Experiment on Boiling Heat Transfer of Refrigerant R134a in Mini-channels

ZHAN Hongbo[1], *SHEN Hao*[2], *WEN Tao*[1], *ZHANG Dalin*[1*]

1. College of Aerospace Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, P.R.China;
2. Shanghai Aircraft Airworthiness Certification Center of CAAC, Shanghai, 200335, P.R.China

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Abstract: The flow boiling heat transfer characteristics of refrigerant R134a flowing inside two different kinds of mini-channels are investigated. One channel is multi-port extruded with the hydraulic diameter of 0.63 mm, and the other one is rectangular with offset fins and a hydraulic diameter of 1.28 mm. The experiments are performed with a mass flow rate between 68 and 630 kg/(m^2·s), a heat flux between 9 and 64 kW/m^2, and a saturation pressure between 0.24 and 0.63 MPa, under the constant heat flux heating mode. It is found that the effect of mass flow rate on boiling heat transfer is related to heat flux, and that with the increase of heat flux, the effect can only be efficient in higher vapor quality region. The effects of heat flux and saturation pressure on boiling heat transfer are related to a threshold vapor quality, and the value will gradually decrease with the increase of heat flux or saturation pressure. Based on these analyses, a new correlation is proposed to predict the boiling heat transfer coefficient of refrigerant R134a in the mini-channels under the experimental conditions.

Key words: flow boiling; heat transfer; two-phase flow; refrigerant R134a; channels with offset fins; multi-port channel

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0 Introduction

With the advance in manufacturing technology, mini and micro size thermal components have been applied to extensive fields, thanks to their excellent heat transfer performance. The principles of heat transfer and flow in mini scale have obtained great attentions. Many scholars have studied the boiling heat transfer characteristics of refrigerant in mini-channels, and some have proposed boiling heat transfer correlations for specific conditions.

Jabardo et al.[1] investigated the boiling heat transfer characteristics in a copper tube with a 12.7 mm hydraulic diameter. The results indicated that when vapor quality was less than 0.8, the heat transfer coefficient would increase with the increase of heat flux, saturation pressure and mass flow rate.

Choi et al.[2] researched the boiling heat transfer in stainless tubes with hydraulic diameters of 1.5 mm and 3 mm. The results showed that the effect of mass flow rate on heat transfer was weak when vapor quality was less than 0.2. When the vapor quality was greater than 0.2, the heat transfer coefficient would obviously increase with the increase of mass flow rate . And in this region, the coefficient would increase with the decrease of hydraulic diameter.

Oh et al.[3] and Copettiet al.[4] investigated a horizontal tube with a 2.6 mm hydraulic diameter, and found that the effect of mass flow rate on boiling heat transfer was related to a threshold of vapor quality. The effect of heat flux on boiling heat transfer was obvious in low vapor quality region, while weak in high vapor quality region. The heat transfer coefficient would increase with the increase of saturation pressure.

The channel with offset fins studied in this pa-

*Corresponding author, E-mail address: zhangdalin@nuaa.edu.cn.

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per is widely used in aviation compact heat exchangers. The adjacent channels are staggered in every other segment. The special structure can increase fluid turbulence and disturbance to destroy heat boundary layer, thus effectively enhance heat transfer performance. By now, a large number of studies on single phase heat transfer in channels with offset fins have been obtained[5-7]. Since the effects of the complex structures on heat transfers are full of uncertainty, the research results lack universality, and are only effective to certain structures. At present, there are few studies on boiling heat transfer characteristics in channels with offset fins.

Pulvirenti et al.[8] compared the boiling heat transfer capability of the tubes with offset fins and flat tubes with similar diameters, and found that at high heat flux, the internal structure had no effect on two-phase heat transfer capability. When the heat flux was low, the tubes with offset fins had stronger capability. Kim et al.[9] researched a 2.84 mm tube with offset fins, and found that the Reynolds number applicable for boiling heat transfer calculation in smooth tube was also applicable for the calculation in tube with offset fins.

