A GENERAL CORRELATION TO PREDICT THE FLOW BOILING HEAT TRANSFER OF R410A IN MACRO/MINI-CHANNELS

Jong-Taek Oh*
Nguyen Ba Chien, Pham Quang Vu, Kwang-Il Choi

DEPT. OF REFRIGERATION AND AIR CONDITIONING ENGINEERING, CHONNAM NATIONAL UNIVERSITY, KOREA.
Contents

1. Background
2. Experimental Models
3. Results and Discussions
4. Conclusions
1. R410A refrigerant is widely used nowadays due to the phase out of R22 in near future.

2. Developing the enhanced heat exchanger using the new type of copper tubes.

3. There is limited correlation that can cover the wide range of tube sizes.

4. Boiling heat transfer coefficient correlation of R410A in macro and mini-channels.
Cu tube 시험부

Pressure Transducer

P;T

T1

Tw

T2

Tw

T3

Tw

T4

Tw

Di (mm): 6.61 and 7.49

7mm

7.49mm

CHONNAM NATIONAL UNIVERSITY  THERMAL & REFRIGERATION ENGINEERING LAB.
1. Experimental Apparatus using Macro-channel

**Experimental Facility**

- Experimental Apparatus diagram for Copper tubes
- Heat Exchanger
- Pump 1
- Flow meter
- Condenser
- AC power supply
- Chiller Unit
- Sub-Cool
- Gear Pump
- Receiver

**Test section**

- Pressure Transducer
- DI (mm): 6.6 and 7.5
- Top
- Bottom
1. Experimental Apparatus Using Mini-Channel

**Experimental Facility**

- Preheater
- Flow Meter
- Refrigerant pump
- Receiver tank
- Condenser
- Subcooler
- Chiller Unit
- Data Acquisition System

**Test section**

- Transformer (40kVA)
- Differential Pressure Transducer
- Thermocouple
- Test Section
  - D [mm]: 1.5 & 3.0 mm
  - Length: 1000 mm
1. Experimental Apparatus

Experimental Facility, Macro-Channel

Experimental Facility, Mini_Channel
## 2. Testing Conditions

<table>
<thead>
<tr>
<th>Working refrigerant</th>
<th>R410</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test section</td>
<td>Horizontal smooth stainless steel mini-channel and Conventional Copper Tube</td>
</tr>
<tr>
<td>Quality</td>
<td>0.2-1.0</td>
</tr>
<tr>
<td>Inner tube diameter (mm)</td>
<td>1.5; 3.0; 6.61 &amp; 7.49</td>
</tr>
<tr>
<td>Tube length (mm)</td>
<td>1000;1200;2000</td>
</tr>
<tr>
<td>Mass flux (kg/m²s)</td>
<td>100 – 600</td>
</tr>
<tr>
<td>Heat flux (kW/m²)</td>
<td>10 – 40</td>
</tr>
<tr>
<td>Inlet $T_{sat}$ (°C)</td>
<td>5-15</td>
</tr>
</tbody>
</table>
2. Effect of Mass Fluxes

- R410A
- $T = 15^\circ C$
- $q = 5 \text{ kW/m}^2$
- $D = 1.5 \text{ mm}$

- $G \text{ [kg/m}^2\text{s]}$

- $h \text{ [kW/m}^2\text{K]}$

- $D = 6.61 \text{ mm}$
- $T_s = 6^\circ C$
- $q = 12 \text{ kW/m}^2$
3. Effect of Heat Fluxes

**Background**

- R410A
- \( T = 15^\circ C \)
- \( G = 300 \text{ kg/m}^2\text{s} \)
- \( D = 1.5 \text{ mm} \)

**Conclusion**

- R-410A
- \( D=7.49 \text{ mm} \)
- \( T_s=6^\circ C \)
- \( G=320 \text{ kg/m}^2\text{s} \)

**Graphs**

- Heat transfer coefficient (kW/m²K) vs. \( x \)
- \( q \) [kW/m²] vs. \( x \)
4. Effect of Inner Diameter

- **Background**

- **Models**

- **Result & Discussion**

- **Conclusions**

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**Graphs:**
- **R410A**
  - **T = 15°C**
  - **q = 10 kW/m²**
  - **G = 400 kg/m²s**
  - **D (mm):**
    - Blue diamond: 3.0
    - Red square: 1.5

- **R-410A**
  - **Ts = 6°C**
  - **q = 9 kW/m²**
  - **G = 260 kg/m²s**
  - **D (mm):**
    - Blue triangle: 6.61
    - Red circle: 7.49

