Sandia Progress on Advanced Heat Exchangers for SCO2 Brayton Cycles

The 4th International Symposium – Supercritical CO2 Power Cycles
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Overview – SCO2 Cycle Exchangers

- Several supercritical carbon dioxide (SCO2) cycles proposed
  - Proposed as an alternative to steam and organic Rankine systems
  - Offer high efficiency, compact turbomachinery, fluid compatibility
  - Recompression Brayton cycles are well-matched to nuclear applications

- Proposed SCO2 cycles are highly recuperated to enhance efficiency
  - Recuperation between 1 and 5 times the net electrical power
  - Require a combination of high temperature and pressure capability
  - Will be a significant portion of demonstration and production cycles

- Key requirements are pressure containment and cost scalability
  - Several types can contain high pressures (PFHE, PCHE, S+T)
  - Current SCO2 test systems use PCHEs almost exclusively
  - Cost and size scaling suggest S+T units are impractical, despite wide use

- Heat Exchanger Developments at SNL
  - Partnering with Vacuum Process Engineering to understand PCHEs
  - Developing cast metal heat exchangers (CMHEs) to reduce cost
HEAT EXCHANGERS BACKGROUND
Supercritical CO$_2$ Brayton Cycle

Recuperation in Brayton Cycles


Net Output: 10 MW, Low Side: 48°C, High Side: 700°C

- **Simple High**
  - Simple, Unconstrained
  - Recomp, Constrained

- **Simple Low**

- **Recompression**
  - High Side Pressure: 25000 kPa
  - Low Side Pressure: 9980 kPa
  - Precooler In: 104.2°C
  - Precooler Q: 8.87 MW
  - Precooler m: 64.0 kg/s

- **Simple**
  - High Side Pressure: 3246 kPa
  - Low Side Pressure: 1840 kPa
  - Precooler In: 97.2°C
  - Precooler Q: 8.70 MW
  - Precooler m: 180.8 kg/s

Thermal Efficiency vs. Total Recuperator Conductance (kW/K)
Early Air CBC Recuperators

Scalable SCO2 CBC Systems

6 ft Person for Scale

PCHEs
- IHX
- HTR
- LTR
- PRE

50 MWe

20 MWe

2 x 150 MWe

Heat Exchanger Requirements

Heat Exchanger Materials Selection
(Application boxes based on $P/S = 0.22$)

Maximum Differential Pressure at $P/S = 0.22$ [MPa]

Maximum Allowable Stress [MPa]

Design Metal Temperature [°C]

SCO2 PRE

SCO2 RECUPERATORS

SCO2 IHX

STEAM BOILERS

SCO2 TURBINE

AIR CBC COOLER

AIR/GAS RECUPERATOR

AIR CBC HEATERS
Approximate Cost Scaling

\[ \text{Cost} = C_{ESDU} F_{\text{mat}} F_{p} F_{UAsp} P_{\text{elec}} \]

- \( C_{ESDU} \) is the UA-specific cost value [\$/\text{(kW/K)}]
- \( F_{\text{mat}} \) is a material cost factor
- \( F_{p} \) is a pressure cost factor
- \( F_{i} \) is an adjustment for inflation
- \( UA_{sp} \) is the cycle power-specific UA [\text{kw/(k-MWe)}]
- \( P_{\text{elec}} \) is the cycle power level [\text{MWe}]

DEVELOPMENTS FOR PCHES
The Printed Circuit Heat Exchanger

Heat Exchanger Core

Core and Manifold Assembly

Diffusion Bonding

Slab
Partnership with VPE on PCHEs

Understand Near-Term Option

- Material and Bond Evaluation
  - Possible materials
  - Bonding defects
  - Develop U-stampable PCHEs

- PCHE Performance Testing
  - Pressure containment
  - Thermal-hydraulic testing
  - Thermal Fatigue testing

- Techno-Economic Optimization
  - Design -> Fabrication -> Testing
Review of 2014 Turbo Expo Results

