Modeling Counter Flow Heat Exchangers with RELAP5-3D

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

IRUG 2006
West Yellowstone, MT

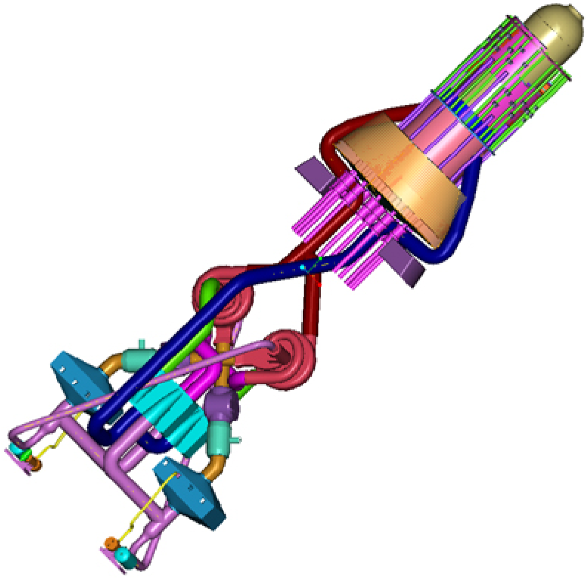
Outline

- 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.

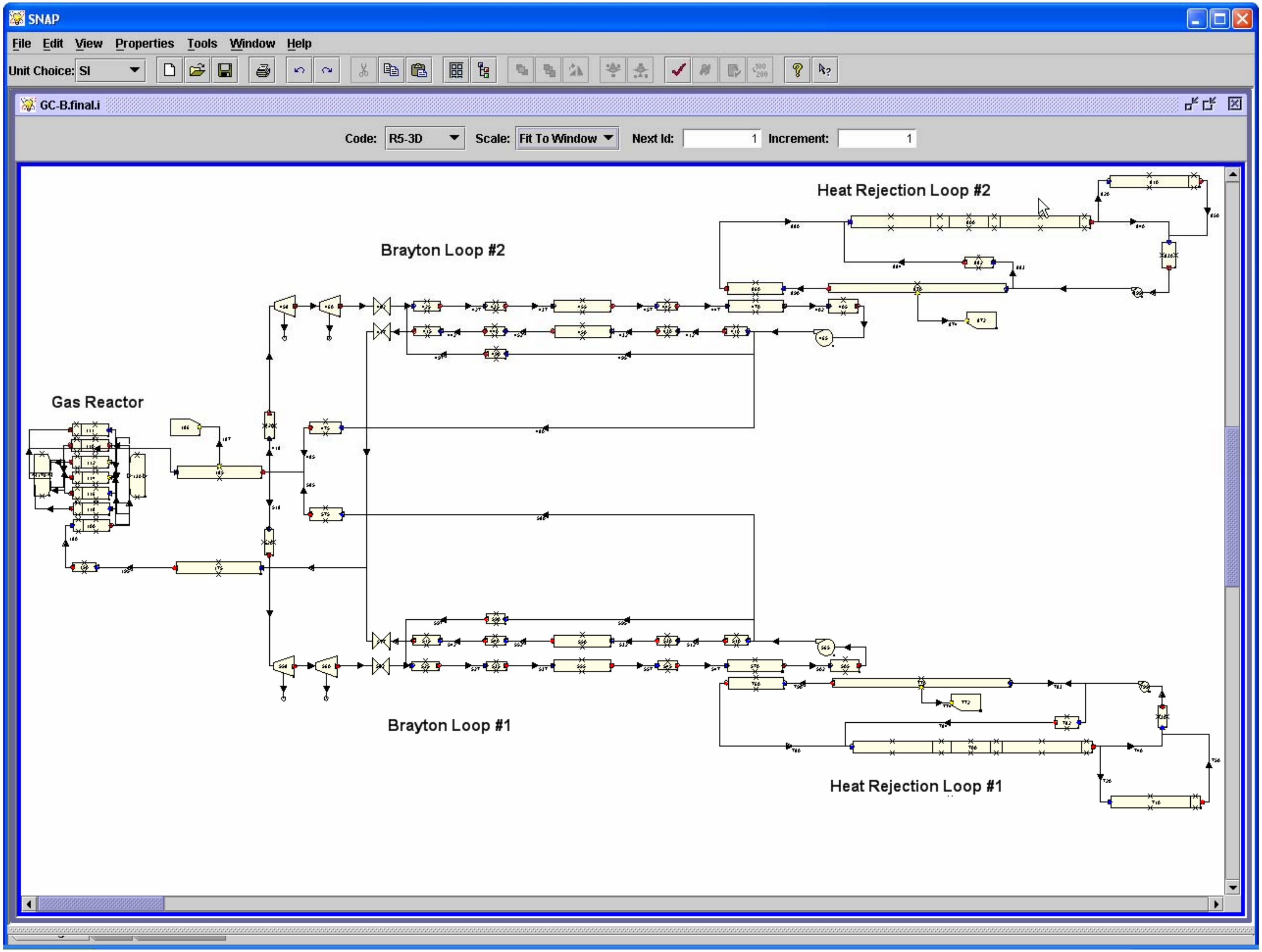
Introduction & Project Overview



- 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

