An experimental study of flow boiling heat transfer of zeotropic mixture R32/R134a in a microchannel heat exchanger

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Abstract. This paper presents experimental data on heat transfer of a binary zeotropic mixture of refrigerants R32/R134a in a microchannel heat exchanger with a high specific surface within a range of parameters that is practically important for the development of cooling systems for microelectronics and space technology. The experiments were carried out in a horizontal heat exchanger with one-sided heating of a copper microchannel plate 20x40 mm, containing 21 rectangular microchannels with a cross-section of 335x930 μm, within the range of mass fluxes from 80 to 250 kg/m²s, and at an absolute pressure in the system ranged from 12 to 14 bar. A zeotropic mixture of refrigerants R32/R134a with a molar concentration of the initial mixture of 65%/35% was used as a working fluid. Experimental data were compared with model-based calculations that take into account the influence of changes in the concentrations of components in the liquid and gas phases.

1. Introduction
Flow boiling heat transfer in microchannels is a highly efficient thermal management technology that provides cooling of electronic components with high power and heat flux [1]. On the other hand, multicomponent refrigerants are widely used in refrigeration and heat pump applications. Using mixture as working fluid is driven by the inevitable rejection of the widely used HFC refrigerants and the lack of adequate alternative refrigerants. It should be noted that most refrigerant mixtures are zeotropic. It is well known that using a zeotropic mixture as a working fluid instead of a pure fluid causes significant deterioration in heat transfer [2]. Thermal diffusion resistance has a significant effect on heat transfer, especially nucleate boiling. This is due to the higher resistance to mass transfer caused by the temperature slip of the mixture, hence the suppression of nucleate boiling. But taking into account the reasonable operating temperature range of electronic components, zeotropic mixtures of refrigerants have played an important role in the selection of electronic coolants, as far as, can increase the critical heat flux during flow boiling. [3]. Over the past decades, numerous correlations have been developed for calculating heat transfer during flow boiling of a mixture; however, most have been developed based on limited experimental data from one or more research projects. Such correlations usually do not provide accurate predictions for a wide range of operating conditions and require verification [4].

The purpose of the present study is to obtain experimental data on flow boiling heat transfer of a binary zeotropic mixture of R32/R134a refrigerants in a microchannel heat exchanger with a high specific surface area within a range of flow parameters that is practically important for the development of cooling systems for microelectronics and space technology, as well as to compare the...
obtained data with the model-based calculations from [5] which takes into account the effect of changes in the temperature slip and the concentrations of the liquid and gas phase components on heat transfer.

2. Experimental equipment and data processing

The experiments were carried out in a horizontal heat exchanger with one-sided heating of a copper microchannel heat sink 20x40 mm, containing 21 rectangular microchannels with a cross-section of 335x930 μm. A zeotropic mixture of R32/R134a refrigerants was used as a working fluid at a molar concentration of components of 65% / 35%, at an absolute pressure in the system ranged from 12 to 14 bar and mass fluxes ranged from 80 to 250 kg/m²s. The schematic diagram of the experimental setup and measurement procedure are described in detail in [6].

During experiments, a single-phase mixture with a temperature 1-2 degrees below the boiling point $T_b$ was fed to the inlet of the heat exchanger. Heat transfer coefficient $h$ was determined as

$$ h = \frac{q_w}{<T_w> - (T_{in} + T_{out})/2} $$

(1)

here $q_w$ is the average wall heat flux; $<T_w>$ is the average wall temperature; $T_{in}$ and $T_{out}$ are the inlet and outlet flow temperature.

The measured pressure and temperature at the outlet $T_{out}$ of the heat exchanger were used to determine the molar concentrations of the components in the liquid phase $x_i$ and the gas phase $y_i$. For the calculation, the equation of state of the R32/R134a binary mixture from [7] was used. The change in the composition of the mixture in the liquid phase was used to determine the temperature slip during the experiments. The temperature difference between the dew point $T_d$ and the boiling point $T_b$ in dependencies on the R32 molar concentration is present in figure 1.

