Optimization of S-Shaped Fin Channels in a Printed Circuit Heat Exchanger for Supercritical CO₂ Test Loop

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Overview

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• Surface geometry of S-shaped fin channels

• Numerical studies
  – Computational domain and numerical simulation setup
  – Selection of simulation cases

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  – Optimization algorithms
  – Discussion of results

• Conclusion
Background

- Advanced nuclear reactor concepts, supercritical CO\textsubscript{2} Brayton cycle & intermediate heat exchangers (IHX)
  - Working fluids at the primary loop include helium, liquid metal and molten salt, etc.
  - Supercritical CO\textsubscript{2} (s-CO\textsubscript{2}) Brayton cycle used as power conversion units are thermally-efficient and compact
  - Intermediate heat exchangers couple the primary and secondary systems (a helium-Gas-cooled Fast Reactor (GFR) is coupled with s-CO\textsubscript{2} Brayton cycle)
  - One of promising IHX candidates is Printed Circuit Heat Exchangers (PCHEs)
    - High Compactness
    - Desired thermal performances
    - Cost reduction
    - ......
Background

- Printed circuit heat exchangers
  - Photo-chemical etched plates stacked up to be diffusion-bonded

Introduction of zigzag and S-shaped fin channels

- **Surface geometries of PCHEs**
  - Straight channels and zigzag channels (Heatric Company)
  - S-shaped fin channels, first investigated by Tokyo Institute of Technology (TIT) in 2007
  - Airfoil fin channels, first investigated by POSTECH in 2008

- **Development of S-shaped fin channels**
  - Wavy channels cut at the bend corner and down-stream fins shifted to form offset configurations
  - Tips of fins are elongated
Project Activity

Objective and technical approach

To optimize design of PCHEs (printed circuit heat exchangers) as IHXs (intermediate heat exchangers) using numerical analysis and multi-objective evolutionary algorithms

- Parametric studies of PCHEs with various kinds of surface geometries
- Numerical studies on thermal performances of proposed PCHE designs
- Thermal-economic multi-objective optimization to PCHE designs
- Evaluation of the structural integrity of proposed the PCHE design using the numerical simulation

To fabricate and test scaled-down prototypic PCHEs

- Design and construction of s-CO₂ test loop (STL) facility
- Design and fabrication of scaled-down prototypic PCHEs with different working fluids
- Experimental tests for steady-state and transient conditions

To study the diffusion bonding techniques

- Post testing from the tested PCHE
Design of s-CO$_2$ Test Loop (STL) Facility

- An s-CO$_2$ Test Loop (STL) is designed to couple with existing high-temperature helium test facility (HTHF) for testing of the IHX Test PCHE
  - The existing HTHF at OSU provides up to 2 MPa and 750 ºC
  - The s-CO$_2$ test loop (STL) is capable of running experiments at 15 MPa and 650 ºC
HX Core to Assembly
Surface Geometry of S-shaped Fin Channels

- S-shaped fin model is based on the experimentally tested S-shaped fin PCHE surface geometry by TIT (2007)
  - In the model the S-shape is formed by sinusoidal functions defined by the fin length $l_f$, fin width $d_f$ and fin angle $\phi$; the configuration of fins can be represented by longitudinal and lateral pitch $p_y, p_x$

\[ y = \xi \sin(\omega(x - a)) + b. \]
Surface Geometry of S-shaped Fin Channels

- **Stress analysis**
  - A simplified stress analysis for zigzag channels is adopted for determining the neighboring fin distance $d_y$ the longitudinal and lateral pitch $p_y$, $p_x$

\[
d_{f,zz} = \left( \frac{\Delta p}{\sigma_D} \right) g_p,
\]

\[
g_p = \frac{d_y}{2}
\]
Numerical Studies—Computational Domain

- Computational domain
  - The selected computational domain is periodic in both x- and y-direction. The periodicity can reduce the computational time.
  - The fluid flowing zones are sandwiched by solid plates. S-Shaped discontinuous fins are located in the fluid zones.

![Computational Domain Diagram]
Numerical Simulation Setup

- **Numerical simulation setup**
  - Inflation layers are required at the vicinity of S-shaped fin walls as well as the upper and lower plate due to the turbulent flow regime.
  - The sweeping method is used in the meshing to further reduce the computational cost.
  - The $k$-$\varepsilon$ Realizable turbulent model is adopted for stable convergence.
Selection of CFD Simulation Cases

- **Design cases selection**
  - Besides the CFD simulation for the reference design, it is necessary to perform CFD simulations for various S-shaped fin channel designs for the shape optimization.
  - In the design space of the fin angle 10° - 60° and the fin length 4 – 16 mm, 9 cases are selected using Latin Hypercube Sampling (LHS).
Shape Optimization-- Surrogate Modeling

- Surrogate modeling
  - To develop the dependence of the pressure drop and the heat transfer on the fin angle and fin length, the second-order Response Surface Method (RSM) is adopted to develop a surrogate model using the simulation results of 9 cases.

