Analysis of Intercoolers in PEM Fuel Cell Systems
Outline of Lecture

1. Heat Exchangers in PEM Fuel Cell Systems
2. Motivation of Topic
3. Novel Investigation
4. Intercooler Analysis
5. Conclusions
Heat Exchangers in PEM Fuel Cell Systems

Hydrocarbon Fuels

Steam Reforming

Anode Exhaust

Anode
Electrolyte
Cathode

H₂

Humidification/Cooling

Radiator

H₂O Condenser/Storage

H₂O

Compressor

H₂O

Air
Heat Exchangers in PEM Fuel Cell Systems

- Used for:
  1. Stack cooling
  2. Cooling of compressed oxidant/air or fuel
  3. Condensation of the cathode exhaust gas
  4. Fuel reforming
# Heat Exchangers in PEM Fuel Cell Systems

<table>
<thead>
<tr>
<th>Component</th>
<th>Volume (%)</th>
<th>Weight (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel cell stack</td>
<td>29</td>
<td>49</td>
</tr>
<tr>
<td>Heat exchangers</td>
<td>30</td>
<td>19</td>
</tr>
<tr>
<td>Fans</td>
<td>17</td>
<td>3</td>
</tr>
<tr>
<td>Compressor</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Controls</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Tanks</td>
<td>9</td>
<td>2</td>
</tr>
<tr>
<td>Others</td>
<td>3</td>
<td>14</td>
</tr>
</tbody>
</table>

Ideal 50 kW net PEMFC system by J. Ferrall et al.
Heat Exchangers in PEM Fuel Cell Systems

Requirements for the heat exchangers

- Volume reduction
- Weight reduction
- Cost reduction
Heat Exchangers
Illustration of the conditioning of the compressed oxidant (air)
Motivation of the Topic

The conditions of the reactant on the cathode side of PEM fuel cell stacks:

- Proper operating temperature (around 80 °C)
- High relative humidity (around 80-100 %)
- Proper operating pressure (around 2 atm)
Motivation of the Topic

1. Reactant air inlet
2. Compressor
3. Humidifier
4. Fuel cell stack
   - Anode
   - Electrolyte
   - Cathode
5. Coolant inlet
6. Intercooler

Water injection
Motivation of the Topic

Higher operating pressure
Less water requirement
Motivation of the Topic

Compressor efficiency $\eta_c$

- 0.55
- 0.65
- 0.75

Higher operating pressure
Higher temperature
Motivation of the Topic

Higher operating pressure

• Easier water management
• More difficult thermal management

Design of the intercooler

Key words: heat load, operating pressure, humidification
Novel Investigation

For volume reduction

• Combined humidifier and intercooler

FC 400 gas to gas humidifier by the PERMA PURE LLC
Novel Investigation

For volume reduction

• Combined humidifier and intercooler

Humidifier core by the Emprise Corporation
Novel Investigation

For cost reduction

• Low cost material (paper)

Lossnay Humidifier by the Mitsubishi Electric co.
Novel Investigation

Problem

1. High cost
   • $3,000 to $5,000 (Humidifier core)
   • The price of Nafion (PERMA PURE LLC)

2. Working limitation
   • Low temperature (Mitsubishi, PERMA PURE LLC)
   • Size of the system (up to 50 kW)

Consideration of improvement of conventional heat exchangers for large systems
Intercooler Analysis

- Plate-fin heat exchangers
- Air-to-air (reactant-to-ambient) or air-to-liquid (reactant-to-water)
- Crossflow
General Aspects

- Heat and mass balance in the intercooler
- Comparison of the intercooler for the air- and water-cooling
Intercooler Analysis
Parameters in the Study

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stack temperature</td>
<td>80 °C</td>
</tr>
<tr>
<td>Injection added water temperature</td>
<td>80 °C</td>
</tr>
<tr>
<td>Relative humidity $\phi_4$</td>
<td>0.9</td>
</tr>
<tr>
<td>Fuel cell stack power $P_e$, kW</td>
<td>100</td>
</tr>
</tbody>
</table>

- Coolant-air is from the ambient (20 °C, 1.5 kg/s)
- Coolant-water is from the stack cooling (70 °C, 1.5 kg/s)
- Evaporative cooling is assumed
Intercooler Analysis
Heat and Mass Balances

Intercooler

\[ m_2 = m_3 = m_{2,a} + m_{2,w} \]
\[ \dot{Q}_{\text{Intercooler}} = \sum m_3 h_3 - \sum m_2 h_2 \]

Humidifier

\[ \dot{m}_4 = \dot{m}_3 + \dot{m}_{w,\text{Injection}} \]
\[ h_3 = h_4 \]
\[ Q_{\text{Humidifier}} = \dot{m}_{w,\text{Injection}} h_{80^\circ C,\text{Evap}} \]
Intercooler Analysis

Boundary Temperature of the Intercooler

Temperature $^\circ$C

Heating

Cooling

$T_{\text{reactant, in}}$

$T_{\text{reactant, out}}$

Pressure $p_2$ (kPa)
Intercooler Analysis

Heat Load in the Intercooler

High heat load with
• High stoichiometry
• High operating pressure
Intercooler Analysis
Heat Exchanger Effectiveness of Intercooler (Crossflow)

- High effectiveness at a high pressure (high volume is expected.)
- Water-cooling has higher effectiveness because of less temperature difference
Intercooler Analysis
Heat Transfer Surface Area of Intercooler (Crossflow)

**Heat transfer surface area (m²)**

**Pressure** $p_2$ (kPa)

- **Air-cooling**
- **Water-cooling**

- **Heat transfer coefficient (assumption):**
  - Air $100 \ \text{W/m}^2\text{K}$
  - Water $1000 \ \text{W/m}^2\text{K}$

- Liquid has one order of magnitude larger heat transfer coefficient
Intercooler Analysis
Comparison of the Cooling Methods of Intercooler (Crossflow)

Water-cooling

• Due to the high heat transfer coefficient and simple assembly, total system size will be smaller than for air-cooling.

• Heat rejection difficult due to the less temperature difference.

Air-cooling

• Additional fan and motor are necessary (consumption 1.5-2 kW).
Summary

• At high pressure and stoichiometry, the demand for the intercooling is large.

Water-cooling

• A compact system can be expected.

• Difficulties in the cooling process due to small temperature difference

Air-cooling

• The system will be large due to the low heat transfer coefficient and additional fan and motor.

• Large temperature difference compensate the cooling.