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Nucleate pool boiling heat transfer coefficients of pure HFC134a, HC290, HC600a and their binary and ternary mixtures

Sun Zhaohu [a,b], Gong Maoqiong [a,*], Li Zhijian [a,b], Wu Jianfeng [a]

[a] Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, P.O. Box 2711, Beijing 100080, China
[b] Graduate School of the Chinese Academy of Sciences, Beijing 10039, China

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Abstract

An experimental test rig for study on the pooling-boiling heat transfer performance of pure and mixed refrigerants were designed and established. With this test system, the heat transfer coefficients (HTCs) of the nucleate boiling on a smooth flat surface were measured for pure fluids of HFC134a, HC290, HC600a and their binary and ternary mixtures. Extensive experimental measures were made for those pure and mixed refrigerants at different heat fluxes from 10 kW m^{-2} to 300 kW m^{-2} and different pressures from 0.2 to 0.6 MPa. Comprehensive measured data are presented in this paper. From experimental results, these binary mixtures and ternary mixtures show different heat transfer features according to their vapor–liquid phase equilibria behaviors. New heat transfer correlations were regressed from the measured data with average deviations within ±15% for pure refrigerants and within ±20% for mixtures.

Keywords: Nucleate pool boiling; Pure refrigerant; Binary mixture; Ternary mixture; Heat transfer coefficient; Correlation

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1. Introduction

In the past few decades, extensive studies have been made on the boiling heat transfer performance of new alternative pure and mixed refrigerants [1,2]. All these efforts were made to know heat transfer characteristics of the new CFCs alternatives. Many generalized correlations for predicting the coefficients have been proposed, which can be applicable to various refrigerants [3]. However, some of those alternatives have huge GWP values. Therefore, some nature gases such as HC290 and HC600a are used as the refrigerants or as a component in the mixed-refrigerants.

The objective of this paper is to get to know the nucleate pool boiling characteristics of three pure refrigerants HFC134a, HC290, HC600a, three binary mixtures HFC134a/HC290, HC600a/HFC134a, HC600a/HC290 and a ternary mixture HC600a/HFC134a/HC290. Mixture concentrations are fully covered and heat flux also varied for a wide range of nucleate boiling. Based on the measured data, several new correlations will be proposed for pure refrigerants and binary, ternary mixtures. For the two and three components mixtures, the mixture effects on boiling heat transfer coefficients will be also discussed.

2. Experiments

2.1. Experimental apparatus

Fig. 1 shows a schematic diagram of the experimental apparatus used in the present measurements. It consists of a boiling vessel, a refrigerant tank, a liquid-nitrogen condensing system, an alternating-current (AC) power heater and a data acquisition system. The boiling vessel is a vertical stainless-steel tube with an inner diameter of 151 mm and a height of 300 mm. Boiling takes place on the upper-end surface of a copper cylinder, 25 mm in diameter, which is fixed on the bottom of boiling vessel. Heat flux is supplied by a loop heater intertwined at the bottom of

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[*] Corresponding author. Tel.: +86 10 82543728; fax: +86 10 62627843.
E-mail address: gongmq@cl.cryo.ac.cn (M. Gong).

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Nomenclature

c_p	specific heat, kJ/kg K
C_1	exponent in Eq. (9), dimensionless
g	gravitational acceleration, m/s^2
E	bubble formation power, J
h_{lv}	heat of evaporation, J/kg
K	influencing factor in Eq. (10), dimensionless
M	molecular weight, dimensionless
n	exponent in Eq. (9), dimensionless
P	pressure, Pa
P_c	critical pressure, Pa
q	heat flux, W/m^2
R_p	surface roughness, µm
T	temperature, K
T_c	critical temperature, K
T_s	saturation or bubble point temperature, K
T_w	heating wall temperature, K
x	mole fraction in liquid, dimensionless
y	mole fraction in vapor, dimensionless

Greek symbols

α	heat transfer coefficient, W/m^2 K
ΔT_{id}	ideal wall superheat, K
ΔT_s	wall superheat, K
ΔT_{bp}	boiling range, i.e., the dew and bubble point temperature difference, K
λ	thermal conductivity, W/m K
μ	viscosity, m^2/s
ρ	density, kg/m^3
σ	surface tension, N/m

Subscripts

l	liquid
v	vapor
id	ideal
0	base point
1	HC600a
2	HFC134a
3	HC290

copper cylinder, which will be discussed later. Different power can be obtained by adjusting an AC regulator. The boiling vessel and heating unit were well insulated in the vacuum chamber by a vacuum pump.

The process parameters such as temperatures, pressures, and mixture compositions are measured with the instruments described as follows. The temperatures are measured by means of PT100 type platinic electrical resistance thermometers. There are three platinum resistance thermometers installed in the copper cylinder at three different depths from the top to the end. And there are two thermometers were set separately in the liquid pool and in the vapor. The PT100 thermometers are calibrated in a temperature range from 70 K to 400 K. Temperatures are measured with an accuracy of ±0.1 K. The experimental data of temperatures are gathered by a data acquisition system (Keithley, Model 2700). The internal pressure of boiling vessel was measured by an AK-2 type pressure transducer. The pressure transducer is calibrated from 0.1 to 1.6 MPa, with an accuracy of ±0.5%. The mixture compositions of the vapor and liquid phases were measured by a gas chromatography. The accuracy of the measurement of mixture composition is about ±0.5%. The repeatability of the experiment was always within 1% of the

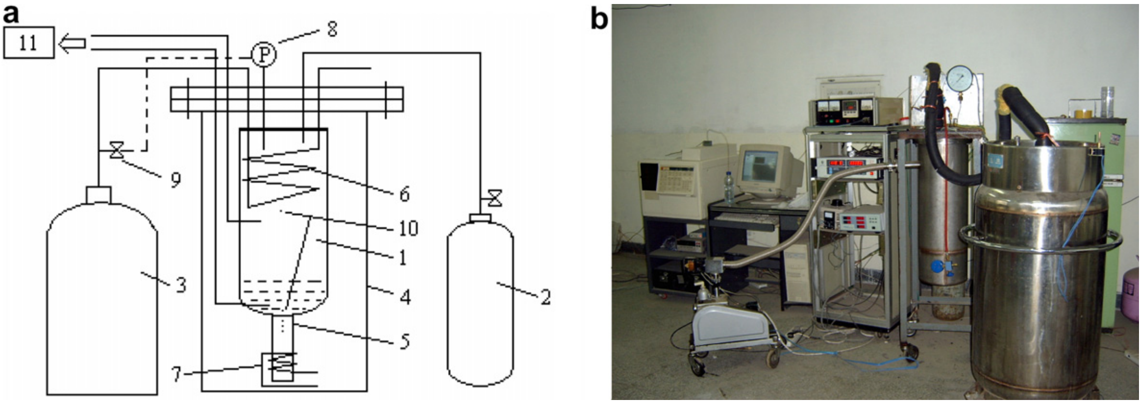

Fig. 1. Experimental apparatus, (a) schematic diagram (b) photo: (1) boiling vessel, (2) refrigerants tank, (3) liquid-nitrogen cryostat, (4) vacuum chamber, (5) copper cylinder, (6) condenser, (7) electric heater, (8) pressure transducer, (9) electric–magnetic valve, (10) platinum resistance thermometers, (11) gas chromatograph instrument.