\[ y = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum_{j=1}^{k} \beta_{jj} x_j^2 + \sum_{i<j=2}^{k} \beta_{ij} x_i x_j \]

\[ \delta P = \frac{P_1 - P_2}{L_{12}} \]

\[ h = \left| \frac{Q}{A_s(T_w - T_b)} \right| \]
Shape Optimization--Algorithms

- One of the Multi-objective Evolutionary Algorithms (MOEAs) NSGA-II is used to optimize the shape of S-shaped fins
  - The objective functions are the heat exchanger thermal effectiveness and the core pressure drop
  - The selected objective functions are usually conflicting with each other
  - The purpose is to seek a set of non-dominated solutions called Pareto-optimal solutions
Shape Optimization--Algorithms

1. START
2. Input the size of population $N$ and number of generations $G$
3. Initialize random chromosomes
4. Non-dominated sorting
5. Crowding distance assignment
6. Tournament selection
7. Crossover and mutation
8. Create a new generation of population of chromosomes
9. Decode $N$ chromosomes
10. Objective function evaluation subroutine
11. All evaluated?
12. Yes: END
13. No: Generation $< G$?
14. Yes: Decode $N$ chromosomes
15. Cluster Pareto-optimal solutions
16. No: Repeat from step 2
Shape Optimization

- **Thermal modeling**
  - A slab heat conduction model is assumed for the calculation of the overall heat transfer coefficient $U$
  - The parameters of the heat exchanger are pre-defined. E.g. the number of channels per plate, the heat exchanger core length and cold side Reynolds number, etc.

\[
\frac{1}{U_{h,A_{s,h}}} = \frac{1}{U_{c,A_{s,c}}} = \frac{1}{h_{h,A_{s,h}}} + \frac{t_w}{k_{w,A_{s,w}}} + \frac{1}{h_{c,A_{s,c}}}
\]
Shape Optimization—Discussion of Results

- Optimization results
  - The entire solution space with 5,000 sampled S-shaped fin designs
  - The distribution of the solutions is consistent with the expectation that the minimization of the pressure drop and the maximization of the heat transfer performance are usually conflicting with each other
• Distribution of Pareto-optimal Solutions
  - The optimized designs can be divided into two groups: the low-angle-fin group and the high-angle-fin group
  - In the low-angle-fin group, both the small-angle and long S-shaped fins are able to reduce the pressure drop; However, the thermal effectiveness is decreased for long fins
Shape Optimization—Discussion of Results

- Distribution of Pareto-optimal Solutions
  - For S-shaped fins with a fin angle of $10^\circ$, a long fin body creates a long fin tip that separates the flow along the fin body, which increases the pressure drop and enhance the heat transfer simultaneously.
  - In the high-angle-fin group, most of the fins are $60^\circ$. Short fins are favorable in terms of the thermal effectiveness. However, the pressure drop increases as the fin length decreases.
## Shape Optimization—Discussion of Results

<table>
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<tr>
<th>Item</th>
<th>Symbol</th>
<th>Units</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
<th>#5</th>
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<tr>
<td>Fin angle</td>
<td>φ</td>
<td>degree</td>
<td>11.6</td>
<td>60.0</td>
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<td>60.0</td>
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<tr>
<td>Fin length</td>
<td>l_f</td>
<td>mm</td>
<td>6.08</td>
<td>13.35</td>
<td>9.95</td>
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<td>HX capacity</td>
<td>Q</td>
<td>kW</td>
<td>13.46</td>
<td>13.60</td>
<td>13.66</td>
<td>13.71</td>
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<td>Cold side mass flow rate</td>
<td>q_m</td>
<td>kg/s</td>
<td>0.067</td>
<td>0.084</td>
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<tr>
<td>Cold side inlet temperature</td>
<td>T_{c,in}</td>
<td>°C</td>
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<tr>
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<td>°C</td>
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<td>HX core cold side pressure drop</td>
<td>Δp</td>
<td>kPa</td>
<td>33.04</td>
<td>56.28</td>
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<td>Cold side heat transfer coefficient</td>
<td>h</td>
<td>kW/m²·°C</td>
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<td>4.329</td>
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<td>Overall heat transfer area</td>
<td>A_s</td>
<td>m²</td>
<td>0.122</td>
<td>0.154</td>
<td>0.156</td>
<td>0.160</td>
<td>0.163</td>
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<td>HX thermal effectiveness</td>
<td>ε</td>
<td>%</td>
<td>90.53</td>
<td>91.51</td>
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<td>4.35</td>
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Conclusion

• A prototypic zigzag-S-shaped-fin PCHE is designed for experimental testing on the coupled facility that is capable of running experiments up to 15 MPa and 750 °C with helium and s-CO₂

• Shape optimization is carried out for the reference S-shaped fin channels using MOEA and RSM

• The optimization results indicate that the small-fin-angle channels with large fin length are able to reduce the pressure drop while the large-fin-angle channels with small fin length are favorable in increasing the heat exchanger thermal effectiveness

• In the future, more design factors need to be taken into account such as the fin arc length and Reynolds number dependence such that the optimization results can be used in broad applications