An experimental study of heat transfer and pressure drop during flow boiling of R134a and R236fa in a microchannel system

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Abstract. An experimental study was made of heat transfer and pressure drop during the boiling of R134a and R236fa refrigerants in a system with two slotted microchannels. A copper block with two microchannels 2.05 mm wide, 0.4 mm deep, and 16 mm long was used as an experimental test section. The mass velocity varied from 500 to 2000 kg/m²s, the initial subcooling was from 40 °C to 0 °C. Data analysis showed that, when the flux of R236fa refrigerant becomes saturated, nucleate bubble boiling is absent. In the case of R134a saturated flow boiling, suppression of nucleate bubble boiling was observed with heat flux increasing.

1. Introduction
Microchannel cooling systems with boiling coolant are promising devices for maintaining a constant temperature of equipment in conditions of high heat [1]. In such systems, it is possible to reliably remove high heat fluxes of up to 100 W/cm² or more. Despite the high values of heat transfer coefficients and critical heat fluxes, a certain limitation on the use of microchannel systems has an increase in hydraulic resistance, especially for bubble boiling, which significantly affects the efficiency of the cooling system [2]. The aim of this work is an experimental study of heat transfer and friction losses during subcooled and saturated flow boiling of R134a and R-236fa refrigerants in a system of two slotted microchannels.

2. Experimental equipment
The experimental section was a copper block 16 mm long with two microchannels with a width of 2050 microns and a depth of 400 microns, separated by a 2000 micron thick partition, with a top cover made of polished stainless steel. A protective nickel coating 2 micrometers thick was applied to the surface of the microchannels. The heat was supplied from heating cartridges mounted in a copper block. At a distance of 3 mm and 13 mm from the entrance to the microchannels, thermocouples measuring the temperature and temperature gradient in the copper block were installed. Temperature and pressure were measured in the inlet and outlet chambers also. The experimental setup scheme and measurement procedure are described in detail in [3].

Test measurements of heat transfer coefficients and pressure drops were carried out under single-phase fluid flow conditions (R134a refrigerant). The measured average heat transfer coefficients \( \alpha_m \) were determined as the ratio of the average heat flux \( q_H \) to the average logarithmic temperature head \( \Delta T_{ln} \).
The experimental data correspond to the Petukhov correlation for heat transfer in a turbulent flow [4], with the entrance correction factor derived by [5], figure 1(a). The data on the measured pressure drop during a single-phase flow is in good agreement with the calculation, figure 1(b). In the calculation, the correlation for the developing flow derived by Philips [6] with the laminar-equivalent Reynolds number for rectangular channel geometries [7] was used. The pressure drop caused by an abrupt flow area changes was calculated according to [8].

3. Results and discussion

The obtained data on heat transfer and pressure drop during flow boiling of refrigerants in the microchannel system are compared with calculations by models. To calculate the wall heat flux during boiling on the wall temperature $T_W$, a model with the actual independence of the mechanisms of heat transfer by single-phase convection and by nucleate boiling of one another derived by Dedov et al. [9] was used.

$$q_W = q_{con} + q_{boil}$$  \hspace{1cm} (2)

Here $q_{con}$ is the heat flux which taken away by forced convection, calculated by [4], $q_{boil}$ is the heat fluxes due to boiling calculated by [10].

To calculate the total pressure drop during flow boiling in the system, it is necessary to take into account the inlet constriction pressure drop $\Delta P_{Constr}$, the pressure drop in the economizer section $\Delta P_{Ec}$, the pressure drop in the sub-cooled boiling section $\Delta P_{Sub\_boil}$, the pressure drop in the saturated boiling section $\Delta P_{Sat\_boil}$, the pressure drop at the outlet of microchannels during the flow expansion $\Delta P_{Ext}$, as well as the pressure drop associated with the acceleration of the flow $\Delta P_{Acc}$. Thus, the total pressure drop $\Delta P_{Total}$ in the system was calculated as:

$$\Delta P_{Total} = \Delta P_{Constr} + \Delta P_{Ec} + \Delta P_{Sub\_boil} + \Delta P_{Sat\_boil} + \Delta P_{Acc} + \Delta P_{Ext}$$  \hspace{1cm} (3)
The channels in the studied system were located horizontally, and the influence of gravity was not taken into account. Since a single-phase liquid flow was supplied to the inlet, \( \Delta P_{\text{Constr}} \) was calculated according to [8]. The pressure drop in the economized section was calculated as for a single-phase flow. To calculate the length of the economizer section \( z_{\text{ec}} \), we used the condition for the equilibrium vapor quality \( x_i \) at which the subcooled boiling, proposed in [11], begins. The dependence of the vapor quality \( x \) on the distance from the beginning of channels \( z \) was determined as

\[
x = \frac{C_p L (T_{\text{in}} - T_{\text{Sat}})}{h_{LV}} + q_w \left( \frac{a + 2b}{Gabh_{LV}} \right)
\]

where \( C_p L \) is the heat capacity of the liquid, \( T_{\text{in}} \) is the inlet temperature of the liquid, \( T_{\text{Sat}} \) is the saturation temperature, \( h_{LV} \) is the latent heat of vaporization, \( G \) is the mass velocity, \( a \) is the channel width and \( b \) is the channel height. To calculate the pressure drop in the subcooled boiling section \( \Delta P_{\text{Sub-boil}} \), the correlation from [12] was used. When calculating the pressure drop associated with the acceleration of the flow, the Zivi correlation was used to determine the void fraction [13]. When calculating the pressure drop during the expansion of the flow at the exit from the microchannels, the model from [14] was used. To calculate friction in the saturated boiling region, we used the models for adiabatic vapor-liquid flow and two-phase flow taking into account the effect of nucleate bubble boiling [15].