![Figure 1. Temperature glide versus R32 molar concentration at a pressure of 13.5 bar.](image)

To calculate the thermophysical properties of the vapor and liquid phases of a binary mixture, we used the properties of pure components and the method described in [8]. To calculate the heat transfer of a binary mixture, a model from [5] was used. The heat transfer coefficient was calculated as

$$ h = \frac{1}{\sqrt{(F \cdot h_{\text{convection}})^2 + (S_{\max} S \cdot h_{\text{boil}})^2}} $$

(2)
here the parameters F and S were calculated as in the model of Liu and Winterton [9]. Cooper’s correlation was used to calculate boiling point [10] for a mixture like,

\[ h_{\text{boil}} = \frac{1}{x_{R32} + x_{R134a} \cdot \frac{h_{\text{boil}R32}}{h_{\text{boil}R134a}}} \]  

(3)

and the equation for laminar convection with three-sided heating was used to calculate convective heat transfer [11]

\[ \text{Nu}_3 = 8.235 \left(1 - 1.833 \cdot \beta + 3.767 \cdot \beta^2 - 5.814 \cdot \beta^3 + 5.361 \cdot \beta^4 - 2 \cdot \beta^5\right) \]  

(4)

Here, \( \beta \) is the aspect ratio of channels.

The mixture factor \( S_{\text{mix}} \) was calculated as

\[ S_{\text{mix}} = \left(1 + \frac{T_d - T_b}{q / h_{id}} \cdot x_{R32} - x_{R32} \right)^{-0.29} \left(\frac{P}{10^5}\right)^{-0.9} \left(1 - 0.87 \exp(-q/3 \times 10^5)\right)^{-1} \]  

(5)

here heat transfer coefficient of an ideal mixture \( h_{id} \) was calculated from the heat transfer coefficients of pure components \( h_i \) as

\[ h_{id} = \frac{1}{x_{R32} + x_{R134a} \cdot \frac{h_{R32}}{h_{R134a}}} \]  

(6)

3. Results and Discussion

The obtained dependencies of the average heat transfer coefficient on the average heat flux on the inner wall of the microchannels for mass fluxes of 85 and 200 kg/m²s are shown in Fig. 2a. The heat transfer coefficients increase with an increase in the heat flux and are practically independent of the mass flux of the mixture, which indicates that in the case under study, nucleate boiling is the dominant mechanism of heat transfer. At heat fluxes at the walls above 50 kW/m², a decrease in the heat transfer growth with an increase in the heat flux is observed, which indicates the suppression of nucleate boiling in microchannels with an increase in the vapor phase velocity. At a heat flux of 80 kW/m² in experiments with a mass flux of 85 kg/m²s, a heat transfer crisis was observed, and for a mass flux of 200 kg/m²s, a complete suppression of nucleate boiling and a transition to the convective mechanism of heat transfer was observed. The dependence of the average heat transfer coefficient on the output vapor quality presented in Fig. 2b for the data shown in Fig. 2a reveals that a heat transfer crisis occurs
when the liquid is completely evaporated in the microchannels. It should be noted that, at a low mass flux of 85 kg/m²s, an increase in the heat transfer coefficients is observed before the crisis, which indicates the absence of the development of dry regions due to poor evaporation of the heavy boiling component and a significant contribution of the evaporation of thin films to heat transfer.

Figure 2. The dependence of the average heat transfer coefficient of the R32/R134a binary mixture in a microchannel heat exchanger, the pressure in the system is 13.5 bar, a) on the heat flux b) on the output vapor quality.

Figure 3. Dependence of the average heat transfer coefficient of R32/R134a binary mixture in a microchannel heat exchanger on the heat flux, compared with the calculation: a) mass flux 85 kg/m²s; b) mass flux 200 kg/m²s.

Comparison of the heat transfer coefficients depending on the heat flux, calculated according to equation (2) for a mass flux of 85 kg/m²s is shown in Figure 3a, and one for a mass flux of 200 kg/m²s is shown in Figure 3b. The calculation is in good agreement with the experimental data for heat fluxes up to 50 kW/m². At higher heat fluxes, increasing the heat transfer coefficients with the heat flux increasing decreases, and the calculations exceed the experimental data regardless of the mass fluxes, which indicates the need to take into account the suppression of nucleate boiling in calculations.
4. Conclusions
An experimental study of heat transfer during flow boiling of R32/R134a zeotropic mixture in a microchannel heat exchanger has been carried out. It has been experimentally revealed that under the experimental conditions at heat fluxes less than 50 kW/m$^2$, boiling is the predominant mechanism of heat transfer; at heat fluxes above 50 kW/m$^2$, nucleate boiling is suppressed and the convective heat transfer mechanism becomes dominant. The obtained data were compared with the calculation according to the model of Zou X. et al. [5]. Under the conditions of dominant nucleate boiling, at heat fluxes less than 50 kW/m$^2$, the experimental data are in good agreement with the calculation. In the case of the prevalence of the convective mechanism of heat transfer, with heat fluxes greater than 50 kW/m$^2$, the calculation overestimates the experimental data, since it does not take into account the conditions for the suppression of nucleate boiling. The main average error of the calculation for all data was 21%.

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