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An investigation of the thermal characteristics of the refrigerants zeotropic mixtures condensation in minichannels

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Abstract

This paper describes the results of experimental investigations of heat transfer during the condensation of the homogenous R134a refrigerant and zeotropic mixtures R404A, R407C and R410A in pipe minichannels with internal diameters 0.31–3.30 mm. The values of the local and average heat transfer coefficient throughout the range of changes in the vapor quality 1–0 were determined. Based on the obtained results, the effect of vapor quality, mass flux density and channel diameter changes on heat transfer coefficient was illustrated. a pronounced effect of the refrigerant properties at the heat exchange efficiency during the condensation process in pipe minichannels was indicated. The results were compared with calculations according to the correlations proposed by other authors. On the basis of the experimental investigations, the authors proposed their own correlation for the calculation of local heat transfer coefficient, obtaining the results of compatibility tests in the range of ±20%.

Keywords: Condensation; Heat transfer coefficient; Mass flux density; Minichannels; Vapor quality; Zeotropic mixture

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Nomenclature

d – minichannel inner diameter, m
G – mass flux density, kg/m^{2}s
L – length, m
$\dot{m}$ – mass flow rate, kg/s
p – pressure, kPa
q – heat flux density, W/m^2
T – temperature, °C
x – quality
Δp – pressure drop, kPa
Nu – Nusselt number
Pr – Prandtl number
Re – Reynolds number
We – Weber number, $\mathrm{We} = \frac{G^2 d}{\sigma \rho g}$

Greek symbols

α – heat transfer coefficient, W/(m^{2}K)
λ – thermal conductivity coefficient of refrigerants, W/(m K)
μ – dynamic viscosity, kg/(m s)
ρ – density, kg/m^3
σ – surface tension, N/m

Subscripts

a – averaging conditions
cr – critical value
exp – experimental values
f – flow of the one phases
g – gas
go – gas only
H – hydrostatic
h – hydraulic diameter
l – liquid
lo – liquid only
r – reduced pressure
s – saturation value
th – theoretical value
TP – two phase
TPF – frictional
x – local value

1 Introduction

The destructive impact of compounds from the group of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) on the environment, especially the destruction of the ozone layer and intensification of global warming, leaded to take radical measures aimed at elimination of chlorinated refrigerants from exploitation. Therefore, these refrigerants are gradually replaced by ecological refrigerants with similar physic and chemical properties. Increasingly popular in refrigeration enjoy a zeotropic (ZEO) and nearly azeotropic mixtures (MBA or NEARM). As substitutes for R22, most commonly proposed are zeotropic mixtures such as R404A and R407C or nearly azeotropic R410A [1]. These refrigerants are mixture of two or more homogenous refrigerants with a defined percentage mass concentration in the mixture. Zeotropic mixtures are characterized by so-called temperature glide of boiling and condensation phase changes. This means that during the phase transition process the concentration of individual components is changing. Temperature glide of these mixtures kind is about $\Delta t_g \approx 10$ K. In contrast, nearly azeotropic mixtures have a small temperature glide and in the phase transition process behave like azeotropic mixtures (azeo) [2]. Due to the difference in the condensation process of these mixtures, the calculation methodology must be properly chosen [3].

The following part of the paper, based upon hydraulic diameter, d_h, presents the results of the analysis of the literature and our own experimental studies on heat transfer during condensation zeotropic mixtures with respect to the uniform R134a refrigerant.

Kandlikar [4] in his paper proposed a classification of channels that are used in exchangers: microchannels ($d_h < 200\,\mu$m), minichannels ($200\,\mu\text{m} \leq d_h < 3$ mm) and conventional channels ($d_h \geq 3$ mm). Regardless of the discrepancies in the given criteria, it is found that minichannels are channels with internal diameter in range $d_h <$ 3–6 mm). This problem is important as the correlations recommended for calculations and which describe heat transfer concern conventional channels in particular. It is proven in many publications that one cannot unquestioningly use those correlations which have been verified for conventional channels in relation to channels with small diameters, especially for those refrigerants which undergo phase changes (boiling or condensation) Cavallini *et al.* [5], Zhang *et al.* [6].

