Compact Heat Exchangers for Nuclear Power Plants

Topical Workshop on New Cross-Cutting Technologies for Nuclear Power Plants

Session 2: Advanced Power Conversion for NPP

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Massachusetts Institute of Technology
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Why Compact HXs?

(Source: Ref. 5)
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- At first glance compact HXs would seem to be the obvious choice
- However, there is much more that needs to be considered

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Why Compact HXs?

- At first glance compact HXs would seem to be the obvious choice
- However, there is much more that needs to be considered
- The selection of HX technology is very much application dependent

(Source: Ref. 5)
Overview

- Functions and Requirements
- HX Types
- Metallic Heat Exchangers
- Ceramic Heat Exchangers
- Heat Exchanger Incentives and Challenges
- Summary Observations
Functions (What?)

- Direct flow of fluids
- Transfer thermal energy
- Maintain pressure boundary integrity
- Transfer loads (internal and external)
# Representative Advanced HX Applications

<table>
<thead>
<tr>
<th>Application</th>
<th>Primary Fluid</th>
<th>Secondary Fluid</th>
<th>Max. Temp. (°C)</th>
<th>HX Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFR</td>
<td>Na</td>
<td>Na</td>
<td>500</td>
<td>IHX</td>
</tr>
<tr>
<td>SFR</td>
<td>Na</td>
<td>H₂O</td>
<td>475</td>
<td>SG</td>
</tr>
<tr>
<td>AHTR</td>
<td>FLiBe</td>
<td>Helium, Air, M-Salt</td>
<td>700</td>
<td>IHX</td>
</tr>
<tr>
<td>AHTR</td>
<td>M-Salt</td>
<td>H₂O</td>
<td>670</td>
<td>SG</td>
</tr>
<tr>
<td>HTGR-SC</td>
<td>Helium</td>
<td>H₂O</td>
<td>750</td>
<td>SG</td>
</tr>
<tr>
<td>HTGR-GT</td>
<td>Helium</td>
<td>N/A</td>
<td>500</td>
<td>Recuperator</td>
</tr>
<tr>
<td>HTGR-PH</td>
<td>Helium</td>
<td>Helium, M-Salt</td>
<td>850-950</td>
<td>IHX</td>
</tr>
<tr>
<td>HTGR-PH</td>
<td>Helium</td>
<td>Process Fluid</td>
<td>800-900</td>
<td>Process Coupling HX</td>
</tr>
</tbody>
</table>
Requirements
(Under what conditions? How well?)

- Thermal rating
- Chemical composition and properties of fluids
  - Heat transfer properties
  - Compatibility with HX materials
- Temperatures, pressures, flow rates
- Steady state and transient operating conditions, design lifetime (duty cycle)
- Structural loadings
  - Internal (e.g. flow induced)
  - External (e.g. seismic, vibration)
- Reliability
  - Pressure boundary integrity requirements – some variation with application (IHX vs. recuperator)
  - Maintaining performance – fouling, channel blocking, bypass, etc.
- Maintainability
- Economic (initial cost plus contribution to plant O&M cost)
GT-MHR Nominal Operating Parameters

- **Reactor**: 488°C (910°F), 7.22 MPa (1047 psia)
- **Precooler**: 26°C (79°F), 2.55 MPa (369 psia)
- **INTERCOOLER**: 848°C (1558°F), 7.07 MPa (1025 psia)
- **HPC**: 110°C (230°F), 7.27 MPa (1054 psia), 2.63 MPa (381 psia)
- **Turbine**: 508°C (946°F)
- **Generator**: 130°C (266°F), 2.58 MPa (374 psia)
Plate-Fin Recuperator

(Courtesy Ingersoll-Rand)
Type: Shell & Tube
Rating (MWt): 840

Primary: Shell Side
Fluid: Sodium
\[ T_{in} \ (°C): \ 499 \]
\[ T_{out} \ (°C): \ 360 \]
\[ W \ (m^3/s): \ 5.4 \]

Secondary: Tube Side
Fluid: Sodium
\[ T_{in} \ (°C): \ 326 \]
\[ T_{out} \ (°C): \ 477 \]
\[ W \ (m^3/s): \ 5.1 \]
Type: Shell & Helical Tube