PRE-DECISIONAL - For planning and discussion purposes only

RELAP5-3D Model



Unit Choice: SI

Code: R5-3D

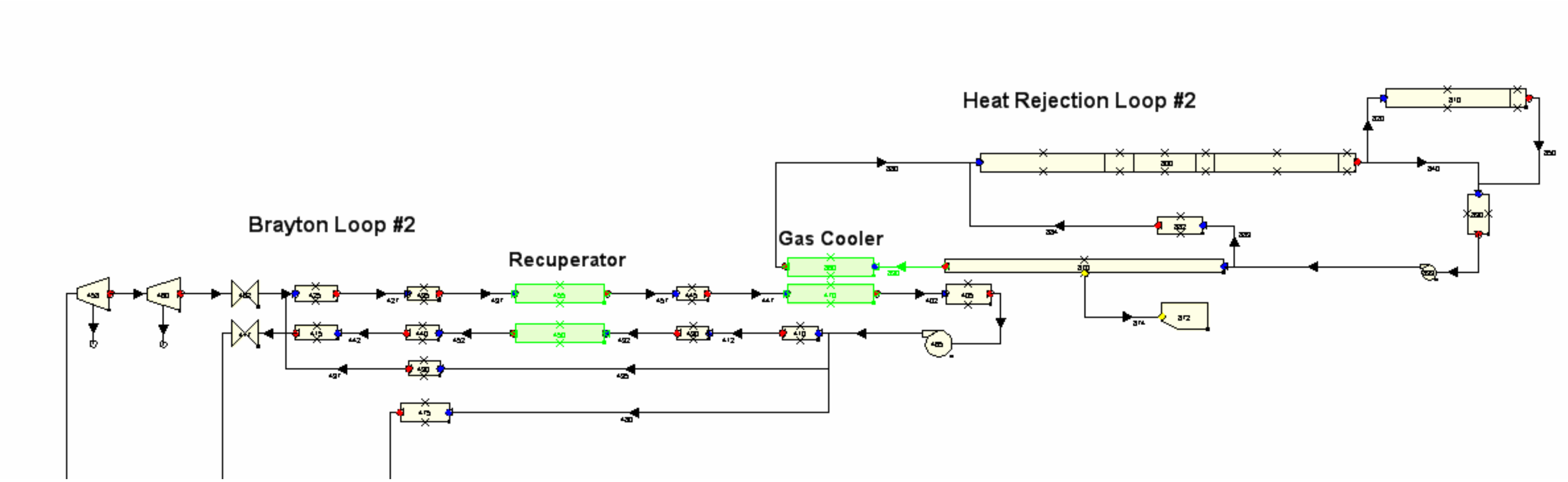
Scale: Fit To Window

Next Id: 1

Increment: 1

PRE-DECISIONAL - For planning and discussion purposes only

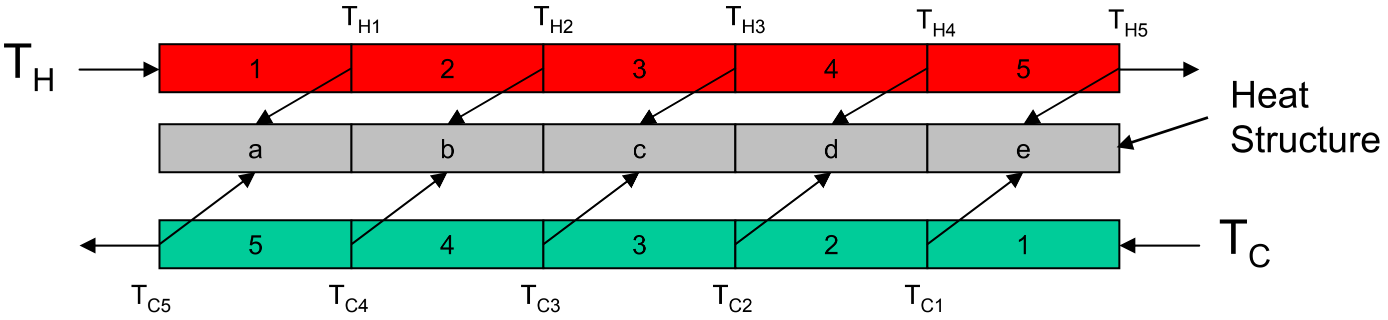
Counter Flow Heat Exchangers

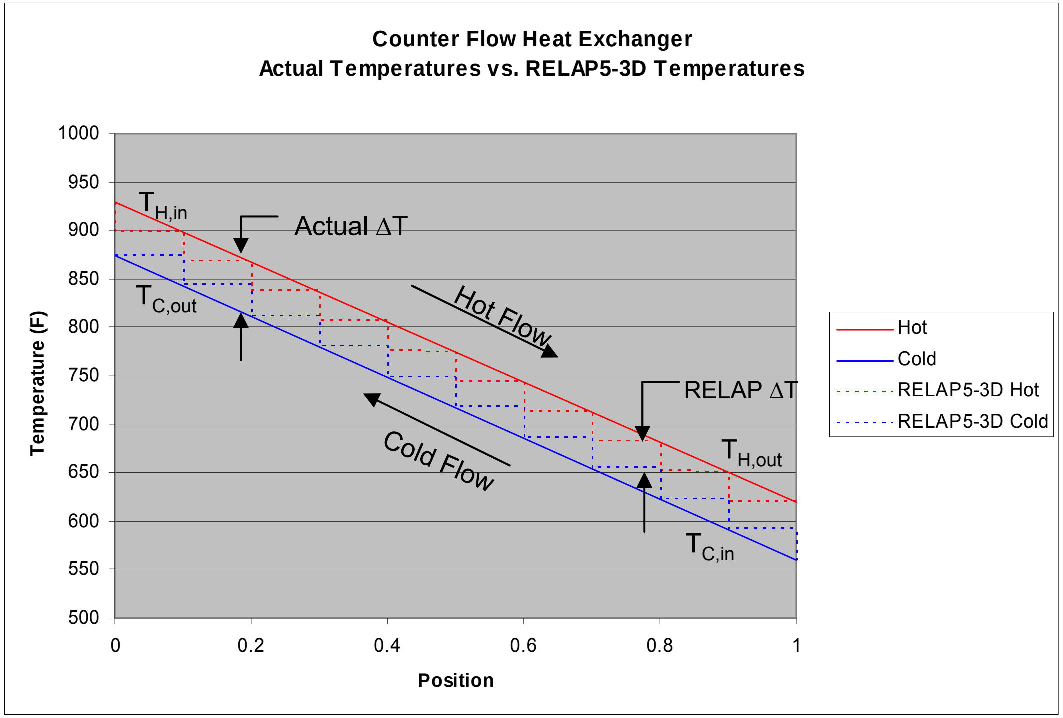


