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Outline

- Background
- Experiment Setup
- Experimental Result and Discussion
- HTC Correlation Development
- Conclusions
Background

Advantage of small diameter tubes:
- Cost and volume can be reduced;
- Refrigerant charge can be reduced

Tube diameter:
- Previous: 9.52 mm, 7.0 mm
- Now: 5.0 mm
- Future: 4.0 mm or smaller

Flow boiling in small diameter tubes

Optimization design is necessary!
Table 1: Existing researches on the correlation for Ref/oil in 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></td>
<td>R134a/150-SUS</td>
<td>9.52 mm O.D.</td>
</tr>
<tr>
<td>Nidegger et al. (1997)</td>
<td>R134a/oil</td>
<td>11.9 mm I.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>

D≥7.0 mm
**Literature review:**

1) Oil-free R410A in tubes (>6.0 mm)
2) R410A-oil mixture in 7.0 mm microfin tube.
3) R22, R407C, R134a, CO₂ and oil in microfin tubes (>6.0mm)

- No research on R410A-oil in small diameter microfin tubes
- Flow and heat transfer performance are different for the tubes with different diameters.

**Research content:**

R410A-oil mixture flow boiling in conventional (≥7.0 mm) and small size (4-5 mm O.D.) microfin tubes
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Experiment Setup

**Oil loop:** (on-line oil injection; adjusting oil concentration of test section)

**Refrigerant main loop:** adjusting test condition

**Refrigerant bypass loop:** adjusting refrigerant mass flow rate

**Test section**
Test tubes

Test tube: 4.0-5.0 mm microfin tubes tubes

(a) Cutaway view of the tested tube                        (b) Cross section of fin

Figure 1 The schematic of internally spiral grooved tubes

Table 2: Details of enhanced tubes

<table>
<thead>
<tr>
<th>parameter</th>
<th>Tube In existing literature</th>
<th>tube#1</th>
<th>tube#2</th>
<th>tube#3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_o$ / mm</td>
<td>7.00</td>
<td>5.00</td>
<td>5.00</td>
<td>4.00</td>
</tr>
<tr>
<td>$t_w$ / mm</td>
<td>0.25</td>
<td>0.20</td>
<td>0.20</td>
<td>0.22</td>
</tr>
<tr>
<td>$l_f$ / mm</td>
<td>0.18</td>
<td>0.14</td>
<td>0.155</td>
<td>0.12</td>
</tr>
<tr>
<td>$n_f$</td>
<td>50</td>
<td>40</td>
<td>48</td>
<td>40</td>
</tr>
<tr>
<td>$\beta$ / °</td>
<td>18</td>
<td>18</td>
<td>18</td>
<td>12</td>
</tr>
<tr>
<td>$\gamma$ / °</td>
<td>40</td>
<td>40</td>
<td>20</td>
<td>40</td>
</tr>
</tbody>
</table>

All data are used for developing correlation
Table 3: Test conditions of the test tubes

<table>
<thead>
<tr>
<th>Test tube</th>
<th>Tube diameter (mm)</th>
<th>Mass flux (kg/m²·s)</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></td>
</tr>
<tr>
<td></td>
<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>
</tr>
<tr>
<td></td>
<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>
</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></td>
</tr>
<tr>
<td></td>
<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>
</tr>
<tr>
<td></td>
<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>
</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></td>
</tr>
<tr>
<td></td>
<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>
</tr>
</tbody>
</table>
### 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>
<tr>
<td>Uncertainties of heat transfer coefficient</td>
<td></td>
<td></td>
<td></td>
<td>±10.4%</td>
</tr>
</tbody>
</table>

\[
\alpha_{tp,r} = \frac{q}{(T_w - T_{bub,r})} \\
\alpha_{tp,r,o} = \frac{q}{(T_w - T_{bub,r,o})} \\
\omega_{no} = \frac{m_o}{(m_o + m_r)} \quad 0\sim5 \text{ wt.\%} \\
\omega_{local} = \frac{m_o}{m_o + m_{r,l}} = \frac{\omega_{no}}{1 - x_{r,o}}
\]
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Result and Discussion

- Heat transfer coefficient in 5.0 mm microfin tube#1

For oil-free R410A

\[ x_{r,o} = 0.6-0.7 \]

