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ABSTRACT

In order to extend the existing heat transfer coefficient correlation of R410A-oil mixture flow boiling in conventional size (7.0 mm) microfin tube to be suitable for widely used small diameter tubes (4.0~5.0 mm), the experiments of R410A-oil mixture flow boiling inside three small diameter microfin tubes with different outside diameters of 4.0~5.0 mm and different microfin structures were performed. For the tested tubes with different diameter, the decrease of tube diameter may weaken the deterioration effect of oil on heat transfer at intermediate and high vapor qualities. For the fixed outside diameter microfin tubes with different microfin structures, larger fin height and contact area of liquid with tube wall may enhance the heat transfer for oil-free R410A, but result in smaller enhancement effect of oil at low vapor qualities and smaller deterioration effect of oil at intermediate and high vapor qualities for R410A-oil mixture. A general correlation to predict the heat transfer coefficients of R410A-oil mixture flow boiling inside conventional size and small diameter microfin tubes was developed, and it agrees with 94% of the experimental data of R410A-oil mixture in 4.0 mm ~ 7.0 mm microfin tubes within a deviation of ±30%.

1. INTRODUCTION

Compact heat exchangers for refrigeration systems are beneficial to reduce cost, charge inventory and leakage of refrigerant, and to improve energy efficiency. Furthermore, in order to intensify heat transfer during flow boiling in evaporators of refrigerating systems, extended surface tubes, e.g., microfin tubes are used widely. Using small diameter tubes is one way to decrease the size of heat exchangers. Currently, small diameter microfin tubes with outside diameter (O.D.) of 5.0 mm and 4.0 mm O.D. are applied in newly developed R410A air conditioners instead of conventional size tubes (e.g. 7.0 mm O.D. microfin tubes). With the decrease of the tube diameter, the heat exchanger area inside the microfin tubes becomes smaller, and the pressure drop becomes much larger, resulting in the decrease of heat exchanger performance. In order to avoid such performance decrease, the heat exchanger should be redesign based on clearly understanding the difference of the heat transfer characteristics between conventional size microfin tubes and small diameter microfin tubes. Moreover, under real working conditions of air conditioner, the working fluid is refrigerant-oil mixture (Shen and Groll, 2005; Thome, 1996). Therefore, in order to achieve optimal designs for the heat exchangers using small diameter tubes instead of conventional size tubes (7.0 mm O.D. microfin tubes), a general heat transfer coefficient correlation for R410A-oil mixture flow boiling inside different diameter microfin tubes is needed.

The existing researches on the correlations for refrigerant-oil mixture flow boiling inside microfin tubes are listed in Table 1, in which the tube diameters are larger than 7.0 mm. However, until now, there is no correlation available for R410A-oil mixture flow boiling inside small diameter microfin tubes.

The existing research on heat transfer characteristics of oil-free R410A flow boiling in microfin tubes has been performed (Kim et al., 2005; Wellsandt et al., 2005; Kim et al., 2002; Goto et al., 2001), and the range of tube diameters is from 7.0 mm to 9.53 mm. The existing experimental research on heat transfer characteristics of refrigerant-oil mixtures in microfin tubes includes R410A-oil mixture in 7.0 mm O.D. tube (Hu et al., 2008), CO₂/oil mixture in 3.04 mm O.D. tube (Gao et al., 2007), R12/oil mixture in 8.94 mm O.D. tube (Ha and Bergles, 1987), R22/oil mixture in 9.52 mm O.D. tube (Schlager et al., 1989, 1990), R134a/oil mixture in 9.52 mm and 12.7 mm O.D. tubes (Eckels et al., 1994, 1998; Nidegger et al., 1997), and R407C/oil mixture in 12.7 mm and 10 mm
O.D. tubes (Targanski and Cieslinski, 2007; Zurcher et al., 1998), etc. The research results show that, microfin tubes tend to suppress the effects of lubricant to promote annular flow and foaming (Shen and Groll, 2005; DEng et al., 2007; Nidegger et al., 1997), and the oil with higher viscosity gives larger deterioration to the heat transfer than the oil with lower viscosity (Schlager et al., 1989c; Eckels et al., 1994). Most of tube diameters in the above studies are larger than 7.0 mm, and there is no paper on R410A/oil mixture flow boiling in small diameter microfin tubes.