Rating (MWt): 840

Primary: Shell Side

Fluid: Sodium

\[ T_{in} \ (°C): \ 477 \]
\[ T_{out} \ (°C): \ 326 \]
\[ W \ (m^3/s): \ 5.1 \]

Secondary: Tube Side

Fluid: H₂O

\[ T_{in} \ (°C): \ 216 \]
\[ T_{out} \ (°C): \ 452 \]
\[ P_{steam} \ (MPa): \ 14.7 \]
\[ W \ (m^3/s): \ 5.1 \]

(Source: Ref. 2)
Type: Shell & Tube
Rating (MWt): 900

Primary: Shell Side
- Fluid: FLiBe
- $T_{in}$ (°C): 600
- $T_{out}$ (°C): 704
- $W$ (m$^3$/s): 1.9

Secondary: Tube Side
- Fluid: FLiNaK
- $T_{in}$ (°C): 570
- $T_{out}$ (°C): 670
- $W$ (m$^3$/s): TBC

(Source: Ref. 11)
**SC-MHR SG Data**

Type: Shell & Helical Tube

Rating (MWt): 352

**Primary: Shell Side**

Fluid: Helium

\( T_{\text{in}} \) (°C): 725

\( T_{\text{out}} \) (°C): 290

\( P_{\text{He}} \) (MPa): 7

W (kg/s): [ ]

**Secondary: Tube Side**

Fluid: H\(_2\)O

\( T_{\text{in}} \) (°C): 193

\( T_{\text{out}} \) (°C): 585

\( P_{\text{steam}} \) (MPa): 16.5

W (kg/s): 130.5

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*THTR SG High-Pressure Bundle during Manufacture (Ref. 3)*

*SC-MHR NGNP Demo Plant SG (Ref. 4)*
VHTR Process Heat Application

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Brayton Energy Unit Cell Plate-Fin IHX

(Source: Ref. 7)
Printed Circuit Heat Exchanger (PCHE)

PCHE Concept (Source: Ref. 7)

He to Molten Salt IHX (Source: Ref. 8)

(Courtesy Heatric)
Capillary Tube Heat Exchanger

For 50MWt FLiNaK, 10 bundles, 2500 tubes/bundle

(Source: Ref. 10)
Strength of Metallic HX Materials at High Temperatures

(Note: 300khrs ~ 40 life at design capacity factor)
Corrosion at High Temperatures

- Primary side chemistry in VHTRs (≥850°C) poses a challenge for compact metallic HXs due to thin cross-sections (Ref. 7)
  - Plate-fin HX thickness: Fins 0.102 mm; Plates 0.38 mm
  - In PCHE, plates are typically ≥0.5 mm; however, flow channels reduce the effective thickness to a value comparable to the plates in the plate-fin design
- Data analyzed in Ref. 7 at 950°C suggest that the predicted depths of internal oxidation could approach or exceed material thickness after only a few years of exposure
- Alloy X had the greatest resistance to corrosion, but strength inferior to Alloy 617 at highest temperatures
  - May be best candidate at <850°C
Ceramatec Ceramic (SiC) HX Concept

Systems Expertise

Ceramatec Expertise

Assembling-up

Numbering-up

Scale-up

Micro-Channels (length-scale for heat transfer)  
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Full-Size Wafer (common repeat unit)  
(Source: Ref. 9)

Stack (modular unit)
Ceramic HX Concepts

SiC HX Concept (Ceramatec)

Unit cell of offset-fin Liquid Si Injected composite plate HX (UC Berkley)
Ceramic HX Tradeoffs

• **Advantages**
  - Temperature capability comparable to VHTR reactor
  - SiC is compatible with a wide range of working fluids
  - Potentially inexpensive materials and manufacture

• **Challenges**
  - Integration with remainder of circuit (ceramic to metallic joints)
  - Reliability (leak tightness, potential for brittle fracture)
  - Significant development effort

• **Observation**
  - 3-D printing may provide basis for breakthrough in compact ceramic microchannel HXs
# Characteristics of Typical Advanced HXs