For R410A-oil mixture

1) \( x_{r,o} < 0.7 \):

\[ \omega_{no} \rightarrow \alpha_{tp,r,o} \]

2) \( x_{r,o} > 0.8 \):

\[ \omega_{no} = 3\% \sim 5\% \]

3) \( x_{r,o} > 0.85 \):

\[ \omega_{no} \rightarrow \alpha_{tp,r,o} \]
Result and Discussion

- Heat transfer coefficient in 5.0 mm O.D. microfin tube#2

1) for oil-free R410A, HTC in tube#2 is always higher than that in tube#1;
2) for R410A-oil mixture, at $x_{r,o} < 0.5$, HTC in tube#2 is 5%~15% higher than that in tube#1;
3) at intermediate vapor qualities, HTC in tube#2 is 10% ~ 15% lower than that in tube#1;
4) while at $x_{r,o} > 0.8$, HTC in tube#2 is 10% ~ 25% higher than that in tube#1.
Result and Discussion

- Heat transfer coefficient in 4.0 mm microfin tube#3

For R410A-oil mixture

1) $x_{r,o} < 0.7$:

2) $x_{r,o} > 0.8$:

For oil-free R410A

$x_{r,o} = 0.6-0.7$
Results:

- for 5.0 mm microfin tubes, $EF$ 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 $x<0.8$ while larger than that of tube#1 at $x>0.8$; 
- for 4 mm microfin tube, the range of the enhancement factor are within 0.93~1.26.

$$EF = \frac{\alpha_{tp,r,o}}{\alpha_{tp,r}}$$
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Correlation development

- Prediction ability of existing correlation for R410A/oil

\[ \alpha_{r,o,tp} = E\alpha_{r,o,L} + S\alpha_{r,o,nb} \]

\[ \alpha_{r,o,L} = 0.023E_{RB} \frac{\lambda_{r,o,L}}{d_f} Re_{r,o,L}^{0.8} Pr_{r,o,L}^{0.4} \]

\[ \alpha_{r,o,nb} = 55P_{re}^{0.12} (\log_{10} P_{re})^{-0.55} M^{-0.5} q_{im}^{0.67} \]

\[ E = 1 + b_1 Bo^{1.16} + b_2 X^{-0.86} \]

\[ S = \frac{1}{1 + c_1 E^{c_2} Re^{1.17}_{r,o,L}} \]

Should be refitted
Correlation development

- New correlation development

\[ \alpha_{r,o,tp} = E\alpha_{r,o,L} + S\alpha_{r,o,nb} \]
\[ \alpha_{r,o,L} = 0.023E_{RB}^{\lambda_{r,o,L}} \frac{\lambda_{r,o,L} \text{Re}^{0.8}}{\text{Pr}^{0.4}} \]
\[ \alpha_{r,o,nb} = 55P_{re}^{0.12} (-\log_{10} P_{re})^{-0.55} \text{M}^{-0.5} q_{im}^{0.67} \]
\[ E = 1 + b_1 B_0^{1.16} + b_2 X_{tt}^{-0.86} \]
\[ S = \frac{1}{1 + c_1 E_{c}^{1.17} \text{Re}^{1.17}} \]

\[ \alpha_{r,o,nb} = \frac{q_{im}}{\Delta T_b} \]
\[ \Delta T_b = C_{sf} \frac{h_{fg}}{c_{p,r,o}} \left[ \frac{q_{im}}{\mu_{r,o} h_{fg}} \sqrt{\frac{\sigma_{r,o}}{g(\rho_{r,o} - \rho_g)}} \right]^{0.33} \left( \frac{c_{p,r,o} \mu_{r,o}}{\lambda_{r,o}} \right)^{a_q} \]
\[ C_{sf} = a_1 + a_2 \omega_{no} + a_3 SP_{wet} / SP_{bf} \]
Correlation development

- New correlation development

![Diagram showing predicted vs experimental values of \( \alpha_{tp,r,o} \). The diagram includes markers for different microfin tubes and a trend line with +/- 30% deviation lines.]
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Conclusions

- 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 for R410A-oil mixture 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%.
Thank you!