In order to develop a new correlation for R410A-oil mixture suitable for both conventional size and small diameter microfin tubes, only the existing experimental data of R410A-oil mixture in conventional size microfin tube of 7.0 mm O.D. are compiled into the databank used in the present study, and additional experimental research for R410A-oil mixture flow boiling in small diameter microfin tubes is needed.

The purpose of this study is to obtain the experimental data of heat transfer characteristics inside small microfin tubes with different diameters of 4.0–5.0 mm and different microfin structures, and to present a general heat transfer coefficient correlation for R410A-oil mixture in conventional size and small diameter microfin tubes.

**Table 1:** Existing researches on the correlations of refrigerant-oil mixture inside microfin tubes

<table>
<thead>
<tr>
<th>Literatures</th>
<th>Fluid</th>
<th>Tube diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schlager et al. (1998)</td>
<td>R22/150-SUS</td>
<td>9.52 mm O.D.</td>
</tr>
<tr>
<td></td>
<td>R22/300-SUS</td>
<td>9.52 mm O.D.</td>
</tr>
<tr>
<td>Eckels et al. (1994, 1998)</td>
<td>R134a/169-SUS</td>
<td>9.52 mm O.D.</td>
</tr>
<tr>
<td></td>
<td>R134a/369-SUS</td>
<td>9.52 mm O.D.</td>
</tr>
<tr>
<td>Nidegger et al. (1997)</td>
<td>R134a/150-SUS</td>
<td>9.52 mm O.D.</td>
</tr>
<tr>
<td>Targanski and Cieslinski (2007)</td>
<td>R407C/oil</td>
<td>10.0 mm O.D.</td>
</tr>
<tr>
<td>Hu et al. (2008)</td>
<td>R410A/POE oil</td>
<td>7.0 mm O.D.</td>
</tr>
</tbody>
</table>

2. EXPERIMENT APPARATUS

The experimental rig consists of three loops: a refrigerant main loop, a refrigerant by-path loop and a lubricant oil loop, as shown in Fig. 1. The experimental rig was introduced in detail by Hu et al. (2008). This experimental rig has the function of investigating the heat transfer performance of oil-free refrigerant and refrigerant-oil mixture.

**Figure 1:** Layout of flow circuits in test facility
The test tubes used in this study are three internally spiral grooved tubes with the outside diameters of 4.0–5.0 mm. The three test tubes include two 5.0 O.D. tube with different microfin structures (named tube#1 and tube#2, respectively) and one 4.0 O.D. tube (named tube#3). The experiments of tube#1 and tube#2 are used to analyze the effect of microfin structures and oil on the heat transfer characteristics under fixed outside diameter, and the experiments of tube#1, tube#2 and tube#3 are used to compare with those of conventional size tube (Hu et al., 2008) for analyzing the effect of tube diameter and oil on heat transfer characteristics. The details of three microfin tubes are listed in Table 2. The refrigerant-oil mixture in the test tube is evaporated by the electric heating tape wrapped around the outside of the test tube. Test conditions of the test tubes are tabulated in Table 3. All signals of temperature, pressure, pressure drop and mass flow rate are collected by a data acquisition system and transmitted to a computer after the system reaches steady state.

Table 2: Details of enhanced tubes

<table>
<thead>
<tr>
<th>parameter</th>
<th>tube#1</th>
<th>tube#2</th>
<th>tube#3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(d_o/\text{mm})</td>
<td>5.00</td>
<td>5.00</td>
<td>4.00</td>
</tr>
<tr>
<td>(t_w/\text{mm})</td>
<td>0.20</td>
<td>0.20</td>
<td>0.22</td>
</tr>
<tr>
<td>(l_f/\text{mm})</td>
<td>0.14</td>
<td>0.155</td>
<td>0.12</td>
</tr>
<tr>
<td>(n_f)</td>
<td>40</td>
<td>48</td>
<td>40</td>
</tr>
<tr>
<td>(\beta/\degree)</td>
<td>18</td>
<td>18</td>
<td>12</td>
</tr>
<tr>
<td>(\gamma/\degree)</td>
<td>40</td>
<td>20</td>
<td>40</td>
</tr>
</tbody>
</table>

