Numerical Analysis of a Fin Arrangement for an Optimal Design of Airfoil Fin PCHE

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• Introduction to the Brayton cycle
• Research Objective
• Methodology for the SCO2 HEX Design Optimization
• CFD Analysis
• Correlation Development
• CFD Result
• Cost Analysis
• Results
**S-CO$_2$ Brayton Cycle**

- Low compressible work
- High heat capacity
- High heat transfer

Various Heat Sources:
- Fossil Fuel
- Nuclear
- Solar
- Geothermal

Supercritical CO$_2$:
- High Pressure 200 bar
- Heat Exchanger
- 200 bar 300–700 °C
- Compressor
- Turbine
- Generator

Cycle Efficiency 45–50%:
- *Steam 30%–35%

SCO2 Symposium, Pittsburgh, USA, Sept 9-10, 2014
Supercritical Carbon dioxide Integral Experimental Loop (2012~2015)

**Goal:** 100 kWe (20 MPa - 500°C)

I. Development of Cycle construction & Operation Techniques (KAERI)

II. Verification of Turbine & Compressor Performance Verification (KAIST)

III. Development of Compact Heat Exchanger (POSTECH)

The SCIEL Facility in Korea (Compressor test loop)

Collaborated work with KAERI, KAIST and POSTECH sponsored by NRF
Research Objectives

- Low heat transfer
- Low pressure loss
- High heat transfer
- High pressure loss

Many optimization researches have been reported.

Optimization of fin configuration with cost analysis
- 3D numerical study about zigzag bending angle (4 cases)
- 3D numerical study about comparing zigzag and airfoil shape PCHE

- 3D numerical study about comparing zigzag and airfoil PCHE
- An Experimental study about comparing zigzag and airfoil PCHE

- Airfoil shape

- Na – SCO2 HEX and SC Interaction

- Fin array optimization

Kim, T.H, et al. (2013~)
- SCO2 HEX Experiments

- CFD analysis for optimized design
Experimental validation of Proposed Airfoil Shape Fin Model (1/4)
Experimental validation of Proposed Airfoil Shape Fin Model (2/4)

→ Total Heat Transfer Rate with respect to the CO2 Flow Rate

[Graph showing the relationship between Heat Transfer (W) and CO2 flow rate (kg/s)]
Experimental validation of Proposed Airfoil Shape Fin Model (3/4)

→ Total Pressure Drop with respect to the CO2 Flow Rate
Experimental validation of Proposed Airfoil Shape Fin Model (4/4)

→ At the same heat transfer performance, airfoil $\Delta P < 1/14$ of Zigzag, $1/6$ of S-shape
These result shows the unlimited increase of the objective function $\frac{Nu}{Eu}$. We should select other objective function or reasonable restriction.

Effectiveness

Euler Number

Factors to find optimized point

Pareto optimal front

Adequate objective function

Method

Problem: the consideration of the weights to each factors

Problem: the lack of physical rationale of the weights to each factors

Other methodology is required to optimization of the airfoil type PCHE.

\[ f_{\text{objective}} = \frac{1}{\text{effectiveness}} + 0.09 \text{Eu} \]


Size of PCHE and energy loss could be calculated from Heat Exchanger Design Process.

Standardize the value of each costs to finished time of power system with The interest rate of 3.82% for the 5-year averaged value of the Korea bank

Cost Analysis

Production Cost

Size of heat exchanger

Production cost: 1.072$/cm³

Corhex Corporation

Operating Cost

Required power for the recuperator from pressure drop

Cost of Electricity: 0.04$/kWh

Production cost of the Korean NPP

Total Cost

Actual PCHE geometry\cite{5}

\Rightarrow \text{Heavy computational cost!}

\textbf{Simulation domain}

- Representative length of 50 mm
- Single unit channel

\Rightarrow \text{To reduce the computational cost!}

\textbf{<Single banking type>}

\cite{5} Corhex Incorporation product
### CFD Simulation Conditions

#### Conditions

- **Hot channel**
  - Inlet temperature, °C: 451.3
  - Inlet pressure, MPa: 7.8
  - Mass flux, kg/m²s: 937.5