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>He Steam Generator</th>
<th>Recuperator</th>
<th>Na-Na IHX</th>
<th>He-He IHX</th>
<th>He-MS IHX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical HX Type</td>
<td>Shell &amp; Tube</td>
<td>Plate-Fin</td>
<td>Shell &amp; Tube</td>
<td>Plate-Fin; PCHE</td>
<td>PCHE, Capillary Tube</td>
</tr>
<tr>
<td>Compact HX</td>
<td>Optional</td>
<td>Required for Economic Viability</td>
<td>Optional</td>
<td>Required for Economic Viability</td>
<td>Optional?</td>
</tr>
<tr>
<td>Maximum Temperature</td>
<td>700°C - 750°C</td>
<td>500°C</td>
<td>500°C</td>
<td>850°C - 1000°C</td>
<td>850°C - 1000°C</td>
</tr>
<tr>
<td>Pressure Differential</td>
<td>Large</td>
<td>Intermediate, potentially varying</td>
<td>Low</td>
<td>Low</td>
<td>Large</td>
</tr>
<tr>
<td>Materials</td>
<td>Alloy 800</td>
<td>Alloy 800, Alloy X</td>
<td>SS</td>
<td>Alloy X, I-617, Ceramics</td>
<td>I-617, Ceramics</td>
</tr>
<tr>
<td>Materials Compatibility w/Working Fluid</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Metallics: Concern w/primary side corrosion (thin x-sections)</td>
<td>Metallics: Concern w/primary &amp; secondary side corrosion</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ceramics: Potentially good</td>
<td>Ceramics: Potentially good</td>
</tr>
<tr>
<td>Pressure Boundary Integrity</td>
<td>High integrity required</td>
<td>Some leakage acceptable - degrades</td>
<td>High integrity required</td>
<td>High integrity required</td>
<td>High integrity required</td>
</tr>
<tr>
<td>Reliability/Lifetime</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Metallics: Life limited by creep, corrosion</td>
<td>Metallics: Life limited by creep, corrosion</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ceramics: Potentially good</td>
<td>Ceramics: Potentially good</td>
</tr>
<tr>
<td>Duty Cycle/Transients</td>
<td>OK</td>
<td>Good</td>
<td>OK</td>
<td>P-F: Good; PCHE: ?</td>
<td>?</td>
</tr>
<tr>
<td>Economics</td>
<td>Higher $/kWt</td>
<td>Good</td>
<td>OK</td>
<td>Potentially good</td>
<td>Potentially good</td>
</tr>
<tr>
<td>Development Status</td>
<td>Current SOA</td>
<td>Current SOA</td>
<td>Current SOA</td>
<td>Developmental</td>
<td>Developmental</td>
</tr>
<tr>
<td>Additional Issues</td>
<td>Channel blockage</td>
<td>Channel blockage, Ceramic-metal joints</td>
<td>Channel blockage, Ceramic-metal joints</td>
<td>Channel blockage, Ceramic-metal joints</td>
<td></td>
</tr>
</tbody>
</table>
Closing Observations

1. Heat exchanger design selections must be driven by functions and requirements
   - Optimum designs will vary significantly with application and requirements
   - Compact HXs are essential for some applications, e.g., HTGR-GT recuperators, HTGR-PH IHX
   - In other applications, incentives are not so clear, e.g. SFR and AHTR IHX

2. Compact metallic HXs are practical to ~850°C in pressure balanced applications
   - Corrosion may govern life at higher temperatures
Closing Observations

4. Compact ceramic HXs would be potentially enabling for higher temperatures and for challenging working fluids

5. Advanced manufacturing (3-D Printing) may enhance potential for very high temperature compact HXs:
   - Reduction of wasted material during manufacture of PCHEs
   - ODS Alloys (current manufacturing processes degrade properties)
   - Ceramic HXs