Table 3: Test conditions of the test tubes

<table>
<thead>
<tr>
<th>Test tube</th>
<th>Tube diameter (mm)</th>
<th>Mass flux (kg/m²s)</th>
<th>Heat flux (kW/m²)</th>
<th>Inlet quality</th>
<th>Outlet pressure (kPa)</th>
<th>Oil concentration (wt. %)</th>
<th>Data points</th>
</tr>
</thead>
<tbody>
<tr>
<td>tube#1</td>
<td>5.0 mm</td>
<td>200±10</td>
<td>7.46</td>
<td>0.1–0.8</td>
<td>934±5</td>
<td>0.1, 2, 3, 4, 5</td>
<td>292</td>
</tr>
<tr>
<td></td>
<td>300±10</td>
<td>11.2</td>
<td>0.1–0.8</td>
<td>934±5</td>
<td>0.1, 2, 3, 4, 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>400±10</td>
<td>14.9</td>
<td>0.1–0.8</td>
<td>934±5</td>
<td>0.1, 2, 3, 4, 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>tube#2</td>
<td>5.0 mm</td>
<td>200±10</td>
<td>7.46</td>
<td>0.2–0.8</td>
<td>934±5</td>
<td>0.1, 3, 5</td>
<td>292</td>
</tr>
<tr>
<td></td>
<td>300±10</td>
<td>11.2</td>
<td>0.2–0.8</td>
<td>934±5</td>
<td>0.1, 3, 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>400±10</td>
<td>14.9</td>
<td>0.2–0.8</td>
<td>934±5</td>
<td>0.1, 3, 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>tube#3</td>
<td>4.0 mm</td>
<td>300±10</td>
<td>12.63</td>
<td>0.1–0.8</td>
<td>934±5</td>
<td>0.1, 3, 5</td>
<td>292</td>
</tr>
<tr>
<td></td>
<td>400±10</td>
<td>16.84</td>
<td>0.1–0.8</td>
<td>934±5</td>
<td>0.1, 3, 5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3. DATA REDUCTION AND UNCERTAINTIES

3.1 Heat Transfer Coefficient

The local flow boiling heat transfer coefficients for oil-free R410A and R410A-oil mixture are defined by Eqs. (1) and (2), respectively (Thome, 1995).

\[
\alpha_{q,r} = \frac{q(T_u - T_{w, r})}{} \quad (1)
\]

\[
\alpha_{q,r,o} = \frac{q(T_u - T_{w, r,o})}{} \quad (2)
\]

3.2 Oil Concentration

Nominal oil concentration and local oil concentration are defined by Eqs. (3) and (4), respectively.

\[
a_{\omega_{\text{n}}} = \frac{m_o}{m_u + m_o} \quad (3)
\]

\[
a_{\omega_{\text{l}}} = \frac{m_o}{m_u + m_o} = \frac{a_{\omega_{\text{n}}}}{1-x_{\text{u,o}}} \quad (4)
\]

3.3 Uncertainties

Based on the error propagation analysis (Moffat, 1998), the uncertainties of instruments and heat transfer coefficient were analyzed, as shown in Table 4. The maximum error of heat transfer coefficient is 10.4% (Hu et al., 2008).
Table 4: Uncertainties of instruments and heat transfer coefficient

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Source of uncertainty</th>
<th>Instrument</th>
<th>Range</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refrigerant mass flow rate</td>
<td>Instrument calibration</td>
<td>Coriolis-effect flowmeter</td>
<td>0~200 kg/h</td>
<td>±0.12% FS</td>
</tr>
<tr>
<td>Oil mass flow rate</td>
<td>Instrument calibration</td>
<td>Coriolis-effect flowmeter</td>
<td>0~20 kg/h</td>
<td>±0.12% FS</td>
</tr>
<tr>
<td>Temperature</td>
<td>Instrument calibration</td>
<td>T-Type thermocouple</td>
<td>-20~100 °C</td>
<td>±0.1°C</td>
</tr>
<tr>
<td>Pressure</td>
<td>Instrument calibration</td>
<td>Absolute pressure transducer</td>
<td>0~2 MPa</td>
<td>±0.12% FS</td>
</tr>
</tbody>
</table>