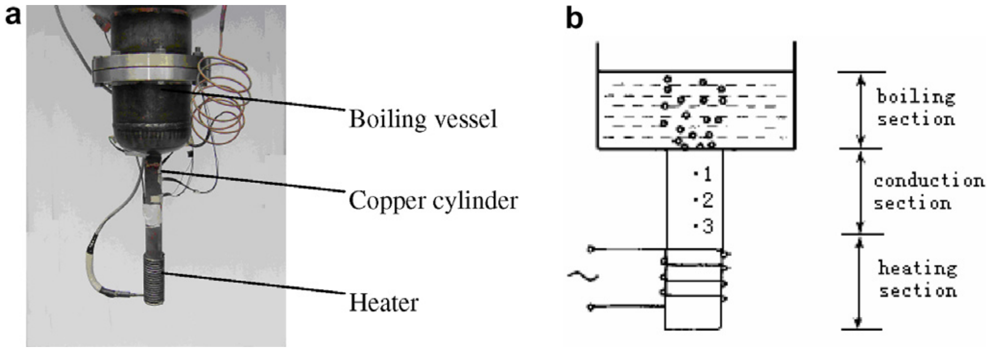

Fig. 2. Electrical heater, (a) photo, (b) temperature measure point distribution.

measurement error. The total experiment uncertainty has been evaluated within ±10%, mostly arising from the heat transferred from the insulation.

2.2. Surface temperature and heat flux determination

An electrical heater was used to provide the necessary heat flux in this work. Fig. 2 shows its simple principle and the real picture.

An adiabatic condition can be ensured with the vacuum insulation. So, there is one-dimensional heat conduction along the copper cylinder. According to the Fourier Law, the following equation could be obtained:

$$q_i = \lambda(T_{i+1} - T_i)/(x_{i+1} - x_i) \tag{1}$$

where T_i, x_i is the temperature and distance to heating surface at the corresponding measurement point, and $i = 1, 2, 3, \ldots, \lambda$ is the heat conductivity of copper cylinder, q_i is the heat flux between the two adjacent measurement points.

There are three measurement points in this work. The average heat flux along the copper cylinder is

$$q_1 = \lambda\left[\frac{T_2 - T_1}{x_2 - x_1} + \frac{T_3 - T_2}{x_3 - x_2}\right]\bigg/2 \tag{2}$$

where $x_1 = 20$ mm, $x_2 = 40$ mm, $x_3 = 60$ mm and the average heating surface temperature was obtained by interpolating the three measurement point values linearly. It was shown as follows:

$$T_w = \left[T_1 - x_1\frac{T_2 - T_1}{x_2 - x_1}\right]\bigg/2 + \left[T_2 - x_2\frac{T_3 - T_2}{x_3 - x_2}\right]\bigg/2 \tag{3}$$

2.3. Refrigerants

In this study, three pure refrigerants HFC134a, HC290, HC600a, three binary mixtures HFC134a/HC290, HC600a/ HFC134a, HC600a/HC290 and a ternary mixture HC600a/HFC134a/HC290 were selected. The mixtures have different boiling range of ΔT_{bp} at different compositions. The maximum temperature difference of the dew and bubble point for the bulk liquid mixture can reach 10.3 K in this test, but some of them have very small ΔT_{bp}, such as HFC134a/HC290, HC600a/HFC134a in their near-azeotropic or azeotropic concentration ranges.

Table 1 lists some basic thermal properties of these pure refrigerants of HFC134a, HC290 and HC600a for references. Tables 2 and 3 show the composition of mixtures tested in this study, as well as the ΔT_{bp} and composition differences between the vapor and liquid phase. ΔT_{bp} and all thermodynamic and transport properties are all calculated with the Peng–Robinson equation of state [4] at the given compositions and pressures. All compositions are mole fractions of the components if not specially mentioned.

3. Results and discussion

With the experimental apparatus presented above, numerous measurements were made for different refrigerants and different test conditions. Typical data are presented in the following sections.

3.1. Pure refrigerants

3.1.1. Data verification

To ensure the validity of experimental apparatus and method used in the present experiment, measured HTCs

Table 1
Some properties of pure refrigerants at the pressure of 0.5 MPa

Refrigerant	T_{sat} (K)	P_r	T_r	λ_l (W m^{-1} K^{-1})	λ_v (W m^{-1} K^{-1})	$\mu_l \times 10^{-6}$ (Pa s)	$\mu_v \times 10^{-6}$ (Pa s)	σ
HFC134a	288.9	0.1231	0.772	0.085	0.013	218.7	11.3	0.0093
HC290	274.9	0.1162	0.743	0.105	0.016	123.5	7.5	0.0099
HC600a	310.9	0.1353	0.762	0.084	0.018	131.3	7.8	0.0087

Table 2
Compositions and phase equilibria data at 0.5 MPa of binary mixtures tested in this study

Mixtures	Mole fractions	ΔT_{bp} (K)	$\lvert y_1 - x_1 \rvert$
HC600a/HC290	0.894/0.106	2.42	0.097
	0.819/0.181	3.89	0.146
	0.765/0.235	4.82	0.173
	0.691/0.309	5.90	0.198
	0.612/0.388	6.80	0.211
	0.491/0.509	7.57	0.209
	0.400/0.600	7.63	0.191
	0.300/0.700	7.10	0.159
	0.186/0.814	5.58	0.108
	0.097/0.903	3.52	0.060
HFC134a/HC290	0.905/0.095	8.63	0.253
	0.826/0.174	10.34	0.287
	0.766/0.234	10.01	0.272
	0.685/0.315	8.40	0.228
	0.576/0.424	0.53	0.151
	0.501/0.499	2.65	0.096
	0.396/0.604	0.14	0.021
	0.295/0.705	0.37	0.039
	0.201/0.799	1.27	0.077
	0.091/0.909	1.57	0.075
HC600a/HFC134a	0.100/0.900	1.47	0.074
	0.198/0.802	0.79	0.058
	0.307/0.693	0.00	0.006
	0.403/0.597	1.87	0.073
	0.501/0.499	5.82	0.146
	0.597/0.493	9.60	0.214
	0.700/0.300	12.45	0.278
	0.801/0.199	13.47	0.309
	0.887/0.113	10.76	0.249

data for HFC134a and HC290 were compared with two typical correlations of Nishikawa et al. [5] and Fujita [6], which are, respectively, expressed as follows:

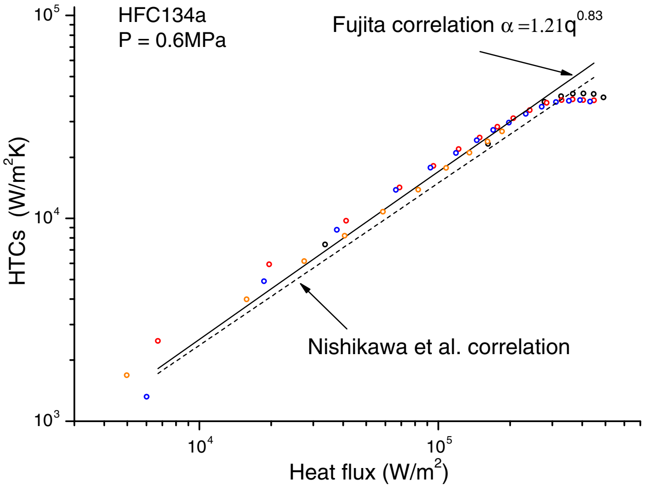

Fig. 3. Heat transfer coefficients for HFC134a.

$$\alpha = \frac{31.4 P_c^{0.2}}{M^{0.1} T_c^{0.9}} (8R_p)^{0.2(1-P/P_c)} \frac{(P/P_c)^{0.23}}{[1-0.99(P/P_c)]^{0.9}} q^{0.8}$$

$$R_p = 0.125\ \mu\text{m} \tag{4}$$

$$\alpha = 1.21 q^{0.83} \tag{5}$$

where Eq. (4) is the correlation of Nishikawa, and Eq. (5) is the correlation of Fujita.