316 Diffusion Bond Tensile Tests

Approx. Stress Criteria

Perpendicular to Bond Lines
- A (failed at internal flaw)
- B
- C

Parallel to Bond Lines
- D
- E
- F

Approx. Strain Criteria

engineering stress (psi)

engineering stress (MPa)

engineering strain
Analysis of the Failed Sample

- Likely due to visible trench
  - Matched on both surfaces
  - Foreign object inclusion (Carbonaceous material)
- Remedies in next blocks
  - Changed plate vendors
  - Tweaked bonding procedure
Two Sets of Satisfactory Samples

316 Diffusion Bond Tensile Tests

Strain Criteria

Approx. Stress Criteria

Perpendicular to Bond Lines
- A1
- A2
- B1
- B2
- C1
- C2

Parallel to Bond Lines
- D1
- D2
- E1
- E2
- F1
- F2

engineering stress (psi)

engineering stress (MPa)
### PCHE Design Software

<table>
<thead>
<tr>
<th>Side A</th>
<th>Side B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Process Fluid</strong></td>
<td><strong>Process Fluid</strong></td>
</tr>
<tr>
<td>Water</td>
<td>Water</td>
</tr>
<tr>
<td><strong>Mass Flow Rate</strong></td>
<td><strong>Mass Flow Rate</strong></td>
</tr>
<tr>
<td>$m_A = 2$ [kg/s]</td>
<td>$m_B = 2$ [kg/s]</td>
</tr>
<tr>
<td><strong>Inlet Temperature</strong></td>
<td><strong>Inlet Temperature</strong></td>
</tr>
<tr>
<td>$T_{A,in} = 338.2$ [K]</td>
<td>$T_{B,in} = 298.2$ [K]</td>
</tr>
<tr>
<td><strong>Outlet Temperature</strong></td>
<td><strong>Outlet Temperature</strong></td>
</tr>
<tr>
<td>$T_{A,out} = 313.2$ [K]</td>
<td>$T_{B,out} = 323.2$ [K]</td>
</tr>
<tr>
<td><strong>Inlet Pressure</strong></td>
<td><strong>Inlet Pressure</strong></td>
</tr>
<tr>
<td>$P_A = 253310$ [Pa]</td>
<td>$P_B = 253310$ [Pa]</td>
</tr>
<tr>
<td><strong>Outlet Pressure</strong></td>
<td><strong>Outlet Pressure</strong></td>
</tr>
<tr>
<td>$P_{A,out} = $ [Pa]</td>
<td>$P_{B,out} = $ [Pa]</td>
</tr>
<tr>
<td><strong>Pressure Drop</strong></td>
<td><strong>Pressure Drop</strong></td>
</tr>
<tr>
<td>$dP_{A} = $ [Pa]</td>
<td>$dP_{B} = $ [Pa]</td>
</tr>
<tr>
<td><strong>Drop / Operating Pressure</strong></td>
<td><strong>Drop / Operating Pressure</strong></td>
</tr>
<tr>
<td>$dP_{A,%} = $ [%]</td>
<td>$dP_{B,%} = $ [%]</td>
</tr>
<tr>
<td><strong>Material</strong></td>
<td><strong>Material</strong></td>
</tr>
<tr>
<td>$mat% = Stainless\text{AI}S1316$</td>
<td>$mat% = Stainless\text{AI}S1316$</td>
</tr>
<tr>
<td><strong>Channel Width</strong></td>
<td><strong>Channel Width</strong></td>
</tr>
<tr>
<td>$w_A = $ [m]</td>
<td>$w_B = $ [m]</td>
</tr>
<tr>
<td><strong>Channel Depth</strong></td>
<td><strong>Channel Depth</strong></td>
</tr>
<tr>
<td>$d_A = $ [m]</td>
<td>$d_B = $ [m]</td>
</tr>
<tr>
<td><strong>Side Margin Thickness</strong></td>
<td><strong>Side Margin Thickness</strong></td>
</tr>
<tr>
<td>$t_1A = $ [m]</td>
<td>$t_1B = $ [m]</td>
</tr>
<tr>
<td><strong>Remaining Plate Thickness</strong></td>
<td><strong>Remaining Plate Thickness</strong></td>
</tr>
<tr>
<td>$t_2A = $ [m]</td>
<td>$t_2B = $ [m]</td>
</tr>
<tr>
<td><strong>Stay Plate Thickness</strong></td>
<td><strong>Stay Plate Thickness</strong></td>
</tr>
<tr>
<td>$t_4A = $ [m]</td>
<td>$t_4B = $ [m]</td>
</tr>
<tr>
<td><strong>Total Plate Thickness</strong></td>
<td><strong>Total Plate Thickness</strong></td>
</tr>
<tr>
<td>$t_{p,A} = $ [m]</td>
<td>$t_{p,B} = $ [m]</td>
</tr>
<tr>
<td><strong>Header Outer Diameter</strong></td>
<td><strong>Header Outer Diameter</strong></td>
</tr>
<tr>
<td>$D_{cyl,A} = $ [m]</td>
<td>$D_{cyl,B} = $ [m]</td>
</tr>
<tr>
<td><strong>Header Shell Thickness</strong></td>
<td><strong>Header Shell Thickness</strong></td>
</tr>
<tr>
<td>$t_{cyl,A} = $ [m]</td>
<td>$t_{cyl,B} = $ [m]</td>
</tr>
<tr>
<td><strong>Header Cap Thickness</strong></td>
<td><strong>Header Cap Thickness</strong></td>
</tr>
<tr>
<td>$t_{cap,A} = $ [m]</td>
<td>$t_{cap,B} = $ [m]</td>
</tr>
</tbody>
</table>