Modeling Counter-Flow Heat Exchangers with Control Volume Codes

- 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 ΔT applied across the heat structure
- Error inversely proportional to number of sub-volumes
- Current wall temperature coupling imposes a lower sub-volume limit

PRE-DECISIONAL - For planning and discussion purposes only

Correcting Temperature Error

$$Q = UA\Delta T$$

Correct the Heat Transfer

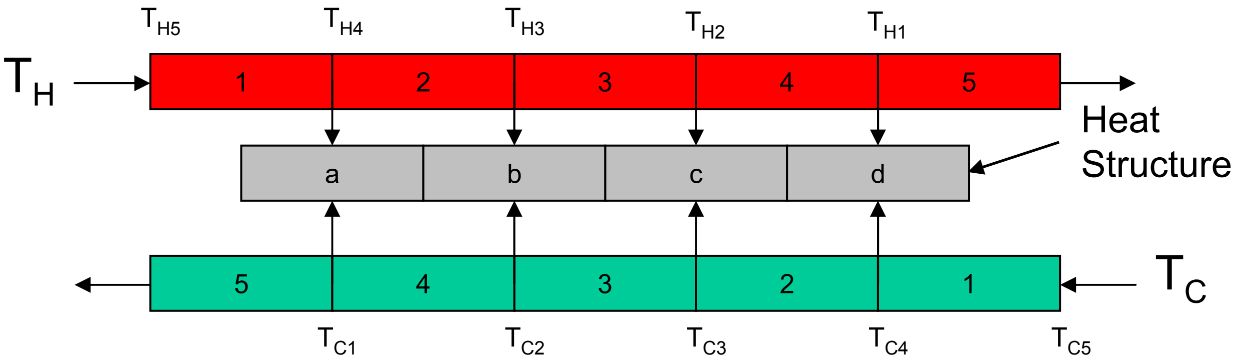
- Use code multipliers to artificially increase U
  - May alter transient behavior
  - Diminishing returns as number of control volumes is decreased
  - All codes may not have this capability
- Arbitrarily increase A
  - May alter transient behavior
  - Diminishing returns