From the above analysis, the conclusions about the effects of mass flow rate, heat flux and saturation pressure on boiling heat transfer are different. In this paper, two kinds of mini-channels are tested, and the main factors affecting boiling heat transfer are discussed. A boiling heat transfer correlation is proposed to provide theoretical and data support for the follow-up engineering application of the two channels.

1 Experimental Apparatus and Method

1.1 Boiling heat transfer test system

The boiling heat transfer test system is schematically presented in Fig. 1. The main components of the system include a refrigerant loop and a data acquisition system.

The refrigerant loop is composed of an air cooling condenser, a gear pump, a mass flow meter, a pre-heater and a test section. Refrigerant R134a is stored in the air cooling condenser, and the condenser is also used to sub-cool the refrigerant. The temperature of the two-phase working fluid can be adjusted by regulating the cold air volume flow through the condenser, and then the saturation pressure can be controlled. The test section is heated with uniform heat flux by a heating film, provided by an DC power supply.

The data acquisition system is composed of a computer, a National Instrument data collector, a mass flow meter, several pressure sensors and thermocouples. The uncertainties of measurement parameters calculated by the precisions of the sensors are shown in Table 1.

Table 1 Uncertainties of the calculation parameters %

Parameter	α	q	P	x	G
Uncertainty	6.8	0.32	0.36	1.2	0.3

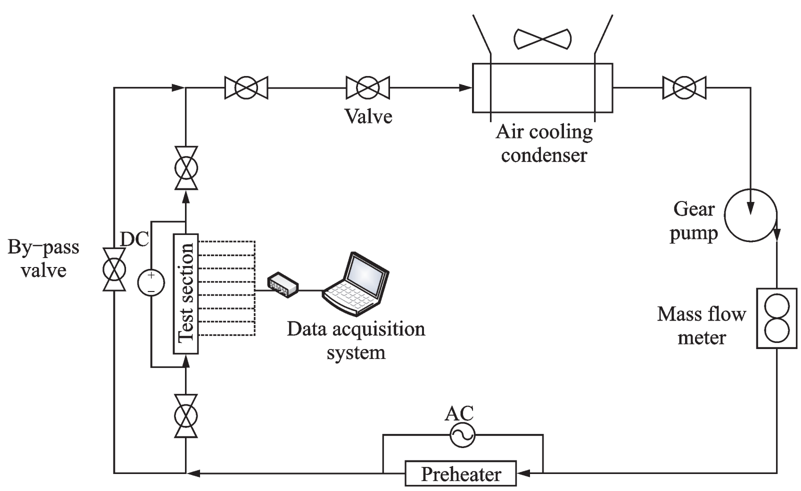

Fig. 1 Schematic of the boiling heat transfer test system

1.2 Test section

The two mini-channels used in the experiments are shown in Figs.2,3, and the structure details are shown in Table 2.

Fig. 2 Cross section photograph of the multi-port extruded channel 1

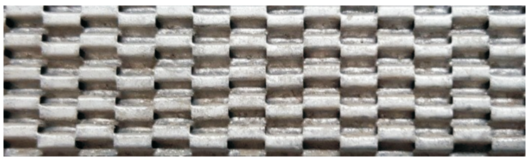

Fig. 3 Physical photograph of channel 2 with offset fins

Table 2 Details of the structure of two channels

Parameter	Channel 1	Channel 2
Channel height/mm	0.85	1.4
Channel wide/ mm	0.5	1.18
Hydraulic diameter/mm	0.63	1.28
Channel number	23	11
Length/ mm	274	274

Fig. 4 shows physical photograph of the test section. Ten thermocouples are evenly arranged on the channel to measure the wall temperatures. An electric heating film is attached to the lower surface of the channel to provide a uniform heat flux, and there are two plexiglass plates arranged on the upper and the lower surfaces of the channel to press it against the film closely by screws. Two epoxy resin heads are connected to both ends of the channel, and a pressure sensor and a thermocouple are arranged in each head to measure the inlet and the outlet parameters of refrigerant.