- **Calculate**
- **Save Inputs**
- **Load Inputs**

$q = 209089$ [W]

$UAsum = 13937$ [W/K]

<table>
<thead>
<tr>
<th>W</th>
<th>L</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>$[m]$</td>
<td>$[m]$</td>
<td>$[kg]$</td>
</tr>
</tbody>
</table>
DEVELOPMENTS FOR CAST METAL HEAT EXCHANGERS (CMHES)
Proposal: Directly cast heat exchanger core geometries.

Key Concept: Using inter-connected flow passages provides essential mechanical integrity to casting cores.

Benefits:
- Reduce cost by as much as a factor of 5
- Reduce lead-time caused high-temperature joining techniques (welding, brazing, bonding)
- Allow for innovative channel geometry
- Greatly expand material possibilities
- Easily incorporate surface features
Transitioning to Casting

CMHE Industrial Precedent

http://www.fedtechgroup.com/advanced_materials/lbs/lbs_cast.html
http://www.ergaerospace.com/project-gallery.htm
http://www.alveotec.fr/nos-actualites/exemples-d-applications-mousses-metalliques_55.html
Industrial Precedent

CMHE Recuperator Geometries

Manufactured fin shape

Designed fin shape

- Requires plate stamping
- Dry-fit multiple casting cores

Unit-Cell Heat Exchanger
BACKUP SLIDES
Current SCO2 CBC HXers

Commercial Unit Potential

Key Requirements:
✓ High Pressure
✓ High Temperature
✓ Corrosion Resistant
✓ High Reliability
✓ Compact Geometry
✓ Scalable to 150 MWe

\[ \beta = \frac{A_s}{V} = \frac{4\phi}{d_h} \]

- **Coil-Wound**
  - 10 to 300 \([\text{m}^2/\text{m}^3]\)

- **Plate-Fin**
  - 200 to 800 \([\text{m}^2/\text{m}^3]\)

- **Printed Circuit**
  - 200 to 5000 \([\text{m}^2/\text{m}^3]\)

- **Shell and Tube**
  - 10 to 200 \([\text{m}^2/\text{m}^3]\)

- **Shell and Plate**
  - 100 to 600 \([\text{m}^2/\text{m}^3]\)
PCHE Thermal-Hydraulic Performance

HEAT EXCHANGER COMPACTNESS

Surface Area Density: \[ \beta = \frac{A_s}{V} = \frac{4\phi}{d_h} \]

**PHE**
120 to 660

**PFHE**
(b) 800 to 1500
(d) 700 to 800

**PCHE**
(d) 200 to 5000

**CBHE**
(Marbond)
Up to 10000
Potential Applications

MARINE
Rolls-Royce WR-21
Type 45 Destroyer

VEHICULAR
Honeywell AGT1500
M1 Abrams Tank

STATIONARY
Solar Turbines
Mercury 50

Coal / Nuclear
Steam Rankine

GenIV Nuclear
Sodium Fast Reactor

Refrigeration
Commercial, Cryogenic
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