Many authors warn against transferring to micro- and minichannels those correlations that have been specified and verified for the flow in a phase change in conventional channels. However, it has to be noted that the correlations developed for low- or medium-pressure refrigerants (e.g., R134a) do not have to be proper for high-pressure refrigerants such as R404A and R410A. This problem will be presented in an example of the use of the correlation by Shah [7] and Akers [8, 9]. In the paper by Webb *et al.* [10], the results of the authors' own research were compared with the calculations according to the correlations mentioned above. The values of heat transfer coefficient, α, calculated from Shahñs correlation were too high relatively to experimental investigation results of other authors, while those calculated from the correlation by Akers *et al.* [8,9] were too low. A study by Chang and Wang [11] confirmed the usefulness of Shah's correlation [7] in the calculation of coefficient α in minichannels, with low values of quality x (however, this is contradictory to the conclusions provided in the paper by Webb *et al.*, [10]. At the same time, the research by Yan and Lin [12] confirms the observations made by Webb *et al.* [10].

Thome [13] presented the calculation model of heat transfer during condensation of zeotropic mixtures in horizontal ducts. He paid attention to three important issues of condensing mixtures:

- the construction of new two-phase flow maps,
- the difference in heat transfer model of zeotropic mixtures and homogeneous factors,
- proposition of a new model for heat transfer of mixtures.

The author proposed a model to calculate the heat transfer coefficient for single-factor and a modified version, including zeotropic mixtures. Two different mechanisms of heat transfer during condensation in the flow were taken into account, i.e., the exchange of heat by convection and heat transfer by condensation of the membrane. In the first case the heat transfer takes place along the channel under the influence of a pressure gradient, and the second correlation model refers to the upper part of the circumference of the tube during movement, with stay dry.

The authors of [14] investigated the condensing refrigerant R134a and R407C in minichannels. On the basis of investigation results was confirmed that the process of zeotropic mixture R407C condensation proceeds otherwise then the condensation process of R134a (homogenous refrigerant). Therefore, the calculation of zeotropic refrigerant mixtures should take into account the temperature glide.

In order to expand its own database, experimental research of heat transfer during the condensation of certain types of zeotropic mixtures was conducted. The experimental results were used to develop thermal characteristics depending on local and average heat transfer coefficient on the parameters of the process. Then the results were compared with other dependences of other authors previously tested for homogenous R134a.

2 Experimental investigations

2.1 Object of the experiments

The experimental studies of heat transfer during condensation in minichannels were conducted on specially designed test stand, which is equipped Laboratory of the Heat Engineering and Refrigeration Department of Koszalin University of Technology. Measuring station was modernized and equipped with new control and measurement instrumentation with elements of the refrigeration and drive system. It allows to measure thermal characteristics during zeotropic mixtures condensation. In all cases, the same research methodology was applied, which enabled the comparison of test results.

2.2 Testing facility

Schematic diagram of the test stand is given in Fig. 1. Section 1 of the pipe minichannel was the basic element of the experimental facility. This section was placed in the horizontal axis of water channel 2, which was made from aluminium with a rectangular section and internal dimensions of 28 mm×24 mm. The refrigerant was supplied to measuring section 1 from the side of pumping compressor 3 of the compressor installation. Before the refrigerant reached the inlet section of the minichannel, its superheated vapour flew through a pipe type exchanger in pipe 10, which was chilled with water. The use of this exchanger allowed not only to collect the superheat but also to prepare the refrigerant's state in the form of a dry, saturated vapour with a quality $x = 1$ (or near this state).