Fig. 3 shows the comparison of experimental results from this study and the predicted data with Eqs. (4) and (5) for HFC134a. From Fig. 3, the present measured data agree well with the correlations of Nishikawa and Fujita. Fig. 4 shows the heat transfer coefficient of pure refrigerant HC290 at 0.5 MPa. The measured data agree well with the predicted data just using the correlation of Nishikawa et al. Therefore, the experimental apparatus and method can be used for testing other refrigerants.

Table 3
Compositions and phase equilibria data at 0.5 MPa of ternary mixtures tested in this study

Mixture	Mole fractions	ΔT_{bp} (K)	$\lvert y_1 - x_1 \rvert$	$\lvert y_2 - x_2 \rvert$	$\lvert y_3 - x_3 \rvert$
HC600a/HFC134a/ HC290	0.149/0.151/0.700	7.52	0.095	0.112	0.017
	0.230/0.235/0.535	9.24	0.148	0.127	0.021
	0.130/0.260/0.610	6.07	0.081	0.089	0.008
	0.338/0.332/0.330	8.32	0.072	0.164	0.092
	0.111/0.365/0.524	3.93	0.066	0.033	0.033
	0.104/0.404/0.492	3.21	0.060	0.008	0.052
	0.447/0.449/0.104	6.82	0.045	0.173	0.129
	0.095/0.098/0.870	5.61	0.062	0.091	0.029
	0.050/0.050/0.900	3.34	0.033	0.057	0.024
	0.047/0.098/0.855	3.78	0.031	0.084	0.053
	0.068/0.853/0.079	6.10	0.021	0.194	0.173
	0.158/0.690/0.152	4.01	0.027	0.121	0.149
	0.224/0.543/0.233	3.38	0.088	0.022	0.109
	0.066/0.674/0.260	6.40	0.020	0.181	0.201
	0.038/0.785/0.177	8.54	0.001	0.244	0.245
	0.720/0.140/0.140	13.18	0.299	0.252	0.047
	0.804/0.100/0.096	11.63	0.282	0.237	0.044
	0.594/0.202/0.204	13.55	0.282	0.236	0.047

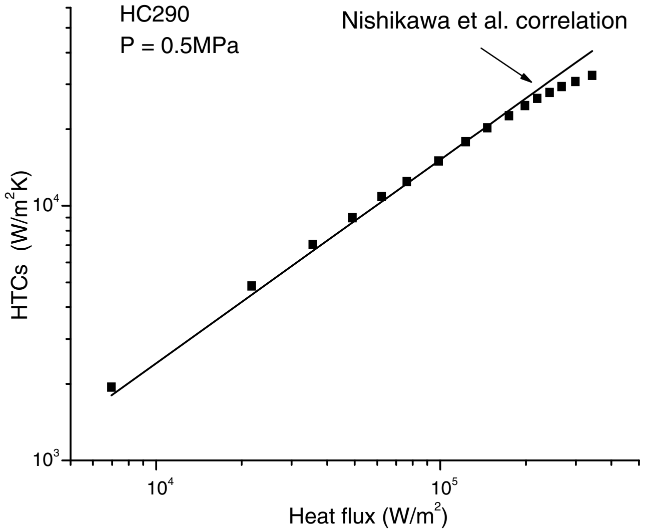

Fig. 4. Heat transfer coefficients for HC290.

3.1.2. Effects of boiling pressure

Pressure is a very important parameter on the boiling heat transfer. Figs. 5–7 show the HTCs of HFC134a, HC600a and HC290 at different pressures. These diagrams show that nucleate boiling HTCs increase with the increase of boiling pressure.

The influence of pressures on pool boiling can be indicated by its influence on the thermodynamic properties of refrigerants. Fig. 8 shows some basic thermophysics properties, as well as the dimensionless bubble formation power of HC290 at different pressures. The dimensionless bubble formation power for uniformity pool boiling of pure refrigerants can be expressed as Eq. (6) [7], which can be expressed as:

$$E/E_0 \propto \frac{(T_s/T_0)^2(\sigma/\sigma_0)^3}{(\rho_v/\rho_{v0})^2(h_{lv}/h_{lv0})^2} \tag{6}$$

The dimensionless bubble formation power includes four parameters: saturation temperature T_s, gas density ρ_v, heat of evaporation h_{lv} and surface tension σ. From Fig. 8, it can be found that the bubble formation power decreases as the pressure increases.

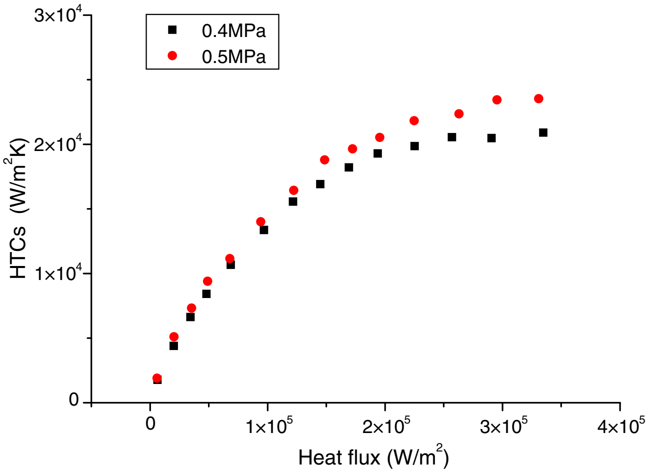

Fig. 5. HTCs of HFC134a at different pressures.

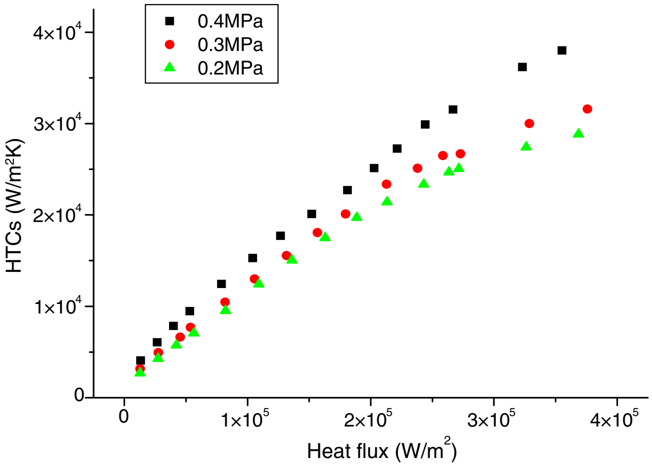

Fig. 6. HTCs of HC600a at different pressures.