3. THTR Steam Generator High-Pressure Bundle during Manufacture, Slide from BBC/HRB presentation, Circa 1981.


<table>
<thead>
<tr>
<th>Metric</th>
<th>Shell &amp; Tube</th>
<th>Capillary Tube</th>
<th>PCHE</th>
<th>Plate-Fin &amp; Prime Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compactness (m²/m³ &amp; MW/m³)</td>
<td>Poor</td>
<td>Intermediate</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Calc t/MWt</td>
<td>13.5</td>
<td>0.88</td>
<td>1.16</td>
<td>0.25</td>
</tr>
<tr>
<td>Materials Utilization (t/MWt)</td>
<td>Poor: (13.5 t/MWt) Unlikely to be commercially viable</td>
<td>Good (0.9 t/MWt)</td>
<td>Good: (estimated to be 1.2 to 1.5 times plate-fin in final form; needs confirmation)</td>
<td>Best: (0.25 t/MWt) Most compact, least materials</td>
</tr>
<tr>
<td>Manufacturing Cost</td>
<td>Established manufacturing process</td>
<td>Manufacturing process looks to be very labor intensive and expensive.</td>
<td>Established manufacturing process, amenable to volume manufacturing</td>
<td>Established manufacturing process, amenable to volume manufacturing</td>
</tr>
</tbody>
</table>

**State-of-the-Art**

| Experience Base                 | HTTR, German PNP Development | None | PBMR DPP Recuperator, other commercial products | Conventional GT recuperators |
| Design & Manufacturing          | Proven designs and manufacturing processes. | Proposed tubesheet manufacturing process not obviously feasible. Shell-side baffling will be very difficult with very large numbers of very small tubes | Proven designs and manufacturing processes. | Proven designs and manufacturing processes. |

(Source: Ref. 7)
### IHX Comparisons

<table>
<thead>
<tr>
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<th>PCHE</th>
<th>Plate-Fin &amp; Prime Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robustness</td>
<td>Best: Simple cylindrical geometry, stresses minimized in HT area. Header interfaces can be easily isolated from HT area.</td>
<td>Simple geometry of tubes a plus. Temperature effects on &quot;tubesheet&quot; unknown.</td>
<td>Good: Thicker plates; local debonding does not immediately affect pressure boundary.</td>
<td>Concern: Thin plates with brazed joints in pressure boundary; stress risers in pressure boundary joints (but normally operate in compression). Small material and braze defects more significant.</td>
</tr>
<tr>
<td>Normal operation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transients</td>
<td>Good: Simple cylindrical geometry avoids stress concentrations in HT area. Potential issues in headers, tube/header interfaces.</td>
<td>&quot;Tubesheet&quot; and tube/tubesheet interfaces are potentially problematical</td>
<td>Differing thermal response characteristics of inner HT core vs. solid outer boundary surrounding HT core raises potential for higher transient thermal stresses vs. plate-in.</td>
<td>Best: Thin sections and flexible design minimizes the effects of transients.</td>
</tr>
</tbody>
</table>

(Source: Ref. 7)