Uncertainties of heat transfer coefficient

±10.4%

4. EXPERIMENT RESULTS AND DISCUSSIONS

4.1 Experimental results of local heat transfer coefficient

Figs. 2 and 3 show the experimental data of R410A-oil mixture in two microfin tubes (tube#1 and tube#2) with outside diameter of 5.0 mm. The local heat transfer coefficients of R410A-oil mixture in 5.0 mm microfin tubes are enhanced with the increase of oil concentration at the range of low and intermediate vapor qualities \(x_{r,o}<0.7\), while at higher vapor quality \(x_{r,o}>0.8\), the local heat transfer coefficients fall off very sharply with the increase of vapor quality at high oil concentration. From the comparison of the heat transfer characteristics of tube#1 and tube#2 as shown in Fig. 3 and Fig. 4, it can be seen that: 1) for oil-free R410A, the local heat transfer coefficient in tube#2 is always higher than that in tube#1; 2) for R410A-oil mixture, at the range of low vapor qualities \(x_{r,o}<0.5\), the local heat transfer coefficient in tube#2 is 5% ~ 15% higher than that in tube#1; at intermediate vapor qualities, the local heat transfer coefficient in tube#2 is 10% ~ 15% lower than that in tube#1; while at high vapor quality \(x_{r,o}>0.8\), the local heat transfer coefficient in tube#2 is 10% ~ 25% higher than that in tube#1.

The main reason for such above phenomenon is as follows. 1) Larger depth of microfin and fin number may lead to much higher turbulence intensity and larger contact area of liquid with tube wall, and promote the earlier transformation of flow pattern from wavy flow to annular flow and delay the flow pattern transformation from annular flow to dryout flow, which is a positive impact of microfin on heat transfer characteristics. 2) Larger depth of microfin and fin number may also result in more oil accumulating between the fins, which is a negative impact of oil. Such negative impact of oil combing with the positive impact of microfin on heat transfer characteristics results in larger heat transfer coefficient of oil-free R410A in tube#2 than that in tube#1 at low and high vapor qualities, while results in better heat transfer characteristic at low and high vapor qualities for tube#2 than that for tube#1, and less heat transfer characteristic at intermediate vapor qualities for tube#2 than that for tube#1.

Fig. 4 shows the experimental data of R410A-oil mixture in microfin tube with outside diameter of 4.0 mm. For oil-free R410A, the local heat transfer coefficient increases with the increasing vapor quality firstly, reaches to the
maximum value at the vapor quality of 0.7, and then falls off with the increasing vapor quality; while for R410A-oil mixture, with the increase of vapor quality, the local heat transfer coefficient initially increases and then decreases, presenting a peak of flow boiling heat transfer coefficient between the vapor quality of 0.65 and 0.7. From the comparison of the heat transfer characteristics of tube#1, tube#2 and tube#3 obtained in the present study with those of 7.0 mm O.D. microfin tube in the literature of Hu et al. (2008), it can be seen that the decrease of tube diameter from conventional size to small diameters may weaken the deterioration effect of oil on heat transfer at intermediate and high vapor qualities.