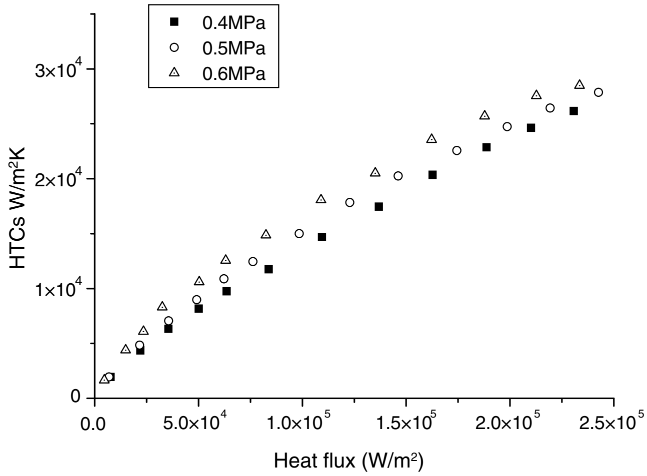

Fig. 7. HTCs of HC290 at different pressures.

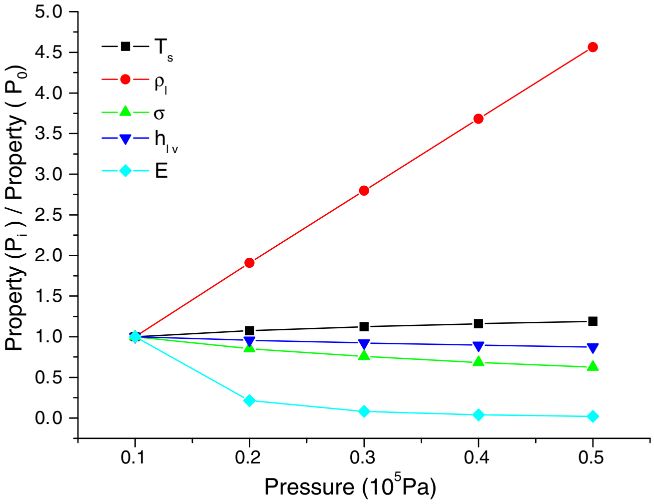

Fig. 8. Some properties of HC290 at different pressures.

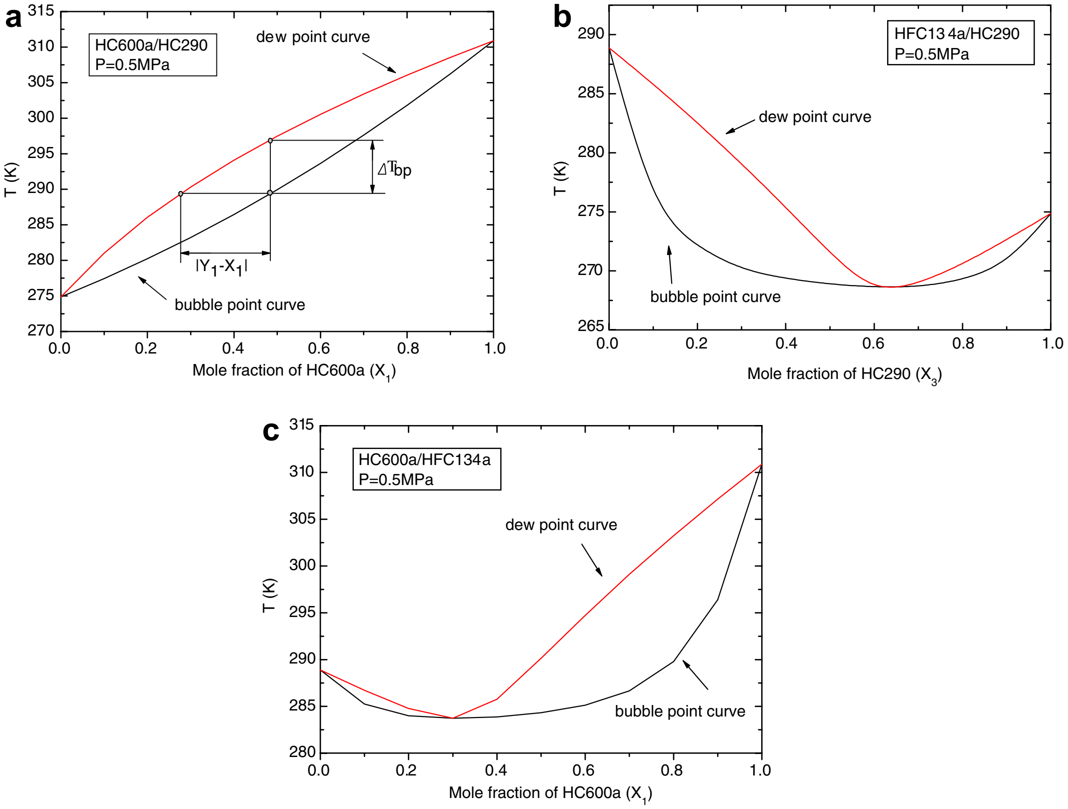

Fig. 9. Phase equilibria curves of three binary mixtures at 0.5 MPa.

3.2. Binary mixtures

Pool boiling is a typical phase change process. So the phase equilibrium behavior is very crucial in the nature of pool boiling heat transfer, especially for those mixtures. Fig. 9 shows the phase equilibrium curves of the three binary mixtures. For HFC134a/HC290 and HC600a/HFC134a, the azeotropic behaviors exist at certain concentrations. The influence of the phase equilibria on the pool boiling is very obvious, which will be presented in the following sections.

3.2.1. HC600a/HC290

Figs. 10 and 11 show the measured data of HTCs, ΔT_{bp} and $|y-x|$ against the mixture concentrations at 0.4 MPa and 0.5 MPa, respectively. As shown in the two figures, HTCs of binary mixture is reduced in the intermediate ranges of the mixture concentrations. The HTCs reach their lowest values in the range of $0.3 < x_1 < 0.7$, in which the heat transfer coefficients are almost independent of the concentrations. As the heat flux increases, the reduction become larger, and this trend becomes more pronounced at a higher heat flux. In other words, the HTC of mixtures is significantly lower compared with their pure components. And according to the concentration coordinate axis, the HTCs of mixtures dramatically deteriorate in the vicinity of single component substances.

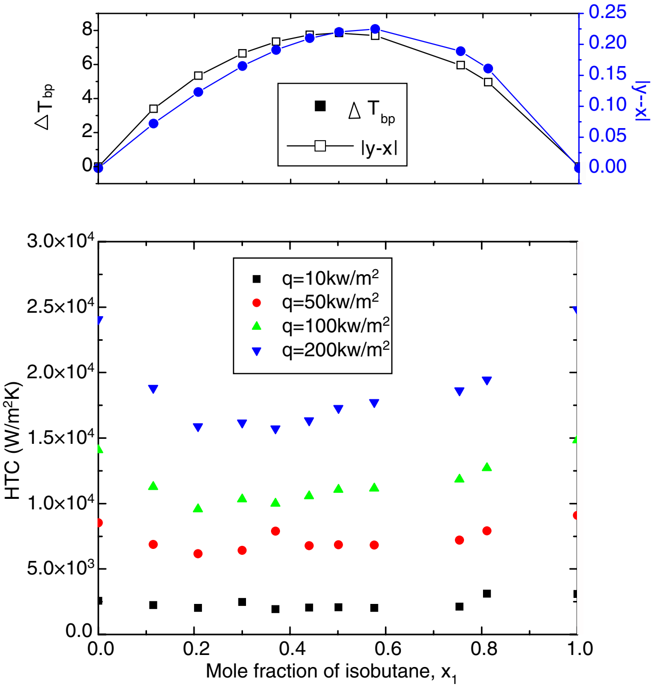

Fig. 10. HTCs of HC290/HC600a at 0.4 MPa.