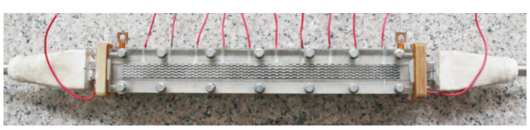

Fig. 4 Physical photograph of test section

1.3 Data reduction

In boiling heat transfer experiments, the enthalpy of super-cooled refrigerant at inlet of the test section h_{in} ($J\cdot kg^{-1}$) can be calculated by the inlet pressure P_{in} (MPa) and inlet temperature T_{in} (℃). When the outlet refrigerant is super-heated, the outlet enthalpy h_{out} can be calculated by outlet pressure P_{out} and outlet temperature T_{out}. So the total heat absorption rate of refrigerant Q_s(W) is given by

$$Q_s = \dot{m} \cdot \left(h_{out} - h_{in}\right) \tag{1}$$

where $\dot{m}$ ($kg\cdot s^{-1}$) is the mass flow of refrigerant. Numerous test results of comparison between the heat absorption rate of refrigerant and the supplied power of the film show that the maximum relative error cannot exceed 3%, which means that the thermal balance of the test system is good.

Since the pressure drop in channel is too low to cause obvious different saturation temperatures between the inlet and the outlet, the mean pressure of inlet and outlet can be approximated as the refrigerant saturation pressure P_{sat}, the corresponding saturation temperature is T_{sat}, and the corresponding enthalpies of saturated liquid and gas are $h_{sat,l}$ and $h_{sat,g}$, respectively.

The test section is heated with uniform heat flux. The ten thermocouples are distributed along the channel evenly, so the refrigerant enthalpy in each subsection can be calculated by

$$h_k = h_{in} + \frac{Q}{\dot{m}} \cdot \frac{L_k}{L} \tag{2}$$

where L is the total heating length and k an integer from 1 to 10.

The vapor quality of refrigerant in each subsection can be determined from

$$x_k = \frac{h_k - h_{sat,l}}{h_{sat,g} - h_{sat,l}} \tag{3}$$

The boiling heat transfer coefficient in each subsection α_k ($W\cdot m^{-2}\cdot K^{-1}$) is given by

$$\alpha_k = \frac{q}{T_k - T_{sat}} \tag{4}$$

where q ($W\cdot m^{-2}$) is the average heat flux, T_k the wall temperature in each subsection measured by the thermocouples.

The mass flow rate of refrigerant in channel G ($kg\cdot m^{-2}\cdot s^{-1}$) is given by

$$G = \frac{\dot{m}}{A} \tag{5}$$

The mean relative deviation and mean absolute relative deviation are defined as

$$\mathrm{MRD}=\frac{1}{N}\sum_{i=1}^{N}\frac{\alpha_{k,\mathrm{cal}}-\alpha_{k,\mathrm{exp}}}{\alpha_{k,\mathrm{exp}}} \tag{6}$$

$$\mathrm{MARD}=\frac{1}{N}\sum_{i=1}^{N}\left|\frac{\alpha_{k,\mathrm{cal}}-\alpha_{k,\mathrm{exp}}}{\alpha_{k,\mathrm{exp}}}\right| \tag{7}$$

where $\alpha_{k,\mathrm{cal}}$ is the calculated value of boiling heat transfer coefficient, and $\alpha_{k,\mathrm{exp}}$ the experimental value of heat transfer coefficient.

2 Results and Discussion

2.1 Effect of hydraulic diameter on boiling heat transfer

Fig. 5 shows the differences of boiling heat transfer coefficients in the two channels under the same experimental conditions. Apparently, channel 1 has better heat transfer performance than channel 2. Generally, the channel with smaller hydraulic diameter has more heat transfer area, so more bubbles can be generated in channel at the same heat flux, and the flow disturbance is enhanced, thus the heat transfer performances is better. But the difference in heat transfer performance between the two channels is not only due to the difference in hydraulic diameters, but also the difference in the structures. For those two channels, the difference in heat transfer coefficients is not as obvious as that in hydraulic diameters, so the structure of the channel with offset fins can probably enhance its heat transfer capability, but more experiments and data will be needed afterward.

