An experimental study of flow condensation with non-azeotropic refrigerant mixtures of R32/R134a in microchannels

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Abstract. This paper aims at experimental study of heat transfer during flow condensation of a binary mixture of refrigerants R32 and R134a in a microchannel heat exchanger. The experiments were performed in a horizontal microchannel condenser with one-sided cooling. The condenser was based on 20 × 40 mm copper plate containing 21 rectangular microchannels with a section of 335 × 930 μm. The non-azeotropic mixture of R32/R134a refrigerants at molar concentrations of the initial mixture of 35% / 65% and 65% / 35% was used as a working fluid. The experiments were carried out in the mass flow range from 100 to 300 kg/m²s and with a vapor quality from 0.05 to 1.0 at an absolute pressure in the system of up to 14 bar. The data obtained are compared with the prediction according to Silver – Bell & Ghaly method.

1. Introduction
Currently, for the design and manufacture of refrigeration equipment, much attention is paid to the use of ozone-safe refrigerant mixtures with a low global warming potential. It should be noted that most refrigerant mixtures are non-azeotropic. During the condensation of non-azeotropic mixtures, an increased thermal resistance is observed in comparison with the condensation of pure fluids. When calculating heat transfer of the mixture, it is necessary to take into account not only the thermal resistance in the liquid film, but also the phase mass transfer resistance. Meanwhile, microchannel heat exchangers allow obtaining higher heat transfer coefficients than those of traditional finned heat exchanger. When designing compact heat exchangers, the microchannel heat exchangers have a great prospect [1]. In this work, experimental data on heat transfer during condensation of a binary non-azeotropic mixture of refrigerants in a microchannel heat exchanger are presented. The data obtained are compared with the calculations using the Silver – Bell & Ghaly method [2, 3].

2. Experimental equipment and measurements
The experiments are carried out in a horizontal condenser with one-sided cooling. The condenser is based on 20 × 40 mm copper plate containing 21 rectangular microchannels with a section of 335 × 930 μm. The microchannel plate is covered with a stainless-steel plate. The installed thermocouples measure the wall temperature along the microchannel heat sink at a distance of 5, 15, 25, and 35 mm. The experiments were performed for the mass flow range from 100 to 300 kg/m²s and vapor quality from 0.05 to 1.0 at an absolute pressure of up to 14 bar. The non-azeotropic mixture of R32/R134a refrigerants at molar concentrations of the initial mixture of 35%/65% and 65%/35% are used as the working fluid. The condenser is located horizontally and cooled from below by a water circuit with Peltier elements.
The experimental equipment and methods for determining the heat flux are presented in more detail in [1].

The average heat transfer coefficient during condensation \( \alpha \) was determined as follows:

\[
\alpha = \frac{q_w}{(T_{in} + T_{out})/2 - 0.25 \cdot \sum_{i=1}^{4} \frac{T_{w,i} + \delta \cdot q_w}{\lambda_w}}
\]  

(1)

here \( T_{in} \) is the input temperature of the two-phase mixture, \( T_{out} \) is the output temperature of the two-phase mixture, \( T_{w,i} \) is the measured local wall temperature in the \( i \)-th position, \( \delta \) is the distance from the thermocouple to the inner surface of the microchannels, \( \lambda_w \) is the thermal conductivity of the microchannel plate. At the inlet of microchannel plate, the two-phase flow was supplied at vapor quality defined in initial vapor generator. The input vapor quality \( x_{in} \) was calculated as follows:

\[
x_{in} = \left[ Q_G - m C_{p_{mix}} (T_0 - T_b) \right] / \left[ m (h_v - h_l) \right]
\]  

(2)

where \( Q_G \) is the heat supplied to the stream on the vapor generator, \( C_{p_{mix}} \) is the heat capacity of the liquid mixture, \( m \) is the mass flow rate, \( T_0 \) is the temperature of the liquid mixture at the inlet of the vapor generator, \( T_b \) is the boiling temperature of the mixture, \( h_v \) and \( h_l \) are the specific enthalpies of the saturated vapor phase and the liquid phase at the dew point and at the point boiling, respectively. The outlet vapor quality \( x_{out} \) was calculated from the inlet vapor quality and removed heat \( Q_C \) as follows:

\[
x_{out} = x_{in} - Q_C / \left[ m (h_v - h_l) \right].
\]  

(3)

The average vapor quality \( x \) for the measuring section was calculated as follows:

\[
x = \frac{x_{in} + x_{out}}{2}.
\]  

(4)

When calculating phase equilibrium diagram for refrigerant mixture at the experimental conditions, the calculation procedure from [4] was used. To calculate the thermophysical properties of the vapor and liquid phases of the binary mixture, the properties of pure components and methods from [5] were used.

