Modeling Counter Flow Heat Exchangers with RELAP5-3D

Jacob T. Crittenden
Space Plant Systems – Bettis Laboratory
Bechtel Bettis, Inc.

IRUG 2006
West Yellowstone, MT
• Introduction & Project Overview
• Modeling Counter Flow Heat Exchangers with Control Volume Codes
• Staggered Mesh Solution
• Accounting for End Volumes
• Errors Introduced
• Limitations
• Compact Heat Exchangers
• Heat Convection Coefficient Correlations
• Conclusion
Introduction & Project Overview

- Bechtel and Lockheed Martin collaborated on a design of a nuclear reactor for the NASA Jupiter Icy Moons Orbiter (JIMO) under Naval Reactors’ cognizance.
- The JIMO mission would have required 100 – 300 kWe to propel the spacecraft to the outer planets, orbit the moons, and perform scientific investigations from lunar orbit.
- A gas-cooled fast reactor (GFR) directly connected to one or more closed-loop Brayton cycles was chosen as the best candidate to meet the mission requirements based on current technology.
- A RELAP5-3D model of the reactor and closed-loop Brayton cycle was developed to perform dynamic analysis of the JIMO reactor plant.
- The RELAP5-3D computer code is used at Bechtel and widely in the commercial nuclear industry for dynamic analysis of nuclear reactor plants.
- The remainder of this presentation discusses a technique developed at Bettis to model the compact counter-flow heat exchangers used in the Brayton cycle.
• Gas coolant is 22% Xenon, 78% helium by mole fraction
  – Low Prandtl Number
• Two Brayton loops depicted here, actual model concept utilized two but the number on the flight unit was yet to be determined.
• Recuperator included in each loop to improve cycle efficiency
• Gas Cooler included in each loop to transfer waste heat
Modeling Counter-Flow Heat Exchangers with Control Volume Codes

- Numerous control volumes required to model counter-flow heat exchangers in RELAP5-3D and other similar codes.
  - Constant temperature assumption over control volume
  - Control volume temperature based on outlet temperature derived from energy conservation
- Large number of control volumes increase problem run time
  - Reduces material Courant Limit
  - Increases number of calculations
- Large number of control volumes may invalidate constitutive requirements
  - Not a concern for single phase heat exchangers
- Small number of control volumes increase calculation error due to constant exit temperature assumption
Temperature Error

- Wall temperature boundary conditions applied from different axial planes
- Error introduced into the $\Delta T$ applied across the heat structure
- Error inversely proportional to number of sub-volumes
- Current wall temperature coupling imposes a lower sub-volume limit
Correcting Temperature Error

\[ Q = UA \Delta T \]

Correct the Heat Transfer

- Use code multipliers to artificially increase \( U \)
  - May alter transient behavior
  - Diminishing returns as number of control volumes is decreased
  - All codes may not have this capability
- Arbitrarily increase \( A \)
  - May alter transient behavior
  - Diminishing returns

Minimize the \( \Delta T \) Error

- Increase sub-volumes
  - Slows problem execution
    - Lowers courant limit
    - Increases calculations
  - May invalidate constitutive models
  - May require excessive sub-volumes to minimize error
    - JIMO recuperator required 1000 sub-volumes to reduce error below 1%
Staggered Mesh Solution

- Wall temperature boundary conditions applied from same axial plane
- Eliminates error introduced into the $\Delta T$ applied across the heat structure
- Does not account for heat structure ends
• End volume extrapolated heat added/subtracted to respective volumes
• Thermal equilibrium maintained by evenly dividing the difference between hot and cold side extrapolated heat values among all heat exchanger volumes
• Successful application of this method for the JIMO project resulted in steady state heat exchanger effectiveness values within 1 percent of those calculated by CCEP calculations carried out at NASA GRC
Errors Introduced

- Method correctly calculates how much heat should be transferred between pseudo-nodes as depicted in the above picture
  - Pseudo-nodes comprised of $\frac{1}{2}$ the sub-volume before and after the temperature point
- Heat is transferred “forward” from hot side 1 to cold side n-1, hot side 2 to cold side n-2, etc.
- Results in a slight discrepancy between this method and the analytic solution
- Total steady state error was less than 1 percent relative to CCEP
Limitations

• Method provided excellent agreement with steady state benchmarking
• Transient solution was not rigorously tested due to project termination
• Method would not have correctly calculated heat transfer during reverse flow conditions
  – No reverse flow operations were planned or anticipated
  – Any reverse flow conditions brought on by equipment malfunctions would have been quickly corrected or isolated
  – Calculations would have returned to normal once the flow reversal was corrected
Compact Heat Exchangers

- Offset strip fin design
  - Required an overall temperature effectiveness to decrement the total heat transfer area used in the analysis code
  - Enhanced heat transfer by preventing fully developed flow
    - Required modifications to the heat convection correlations
- The He Xe mixture proposed for the primary system had an extremely low Prandtl number (~0.2)
  - Required modified heat convection correlations
Temperature Effectiveness:

\[ \eta_0 = 1 - \frac{A_f}{A} \left( 1 - \eta_f \right) \]

Fin Effectiveness:

\[ \eta_f = \frac{\tanh (m \cdot L)}{m \cdot L} \]