3.2.2. HFC134a/HC290

Figs. 12 and 13 show the measured HTCs, ΔT_{bp} and $|y-x|$ of HFC134a/HC290 against the mixture

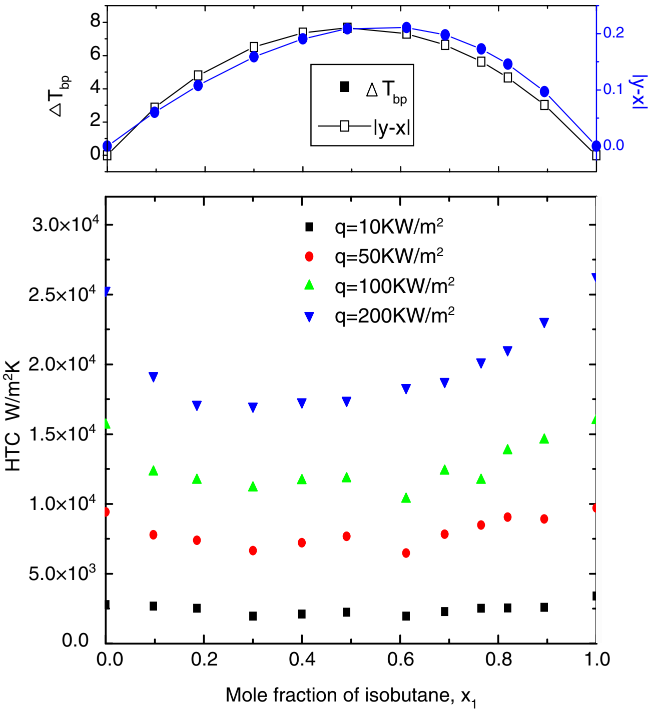

Fig. 11. HTCs of HC290/HC600a at 0.5 MPa.

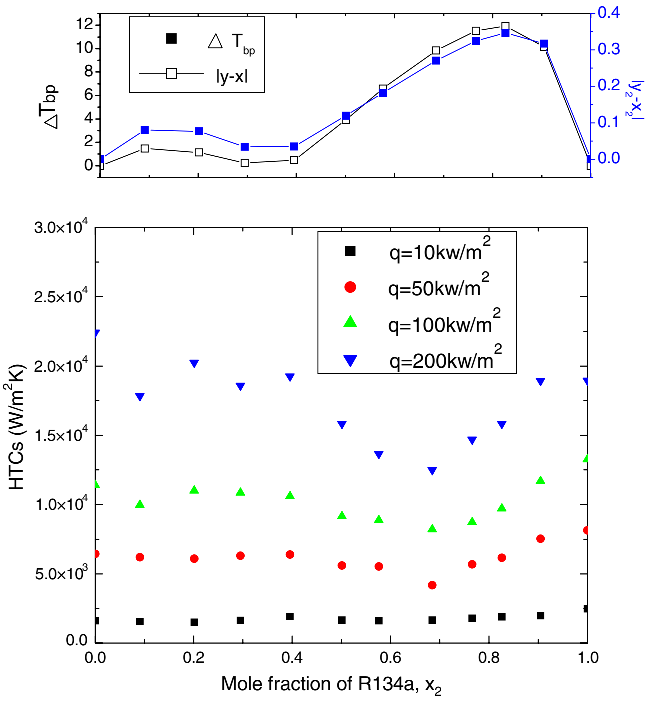

Fig. 12. HTCs of HC290/HFC134a at 0.4 MPa.

concentrations at 0.4 MPa and 0.5 MPa, respectively. As shown in the two figures, HTCs have two fluctuations vertexes against the mixture concentration. The difference of this binary mixture from that of HC600a/HC290 is that the mixture of HFC134a/HC290 shows an azeotropic behavior. In the azeotropic composition range, the values of ΔT_{bp} and $|y-x|$ are quite small, that is the mass diffusion effect reduces greatly. The mixture just behaves as a pure refrigerants. In some cases, the binary azeotropic mixture has a lower boiling point than both of the two components. So the HTCs at the same pressure and heat flux are even larger than that of the two pure refrigerants.

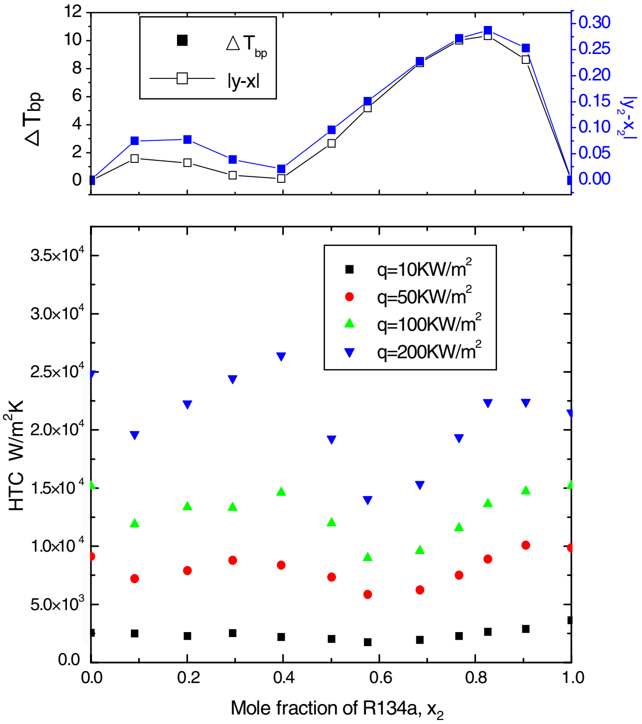

Fig. 13. HTCs of HC290/HFC134a at 0.5 MPa.

3.2.3. HC600a/HFC134a

The measured data of HTCs, ΔT_{bp} and $|y-x|$ of HC600a/HFC134a were shown in Fig. 14 against the mixture concentrations with different heat fluxes at 0.5 MPa. The heat transfer coefficients variations are quite similar to that of the binary mixture HFC134a/HC290. The binary mixture of HFC134a/HC600a can also form an azeotropic mixture at the molar fraction ranges of HC600a near 0.3.

3.2.4. Effect of boiling pressure

Fig. 15 shows the boiling curve of the binary mixture of HC290/HC600a at different pressures. It is found that HTCs of the binary mixture increase with the increase of boiling pressure, but the effect of pressure on HTCs tends to be smaller of the mixtures than that of pure substances. The situation of the influence of the pressures on the boiling heat transfer is same for other mixtures.