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**Legend:**
- Blue diamond: 3.0
- Red square: 1.5
- Blue triangle: 6.61
- Red circle: 7.49

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**Notes:**
- **Heat transfer coefficient (kW/m²K)**
- **x**

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Thermal & Refrigeration Engineering Lab
1. Data Distribution of R410A

**Summary**

<table>
<thead>
<tr>
<th>Flow regime</th>
<th>Macro-channel</th>
<th>Minichannel</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laminar-Turbulence</td>
<td>9 pts</td>
<td>70 pts</td>
<td>79 pts</td>
</tr>
<tr>
<td></td>
<td>14.75%</td>
<td>17.90%</td>
<td>17.48%</td>
</tr>
<tr>
<td>Turbulence - Turbulence</td>
<td>46 pts</td>
<td>281 pts</td>
<td>327 pts</td>
</tr>
<tr>
<td></td>
<td>75.41%</td>
<td>71.87%</td>
<td>72.35%</td>
</tr>
<tr>
<td>Turbulence - Laminar</td>
<td>0 pts</td>
<td>0 pts</td>
<td>0 pts</td>
</tr>
<tr>
<td></td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Laminar - Laminar</td>
<td>0 pts</td>
<td>0 pts</td>
<td>0 pts</td>
</tr>
<tr>
<td></td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>
1. Data Distribution of NH3 in minichannels (1.5 & 3.0 mm)

- **Reₚ > 3000, Reₕ < 2300**
  - Martinelli Param: Xₑₑ
  - Chrisholm Param: C = 10
  - N. of data: 59 (4.63%)
- **Reₚ > 3000, Reₕ > 3000**
  - Martinelli Param: Xₑₑ
  - Chrisholm Param: C = 20
  - N. of data: 551 (43.4%)
- **Reₚ < 2300, Reₕ < 2300**
  - Martinelli Param: Xₑₑ
  - Chrisholm Param: C = 5
  - N. of data: 22 (1.73%)
- **Reₚ < 2300, Reₕ > 3000**
  - Martinelli Param: Xₑₑ
  - Chrisholm Param: C = 12
  - N. of data: 416 (32.78%)
### 3. Properties of R410A

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>$T_{\text{sat}}$ (°C)</th>
<th>$P$ (Mpa)</th>
<th>$\rho_f$ (kg/m³)</th>
<th>$\rho_g$ (kg/m³)</th>
<th>$\rho_f/\rho_g$</th>
<th>$\mu_f$ (10⁻⁶ Pas)</th>
<th>$\mu_g$ (10⁻⁶ Pas)</th>
<th>$\mu_f/\mu_g$</th>
<th>$\sigma$ (10⁻³ N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R410A</td>
<td>5</td>
<td>0.936</td>
<td>1149</td>
<td>35.86</td>
<td>32.04</td>
<td>151.8</td>
<td>12.47</td>
<td>12.17</td>
<td>8.28</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1.088</td>
<td>1128</td>
<td>41.91</td>
<td>26.91</td>
<td>142.76</td>
<td>12.75</td>
<td>11.19</td>
<td>7.51</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>1.258</td>
<td>1106</td>
<td>48.85</td>
<td>22.64</td>
<td>134.11</td>
<td>13.04</td>
<td>10.28</td>
<td>6.75</td>
</tr>
</tbody>
</table>

### 4. Properties of NH3

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>$T_{\text{sat}}$ (°C)</th>
<th>$P$ (Mpa)</th>
<th>$\rho_f$ (kg/m³)</th>
<th>$\rho_g$ (kg/m³)</th>
<th>$\rho_f/\rho_g$</th>
<th>$\mu_f$ (10⁻⁶ Pas)</th>
<th>$\mu_g$ (10⁻⁶ Pas)</th>
<th>$\mu_f/\mu_g$</th>
<th>$\sigma$ (10⁻³ N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R717</td>
<td>5</td>
<td>0.515</td>
<td>631.66</td>
<td>4.11</td>
<td>153.68</td>
<td>161.23</td>
<td>9.20</td>
<td>17.52</td>
<td>3.12</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.615</td>
<td>624.64</td>
<td>4.86</td>
<td>128.39</td>
<td>153.03</td>
<td>9.36</td>
<td>16.34</td>
<td>2.95</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>0.728</td>
<td>617.49</td>
<td>5.72</td>
<td>107.95</td>
<td>145.42</td>
<td>9.51</td>
<td>15.29</td>
<td>2.79</td>
</tr>
</tbody>
</table>
5. Comparison with some well known correlations