2.2 Effect of mass flow rate on boiling heat transfer

In Fig.6(a), when heat flux is 16 kW/m^2 and vapor quality is greater than 0.2, mass flow rate starts to affect boiling heat transfer, and heat transfer coefficient will obviously increase with the increase of mass flow rate. But in Fig. 6(b), when heat flux is 27 kW/m^2 and vapor quality is less than 0.6, the effect of mass flow rate can be neglected. Accordingly, the effect of mass flow rate on boiling heat transfer is related to heat flux, and with increase of heat flux, the effect can only be efficient in higher vapor quality region.

2.3 Effect of heat flux on boiling heat transfer

As shown in Fig.7, for all six boiling curves, when the vapor quality is greater than a certain value (vapor quality of the inflection point), the boiling heat transfer coefficient decreases sharply[10]. When vapor quality is less than the value, boiling heat transfer coefficient is almost only affected by heat flux, and increases obviously with the increase of heat flux. But when vapor quality is greater than the value, the boiling heat transfer coefficient will barely change with the change of heat flux. The threshold value will decrease with the increase of heat flux. Generally, in the region with strong heat flux effect, as heat flux increases, the bubble generation rate will increase, and that will increase the flow velocity and turbulence intensity of fluid[11], thereby the performance of boiling heat transfer will

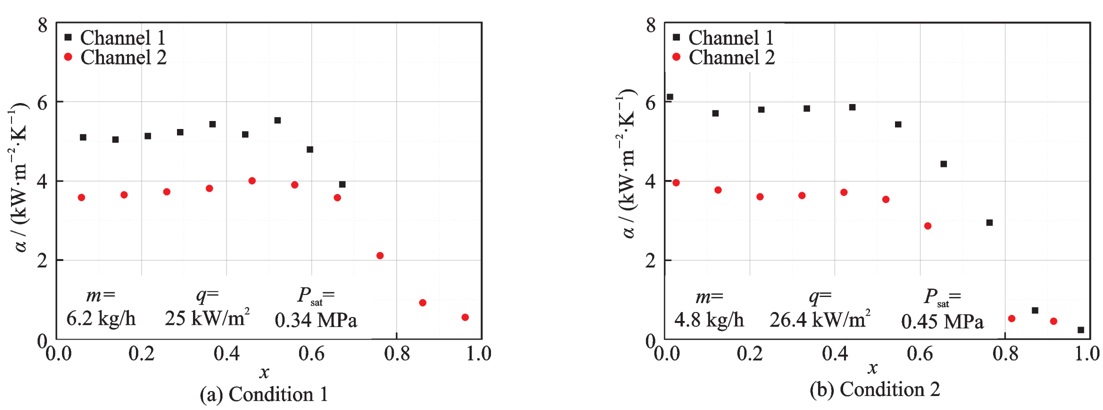

Fig. 5 Variations of local boiling heat transfer coefficients with hydraulic diameters