3.3. Ternary mixture of HC600a/HFC134a/HC290

For ternary mixtures, there are three composition differences, $|y_i - x_i|$, $i = 1,2,3$. The concentration difference of the vapor and liquid phases is quite complicated. So an average of $|y-x|$ for total three components is used.

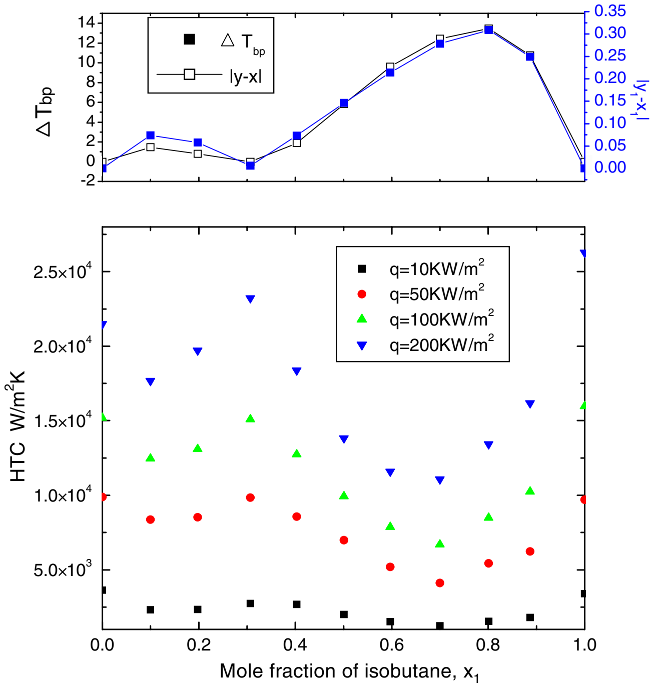

Fig. 14. HTCs of HFC134a/HC600a at 0.5 MPa.

Figs. 16–18 show the measured data of HTCs, ΔT_{bp} and $|y_i - x_i|$ of HC600a/HFC134a/HC290 at different composition, respectively. As seen from these three figures, the ternary mixture of HC600a/HFC134a/HC290 also show fluctuations of HTCs, which is a consistent trend as with the binary mixture. The boiling range of ΔT_{bp} is one of most important parameters which is obviously relative with HTCs. The reduction of HTCs increases while the boiling range is large. So, in the following section, the ΔT_{bp} is used to regress the correlation of the heat transfer coefficient.

The inner reasons of the deterioration of the heat transfer coefficients are quite complicated for mixed-refrigerant compared to pure ones. The precise quantitative methods to determine those effects on the deterioration of the heat transfer coefficients are far from practice. However, there are many effects to try to find a reasonable explanation

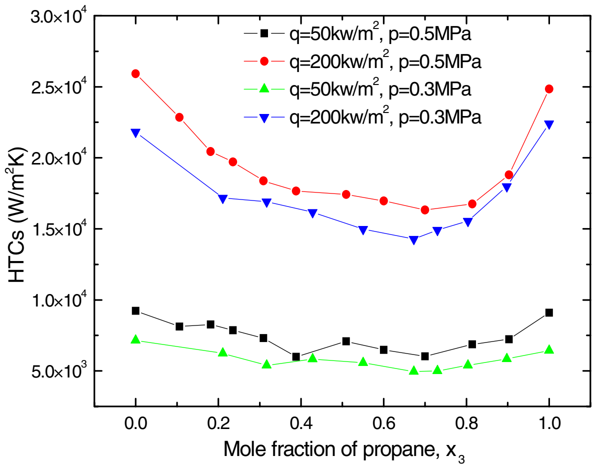

Fig. 15. HTCs of HC290/HC600a mixtures at different pressures.

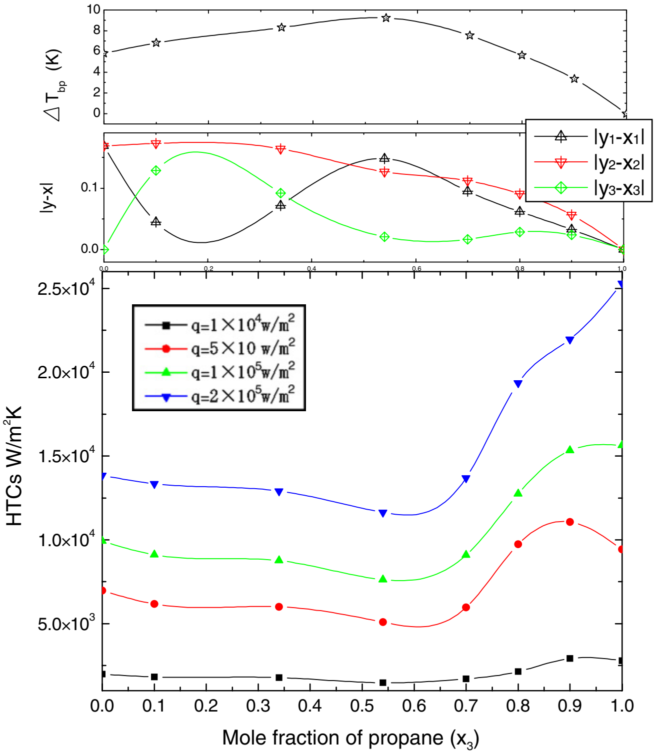

Fig. 16. HTCs of HC600a/HFC134a/HC290 ($x_1/x_2 = 1$).

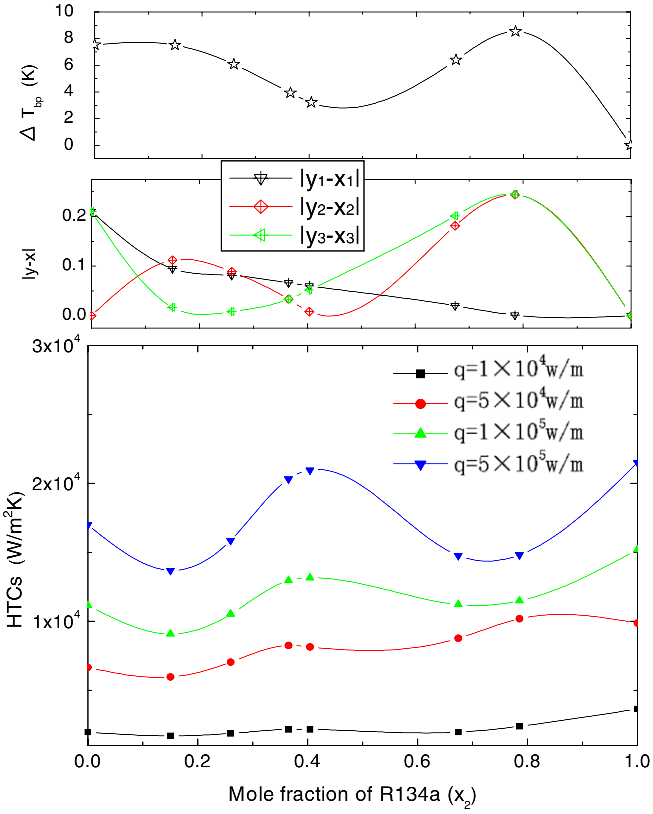

Fig. 17. HTCs of HC600a/HFC134a/HC290 ($x_1/x_3 = 1{:}4.67$).

