Thermal-Hydraulic Performance of Printed Circuit Heat Exchanger in Supercritical CO₂ Cycle

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Study Incentives

- Supercritical CO\textsubscript{2} cycle demonstrates some advantages in comparison to He cycle
  - higher cycle efficiency (Y. Kato, 2003),
  - better turbomachinery (Y. Muto, 2003),
  - power generation cost is expected to be smaller.

- High efficiency recuperator is a crucial component of supercritical CO\textsubscript{2} cycle. The targeted recuperator effectiveness is as high as 95%.

- PCHE is a promising heat exchanger because it
  - is able to withstand the pressure up to 50 MPa and the temperature up to 700\textdegree C (reliability),
  - has a high compactness and high efficiency (cost reduction).

PCHE = Printed Circuit Heat Exchanger
What is the PCHE?

- Fluid flow channels are **etched chemically** on metal plates.
  - Typical plate: thickness = 1.6mm, width = 600mm, length = 1200mm,
  - Channels have semi-circular profile with 1-2 mm diameter.
- Etched plates are stacked and **diffusion bonded** together to fabricate a block.
- The blocks are then welded together to form the complete heat exchanger core.
Construction of PCHEs

**Plate stacking**

**Diffusion bonding**

the bond strength is achieved by pressure, temperature, time of contact, and cleanliness of the surfaces
Advantages of PCHE

- Photo-etching technology:
  - Micro channels with smaller hydraulic diameter $D_h$:
    - Pressure capability in excess of 50 MPa.
    - Compact size ($L$) or Higher efficiency (98%).
    - No plate-fin brazing:
      - Manufacturing cost reduction.

- Diffusion bonding technology:
  - Maintain parent material strength:
    - Extreme temperature from cryogenic up to 700°C.
Experimental Loop

**Symbols Used:**
- **T**: thermocouple
- **P**: pressure meter
- **ΔP**: differential pressure meter
- **FR**: flow rate meter

**Diagram Details:**
- **CO₂ tank**
- **Compressor**
- **Cooler 1**
- **Cooler 2**
- **Oil Separator**
- **PCHE**
- **Heater 1**
- **Heater 2**
- **Pressure Reducer**
PCHE Test Section

Dimension of 896 x 76 x 71 mm and a dry mass of 40 kg

<table>
<thead>
<tr>
<th></th>
<th>Channel geometry (mm)</th>
<th>Area, (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Channels number, (n)</td>
<td>Diameter, (D)</td>
</tr>
<tr>
<td>Hot side</td>
<td>144</td>
<td>1.69</td>
</tr>
<tr>
<td>Cold side</td>
<td>66</td>
<td>1.69</td>
</tr>
</tbody>
</table>
## Experimental Conditions

<table>
<thead>
<tr>
<th>No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Pressure, MPa</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cold side</td>
<td>6.5</td>
<td>7.4</td>
<td>8.5</td>
<td>9.5</td>
<td>10.2</td>
</tr>
<tr>
<td>Hot side</td>
<td>2.2</td>
<td>2.5</td>
<td>2.8</td>
<td>3.0</td>
<td>3.3</td>
</tr>
<tr>
<td><strong>Temperature, °C</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cold side</td>
<td>90-108</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot side</td>
<td>280-300</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Flow rate, kg/h</strong></td>
<td>-</td>
<td></td>
<td></td>
<td>From 40 to 80 with 5 kg/h increment</td>
<td></td>
</tr>
</tbody>
</table>
Overall Heat Transfer Coefficient, \( U \)

- LMTD method:

\[
U = \frac{1}{2} \left( \frac{|Q_c| + |Q_h|}{A_h F_G \frac{(T_{h,i} - T_{c,o}) - (T_{h,o} - T_{c,i})}{\ln\left(\frac{(T_{h,i} - T_{c,o})}{(T_{h,o} - T_{c,i})}\right)}} \right)
\]

where

\[
Q_c = W_c (h_{c,o} - h_{c,i})
\]

\[
Q_h = W_h (h_{h,o} - h_{h,i})
\]

- \( A \) - Heat transfer area, 0.664 m\(^2\)
- \( F_G \) - Geometric factor, 0.9624
- \( h, c \) - hot, cold side
- \( o, i \) - outlet, inlet
Heat Loss Estimation (1)

Total value:

1) From outer surface temperature of PCHE insulator

\[ Q_{loss} = \sum_{i=1,10} A_i^{ins} \left[ \varepsilon \sigma (T_{s,i}^4 - T_{surr}^4) + h_{\text{conv},i} (T_{s,i} - T_{surr}) \right] \approx 110 \sim 120 \text{ [W]} \]