<table>
<thead>
<tr>
<th></th>
<th>MD(%)</th>
<th>AD(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro.</td>
<td>50.47</td>
<td>50.12</td>
</tr>
<tr>
<td>Mini.</td>
<td>35.73</td>
<td>17.01</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>MD(%)</th>
<th>AD(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro.</td>
<td>45.80</td>
<td>-43.83</td>
</tr>
<tr>
<td>Mini.</td>
<td>82.63</td>
<td>68.45</td>
</tr>
</tbody>
</table>
5. Comparison with some well known correlations

### Gungor & Winterton (1987)

- **Experimented heat transfer coefficient (kW m\(^{-2}\)K\(^{-1}\))**
- **Predicted heat transfer coefficient (kW m\(^{-2}\)K\(^{-1}\))**

<table>
<thead>
<tr>
<th>MD(%)</th>
<th>AD(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro.</td>
<td>25.31</td>
</tr>
<tr>
<td>Mini.</td>
<td>124.77</td>
</tr>
</tbody>
</table>

### Liu & Winterton (1991)

- **Experimented heat transfer coefficient (kW m\(^{-2}\)K\(^{-1}\))**
- **Predicted heat transfer coefficient (kW m\(^{-2}\)K\(^{-1}\))**

<table>
<thead>
<tr>
<th>MD(%)</th>
<th>AD(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro.</td>
<td>50.28</td>
</tr>
<tr>
<td>Mini.</td>
<td>35.29</td>
</tr>
</tbody>
</table>
5. Comparison with some well known correlations

### Tran et al. (1996)

- **Exp. heat transfer coefficient**
- **Predicted heat transfer coefficient**
- **MD(%)** 33.36, **AD(%)** -31.69
- **MD(%)** 31.98, **AD(%)** 8.01

### Bertsch et al. (2009)

- **Exp. heat transfer coefficient**
- **Predicted heat transfer coefficient**
- **MD(%)** 54.84, **AD(%)** 54.84
- **MD(%)** 36.65, **AD(%)** 12.37
6. Summary of comparison

- Minichannel
  - Developed for minichannel.
  - Almost show much high deviation when predicting the minichannel data compared to macro ones.

- Conventional channel
  - Developed for conventional channel.
  - Almost show much high deviation when predicting the minichannel data compared to macro ones.

The difference of dominant heat transfer regime between minichannel and conventional channel.
7. Develop new heat transfer coefficient correlation

Using regression program, a suitable factor was obtained

\[ h_{ip} = S h_{abc} + F h_t \]

\[ S = 0.238 \frac{C_o}{C_f^{1.11}} \]

\[ F = 1.061 \exp \left( \frac{0.042}{C_o} \right) \]

\[ h_{abc} = 55 Pr^{0.12} \left( -0.4343 \ln Pr \right)^{-0.55} M^{-0.5} q^{0.67}, \text{ where } q \text{ is in Wm}^{-2} \]

\[ h_{fo} = 0.023 Re^{0.8} Pr^{0.4} \frac{k_l}{D} \]

\[ C_o = \left( \frac{1-x}{x} \right)^{0.8} \left( \frac{\rho_g}{\rho_l} \right)^{0.5} \]

\[ C_f = \frac{1}{D} \sqrt{\frac{\sigma}{g(\rho_l - \rho_g)}} \]

\[ f \begin{cases} = 16 Re^{-1} \text{ for } Re < 2300 \\ = 0.079 Re^{-0.25} \text{ for } Re > 3000 \end{cases} \]
Summary of the new heat transfer coefficient correlation

\[ h_{tp} = Sh_{nbc} + Fh_f \]

\[ S = a2(\phi^2_f) b2 Bo c2 \]

\[ F = \text{MAX}\left[ a1\phi^b1 + c1, 1 \right] \]

\[ h_{nbc} = 55P_r^{0.12}(−0.4343 \ln P_r)^{-0.55} M^{-0.5} q^{0.67}, \text{ W} \]

where \( q \) is in Wm\(^{-2}\)