After the condensation of the refrigerant's vapour in a flow through a pipe minichannel, the refrigerant's liquid flew to subcooler 11 on the outlet, from which the refrigerant's flow rate was measured with the aid of a Coriolisa type flowmeter 15. The refrigerant's flow rate was measured for control purposes with the aid of a system of calibrated vessels. Then, the refrigerant returned to the refrigeration system that was fed from unit 3 with a condenser with chilled air 4 and a fan cooler 8. On length $L = 950$ mm of this minichannel section, nine thermocouples of the K-type were installed that were arranged in even distances for the purpose of measuring the external temperature of the minichannel surface. In each of these nine measuring sections, the temperature of the cooling water that flew into water channel 2. The thermocouple welds for the water temperature measurement were placed 19 mm from the bottom of water channel 2 in its vertical axis. The thermocouple wires of the temperature sensors were led to connectors 22 and 23 and to data canvassing system 18.

Before installation, all of the thermocouples were recalibrated in relation to a standard glass thermometer with a $0.05\,^\circ$C scale interval. Individual thermoelectric characteristics were made. The pressure of the refrigerants on the inlet to the measuring section was measured with a piezoresistant sensor with a transducer of 0.4 class, while the pressure drop was measured with the aid of a differential pressure sensor with a transducer of the same class. Once the tests had been conducted with the pipe minichannel of internal diameter d, measurements were conducted for minichannels with other diameters. Electronic flowmeter 16 was used to measure the chilling water flow rate.

The control and measuring instrumentation allowed for direct determination of the process parameters like:

- refrigerant temperature,
- cooling water temperature,
- minichannel outer wall temperature,
- mass flow rate of refrigerant and water,
- refrigerant pressure,
- refrigerant flow resistance along the length of the measurement section.

The heat and flow researches were carried out for R134a, R404A, R410A and R407C environment friendly refrigerants in relation to the following parameters:

inner diameter of minichannel: $d_h = 0.31\text{–}3.30$ mm,
mass flux density: $G = 0\text{–}2500$ kg/(m^{2}s),
heat flux density: $q = 0\text{–}100$ kW/m^2,
saturation temperature: $t_s = 20\text{–}40\,^\circ$C,
vapor quality: $x = 1\text{–}0$.

The values of heat flux density q, vapor quality x and heat transfer coefficient, α, was determined indirectly by heat balance method. The aim of the experimental thermal study was to determine the averages and the local heat transfer coefficient during condensation.