2) From heat balance

\[ |Q_{loss}| = |Q_h| - |Q_c| \]

From heat balance

<table>
<thead>
<tr>
<th>Pressure range, [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.5-2.2</td>
</tr>
<tr>
<td>7.4-2.5</td>
</tr>
<tr>
<td>8.5-2.8</td>
</tr>
<tr>
<td>9.5-3.0</td>
</tr>
<tr>
<td>10.2-3.3</td>
</tr>
</tbody>
</table>

From outer surface temperature

Heat loss, [W]

Flow rate, [kg/h]
Heat Loss Estimation (2)

Effect on the outlet temperatures:

3) From 2D FLUENT CFD calculations (with(2)/without(1) heat loss)

4) From the heat loss compensation experiments

\[ Q_{\text{loss}} \approx 0 \]

\[ T_{\text{PCHE-surf}} = T_{\text{near-heater-surf}}^k \]

\[ \Delta T_{\text{hot, out}} : W_{\text{hot}} \times \int_{T_{\text{hot, out}}}^{T_{\text{hot, out}} + \Delta T_{\text{hot, out}}} C_p(P(T), T) dT = -0.35Q_{\text{loss}} \]

\[ \Delta T_{\text{cold, out}} : W_{\text{cold}} \times \int_{T_{\text{cold, out}}}^{T_{\text{cold, out}} + \Delta T_{\text{cold, out}}} C_p(P(T), T) dT = -0.65Q_{\text{loss}} \]
Overall heat transfer coefficient, $U$

$$U = (18.6 \pm 6.8) + (0.105 \pm 0.002) \times \text{Re}, \quad 2 \times 10^3 < \text{Re} < 6 \times 10^3$$
Pressure factor, \( f_P \)

\[
\begin{align*}
    f_{P_{\text{hot}}} & = (0.032 \pm 0.002) - (1.01 \times 10^{-6} \pm 6 \times 10^{-8}) \times \text{Re}, & 2 \times 10^3 \leq \text{Re} \leq 6 \times 10^3 \\
    f_{P_{\text{cold}}} & = (0.066 \pm 0.001) - (1.11 \times 10^{-6} \pm 7 \times 10^{-8}) \times \text{Re}, & 6 \times 10^3 \leq \text{Re} \leq 12 \times 10^3
\end{align*}
\]
PCHE cross-section
Head loss in PCHE

\[ \Delta p = \rho g \Delta H = \sum m \rho_m K_b \frac{U_m^2}{2} + \sum m \rho_m 0.316 \text{Re}^{-0.25} \frac{L_a U_m^2}{md} \]

loss in elbows + loss in a straight pipe

I. \[ K_b = K_1 * K_2 * K_3 \]
    from Hydraulic Engineering, A. Lencastre, 1987

II. \[ K_b = 0.946 \sin^2 \left( \frac{\theta}{2} \right) + 2.047 \sin^4 \left( \frac{\theta}{2} \right) \]
    from JSME Textbook, 2003

III. CFD FLUENT

\[ \left| \frac{\Delta p_{\text{calc}} - \Delta p_{\text{exp}}}{\Delta p_{\text{exp}}} \right| = 14 - 37\% \]

\[ \left| \frac{\Delta p_{\text{calc}} - \Delta p_{\text{exp}}}{\Delta p_{\text{exp}}} \right| = 6 - 32\% \]

: N/A yet
PCHE’s Effectiveness

Effectiveness: \[
\eta = \frac{\dot{Q}}{\dot{Q}_{\text{max}}} = \frac{C_c(T_{c,\rho} - T_{c,i})}{C_{\text{min}}(T_{h,i} - T_{c,i})}
\]

PCHE’s effectiveness reaches value up to 98.7%.

1% of recuperator effectiveness ➔ the gas turbine cycle efficiency 0.6%
MUSE Code Simulation

- Developed for **plate-fin** heat exchanger,
- Use **Wavy fin** plate heat exchanger model,
- This model is the most similar model to our tested PCHE.
The different slopes may be due to:

- Difference of PCHE from wavy fin model,
- Neglect of cross flow in the distributor sections.
Conclusions

- The overall heat transfer coefficient and pressure loss factor of PCHE were investigated both experimentally and numerically; the empirical correlations are proposed.

- The method to take into account the heat loss for overall heat transfer coefficient estimations has been established.

- The overall heat transfer coefficient varies from 300 to 650 W/m²K while the heat transfer effectiveness reaches up to 98.7%.

- PCHE might be judged as a promising compact heat exchanger for the high efficiency recuperator.

- The experimental data are currently used for CFD FLUENT code verification and developing the new heat exchanger type.