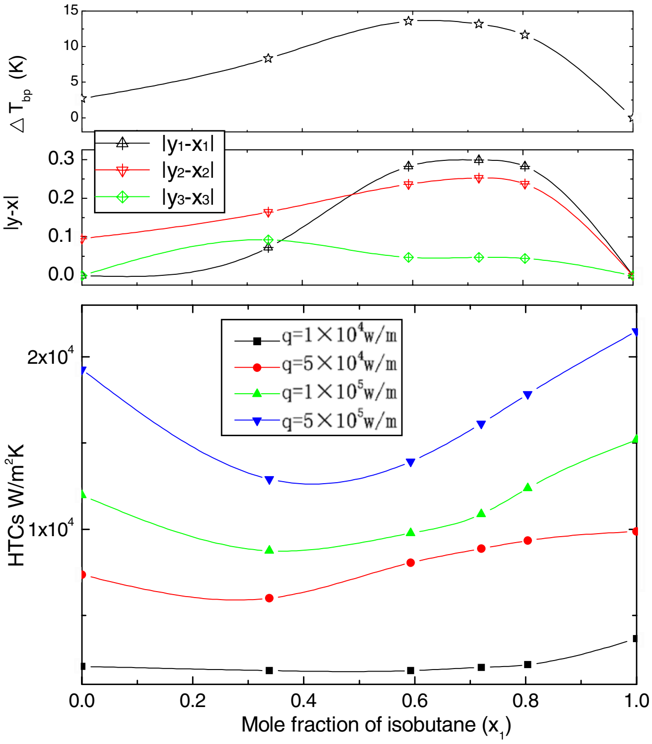

Fig. 18. HTCs of HC600a/HFC134a/HC290 ($x_2/x_3 = 1{:}1$).

on this deterioration. One of the most possible reasons is the effect of mass diffusion. That is, with the boiling of the volatile component, there is a concentration difference of the liquid layer near the heater surface from the bulk liquid. This causes an additional resistance for heat transfer from the mass diffusion. There are two important parameters required to describe this heat transfer process: one is the boiling range of ΔT_{bp}, and the other is composition difference of one component in the vapor and liquid phase $|y - x|$. Boiling range has a great influence on pool boiling heat transfer, so it is often used in many heat transfer correlations to regress pool nucleate boiling. Both of the two parameters of $|y - x|$ and ΔT_{bp} just indicate the phase equilibria behaviors of the mixtures.

From the result presented above, generally said, HTCs decrease as the ΔT_{bp} and $|y - x|$ increases and vice versa. HTCs have the minimum value as ΔT_{bp} and $|y - x|$ reach maximum. But when ΔT_{bp} and $|y - x|$ is minimum, HTCs nearly reach the maximum value and are even higher than those of the pure refrigerants. This is expected since it is a near-azeotrope of very small ΔT_{bp} and hence little mass transfer resistance.

4. Heat transfer correlations development

A heat transfer correlation with acceptable precision is necessary for industry design. To develop such a heat transfer correlation from the experimental measured data is also one of the research purposes. In the following sections, many efforts were made to develop heat transfer correlations for those pure and mixed refrigerants.

4.1. Pure refrigerants

From above experiments, it is clear that nucleate pool boiling heat transfer is affected by heat flux, surface condition, wall superheat, density difference between the liquid and vapor, heat of evaporation, characteristic length, and other thermodynamic properties. The relationship may be summarized as shown in Eq. (7) [8]

$$\alpha = \alpha(q, R_{\mathrm{p}}, \Delta T_{\mathrm{s}}, g(\rho_{\mathrm{l}} - \rho_{\mathrm{v}}), h_{\mathrm{lv}}, \sigma, C_p, \lambda, \mu, \ldots) \tag{7}$$

In refrigeration fields, Stephan–Abdelsalam's correlation [9] and Cooper's correlation [10] have been used in the prediction of nucleate boiling HTCs of refrigerants. The HTCs measured in this work were compared against these correlations. Figs. 19 and 20 show the comparison results, respectively. As shown in these two figures, the

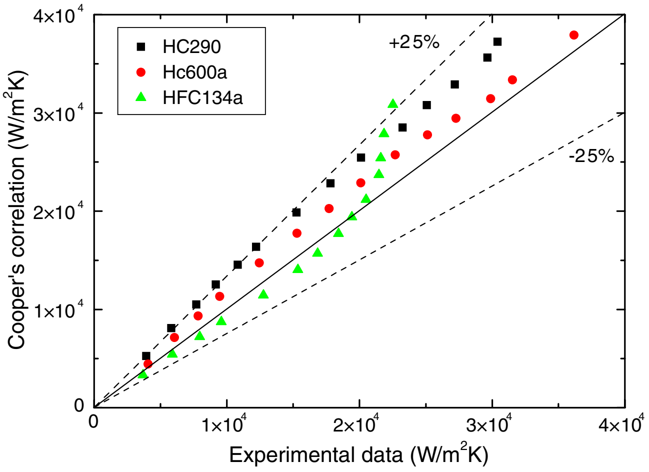

Fig. 19. Comparison of the present data with Cooper's correlation.

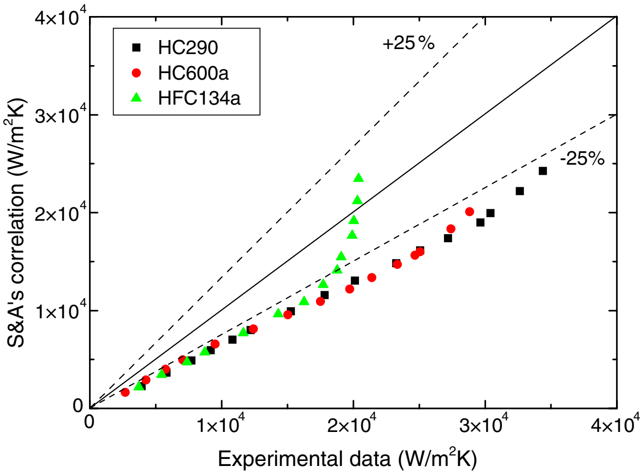

Fig. 20. Comparison of the present data with Stephan–Abdelsalam's correlation.

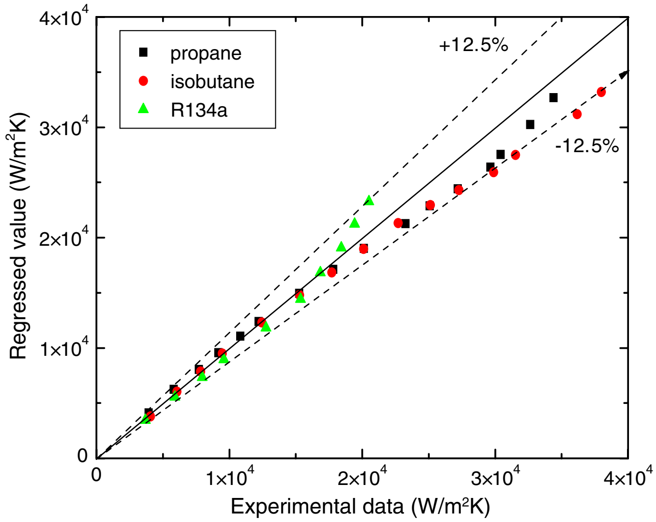

Fig. 21. Comparison of new correlation against the pure refrigerants data.