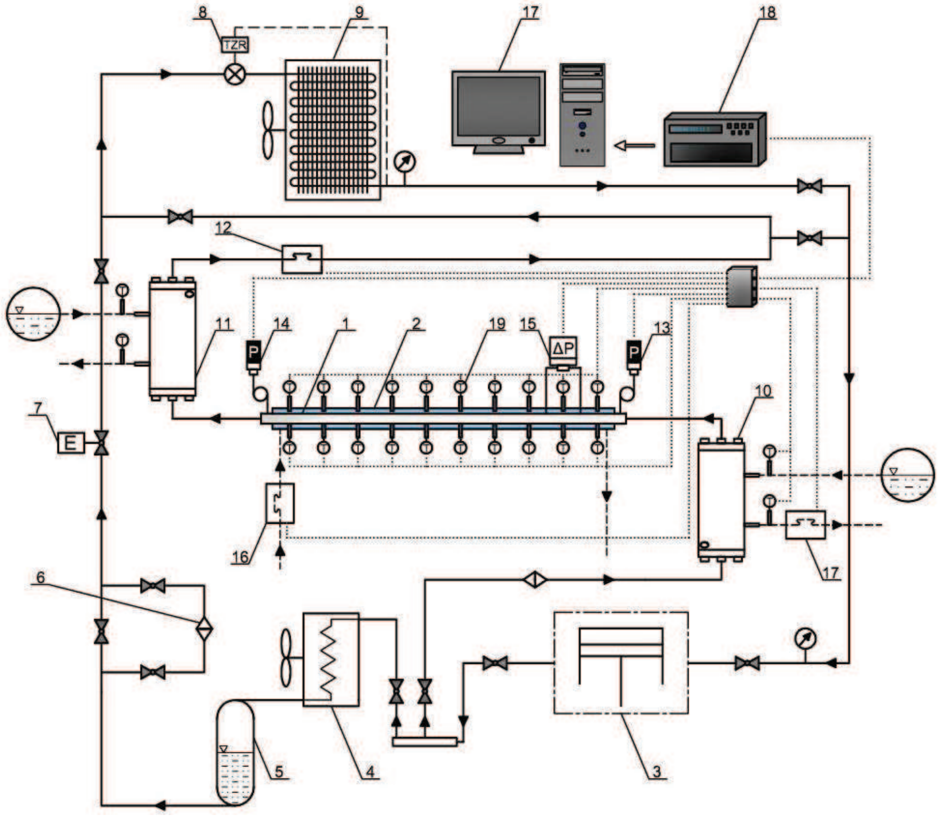

Figure 1: Schematic diagram of the test stand: 1 – measuring section of pipe minichannel, 2 – water channel, 3 – refrigeration compressor unit, 4 – air cooled condenser, 5 – tank of liquid refrigerant, 6 – filter - drier of refrigerant, 7 – electromagnetic valve, 8 – thermostatic expansion valve, 9 – air cooler, 10 – heat exchanger for removal of superheating, 11 – liquid refrigerant subcooler, 12 – electronic flowmeter of refrigerant, 13 – pressure sensor of refrigerant on inlet to the test section, 14 – pressure sensor of refrigerant at the outlet of the test section, 15 – differential pressure sensor, 16 – electronic water flowmeter, 17 – computer, 18 – data acquisition system, 19 – temperature sensors (thermocouple type K).

3 Results of the investigation and analysis

The results of experimental studies focused on analysis of the thermal characteristics of zeotropic mixtures condensation in the flow in minichannels. Experimental studies of condensation were performed under local and averages conditions for minichannels with internal diameter $d_h = 0.31$–3.30 mm.

The conducted study aimed to investigate the effect of process parameters changes and properties of the refrigerant on heat transfer coefficient.

The comparison of the condensation characteristics of different refrigerant type is very interesting. Figures 2 and 3 show an example of the comparative characteristics of the average heat transfer coefficient α_a for R134a, R404A, R407C and R410A refrigerants.

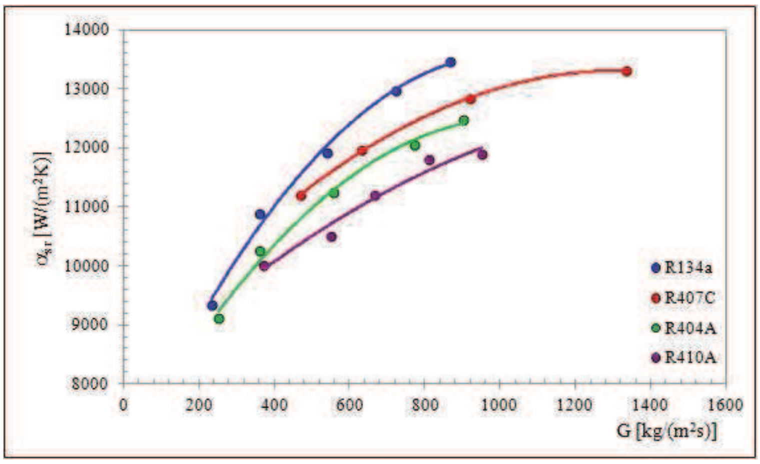

Figure 2: Experimental results of dependence of average heat transfer coefficient refrigerants condensation in average conditions $\alpha_a = f(G)$ for $x = 0.8$, minichannels with internal diameter $d_h = 1.40$ mm.

The results indicate that in the case of zeotropic mixtures, in minichannels with internal diameter $d_h = 0.64$ mm for the R407C refrigerant were obtained the highest values of average heat transfer coefficient. Values of coefficient, α_a, are higher for R407C and R410A refrigerant relative to R404A refrigerant, and the increase is in the range of 10% to 15%, while for the channels with an internal diameter less than 1 mm about 30–40%.

Figure 4 shows the sample of experimental thermal characteristics in the form of dependence $\alpha_x = f(x)$, that is, the local heat transfer coefficient on the vapor quality, x, during condensation of homogenous R134a refrigerant and zeotropic mixtures in the pipe minichannels with internal diameter $d_h = 0.64$ mm and $d_h = 2.30$ mm.