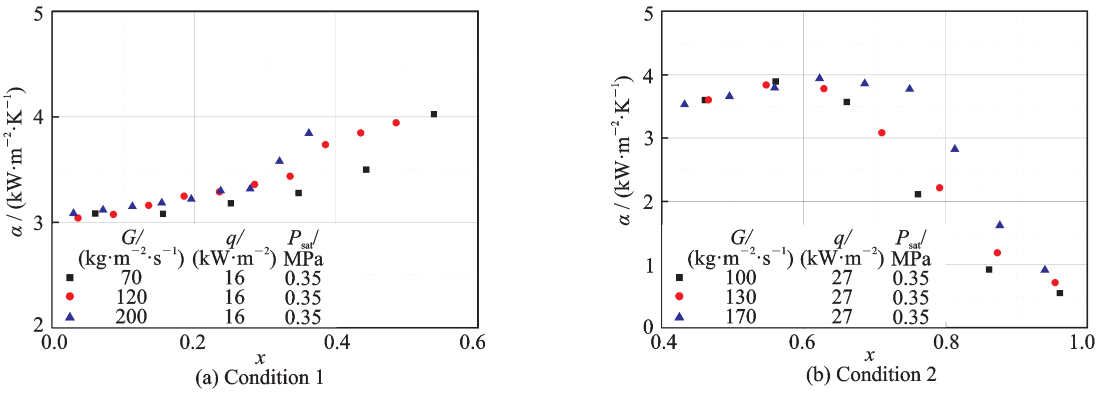

Fig. 6 Variations of local boiling heat transfer coefficients with mass flow rates for channel 2

be enhanced.

2.4 Effect of saturation pressure on boiling heat transfer

As shown in Fig. 8, the effect of saturation pressure on boiling heat transfer is similar with that of heat flux, and vapor quality of the inflection point will decrease with the increase of saturation pressure. When vapor quality is less than the value, the effect of saturation pressure is obvious.

Basically, the latent heat of vaporization decreases with the increase of saturation pressure, so more liquid is evaporated to dissipate the heat flux, resulting in the decrease of film thickness and increase of bubble generation rate, thereby the heat transfer performance will be enhanced[12].

2.5 Correlation for predicting boiling heat transfer coefficient in mini-channels

Based on the experimental data, and the analyses on relationships between local boiling heat transfer coefficients and vapor quality, mass flow rate,

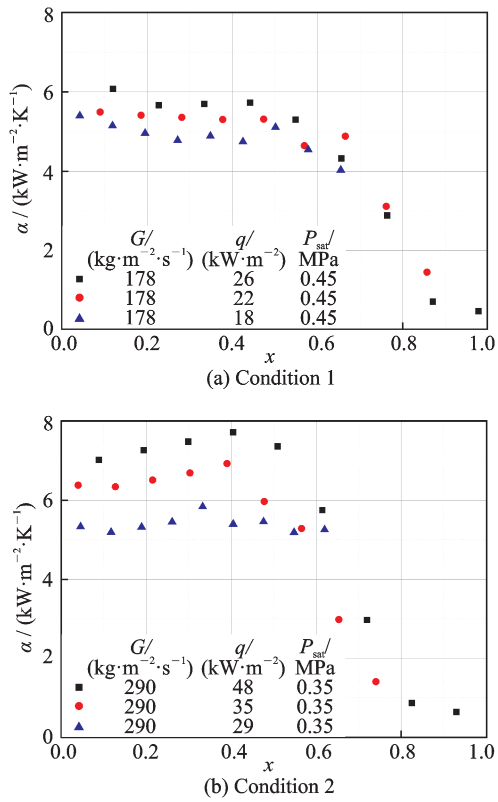

Fig. 7 Variations of local boiling heat transfer coefficients with heat fluxes for channel 1

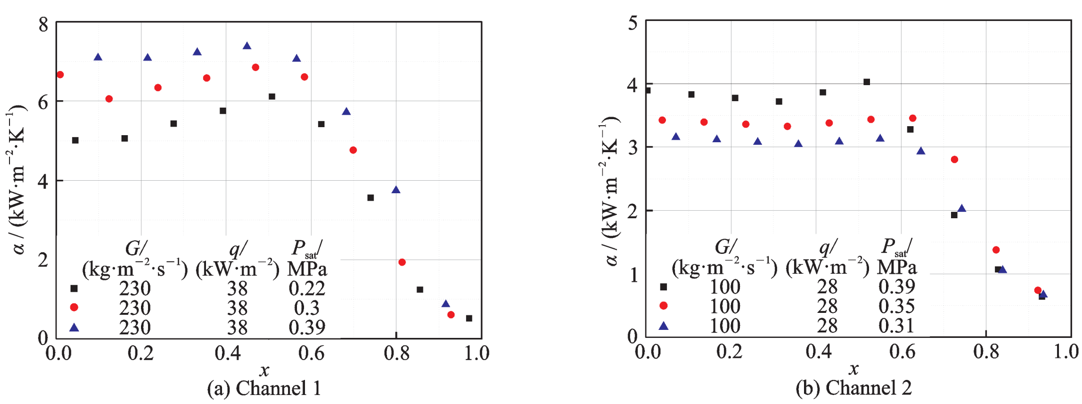

Fig. 8 Variations of local boiling heat transfer coefficients with saturation pressures.