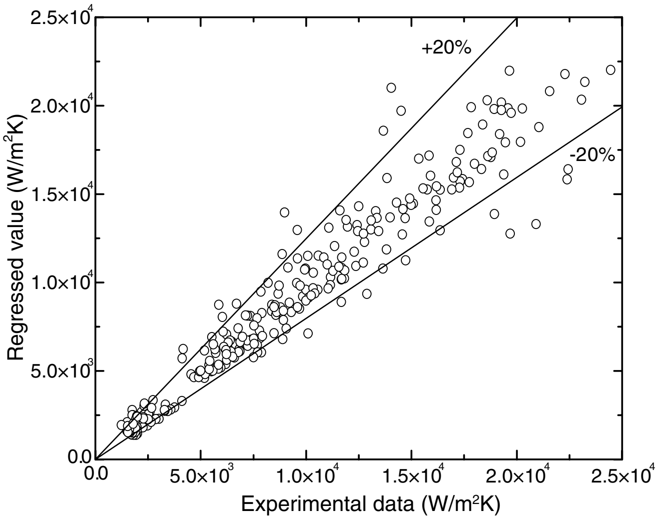

Fig. 22. Comparison of the new correlation against the binary mixture data.

predicted data with Cooper's correlation are larger than the experimental data with a small deviation while Stephan–Abdelsalam's correlation calculation values are smaller than the experimental data with a large deviation.

Based on the experimental data presented above, a new formula of HTC is regressed with some critical properties and molecular weight of pure refrigerants according to the Cooper's correlation, which can be presented as follows:

$$\alpha = 90 \cdot q^{C_1}\left(\frac{P}{P_c}\right)^n(-\log_{10}(P/P_c))^{-0.85}M^{-0.5} \tag{8}$$

where $C_1 = 0.696\left(\frac{T}{T_c}\right)^{2.9}\left(\frac{P}{P_c}\right)^{-0.4}$, $n = 0.12 - 0.2\log_{10}R_p$, $R_p = 0.4$.

The new correlation takes into account the exponent to the heat flux term which varies significantly among fluids and also is a strong function of the reduced pressure. Fig. 21 shows the comparison between the present data with the newly developed correlation. The average deviation was found to be less than ±15% for all refrigerants measured. The experimental heat flux range is $1 \times 10^4 \leqslant q \leqslant 4 \times 10^5$ W/m^2 and the pressure range is from 0.1 to 0.6 MPa.

4.2. Binary mixtures

Many nucleate boiling heat transfer correlations developed for mixtures use the composition difference between the vapor and liquid phases, ($|y - x|$) and/or boiling range (ΔT_{bp}) to account for the mixture effect. Generally, the mixture correlation can be expressed as follows [11]:

$$\frac{\alpha}{\alpha_{id}} = \frac{1}{1+K} \tag{9}$$

where K is a factor representing the heat transfer reduction. Here α_{id} is the ideal HTC defined using an ideal wall superheat of ΔT_{id}, that is determined as a molar interpolation of the wall superheats for mixture components evaluated at the same heat flux as the mixture, that is

$$\Delta T_{id} = \frac{q}{\alpha_{id}} = \frac{q}{\sum(x_i/\alpha_i)} \tag{10}$$

In order to derive K in Eq. (9), a regression analysis was carried out with dimensionless parameters responsible for the reduction of HTCs of the binary mixtures. A correlation for K is developed based on the experimental data obtained in this work, which can be expressed as:

$$K = \frac{1}{\Delta T_{id}}(y-x)^{-0.1}\Delta T_{bp}^{0.9}(P/10^5)^{-0.04} \times \left[1 - 0.85\exp\left(-\frac{q}{3\times 10^5}\right)\right] \tag{11}$$

Fig. 22 shows the comparison between the present experimental data with the predicted results by the new developed correlation. Most of the deviations were found to be less than ±20%, but for the mixture with a small ΔT_{bp}, the deviations were found a bit large.

4.3. Ternary mixtures

It is difficult to use the composition difference of ternary mixtures for such a correlation development. Since the boiling range is a single function of the mixture concentration and uniquely determined from the phase diagram, a new heat transfer correlation with a simple form is obtained as follows:

$$K = \frac{\Delta T_{bp}}{\Delta T_{id}}\left[1 - 0.85\exp\left(-\frac{q}{3\times 10^5}\right)\right](P/10^5)^{-0.01} \tag{12}$$

Eq. (12) is obtained on the base of the correlation of Fujita–Tsutsui [12], meanwhile, the influence of the pressure on the heat transfer was considered in this new correlation. Fig. 23 shows the comparison between the present

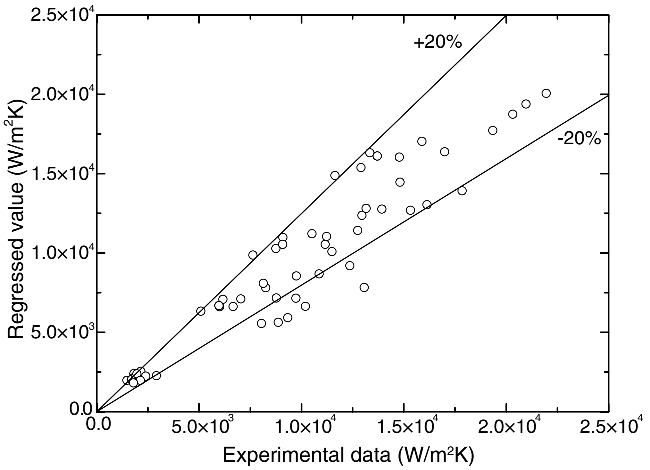

Fig. 23. Comparison of new correlation against the ternary mixture data.

experimental data with the new developed correlation of Eq. (12). Most of the deviations were found to be less than ±20%.

5. Summary and conclusions

In this work, an experimental apparatus was designed and built to investigate pool boiling heat transfer characteristics for pure refrigerants of HFC134a, HC290, HC600a and their binary and ternary mixtures. The nucleate pool boiling heat transfer coefficients were measured at different boiling pressures and different heat fluxes. Some new correlations were developed utilizing only the phase equilibrium data and physical properties for pure refrigerants, binary and ternary mixtures. From the study presented above, a few conclusions can be drawn, which can be expressed as follows:

(1) Refrigerants with higher vapor pressures show higher HTCs consistently. The influence of pressures on pool boiling is mainly due to the change of thermodynamic properties of refrigerants by the variation of pressures. For example, the increase of pressure decreases the bubble formation power and then enhance the heat transfer.
(2) For pure refrigerants, HTCs increase as the heat fluxes increase, and this trend become slow with higher heat fluxes. For binary and ternary mixtures, the HTCs also increase, but the reduction of HTCs become more pronounced with higher heat fluxes.
(3) The boiling range and concentration difference are the key parameters to account for heat transfer reduction in boiling of mixtures.
(4) The new developed correlations agree quite well with the experimental data. The average deviations are less than ±15% for pure refrigerants and less than ±20% for mixtures. All the correlations took into account influencing factor of pressure.
(5) The measured data and the new developed correlations obtained in this work can be used as references for industry design.

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