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<table>
<thead>
<tr>
<th>Metric</th>
<th>Shell &amp; Tube</th>
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<th>PCHE</th>
<th>Plate-Fin &amp; Prime Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental Compatibility</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coolant chemistry/corrosion effects (Assumes PHTS on tube side or inside of compact HX cells, SHTS on shell/outside)</td>
<td>Best: Thick tubes provide maximum resistance</td>
<td>Favorable tube-side geometry. Intermediate section thickness and susceptibility to corrosion effects.</td>
<td>Intermediate section thickness and susceptibility to corrosion effects. Potential greater for &quot;hideout&quot; effects than tubular designs.</td>
<td>Worst: Thin plates and fins, potentially aggravated by &quot;hideout&quot; locations, may be more susceptible to coolant chemistry effects.</td>
</tr>
<tr>
<td>Dust, erosion (Assumes PHTS on tube side or inside of compact HX cells, SHTS on shell/outside)</td>
<td>Best: Large tube IDs, thick tubes make dust/erosion an non-issue.</td>
<td>Intermediate: Will be more prone to dust collection due to smaller diameters, but low likelihood of direct impingement</td>
<td>More prone to dust deposition and erosion (small passages, potentially with features to enhance HT). PCHE cross-sections are thicker than plate-fin/prime surface.</td>
<td>More prone to dust deposition and erosion (small passages, with features to enhance HT). Fin cross-sections are thinner than PCHE cross-sections.</td>
</tr>
<tr>
<td>Tritium transport</td>
<td>Best: Thick tubes provide maximum resistance.</td>
<td>Intermediate. Thinner tubes</td>
<td>Worse. Average PCHE cross-sections thicker, but minimum cross-sections comparable to plate-fin/prime surface.</td>
<td>Worst: Thin plates provide least resistance to tritium transport.</td>
</tr>
<tr>
<td>Reliability &amp; Integrity Management (RIM)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detection of degradation and/or leaks during operation (Assumed SHTS to PHTS pressure bias)</td>
<td>Equivalent. Essentially pressure balanced during normal operation with SHTS at slightly higher pressure. Indication of significant leakage would be manifested as inability to maintain higher SHTS pressure and/or increased injection of SHTS helium and increased withdrawal of PHTS helium.</td>
<td>Design allows access to individual tubes to identify presence of leaks. However, a lot of tubes</td>
<td>Leaks can be detected at module level with concept similar to that proposed for plate-fin</td>
<td>Concept developed to detect leaks at module level.</td>
</tr>
<tr>
<td>Detection of degradation and/or leaks during outages</td>
<td>Large tube diameters may allow internal inspection of individual tubes to assess condition.</td>
<td></td>
<td>Leaks can be isolated at module level with concept similar to that proposed for plate-fin.</td>
<td></td>
</tr>
<tr>
<td>Leak location; isolation, repair or replacement of failed components</td>
<td>Design allows location of leaks in individual tubes and plugging.</td>
<td>Design allows location of leaks in individual tubes and plugging. However, a lot of tubes.</td>
<td>Leaks can be isolated at module level with concept similar to that proposed for plate-fin.</td>
<td>Concept developed to locate and isolate leaks at module level.</td>
</tr>
</tbody>
</table>

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## IHX Comparisons

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<tr>
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<th>Plate-Fin &amp; Prime Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HX Integration</strong></td>
<td><strong>Integration with Vessels &amp; Piping</strong></td>
<td><strong>Integration with piping needs further evaluation</strong></td>
<td><strong>OK (by inference from plate-fin work)</strong></td>
<td><strong>OK</strong></td>
</tr>
<tr>
<td></td>
<td>Headers and HX-vessel integration demonstrated (e.g., HTTR, German PNP)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Compatibility with Multi-Stage IHX Designs</strong></td>
<td>Large vessels tend to make less attractive</td>
<td>High manufacturing costs would make less attractive.</td>
<td><strong>Compatible with multi-stage designs.</strong></td>
<td><strong>Compatible with multi-stage designs.</strong></td>
</tr>
<tr>
<td><strong>Compatibility with Multi-Module IHX Designs</strong></td>
<td>Large tubes, headers likely incompatible with multi-module designs.</td>
<td>High manufacturing costs would make less attractive.</td>
<td><strong>Compact cores are good match with multi-module designs.</strong></td>
<td><strong>Very compact cores are best match with multi-module designs.</strong></td>
</tr>
<tr>
<td><strong>Compatibility with Alternate HT Fluids (PHTS to SHTS)</strong></td>
<td>Poor tube-side HT characteristics problematical for alternate gases with lower conductivity. Potentially best choice for LS designs with LS on tube side (drainable). Headers would be an issue for high-temperature outlet.</td>
<td>Poor tube-side HT characteristics problematical for alternate gases with lower conductivity. May be OK for LS designs with LS on tube side (drainable). Tubesheets would be an issue for high-temperature outlet.</td>
<td><strong>Design provides flexibility for matching characteristics of differing HT fluids, including LS. May be difficult to develop drainable design for LS.</strong></td>
<td><strong>Likely not compatible with liquid salt HT fluids. Good flexibility for matching HT characteristics of alternate gases.</strong></td>
</tr>
<tr>
<td><strong>Design/Licensing</strong></td>
<td><strong>Code Basis for Design</strong></td>
<td><strong>Existing Section VIII Code design basis for tubes, but header design has no Code precedents.</strong></td>
<td><strong>No existing design Code basis</strong></td>
<td><strong>No existing design Code basis</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Existing Sect VIII Code design basis for tubular geometries and likely header designs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Typical GT Applications

DIRECT CYCLE

INDIRECT CYCLE
Typical Process Heat Application