![Figure 3: Heat transfer coefficient in 5.0 mm O.D. microfin tube#2](image)

(a) $G = 300 \text{ kg/m}^2\cdot\text{s}$
(b) $G = 400 \text{ kg/m}^2\cdot\text{s}$

Figure 3: Heat transfer coefficient in 5.0 mm O.D. microfin tube#2

![Figure 4: Heat transfer coefficient in 4.0 mm O.D. microfin tube#3](image)

(a) $G = 300 \text{ kg/m}^2\cdot\text{s}$
(b) $G = 400 \text{ kg/m}^2\cdot\text{s}$

Figure 4: Heat transfer coefficient in 4.0 mm O.D. microfin tube#3

### 4.2 Oil Influence on Heat Transfer Coefficient

Enhancement factor, $EF$, is generally used to address oil influence on heat transfer. $EF$ is the ratio of heat transfer coefficient of refrigerant-oil mixture to that of pure refrigerant, presented as Eq. (5).

$$EF = \frac{\alpha_{r\text{,oil}}}{\alpha_{r\text{,t}}}$$  \hspace{1cm} (5)

Figure 5 shows the enhancement factor ($EF$) changing with local vapor quality at different nominal oil concentrations. For 5.0 mm O.D. microfin tubes, the ranges of $EF$ under the present experimental conditions are within 0.8~1.37 and 0.95~1.18 for tube#1 and tube#2, respectively, and $EF$ of tube#2 is smaller than that of tube#1 at vapor qualities smaller than 0.8 while larger than that of tube#1 at vapor quality larger than 0.8; while for 4 mm microfin tube, the range of the enhancement factor are within 0.93~1.26. For all the three microfin tubes, at vapor qualities lower than 0.8, the enhancement factors are higher than 1.0, meaning the heat transfer is enhanced by the oil; while at high vapor qualities ($0.85<x_{r\text{oil}}<0.9$), the enhancement factors are smaller than 1.0 and decrease rapidly with increasing nominal oil concentration and vapor quality, meaning the heat transfer is deteriorated by the oil.

The influence of oil on heat transfer coefficient of R410A-oil mixture flow boiling in microfin tubes may contain positive and negative impact factors. The positive impact factors of oil on flow boiling heat transfer coefficient include: 1) the presence of oil increases the wetted surface, causing the enhancement of flow boiling heat transfer; 2) the presence of oil accelerates the transformation of flow pattern from stratified flow to intermittent flow and
annular flow, retards the transformation of flow pattern from annular flow to dryout flow, which leads to the enhancement of flow boiling heat transfer; 3) the presence of oil increases the nucleate boiling heat transfer (Kedzierski, 2000; Thome, 1996), which leads to the enhancement of flow boiling heat transfer; 4) the presence of oil creates a surfactant effect and promotes foaming (Filho et al., 2009), causing the enhancement of flow boiling heat transfer. The negative impact factors of oil on flow boiling heat transfer coefficient include: 1) the presence of oil increases the mixture viscosity and surface tension, thus deteriorates the convective heat transfer (Shen and Groll, 2005), which leads to the deterioration of flow boiling heat transfer; 2) the oil retained between microfins reduces the disturbing effect of microfin on fluid, thus deteriorates the convective heat transfer, which leads to the deterioration of flow boiling heat transfer, especially for 5 mm microfin tube#2; 3) the oil tends to accumulate at the interface of evaporation and forms the oil-rich layer, thus slows down the diffusion of refrigerant through this oil-rich layer, which leads to the deterioration of flow boiling heat transfer (Filho et al., 2009); 4) enhanced tubes tend to suppress the effects of lubricant to promote annular flow and foaming (Shen and Groll, 2005; Ha and Bergles, 1993), and cavities for nucleate boiling are filled by the oil film (DEng et al., 2007; Nidegger et al., 1997), resulting in negative effect on heat transfer.

The conjunct role of positive and negative impact factors determine the effect of oil on heat transfer. For two 5.0 mm O.D. microfin tubes, at vapor quality smaller than 0.8, the negative impact for 5.0 mm O.D. microfin tube#2 is more obvious than that for 5 mm microfin tube#1 due to much more oil accumulated between fin of tube#2 caused by larger fin height and contact area of oil with tube wall, therefore, EF of 5 mm microfin tube#2 is smaller than that of 5 mm microfin tube#1. For the three microfin tubes, at vapor quality smaller than 0.7, the positive impact factors always dominate, which causes the enhancement of flow boiling heat transfer; while at vapor quality higher than 0.8, the negative ones become the main impact factors, which leads to the deterioration of flow boiling heat transfer.

