An experimental study on the subcooled flow boiling pressure drop of R141b in the system of two microchannels

A. S. Shamirzaev
Institute of Thermophysics, 630090, Ac. Lavrentyev Ave. 1, Novosibirsk, Russia
alisham@itp.nsc.ru

Abstract. An experimental study of the pressure drop under subcooled flow boiling of the refrigerant R141b in a system with two slotted microchannels was carried out. A copper block with two microchannels 2 mm wide, 0.4 mm deep, and 16 mm long was used as an experimental section for testing. The mass flow rate varied in the range from 1 to 4 g/s, the initial subcooling from 20°C to 50°C. Experimental data show a significant decrease in the pressure drop when the critical heat flux is reached. The experimental data are compared with the model known from the literature. Experimental data show that the occurrence of nucleate boiling incipience at subcooled boiling corresponds to a larger heat flux than that given by the recommended correlation.

1. Introduction
Subcooled boiling is widely used for cooling heat-stressed equipment, as it allows an increase in the amount of heat removed and critical heat fluxes. At the same time, an increase in the pressure drop during nucleate boiling in the subcooled boiling region can significantly affect the efficiency of cooling systems, especially for microchannel cooling systems. Methods for predicting the pressure drop for microchannel cooling systems use the correlations for the nucleate boiling incipience obtained for conventional channels, such as in Takashi & Matsumura [1]. Such correlations do not take into account the confinement space influence on the nucleate bubble and may be incorrect when applied to microchannel devices. Thus, the problem of determining the pressure drop under subcooled boiling conditions in microchannels and the verification of existing calculation methods is urgent. The aim of this work is to study the pressure drop under subcooled flow boiling of the refrigerant R141b in the system of 2-slot microchannels and to compare the obtained data with the well-known model from the work of Kim Mudawar [2].

2. Experimental equipment and data treatment
The experiments were carried out in a closed-loop which included: a pump, a thermostat, a flow meter, an experimental test section, and a cooling condenser. The working fluid was R141b refrigerant. A heated copper block with two microchannels coupled to the inlet and outlet chambers was used as an experimental section. The depth of the microchannels \( a = 0.4 \text{ mm} \), the width of the microchannels \( b = 2 \text{ mm} \), the length \( L_{ch} = 16 \text{ mm} \), and the distance between the channels was \( 2 \text{ mm} \). Thermocouples that measure the wall temperature at a depth of 1 and 5 mm from the surface of the microchannels at a distance of 3 and 13 mm from the entrance to the microchannels were placed in the body of the copper block. The surface of the microchannels was covered with a protective nickel coating, according to the data of interference microscopy, the surface roughness was \( Ra = 0.46 \mu m \).
Temperature and pressure were measured in the inlet and outlet chambers. The cross-section of the chambers was much larger than the cross-section of the channels and it was 50.3 mm$^2$. The experimental setup scheme and measurement procedure are described in detail in Kuznetsov, Shamirzaev [3]. The experiments were carried out in the range of mass flow rates from 1 to 4 g/s and initial subcooling of the liquid from 20 to 50°C.

When calculating the pressure drop under subcooled boiling conditions, it is necessary to take into account the following parameters: the pressure drop due to a sudden contraction of the flow at the inlet to the microchannels $\Delta P_c$, the pressure drop under the conditions of the developing flow in the non-boiling section $\Delta P_{nb}$, the pressure drop in the subcooled boiling section $\Delta P_{sb}$, and the pressure drop due to sudden enlargement at the outlet of the microchannels $\Delta P_{ex}$. The total pressure drop is calculated as

$$\Delta P = \Delta P_c + \Delta P_{nb} + \Delta P_{sb} + \Delta P_{ex}$$  \hspace{1cm} (1)

Figure 1 shows a comparison of the dependence of the measured pressure drop on the mass velocity in a single-phase fluid flow with the calculation. Here, according to Collier Thome [4], the pressure drop at the narrowing of the flow at the inlet to the microchannels is calculated as

$$\Delta P_c = \frac{G^2}{2\rho_{liq}} \left[ \left( \frac{1}{C_c} - 1 \right) + (1 - \sigma_c^2) \right]$$  \hspace{1cm} (2)

here $\sigma_c$ is the contraction area ratio, and the contraction coefficient $C_c$ is calculated as in Geiger [5]

$$C_c = 1 - \frac{1 - \sigma_c}{2.08(1 - \sigma_c) + 0.5371}$$  \hspace{1cm} (3)

Figure 1. Total pressure drop vs. mass flux under adiabatic single phase flow.
The exit pressure loss is calculated as in [4]

\[ \Delta P_{ex} = -\frac{G^2}{\rho_{liq}}\sigma_c (1 - \sigma_c) \]  

(4)

The pressure drop under the conditions of the developing flow of a single-phase liquid is calculated using data from Shah and London [6] for the laminar flow and for the turbulent flow according to Zhiqing analytical solution for a circular tube [7] as recommended in [2]. The measured pressure drops are in good agreement with the calculated model; in the region of the transition from the laminar flow to the turbulent regime, the calculation is slightly less than the experimental data, see figure 1.