The significant impact of vapor quality changes x, with $G = const$, on the course of characteristics is observed. With the decrease of the vapor quality followed by an initial increase in the local heat transfer coefficient, reaching a maximum value at $x \approx 0.8$, and then significant decrease,

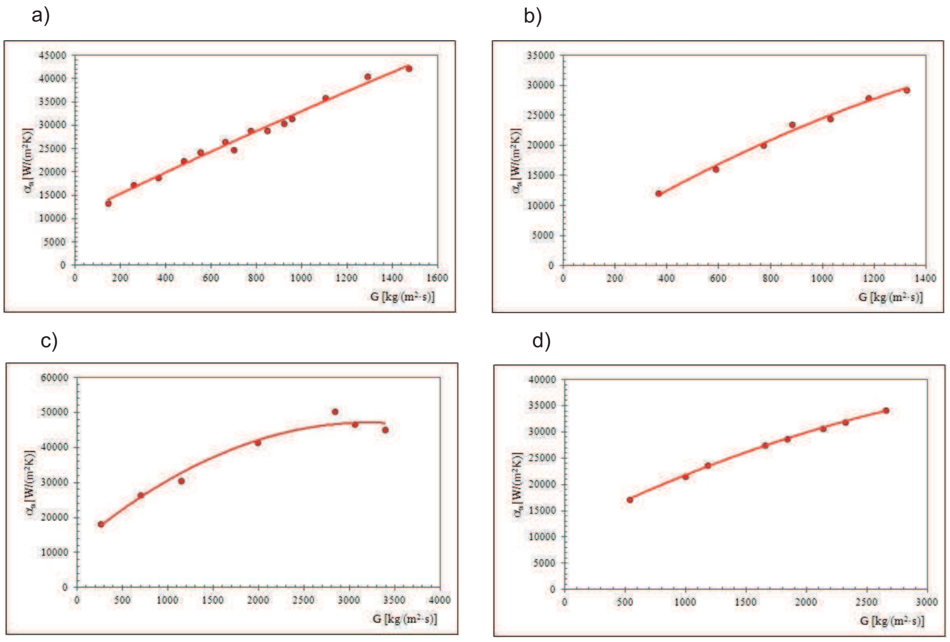

Figure 3: Example heat characteristics of a) R134a, b) R404A, c) R407C and d) R410A refrigerants condensation in verage conditions $\alpha_a = f(G)$ for $x = 0.8$ and minichannels with internal diameter $d_h = 0.31$ mm.

which is visible especially for the minichannels with internal diameter of less than 1 mm. On the basis of the comparative analysis, it is concluded that the value of the local heat transfer coefficient for minichannel internal diameter $d_h = 2.30$ mm obtained with R404A and R407C refrigerant are comparable with each other.

4 Analysis of the experimental investigation results

Own experimental results were used for comparison with the calculation results of the correlation of other authors. Comparative analysis of the test results of the local heat transfer coefficient, α_x, with calculation models proposed by other authors showed that the experimental results for R404A preferably correspond to the results of calculations by a) Shah [7], b) Akers [8], c) Thome, [13] and d) Cavaloni [6] correlations. Figure 5 shows a comparative summary of the test results for the four tested refrigerants:

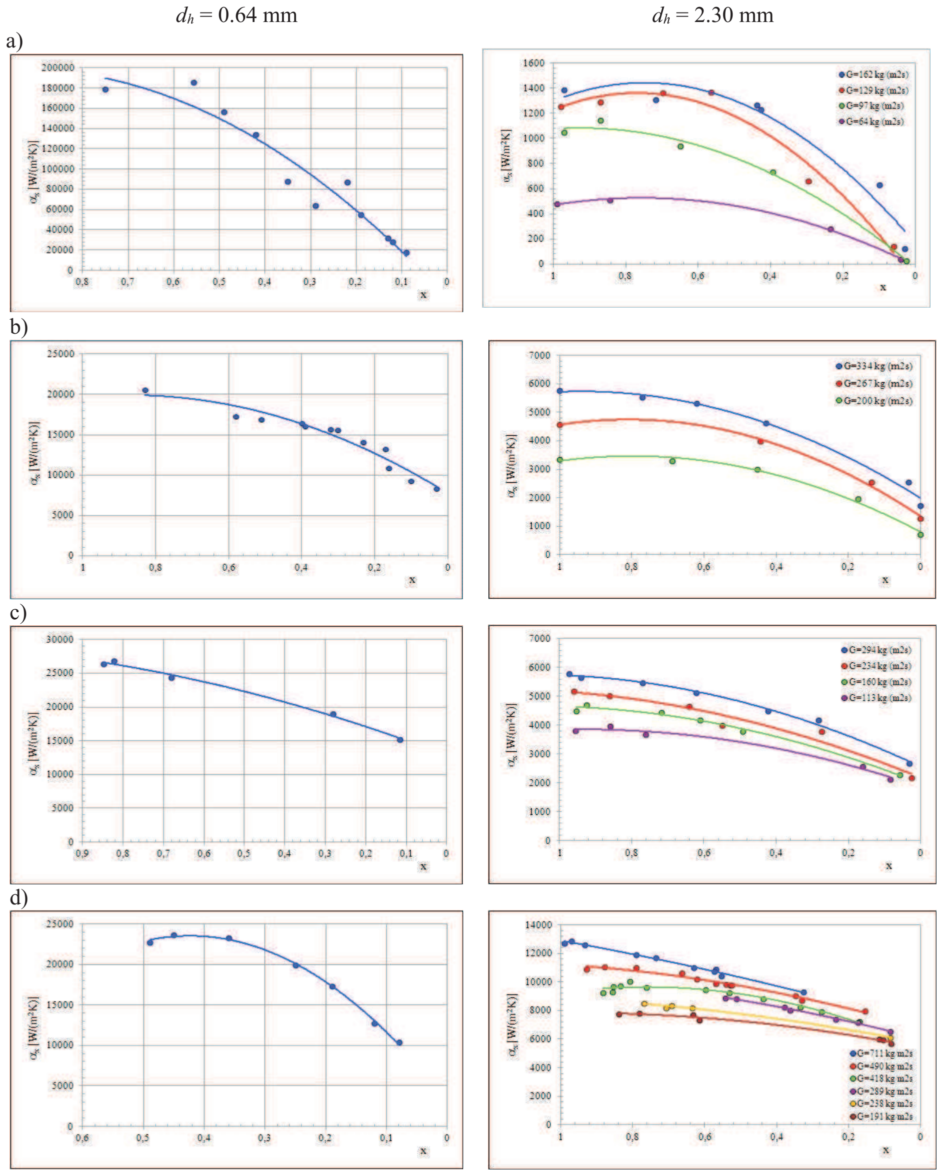

Figure 4: Summary of experimental characteristics of refrigerants condensation in local conditions $\alpha_x = f(x)$ for minichannels with internal diameter $d_h = 0.64$ mm and $d_h = 1.40$ mm, when $G = const$, for refrigerants: a) R134a, b) R404A, c) R407C, d) R410A .

R134a, R404A, R407C and R410A. In the case of R407C, and R410A refrigerants results correspond better with the Shah correlation, while the correlation Akers gives too large discrepancies in the range of ±50%, which can not be recommended for design the calculations.

