \kappa = \rho_{\text{liq}} \frac{\rho_{\text{gas}} g a}{\sigma} \), \( Bo = \rho_{\text{liq}} \frac{\rho_{\text{gas}} g a}{\sigma} \), \( Ga = A_0 / (6 \alpha^2 \sigma) \), the dimensionless film thickness is scaled via initial film thickness \( m = \delta_0 / \delta_0 \) longitudinal \( x \) and transverse \( y \) dimensionless coordinates are scaled via \( \sqrt{\frac{\mu \gamma}{\rho_{\text{liq}}} \frac{\rho_{\text{gas}} g a}{\sigma}} \) and \( a \) respectively, \( \tau \) is shear stress at the interface, \( A_0 \) is the Gamaker's constant, \( G_i = \lambda_{\text{liq}} \frac{T_{w,i}}{(h_{\text{fg}} \alpha a) \Theta_{w,i}} = (T_{w,i} - T_{\text{sat}}) / T_{\ast} \) are determined by temperature of the inner wall \( T_{w,i} \), saturation temperature \( T_{\text{sat}} \) and characteristic temperature which is \( T_{\ast} = T_{w,e} - T_{\text{sat}} \) for constant temperature of the external wall \( T_{w,e} \) and \( h_{\text{fg}} \) is the latent heat of vaporization. A special feature of the approach proposed in this paper is consideration of the shear stress in the liquid surface using the model [6]. The account of disjoining pressure is important for the walls with a very low roughness that provides the last terms in the equation (1).

Equation (1) is solved numerically together with the equations for liquid flow in the meniscus and total liquid flow conservation by the finite-difference method. The boundary conditions are the symmetry conditions at the center of the channel and conditions \( m_x = 0 \) and \( m_y = 1 / (r \varepsilon) \) at the point of conjunction of interface solutions for the liquid film and the meniscus, where \( r = R / a \). Solving Poisson equation for the liquid flow in a corner of the channel bounded by the meniscus with known curvature, the dependence of the flow rate on radius curvature of meniscus \( R_m \), its configuration, contact angle and shear stress at the interface was obtained in the form of polynomials in [5]. When interface shape is determined, the Fourier equations for liquid and wall area are solved together to define the temperature field, and the mass flux at the interface is determined using the assumption of conductive heat transfer in a liquid film.

3. Results and Discussion

The numerical calculations were carried out for initially uniform liquid film in the channel cross-section with inlet vapor quality of 0.995 and outlet pressure of 0.1 MPa. The calculations were done to compare the calculation results with experimental data [7] obtained for surface roughness of 2.5 \( \mu \)m. The calculation results show the accumulation of liquid in a short side of the channel and the formation of curved liquid film on the long side of the microchannel, which has a minimum thickness near the meniscus. The obtained distribution of the thickness of the waveless film in the symmetry element of a rectangular channel for mass flux of 120 kg/m²s is shown in figure 1 for two local vapor qualities \( x = 0.91 \) and 0.73. As it can be seen, the preferential accumulation of liquid in the meniscus near the channel corners occurs along the length of the channel that causes thinning of liquid layer and increasing local heat flux in this area. The results of numerical calculations show that non-uniform liquid film thickness produces a high value of local heat transfer coefficient near the meniscus and enhances the heat transfer considerably.
The dependence of average heat transfer coefficient during flow condensation of perfluorhexane on vapor quality obtained from numerical calculations of equation (1) is shown for \( G = 120 \text{ kg/m}\text{s} \) in figure 2 as a dotted line. The points are corresponded to the experimental data [7] for the same conditions. As it is seen, calculation results agree well with experimental data if vapor quality exceeds 0.5. For less vapor quality, the calculations overpredict the experimental data. The possible reason for this trend is the formation of a thick liquid layer on the short side of the channel and formation of the waves in menisci area that causes the levelling of liquid surface and suppression of the heat transfer enhancement. This reason is confirmed by the results of calculation of the heat transfer coefficients during condensation for uniform liquid film and turbulent vapor flow according to the model of convective heat transfer [8] with an account of interfacial friction from [9]. These results are shown as a solid line in figure 2. As it can be seen, the results obtained according to the uniform liquid film model are located slightly below the experimental data in the whole range of vapor quality. Uniform liquid film model does not account the fundamental features of the flow such as the existence of the

![Figure 1](image1.png)

**Figure 1.** Interface shape for vapor quality \( x_v = 0.91 \) (a) and \( x_v = 0.73 \) (b) during condensation with mass flux of 120 kg/m\text{s}.

![Figure 2](image2.png)

**Figure 2.** Dependence of average heat transfer coefficient on vapor quality for non-uniform liquid film from numerical calculation of equation (1), and uniform film according to the models of [8, 9], points are experimental data [7] for \( G = 120 \text{ kg/m}\text{s} \).
menisci near the channel corners; nevertheless, its advantage is reasonable averaging of heat transfer along the channel perimeter for the conditions under consideration.

The calculation of heat transfer coefficients for the uniform liquid film according to the conductive model of heat transfer based on the liquid thickness calculations according to [8] are shown in figure 2 as a dashed line and poorly matched the experimental data.

Conclusions
The above results of numerical calculations of flow condensation of dielectric liquid at low reduced pressure show that non-uniform flow of condensate along the perimeter of the microchannel due to the predominant influence of the capillary forces causes considerable enhancement of heat transfer near the channel corners, this compensates heat transfer deterioration in the meniscus area. The numerical method is validated against experiments and predicts the average heat transfer coefficients well for vapor quality higher than 0.5 where the wave formation in the meniscus area is suppressed. The calculations according to uniform liquid film model based on convective heat transfer do not account the fundamental features of the flow such as the existence of the menisci near the channel corners; nevertheless, its advantage is reasonable averaging of the heat transfer along the channel perimeter for the conditions under consideration.

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