\[ h_f = \begin{cases} 
4.36 \frac{k_f}{D} & \text{if } Re_f < 2300 \\
\left( \frac{Re_f - 1000}{Pr_f} \right) \left( \frac{f_f}{2} \right) \left( \frac{k_f}{D} \right)^{0.5} & \text{if } 3000 \leq Re_f \leq 10^4 \\
1 + 12.7 \left( \frac{Pr_f^{2/3} - 1}{f_f / 2} \right) & \text{if } 10^4 \leq Re_f \leq 5 \times 10^6 \\
1 + 12.7 \left( \frac{Pr_f^{2/3} - 1}{f_f / 2} \right) & \text{if } 10^4 \leq Re_f \leq 5 \times 10^6 \\
0.023 \frac{k_f}{D} \left[ \frac{G(1-x)D}{\mu_f} \right]^{0.8} \left( \frac{C_pf \mu_f}{k_f} \right)^{0.4} & \text{if } Re_f \geq 5 \times 10^6 
\end{cases} \]

\[ \phi^2_f = 1 + \frac{C}{X} + \frac{1}{X^2} \]

\[ X = \left( \frac{f_f}{f_g} \right)^{1/2} \left( \frac{1 - x}{x} \right) \left( \frac{\rho_g}{\rho_f} \right)^{1/2} \]

\[ \begin{align*}
&= 5 \text{ for } Re_f < 2300 \text{ and } Re_g < 2300 \\
&= 10 \text{ for } Re_f > 3000 \text{ and } Re_g < 2300 \\
&= 12 \text{ for } Re_f < 2300 \text{ and } Re_g > 3000 \\
&= 20 \text{ for } Re_f > 3000 \text{ and } Re_g > 3000 \\
\end{align*} \]

\[ f_r = \begin{cases} 
16Re^{-1} & \text{for } Re < 2300 \\
0.079Re^{-0.25} & \text{for } Re > 3000 
\end{cases} \]

Coefficients for the Convective two-phase multiply factor \( F \)

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>a1</th>
<th>b1</th>
<th>c1</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-22</td>
<td>0.003</td>
<td>1.6</td>
<td>0.498</td>
</tr>
<tr>
<td>R-134a</td>
<td>0.01</td>
<td>1.3</td>
<td>0.1</td>
</tr>
<tr>
<td>R-1234yf</td>
<td>0.07</td>
<td>0.82</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Coefficients for the nucleate boiling factor \( S \)

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>a2</th>
<th>b2</th>
<th>c2</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-22</td>
<td>0.99</td>
<td>0.181</td>
<td>0.262</td>
</tr>
<tr>
<td>R-134a</td>
<td>1</td>
<td>0.17</td>
<td>0.196</td>
</tr>
<tr>
<td>R-1234yf</td>
<td>15.85</td>
<td>-0.14</td>
<td>0.27</td>
</tr>
</tbody>
</table>
8. Comparison with new proposed correlation

<table>
<thead>
<tr>
<th></th>
<th>MD(%)</th>
<th>AD(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro.</td>
<td>20.66</td>
<td>-1.18</td>
</tr>
<tr>
<td>Mini.</td>
<td>21.06</td>
<td>-0.83</td>
</tr>
</tbody>
</table>
9. Comparison with some well known correlations

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>36.36</td>
<td>36.36</td>
<td>31.98</td>
<td>25.31</td>
<td>45.80</td>
<td>50.48</td>
</tr>
<tr>
<td>20%</td>
<td>20.66</td>
<td></td>
<td>33.36</td>
<td>35.30</td>
<td>82.63</td>
<td>50.23</td>
</tr>
<tr>
<td>40%</td>
<td></td>
<td></td>
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<td>36.36</td>
<td>124.78</td>
<td>54.84</td>
</tr>
<tr>
<td>60%</td>
<td></td>
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<td></td>
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<td>124.78</td>
<td></td>
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<tr>
<td>80%</td>
<td></td>
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<tr>
<td>100%</td>
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<tr>
<td>120%</td>
<td></td>
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</tbody>
</table>

Legend:
- **Macro:**
- **Mini:**
The heat transfer coefficients of R410 increase with the increasing of mass flux (for conventional tube), heat flux and the decreasing of tube diameter.

The data was compared with some well known correlations. Tran et al. (1996) correlation gave the best accuracy.

A new correlation for two-phase flow boiling heat transfer coefficient of R410A in micro/macro tube was developed with the MD and AD of about 20%.
Thank you for your attention!
Heat Transfer Coefficient Comparison
R-1234yf with the Tested Refrigerants

$G = 300 \text{ kg/m}^2\text{s}$
$q = 20\text{ kW/m}^2$
$D_i = 3.0 \text{ mm}$
$T_{\text{sat}} = 10^\circ\text{C}$