A comparison of the dependence of the average heat flux on the average wall temperature with the calculation according to equation (2) when flow boiling at a mass flow rate R236fa equal to 1040 kg/m²s with initial subcooling by 28 °C to the saturation temperature is shown in figure 2(a). The experimental data are in good agreement with the calculation up to a heat flux of 80 W/cm², after which a sharp deterioration in heat transfer is observed. In this case, the heat transfer deterioration coincides with the moment when the outlet flow becomes saturated, that is, the equilibrium vapor content at the exit of the microchannels becomes equal to zero. It can be assumed that the decrease in heat transfer, in this case, is caused by the suppression of nucleate bubble boiling in the saturated flow region and, as a result, a significant decrease in heat transfer caused to critical phenomena.

Figure 2. Boiling curve (a) and pressure drop vs. the outlet vapor quality (b) during boiling of R236fa at input subcooling 28 °C. Pressure drop calculation: taking into account the influence of saturated boiling –line 1, without taking into account the effect of saturated boiling –line 2.
The dependence of the pressure drop on the output vapor quality for the data in figure 2(a) is shown in figure 2(b). The pressure drop data are compared with the calculation according to equation (3) taking into account the effect of bubble boiling on friction in the saturated boiling region (line 1) and with the calculation of friction in the saturated boiling region as for the adiabatic flow (line 2). Until the occurrence of a saturated flow, the calculation slightly exceeds the experimental data, and line 1 and line 2 coincide. Nucleate boiling in the saturated flow region should cause additional friction, but increasing in pressure drop corresponding calculation for line 1 is not observed.

Figure 3. Boiling curve (a) and pressure drop vs. the outlet vapor quality (b) during boiling of R236fa at input subcooling 5 ºC. Pressure drop calculation: taking into account the influence of saturated boiling – line 1, without taking into account the effect of saturated boiling – line 2.

Figure 4. Boiling curve (a) and pressure drop vs. the outlet vapor quality (b) during boiling of R13a at input subcooling 3 ºC. Pressure drop calculation: taking into account the influence of saturated boiling – line 1, without taking into account the effect of saturated boiling – line 2.
The boiling curve for data with a decrease in the initial subcooling of R236fa refrigerant to 5 ºC is shown in figure 3(a). Under these conditions, the flow becomes saturated at the outlet at lower values of the heat flux. Even with heat fluxes above 30 W/cm², lower values of heat transfer coefficients are observed than with nucleate boiling in a large volume. The comparison of the measured pressure drop for the this data in figure 3(b) with the calculated values shows good agreement with the calculation without taking into account the effect of bubble boiling on friction (line 2). Thus, the experimental data indicate the suppression of nucleate boiling in the saturated flow region for R236fa refrigerant.

Unlike R236fa refrigerant, the experimental data for flow boiling R134a refrigerant with low subcooling of the liquid at the entrance to the microchannels, see figure 4, the possibility of nucleate bubble boiling in saturated region show. The dependence of the heat flux on the wall temperature in figure 4(a) shows a deviation from the calculated boiling curve at a heat flux above 50 W/cm², this heat flux corresponds to an output equilibrium vapor quality equal to 0.2. A comparison of the corresponding experimental data on the pressure drop with the calculation in figure 4(b) shows that for the data with output vapor quality is less than 0.15, the data are described by the model taking into account the effect of bubble boiling on friction in the saturated flow region (line 1). With an increase in the heat flux and, accordingly, the vapor quality of the flow, a decrease in friction is observed in comparison with the calculated, accordingly line1, values. At output vapor quality above 0.25, the measured pressure drops correspond to the calculation with the absence of nucleate bubble boiling, and an essential deterioration in heat transfer, compared with the calculation according to equation (2), is observed.

4. Summary
The heat transfer and pressure drop during the flow boiling of R134a and R236fa refrigerants in the slotted system with two microchannel were measured. In the presence of nucleate bubble boiling in the microchannel system, the data on heat transfer are in good agreement with the calculation according to the Dedov model [9] using the Yagov dependence [10] for boiling heat transfer in a large volume. Upon transition to a saturated flow at the exit from the microchannels, bubble boiling can be suppressed, and a decrease in heat transfer is observed. The experimental data showed that upon the flow boiling of R236fa refrigerant under the studied conditions, the transition to a saturated flow causes a sharp suppression of nucleate bubble boiling. Upon the flow boiling R134a refrigerant, a smooth suppression of nucleate boiling in the saturated flow region with increasing vapor quality and heat flux is observed.

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