- **Cold channel**
  - Inlet temperature, °C: 216.1
  - Inlet pressure, MPa: 19.8
  - Mass flux, kg/m²s: 937.5

#### Wall boundary condition

- Continuity equation
- Momentum equation
- Energy equation

⇒ The SIMPLE algorithm
(Semi-Implicit Method for Pressure Linked Equations)

#### SCIEL operation condition
(designed for high temperature recuperator)

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Hot channel</th>
<th>Cold channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet temperature, °C</td>
<td>451.3</td>
<td>216.1</td>
</tr>
<tr>
<td>Inlet pressure, MPa</td>
<td>7.8</td>
<td>19.8</td>
</tr>
<tr>
<td>Mass flux, kg/m²s</td>
<td>937.5</td>
<td>937.5</td>
</tr>
</tbody>
</table>

- ANSYS CFX
- About 2 million tetrahedral mesh
- NIST chemistry CO₂ properties
- k-ε turbulence model*
- Standard wall function
UWM S-CO$_2$ PCHE test


NACA0020 wind tunnel experiment

Geometry Analysis

**Dimensionless**

\[ \zeta_s = \frac{2L_s}{L_h} \]

\[ \zeta_h = \frac{L_h}{L_c} \]

\[ \zeta_v = \frac{L_v}{L_t} \]

- \( L_v \): Vertical pitch
- \( L_h \): Horizontal pitch
- \( L_s \): Staggered pitch
- \( L_t \): Thickness
- \( L_c \): Chord length

**Fin Configuration**

Airfoil fin shape
NACA0020 (Choi, 2010)
- \( L_t = 0.8 \text{ mm} \)
- \( L_c = 4 \text{ mm} \)
<table>
<thead>
<tr>
<th>Name</th>
<th>Heat Transfer</th>
<th>Pressure Drop</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Definition</strong></td>
<td>$Nu = \frac{h}{k / D_h} = \frac{q'' D_h}{k(T_w - T_m)}$</td>
<td>$f = \frac{\tau_w}{\rho u_m^2}$</td>
</tr>
<tr>
<td><strong>Physical Meaning</strong></td>
<td>Ratio of convection heat transfer to conduction heat transfer</td>
<td>Ratio of wall shear stress to the flow kinetic energy per unit volume</td>
</tr>
<tr>
<td><strong>Traditional Equation</strong></td>
<td>$Nu = 0.023 \text{Re}^{0.8} \text{Pr}^n$</td>
<td>$f = 0.079 \text{Re}^{-0.25}$</td>
</tr>
</tbody>
</table>
Modified Equation with correction factor

- Nusselt number
  \[ Nu = a \, Re^b \, Pr^c \, \zeta_v^d \, \zeta_h^e \]

- Fanning friction factor
  \[ f_{total} = f_{surface} + f_{airfoil} = a \, Re^b + c \, Re^d \, \zeta_v \, \zeta_h \]
  (a,b,c,e,d,f = arbitrary constant)

Separated Pressure drop with its reason

\[ \Delta P_{Total} = \Delta P_{surface \_friction} + \Delta P_{airfoil} + \Delta P_{acceleration} \]

CFD SCOPE

<table>
<thead>
<tr>
<th>Scope</th>
<th>CFD SCOPE</th>
<th>#</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Flux</td>
<td>312.5 kg/m²s</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>– 2187.5 kg/m²s</td>
<td></td>
</tr>
<tr>
<td>Vertical Pitch</td>
<td>1.25 - 3.5</td>
<td>14</td>
</tr>
<tr>
<td>Horizontal Pitch</td>
<td>1.1 - 3.5</td>
<td>15</td>
</tr>
</tbody>
</table>

Boundaries of Regression Analysis

Density difference between inlet and outlet

Inlet
Nusselt number almost linearly increases with the increase of the mass flux.

Correlation results are matched well to simulation results with the maximum 6% error.
Friction factor shows inverse proportional relationship of the mass flux.