The measurements of average heat transfer coefficients for single-phase laminar flow of liquid refrigerant were performed for testing the measurement system. The measured heat transfer coefficient for single-phase flow \( \alpha_m \) was determined as the ratio of the average heat flux \( q_w \) to the log temperature head \( \Delta T_{ln} \)

\[
\alpha_m = \frac{q_w}{\Delta T_{ln}}.
\]  

(5)

Experimental data on the dependence of heat transfer coefficient on mass flux for simultaneously developing flow under the conditions of constant wall temperature are presented in figure 1. For the three-side cooling case, the method from [6] was used as follows

\[
Nu_{m,3}(z^*) = Nu_{m,4}(z^*) \frac{Nu_{fd,3}(z^*)}{Nu_{fd,4}(z^*)}
\]  

(6)
where $\text{Nu}_{m,3}$ and $\text{Nu}_{m,4}$ are the Nusselt numbers for the simultaneously developing flow under three- and four-sided heating conditions, respectively, and $\text{Nu}_{fd,3}$, $\text{Nu}_{fd,4}$ are the Nusselt numbers for a fully developed flow. The dependence of averaged heat transfer coefficient on dimensionless length $z^* = (L/D_h)/\text{RePr}$ for developing flow in four-sided cooling case was used from [7].

![Figure 1. Average heat transfer coefficients for single-phase flow, the points show experimental data, line is the calculations according to (6).](image)

3. Results

The dependence of the measured heat transfer coefficients on the vapor quality for the mass flow rate $G = 200 \text{ kg/m}^2\text{s}$ and the absolute pressure of 12 bar for two molar concentrations of the refrigerants is shown in figure 2. As it is shown, an increase of the concentration of fugacious component R32 in the mixture leads to an increase in heat transfer coefficients at high vapor contents. With vapor quality less than 0.5, the variation in molar concentration of the refrigerants does not significantly influence the heat transfer.

![Figure 2. The dependence of local heat transfer coefficient on the equilibrium vapor quality for two molar mixture compositions at $G=200 \text{ kg/m}^2\text{s}$ and absolute pressure of 12 bar.](image)
To predict the heat transfer coefficients during condensation of single component vapor in microchannels, the correlation from [8] can be used. In case of binary mixture, to calculate the heat transfer coefficient it is necessary to take into account the mass transfer resistance. In this case, the Silver – Bell & Ghaly balance method [2, 3] can be used for heat transfer predictions. Using this method heat transfer coefficient $\alpha$ can be calculated as follows:

$$\frac{1}{\alpha} = \frac{1}{\alpha_0} + x C_{\rho V} \frac{\Delta T_{LV}}{(h_V - h_L)} \frac{1}{\alpha_V}$$  \hspace{1cm} (7)

where $\alpha_0$ is the heat transfer coefficient calculated as for single-component fluid, $\alpha_V$ is the heat transfer coefficient calculated only for the vapor phase by [9], $C_{\rho V}$ is the vapor specific heat and $\Delta T_{LV}$ is the temperature glide. The temperature glide shown in figure 3 was calculated from equilibrium diagram of [4].

Comparisons of the calculation results according to (7) with experimental data are shown in figure 2 as lines. Experimental data fairly correspond to the calculations. The value of temperature glide for (7) was determined from figure 3 for the initial concentration of the mixture. The growth of the concentration of R32 leads to the increase in thermal conductivity of the mixture, increasing the heat transfer coefficients. As it seen in figure 2, at low concentration of the fugacious component R32 and vapor quality over 0.5, stronger phase mass transfer resistance is observed compared to that predicted by the calculations.

**Conclusion**

Heat transfer coefficients during flow condensation of non-azeotropic refrigerant mixtures of R32/R134a in multi-microchannel condenser show strong dependence on vapor quality and low dependence on the concentration of fugacious component R32. The Silver-Bell & Ghaly balance method applied to the Kim and Mudawar [8] correlations for the case of binary mixture show good agreement with experimental data. Nevertheless, at low concentration of the fugacious component R32 and vapor quality lower than 0.5, the observed phase mass transfer resistance is larger than it is predicted in the calculations.
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