When calculating the subcooled boiling pressure drop, an important parameter is a condition for nucleate boiling incipience. In the work of Kim Mudawar [2], it is recommended to use the heat flow condition from the work of Takashi Matsumura [1]

\[ q_{ONB} = \frac{k_{liq} h_{fg} \rho_{gas} (T_w - T_{Sat})^2}{8\sigma (T_{Sat} + 273.15)} \]  

(5)

and the wall temperature at which nucleate boiling incipience occurs \( T_{ONB} \) depends on the heat transfer coefficients during single-phase convection \( h \) and the local temperature of the liquid \( T_{flow} \) and is defined as

\[ T_{ONB} = T_{Sat} + \frac{4\sigma (T_{Sat} + 273.15)h}{k_{liq} h_{fg} \rho_{gas}} \left( 1 + \sqrt{1 + \frac{k_{liq} h_{fg} \rho_{gas}}{2\sigma (T_{Sat} + 273.15)h} \left( T_{Sat} - T_{flow} \right) \right) \]  

(6)

The local heat transfer coefficient for thermally developing laminar region is calculated by data from Shah and London [6], and for thermally developing turbulent region it is calculated by correlation from Al-Arabi [8] as

\[ h_L = \frac{k_{liq}}{D_h} \left( \frac{0.023 Re_{liq}^{0.8}}{Pr_{liq}^{0.4}} \right)^{-0.09} \left( \frac{L}{D_h} \right)^{-0.68} \left( \frac{3000}{Pr_{liq}^{0.81}} \right) \]  

(7)

The increase in the pressure drop associated with subcooled boiling is recommended to be calculated using the Kim Mudawar model [2] in the form

\[ \frac{\Delta P_{sh}}{\Delta P_{ad}} = 20.73 Ja^{-0.98} \left( \frac{\min(a,b)}{\max(a,b)} \right)^{0.42} \left( \frac{L}{D_h} \right)^{-0.54} \frac{L_{sh}}{L_{sat}} \]  

(8)

where \( a \) and \( b \) are the width and depth of the channel and
Here, $L_{\text{Sat}}$ is defined as the length at which the flow becomes saturated

$$L_{\text{Sat}} = \frac{m c_p,\text{liq} (T_{\text{Sat}} - T_{\text{flow,in}})}{q (a + 2b)}$$

(10)

if $L_{\text{Sat}} > L_{\text{ch}}$ then $L_{\text{Sat}} = L_{\text{ch}}$ where $L_{\text{ch}}$ is the channel length

And $L_{\text{nb}}$ is the length, at which the incipience boiling condition is reached, is calculated as

$$L_{\text{nb}} = \frac{m c_p,\text{liq} (T_{\text{W,ONB}} - \left( T_{\text{flow,in}} + \frac{q}{h} \right))}{q (a + 2b)}$$

(11)

And the length, at which subcooled boiling $L_{\text{sb}}$ occurs, is calculated as

$$L_{\text{sb}} = L_{\text{Sat}} - L_{\text{nb}}$$

(12)

If $L_{\text{sb}} < 0$, then the conditions for the occurrence of subcooled boiling are not achieved.

3. Results and Discussions

Figure 2a shows a comparison of the dependence of the measured pressure drop on the average heat flux with the calculation according to the Kim Mudawar model \[2\]. The solid line shows the calculation under subcooled boiling conditions, according to equation (1), when the outlet flow does not reach saturation. In the case when the equilibrium vapor quality at the outlet from the channel becomes more than zero, the additional contribution of the saturated boiling section to the pressure drop was also taken into account using the correlations from the work of Kim Mudawar \[9\], this calculation is shown by the dashed line. The same data depending on the outlet equilibrium vapor quality of the flow are shown in Figure 2b. According to the calculation for the studied channel, an increase in the pressure drop due to nucleate boiling under subcooling conditions occurs not at the moment of nucleate boiling incipience at the outlet from the channels, indicated by a gray arrow in Figure 2, but when nucleate boiling extends to almost the entire channel. Consequently, in our case, the condition under which subcooled boiling makes a perceptible contribution to the pressure drop is the occurrence of nucleate boiling at the entrance to the microchannels, indicated by a black arrow in Figure 2. At the same time, a comparison of the experimental data with the calculation shows that the effect of nucleate boiling on the pressure drop manifests itself at larger values of the heat flux than it is shown by the calculation. In the experiment, a higher increase in the pressure drop with an increase in the heat flux is observed than predicted by equation (8). Under conditions when the equilibrium vapor quality of the flow at the exit from the microchannels becomes more than zero, a sharp increase in the pressure drop does not occur, which may be associated with the development of critical phenomena. When the critical heat flux is reached, a sharp drop in the pressure drop is observed.
Psat=4bar
T_{Sat}-T_{ inlet}=50 \, ^{\circ}C
G=1260 \, kg/m^{2}s