Correlation results are matched well to simulation results with the maximum 10% error.
\[ \text{Nu} = a \text{Re}^b \text{Pr}^c \zeta_v^d \zeta_h^e (a, b, c, d, e = \text{constant}) \]

<table>
<thead>
<tr>
<th>Mode</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
<th>R²</th>
<th>Average Error</th>
<th>Maximum Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling mode</td>
<td>0.0314</td>
<td>0.794</td>
<td>0.3</td>
<td>-0.0509</td>
<td>-0.0846</td>
<td>0.996</td>
<td>0.09%</td>
<td>5.72%</td>
</tr>
<tr>
<td>Heating mode</td>
<td>0.0113</td>
<td>0.889</td>
<td>0.4</td>
<td>-0.0488</td>
<td>-0.0492</td>
<td>0.998</td>
<td>0.02%</td>
<td>2.63%</td>
</tr>
</tbody>
</table>

\[ f_{\text{total}} = f_{\text{surface}} + f_{\text{airfoil}} = a \text{Re}^b + c \text{Re}^d \zeta_v^e \zeta_h^f \]

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<th>Mode</th>
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<th>f</th>
<th>R²</th>
<th>Average Error</th>
<th>Maximum Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling mode</td>
<td>0.0237</td>
<td>-0.211</td>
<td>0.0306</td>
<td>-0.182</td>
<td>-0.768</td>
<td>-0.153</td>
<td>0.83</td>
<td>0.05%</td>
<td>9.9%</td>
</tr>
<tr>
<td>Heating mode</td>
<td>0.0087</td>
<td>-0.301</td>
<td>0.0171</td>
<td>-0.113</td>
<td>-0.726</td>
<td>-0.0346</td>
<td>0.85</td>
<td>0.03%</td>
<td>9.4%</td>
</tr>
</tbody>
</table>
Low mass flux make the low total cost, both vertical and horizontal cases.

At low mass flux, variation of horizontal pitch makes much changes.

Optimal point of Vertical cases: Mass flux = 312.5kg/m², Vertical pitch = 2.75

Optimal point of Horizontal cases: Mass flux = 312.5kg/m², Horizontal pitch = 1.1
Airfoil type PCHE provide better performance than zigzag type PCHE, and requires fin array optimization.

Defining objective functions with cost factor provide reasonable weight to 2 factors which shows the performance of the PCHE.

Nusselt number and Fanning friction factor are selected and modified to predict the value of these factors with the maximum error of 10%.

Cost analysis shows the optimized point of the airfoil type PCHE configuration (Mass flux = 312.5kg/m², Vertical pitch = 2.75, Horizontal pitch = 1.1)

The results show that the cost analysis could provide the constraint on the objective function of PCHE, since the minimum costal point exists in the domain.

Still, pressure drop work as the dominant part of PCHE.

There are many uncertainties in the assumptions and also manufacturing difficulties (such as DB issues at the mechanical stress at the airfoil edge) can also be considered as a constraint factor for the cost analysis.
Appendix
Appendix 1: ε-NTU method

\[ \varepsilon = \frac{q}{q_{\text{max}}} = \frac{q}{C_{\text{min}} (T_{h,i} - T_{c,i})} \]

Definintion of Effectiveness

\[ NTU = \frac{UA}{C_{\text{min}}} = \frac{1}{C_r - 1} \ln \left( \frac{\varepsilon - 1}{\varepsilon C_r - 1} \right) \]

Definintion of NTU (assume that pipe flow)

\[ \frac{1}{UA} = \frac{1}{(hA)_c} + \frac{1}{(hA)_h} = \frac{1}{A} \left( \frac{1}{h_c} + \frac{1}{h_h} \right) \]

Definintion of UA
(ignore the wall heat resistance)

From these equation, we could know the NTU, UA from effectiveness and thermodynamic properties. Heat transfer coefficient \( h \) could be predicted from Nusselt number correlation. Finally, required heat transfer area is obtained.
Inlet boundary condition of counter flow heat exchanger is used to analyze small parts of whole PCHE channel, so it represent concurrent flow heat exchanger. Obtained correlation should be tested on the case of counter flow Heat exchanger.
[5] Corhex Incorporation product