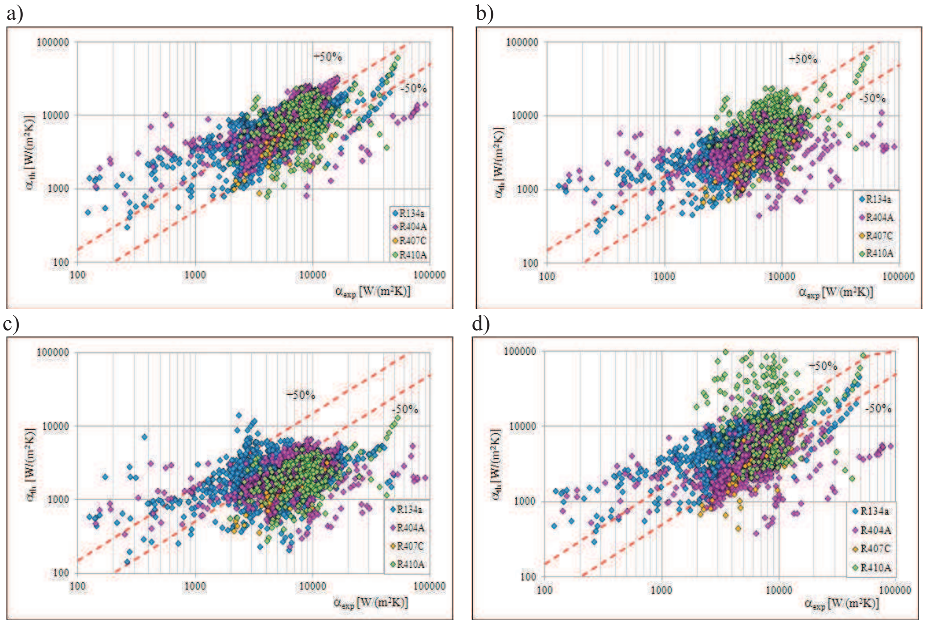

Figure 5: Comparison of experimental heat characteristics of zeotropic mixtures condensation in minichannel with calculation results for correlations by: a) Shah [7], b) Akers [8], c) Thome [13], d) Cavallini [14].

The use of other authors correlation than [7] and [8], leads to a much larger gap than ±50. As a result of analysis, it is limited to the possibility of applying the correlation mentioned above for the calculation of the local heat transfer coefficient. Range of ±50% discrepancy is too wide for the recommendation of these relationships for the testing type of minichannels and refrigerants.

The thermal characteristics of zeotropic mixtures condensation in minichannels building based on correlation [7,8,13,14] gave too large discrepancies with experimental results. So it is necessary to develop their own local generalized correlation describing the process of heat transfer during condensation of zeotropic mixtures in pipe minichannels. Therefore employees of the Heat Engineering and Refrigeration Department of Koszalin Univer-