![Enhancement factor (EF) of R410A-oil mixture in three small diameter microfin tubes](image)

**Figure 5:** Enhancement factor (EF) of R410A-oil mixture in three small diameter microfin tubes

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5. HEAT TRANSFER COEFFICIENT CORRELATION FOR R410A-OIL MISTURE IN MICROFIN TUBES

The available heat transfer coefficient correlations of refrigerant-oil mixture flow boiling inside horizontal microfin tubes are listed in Table 1. The outside diameters (O.D.) or inside diameters (I.D.) in the existing research are larger than 7.0 mm. The predictabilities of these correlations to the experimental data of R410A-oil mixture flow boiling in small microfin tubes are uncertain and should be verified.

Among the existing correlations, enhancement factor correlations (Eckels et al., 1998; Nidegger et al., 1997; Targanski and Cieslinski, 2007) and log-linear model with simple algebraic manipulation (Usmani and Ravigururajan, 1999) belong to statistical model, and the mixture properties are not reflected in these correlations. The predicted values of these correlations were compared with the present experimental data, and the comparison results show that the deviations are higher than 100% at many experimental conditions.

The existing correlation of Hu et al. (2008) is developed for conventional size tube based on the refrigerant-oil mixture properties. Figure 6 depicts the comparison of the predicted values of Hu et al. correlation (2008) with the present experimental data for small microfin tube with outside diameters of 4.0-5.0 mm. It shows that Hu et al. correlation has a deviation of -50% ~ +40%. Thus modifications of this correlation should be done to develop a general correlation for conventional size and small diameter microfin tubes.

![Figure 6: Prediction of Hu et al. correlation (2008) vs. experimental α_{tp,r,o} in small diameter microfin tubes](image)

In order to extend Hu et al. correlation (2008) to a general correlation suitable for conventional size and small diameter microfin tubes, the disadvantages of Hu et al. correlation should be analyzed firstly by verifying whether all of the effect factors of oil, tube diameter and microfin structures have been reflected in the correlation or not, and modifications should be made corresponding to the disadvantages.

In Hu et al. correlation, the heat transfer coefficient of R410A-oil mixture α_{r,o,tp} was expressed as the sum of the convective contribution (\(E\alpha_{r,o,L}\)) and the nucleate boiling contribution (\(S\alpha_{r,o,nb}\)), as shown in Eq. (6). For the convective contribution (\(E\alpha_{r,o,L}\)) in the correlation, the effect factors of oil, tube diameter and microfin structures were reflected by introducing the mixture properties and ribbed tube enhancement factor (\(E_{RB}\)), as shown in Eqs. (7) and (8); while for the nucleate boiling contribution (\(S\alpha_{r,o,nb}\)), Cooper correlation (Eq. (9)) was used, and the effect factors of oil, tube diameter and microfin structures were not reflected, which should be modified.

Moreover, in Eqs. (10) and (11), the items depending on the experimental data were fitted only based on conventional size tube of 7.0 mm O.D. tube in Hu et al. (2008) correlation, and they should be modified based on the experimental data of conventional size and small diameter microfin tubes.
In the development of new correlation, two modifications of Hu et al. correlation are made: 1) Rohsenow correlation (Rohsenow, 1952) is used in the new correlation to replace the Cooper correlation in Hu et al. (2008) correlation, as shown in Eq. (12), and it can reflect the mixture properties and the heating surface characteristics; furthermore, the nominal oil concentration and wetted perimeter of microfin tube are reflected in C_{sf} of Resenow correlation, shown as Eq. (13); 2) the items in Eqs. (10) and (11) depending on the experimental data are re-fitted by considering the experimental data of R410A-oil mixture in four microfin tubes with outside diameters of 4.0 mm ~ 7.0 mm.

\[
\alpha_{t.o,\text{nb}} = \frac{q_{\text{in}}}{\Delta T_b}
\]

\[
\Delta T_b = C_{sf} \left[ \frac{h_{\text{lg}}}{c_{p,o} \rho_o \mu_o h_x} \left( \frac{\sigma_{t,o} \rho_o}{\sigma_{t,o} \rho_o - \rho_x} \right)^{0.33} \left( \frac{\epsilon_{p.o} \mu_o}{\lambda_{t,o}} \right)^{\nu_x} \right]
\]

\[
C_{sf} = a_1 + a_2 \alpha_{t,o} + a_3 S_f / S_{t,f}
\]