*Figure 2.* Total pressure drop vs.: (a) wall heat flux; (b) outlet vapor quality.

It should be noted that under subcooled boiling conditions in microchannels, the void fraction is greater than zero and the true vapor quality \( x_r \) is greater than the equilibrium one. In contrast to large channels, in microchannels the size of bubbles is comparable to the size of the channel, and, therefore, equation (4) will underestimate the pressure drop as the flow expands at the exit from the microchannels, and the pressure drop inside the microchannels will be greater. To calculate the exit pressure loss, one can use the equation recommended in Kandlikar et al. [10] in the form

\[
\Delta P_{ex} = -\frac{G^2}{\rho_{liq}}\sigma_r (1 - \sigma_r) \left[ 1 + \left( \frac{\rho_{liq}}{\rho_g} - 1 \right) \left( 0.25 x_r (1 - x_r) + x_r^2 \right) \right],
\]  

(13)

however, this raises the problem of determining the true vapor quality of the flow at the exit of microchannels.

The increase in the pressure drop in the microchannel under study relative to the pressure drop under the adiabatic conditions, depending on the wall overheating relative to the boiling point of the flow at the inlet to the microchannels under conditions when the equilibrium vapor quality of the flow at the outlet from the microchannels is less than zero for all presented data is shown in figure 3. The presented graph demonstrates that a noticeable increase in the pressure drop is observed when the wall overheats by 8-10 degrees higher than it is predicted by equation (6). Under the conditions under consideration, the error in calculating the heat transfer coefficients in the case of a laminar and turbulent developing flow does not significantly affect the value of the wall temperature at which nucleate boiling occurs. When the heat transfer coefficients change by a factor of two, \( T_{ONB} \) changes by no more than one degree. Data on pressure drops and experiments on heat transfer of R141b refrigerant in a similar system of two slotted microchannels presented in [11] show that nucleate boiling incipience in microchannels occurs at higher heat fluxes than predicted by the equation (5) recommended in the Kim Mudawar [2].
4. Summary
Analysis of all experimental data showed that the average absolute calculation error for the Kim Mudawar model [2] for the subcooling flow boiling pressure drop reaches 20%. Experimental data show a significant decrease in the pressure drop when the critical heat flux is reached. The study showed that in order to calculate the pressure drops during subcooled boiling in microchannels, it is necessary to investigate in more detail the conditions for the occurrence of nucleate boiling in confinement space. The problem of determining the true void fraction and vapor quality under substantially non-equilibrium conditions of subcooled boiling is equally important.

Funding
This work was performed at the Kutateladze Institute of Thermophysics SB RAS by a state contract with IT SB RAS. The project state registration number is 121031800215-4.

References
[1] Takashi S, and Matsumura H. 1964 Bulletin of JSME 26 392
[2] Kim S M, Mudawar I 2012 Int J Heat and Mass Transfer 55 3720
[3] Kuznetsov V V, Shamirzaev A S 2018 Technical Physics Letters 44 (10) 938
[4] Collier, J. G., and J. R. Thome. Convective boiling and condensation, 3rd edn. Clarendon 1996
[5] Geiger G E 1964 Ph.D.Thesis, University of Pittsburgh, PA
[6] Shah R.K., London A.L., Laminar Flow Forced Convection in Ducts:, New York, 1978 (Supl 1)
[7] Zhi-qing W 1982 Appl. Math. Mech. 3 433.
[8] Al-Arabi M., 1982 Heat Transfer Eng. 3 76
[9] Kim S M, Mudawar I 2013 Int. J. Heat and Mass Transf. 58 (1-2) 718
[10] Kandlikar, Satish, et al. Heat transfer and fluid flow in minichannels and microchannels. elsevier, 2005.
[11] Shamirzaev AS, Mordovskoy AS, & Kuznetsov VV 2019 J Phys Conf. Ser. 1382 (1) 012117.