heat flux and saturation pressure, an empirical correlation is established for predicting the boiling heat transfer coefficient of refrigerant R134a in mini-channels under this experimental condition. The boiling heat transfer coefficient α_{boi} is given by

$$\alpha_{boi} = \frac{1}{1 + e^{\frac{x-S}{S/10}}} \alpha_{nb} + \alpha_{sp} \tag{8}$$

The boiling heat transfer is composed of nuclear boiling and convective heat transfer. The nuclear boiling heat transfer coefficient α_{nb} and the convective heat transfer coefficient α_{sp} are given by

$$\alpha_{nb} = 10\,000 P_R^{0.12} \left(-\lg P_R \right)^{-0.55} M^{-0.5} q^{0.17} \left(We/Fr \right)^{-0.39} \tag{9}$$

$$\alpha_{sp} = x \alpha_{sp,go} + (1-x) \alpha_{sp,lo} \tag{10}$$

For the multi-port extruded channel, $\alpha_{sp,ko}$ can be calculated by Gnielinski[13] correlation

$$\alpha_{sp,ko} = \frac{\lambda_k}{D_h} \left(3.66 + \frac{0.066\,8 Re_{ko} Pr_k D_h / L}{1 + 0.04 \left(Re_{ko} Pr_k D_h / L \right)^{2/3}} \right) \tag{11}$$

For the channel with offset fins, $\alpha_{sp,ko}$ can be calculated with Colburn factor j

$$\alpha_{sp,ko} = \frac{\lambda_k}{D_h} \left(j Pr_k^{1/3} Re_{ko} \right) \tag{12}$$

where

$$S = (Bo \cdot We)^{0.06}$$

Boiling number: $Bo = q / \left(G h_{lg} \right)$

Webber number: $We = G^2 D_h / \left(\sigma \rho_l \right)$

Froude number: $Fr = G^2 / \left(g D_h \rho_l^2 \right)$

Reduced pressure: $P_R = \frac{P}{P_{crit}}$, $P_{crit} = 4\,059.3$ kPa

Reynolds number: $Re_{lo} = \frac{G D_h}{\mu_l}$, $Re_{go} = \frac{G D_h}{\mu_g}$

Where M is the molar mass (kg / kmol); D_h the equivalent diameter (m); λ the thermal conductivity (W/(m·k)); Pr the Prandtl number, h_{lg} the latent heat (J/kg); σ the surface tension (N/m), μ the dynamic viscosity (Pa·s); subscripts l is liquid and g gas; and subscript lo all flow taken as liquid, go all flow taken as gas.

Kays et al.[14] has investigated the single-phase convective heat transfer characteristics of 21 common channels with offset fins, and arranged the relationship of Reynolds number and heat transfer factor j, so the factor j of the channel that has similar channel size with channel 2 can be used in correlation 11.

In boiling heat transfer process, in low vapor quality region, nuclear boiling is dominant, and boiling heat transfer is mainly effected by heat flux and saturation pressure[15]. When vapor quality is larger than the certain value, nuclear boiling coefficient decreases sharply, and the proportion of convective heat transfer will increase, thereby the effect of mass flow rate will be obvious. Besides, with the decrease in heat flux, the nuclear boiling is weakened, thus the effect of mass flow rate will gradually increase, and its effect region will also be expanded. In addition, the calculation results of the two correlations show that the boiling heat transfer capacity of rectangular channel with offset fins is slightly stronger than that of multi-port channel under the same working conditions and the same equivalent diameter.