The key to develop the new correlation is to obtain the parameters of \(a_0, a_1, a_2, a_3, b_1, b_2, c_1, \) and \(c_2\) in Eqs. (10)~(14). The parameters of \(a_0, a_1, a_2, a_3, b_1, b_2, c_1, \) and \(c_2\) for the new correlation are obtained by nonlinear programming solution method, and their values are 1.73, 0.0517, 4.24, 0.066, 16921, 1.231, 1.203×10^{-4} and 1.25, respectively.

Figure 7 presents a comparison of the predicted values of the new correlation with the experimental data. The new correlation agrees with 94% of the experimental data within a deviation of ±30%, and the application range can cover not only conventional size but also small diameter microfin tubes.
6. CONCLUSIONS

- The presence of oil enhances the heat transfer at vapor qualities lower than 0.7, while at high vapor qualities higher than 0.8, the local heat transfer coefficient falls off rapidly with the increase of nominal oil concentration and vapor quality.
- For the tested tubes with different diameter, the decrease of tube diameter may weaken the deterioration effect of oil on heat transfer at intermediate and high vapor qualities. For the fixed outside diameter microfin tubes with different microfin structures, larger fin height and contact area of liquid with tube wall may enhance the heat transfer for oil-free R410A, but result in smaller enhancement effect of oil at low vapor qualities and smaller deterioration effect of oil at intermediate and high vapor qualities for R410A-oil mixture due to more oil retained between the fins.
- A general correlation was developed based on refrigerant-oil mixture properties to predict the local heat transfer coefficients of R410A-oil mixture flow boiling inside the conventional size and small diameter microfin tubes, and the oil, tube diameter and microfin structures were reflected in the new correlation. The new correlation agrees with 94% of the experimental data within a deviation of ±30%.

NOMENCLATURE

\begin{align*}
Bo & = \text{boiling number, } q/(Gh_\text{fg}) \\
C_p & = \text{isobaric specific heat (J/kg K)} \\
C_{sf} & = \text{coefficient in Eq. (12)} \\
d_t & = \text{diameter at bottom of the fin (m)} \\
d_o & = \text{outside diameter (m)} \\
e_t & = \text{microfin height (mm)} \\
E & = \text{two-phase convection multiplier} \\
E_{RB} & = \text{ribbed tube enhancement factor} \\
EF & = \text{enhancement factor for heat transfer} \\
G & = \text{mass flux (kg/m²·s)} \\
l_f & = \text{groove depth (mm)} \\
\alpha & = \text{heat transfer coefficient (W/m²·K)} \\
\beta & = \text{helix angle of the microfin (°)} \\
\gamma & = \text{top angle of the fin (°)} \\
\lambda & = \text{Thermal conductivity (W/m·K)} \\
\omega & = \text{oil concentration (kg/kg)} \\
\mu & = \text{dynamic viscosity (Pa·s)} \\
\sigma & = \text{surface tension (N/m)}
\end{align*}

Greek

\begin{align*}
\nu & = \text{Prandtl number} \\
Re & = \text{Reynolds number} \\
S & = \text{two-phase boiling suppression factor} \\
\eta & = \text{two-phase convection multiplier} \\
\tau & = \text{bottom thickness (mm)} \\
T & = \text{temperature (°C)}
\end{align*}

Subscript

\begin{align*}
\text{bub} & = \text{bubble} & \text{im} & = \text{inner heating area of microfin tube} & \text{o} & = \text{oil} \\
\text{L} & = \text{liquid} & \text{nb} & = \text{nucleate boiling} & \text{r} & = \text{refrigerant} \\
\text{no} & = \text{nominal} & \text{sp} & = \text{sp} & \text{tp} & = \text{two-phase} \\
W & = \text{wall}
\end{align*}

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