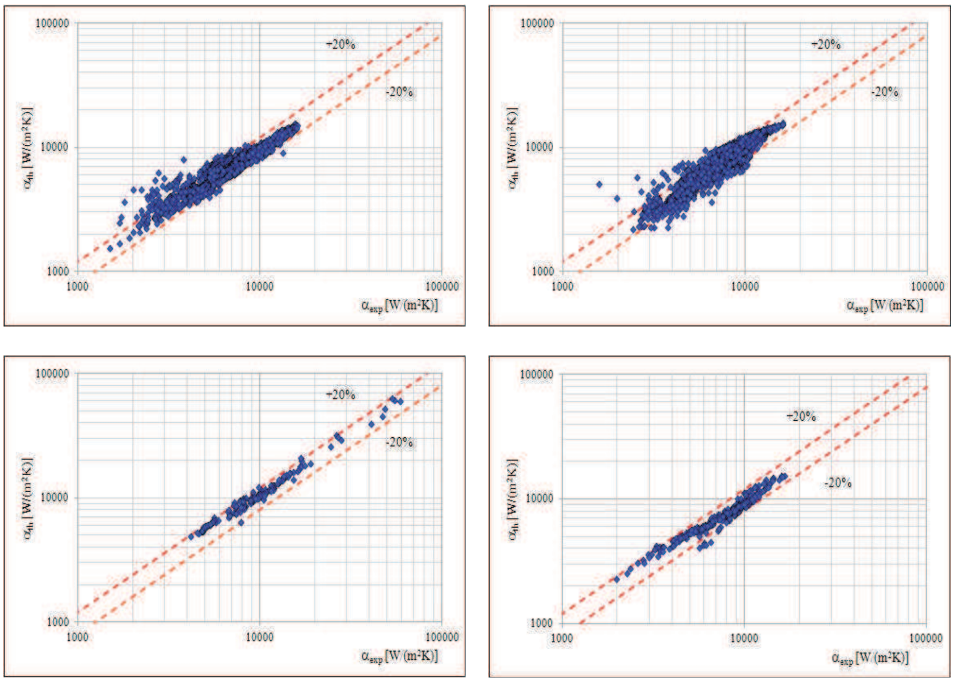

Figure 6: Comparison of the results of experimental tests concerning local heat transfer coefficient, α_x, during condensation of the refrigerants, α_{exp}, with the results of calculations from correlation (3), α_{th}, in pipe minichannels with internal diameter $d = 0.31 \div 3.30$ mm: a) R134a, b) R404A, c) R407C, d) R410A.

sity of Technology created a new correlation based on dimensional analysis. For this purpose a nonlinear regression model with the quasi-Newton and simplex method was used. It allows determining the coefficients, including the constant and exponents in the equation. This allows to determine experimental correlation, that describes the value of the local Nusselt number in the form [15]:

$$(\mathrm{Nu}) = 25.084\,\mathrm{Re}_l^{0.258}\,\mathrm{Pr}_l^{-0.495}\,p_r^{-0.288}\left(\frac{x}{1-x}\right)^{0.266}, \tag{1}$$

where

$$p_r = \frac{p_s}{p_{cr}}, \tag{2}$$

where: p_r – reduced pressure, p_s – saturation pressure, p_{cr} – critical pressure in the dimensional form of Eq. (2) can be written

$$\alpha_x = \frac{(\mathrm{Nu})\,\lambda_l}{d}, \tag{3}$$

where λ_l is the heat conductivity coefficient of zeotropic mixture liquid phase. Reduced pressure p_r described by Eq. (2) allows for the extension of the applicability of Eq. (1) for factors medium – and high-pressure refrigerants including R404A, R407C, and R410A.

Based on the analysis, it is concluded, that compatibility of the experimental studies results of refrigerants R134a, R404A, R407C and R410A ($d = 0.31$–3.30 mm, $x = 1$–0, $T_s = 20$–50 °C, and $G = 100$–1300 kg/(m^2 s)) heat exchange with calculation by the correlation (3) is in the range of ±20%, which is considered as satisfactory result.

In the Fig.6 is shown compatibility of the experimental studies results of refrigerants R134a, R404A, R407C and R410A ($d_h = 0.31$–3.30 mm, $x = 1$–0, $T_s = 20$–$50\,^\circ$C, and $G = 100$–1300 kg/(m^2 s)) heat exchange with calculation by the correlation (3) in the range of ±20%.

5 Conclusions

1. Thermal experimental investigations of the homogenous R134a refrigerant and zeotropic mixtures R404A, R407C and R410A condensate in stainless steel pipe minichannels with internal diameters $d_h = 0.31$–3.30 mm.
2. Thermal characteristics describing the condension of refrigerants were performed with a description of dependences of local and average heat transfer coefficient, depending on the vapour quality and mass flow density. It is found that the heat transfer coefficient depends on parameters such as thermal parameters of condensation process (saturation temperature), the internal diameter of the tubular minichannel, mass flow density and vapor quality.
3. A comparative analysis was conducted on the results of the experimental tests with the results of calculations from correlations proposed by other authors. It was demonstrated that, of these correlations, which serve to determine the local heat transfer coefficient, those proposed by Akers [8] and Shah [7] can be used within a limited range depending on the internal diameter, d_h, of the minichannel and the density, G, of the mass flux of the refrigerant. Despite the fact that the area

of their applications is limited, the discrepancies between the experimental results and the calculation results exceeded the range of ±50%, which gives unsatisfactory results.

4. On the basis of their own relationship, calculation for the value of heat transfer coefficient during the condensation of the homogenous R134a refrigerant and ecological zeotropic mixtures R404A, R407C and R410A in pipe minichannels was developed. The proposed correlation is consistent with experimental results within ±20%, and can be recommended for the calculations.

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