Fig.9 shows the comparison of experimental data in the two channels and the correlation predictions, and it is known that the correlation can well predict the boiling heat transfer coefficients of refrigerant R134a in the two channels. There is a MARD of 16.1%, and a MRD of −5.6%, with 77% of the data having a relative deviation within ±20%.

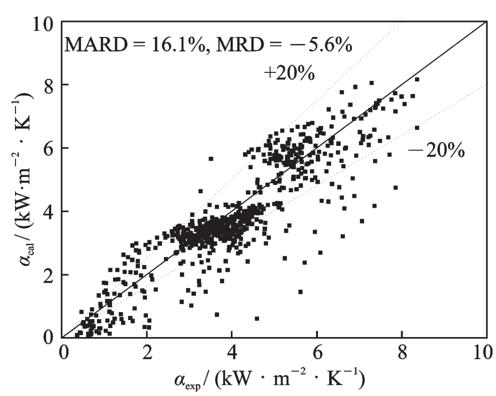

Fig. 9 Comparison between experimental data and the correlation predictions

The results of the Comparison of the predictions of the new correlation and several correlations that are suitable for calculating boiling heat transfer coefficient in mini-channel[16] are shown in Table 3. The prediction accuracy of the new correlation is obviously higher than that of others.

Table 3 Comparison between the predictions of the new correlation and several well-known correlations

Correlation	MRD/%	MARD/%
New correlation	−5.6	16.1
Cooper[17]	18.7	30.0
Liu-Winterton[18]	29.4	38.5
Kew-Cornwell[19]	30.41	40.1
Bertsch et al.[20]	20.3	27.5

3 Conclusions

The boiling heat transfer characteristics of R134a flowing inside two mini-channels is investigated. The main conclusions are drawn as follows.

(1) The effect of mass flow rate on boiling heat transfer is related to heat flux. With the increase of heat flux, the effect can only be efficient in higher vapor quality region.

(2) The effects of heat flux and saturation pressure on boiling heat transfer are similar, and related to a threshold value (vapor quality of the inflection point). When vapor quality is less than the value, the boiling heat transfer coefficient will increase obviously with the increase of heat flux and saturation pressure. When vapor quality is greater than the value, the boiling heat transfer coefficient will decrease sharply, and the effects of heat flux and saturation pressure can be neglected. The value will decrease with the increase in heat flux and saturation pressure.

(3) A correlation for predicting the boiling heat transfer coefficient of refrigerant R134a in mini-channels is proposed, and the predictions agree well with experimental data.

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Authors Dr. **ZHAN Hongbo** received the Ph.D degree from Nanjing University of Aeronautics and Astronautics (NUAA) in 2017. His main research interest is aircraft environmental engineering. In November 2017, he joined Nanjing Engineering Institute of Aircraft Systems, Aviation Industry Corporation of China.

Mr. **SHEN Hao** received B.S degree from Nanjing University of Aeronautics and Astronautics in 2000. He worked for Hongdu Aviation Industry Group from 2000—2008. In 2008, he joined in Shanghai aircraft airworthiness certification center of CAAC as a senior engineer at the mechanical system department.

Mr. **WEN Tao** received the Master degree from Nanjing University of Aeronautics and Astronautics in 2016. He is now a doctoral candidate at Hong Kong Polytech University.

Prof. **ZHANG Dalin** received the Ph.D. degree from Nanjing University of Aeronautics and Astronautics in 2002. He is now a professor and doctoral supervisor at college of Aerospace Engineering, NUAA. His research is focused on aircraft environmental engineering.

Author contributions Dr. **ZHAN Hongbo** completed the experiments, conducted the analysis and wrote the manuscript. Mr. **SHEN Hao** contributed to the discussion and background for the study. Dr. **WEN Tao** participated in the experiments. Prof. **ZHANG Dalin** designed the study and guided the experiments.

Competing interests The authors declare no competing interests.

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