Fin Parameter:

\[ m = \sqrt{\frac{h \cdot P}{k \cdot A_c}} = \sqrt{\frac{2 \cdot h}{k \cdot t}} \]

- Temperature effectiveness used as a heat transfer design factor to directly decrement the heat transfer coefficient. It could also be used in pre-processing to decrement the heat transfer area.
- Temperature effectiveness is a function of heat transfer coefficient (h) and may vary during transients.
  - Input as a constant for JIMO. This would have been investigated had the project continued.
Heat Convection Coefficient Correlations

- Two constant Nusselt Number laminar correlations available in RELAP5-3D
  - Exact solution for circular tubes (Sellars, Tribus, and Klein)
    \[ \text{Nu} = 4.36 \]
  - Exact solution for large aspect ratio flat plates (ORNL)
    \[ \text{Nu} = 7.63 \]
  - Flat plate solution more accurately represents the compact heat exchangers
- RELAP5-3D also has a Reynolds Number dependency relation for laminar flow (PSU)
  \[ \text{Nu}_{l\text{am}}(\text{Re}) = \text{Nu}_{\text{analytic}} \left( 0.414 + 5.91 \cdot 10^{-4} \cdot \text{Re} \right) \]
• Modified RELAP correlation has essentially the same slope as the empirical correlation developed by Kays & London for a similar heat exchanger
• Nusselt Number predictions over the range of Reynolds Number of interest are within 15 percent
Correction for Entrance Effects

- ORNL Nusselt Number increased by 13% (Nu = 8.63) to account for entrance effects
- RELAP5-3D prediction nearly identical to Kays and London
Bounding the Proposed Nusselt Number Increase

- Each of the strip fins in the compact heat exchangers considered for JIMO had a length of 0.125 in.
- Integrating and normalizing the Polhausen analytical solution for the heat transfer coefficient over the length of a fin provides an upper bound for the Nusselt Number increase.

\[
Nu = \frac{hx}{k} = 0.332 \frac{Pr^{\frac{5}{2}}}{Re} \frac{1}{Pr^{\frac{1}{3}}}
\]

\[
h(x) = 0.332k \left(\frac{\rho u}{\mu}\right)^{\frac{1}{2}} x^{-\frac{1}{2}} Pr^{\frac{1}{3}}
\]

\[
\bar{h} = \frac{1}{L} \int_0^L 0.332k \left(\frac{\rho u}{\mu}\right)^{\frac{1}{2}} x^{-\frac{1}{2}} Pr^{\frac{1}{3}} dx
\]

\[
\bar{h} = \frac{1}{L} \int_0^L x^{-\frac{1}{2}} dx = 2 \left(\frac{\rho u}{\mu}\right) Pr^{\frac{1}{3}} \left[L^{-\frac{1}{2}}\right] = 2
\]

\[
k = \frac{\rho u}{\mu} L^{-\frac{1}{2}} Pr^{\frac{1}{3}}
\]

- 13 percent is well within the factor of two increase shown here.
## Results

<table>
<thead>
<tr>
<th></th>
<th>Kays &amp; London</th>
<th>RELAP5-3D</th>
<th>Relative Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Recuperator (Nu = 7.63)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>0.9449</td>
<td>0.9412</td>
<td>-0.38</td>
</tr>
<tr>
<td>Q (kW)</td>
<td>366.7</td>
<td>365.3</td>
<td>-0.38</td>
</tr>
<tr>
<td>$T_{H,in}$ (K)</td>
<td>920.6</td>
<td>920.6</td>
<td></td>
</tr>
<tr>
<td>$T_{H,out}$ (K)</td>
<td>564.1</td>
<td>566.0</td>
<td>0.53</td>
</tr>
<tr>
<td>$T_{C,in}$ (K)</td>
<td>535.1</td>
<td>535.1</td>
<td></td>
</tr>
<tr>
<td>$T_{C,out}$ (K)</td>
<td>899.4</td>
<td>895.3</td>
<td>1.15</td>
</tr>
<tr>
<td><strong>Modified Recuperator (Nu = 8.63)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>0.9449</td>
<td>0.9490</td>
<td>0.43</td>
</tr>
<tr>
<td>Q</td>
<td>368.6</td>
<td>370.2</td>
<td>0.43</td>
</tr>
<tr>
<td>$T_{H,in}$</td>
<td>920.4</td>
<td>920.4</td>
<td></td>
</tr>
<tr>
<td>$T_{H,out}$</td>
<td>562.7</td>
<td>561.6</td>
<td>-0.31</td>
</tr>
<tr>
<td>$T_{C,in}$</td>
<td>533.5</td>
<td>533.5</td>
<td></td>
</tr>
<tr>
<td>$T_{C,out}$</td>
<td>899.1</td>
<td>898.0</td>
<td>-0.31</td>
</tr>
</tbody>
</table>
Conclusions

• Improved calculation accuracy
  – Staggered heat structure mesh imposed more realistic wall temperatures
  – Temperature effectiveness corrected heat transfer area
  – ORNL/PSU convection correlation agrees closely with empirical data
• Staggered heat structure mesh reduced JIMO heat exchanger sub-volumes by a factor of 4.
  – Increased Material Courant Limit
  – Decreased problem run-time
• Increased volume aspect ratio to satisfy RELAP5-3D constitutive requirements
• Code modifications being made by the INL to allow volume average temperature selection for wall boundary conditions