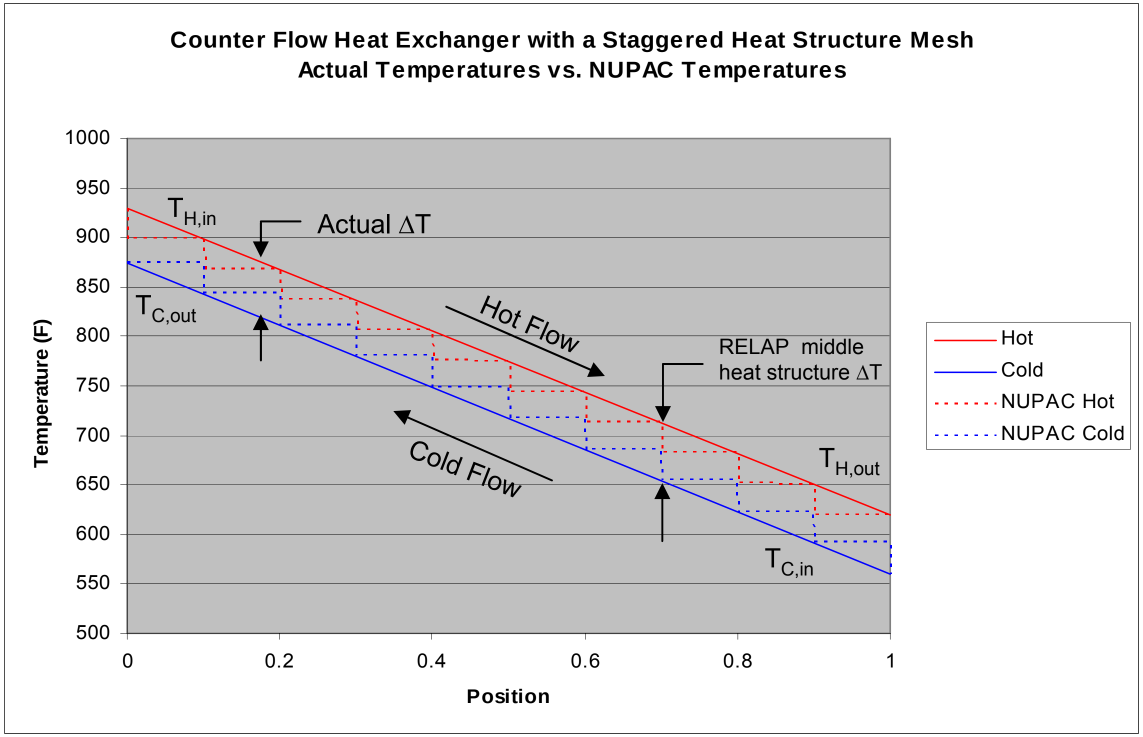
Minimize the ΔT Error

- 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%

PRE-DECISIONAL - For planning and discussion purposes only

Staggered Mesh Solution

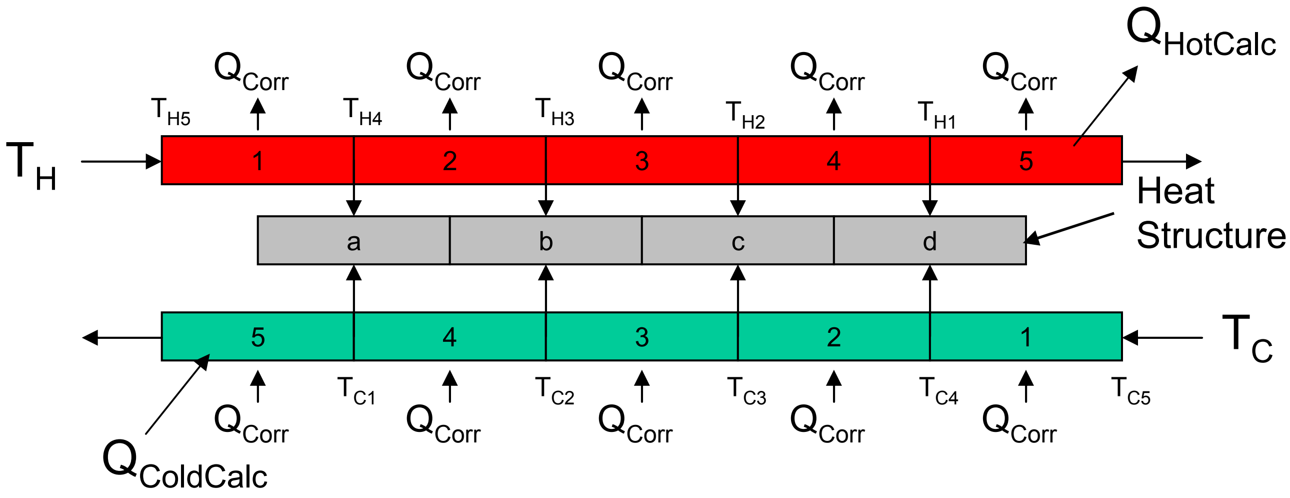




- Wall temperature boundary conditions applied from same axial plane
- Eliminates error introduced into the ΔT applied across the heat structure
- Does not account for heat structure ends

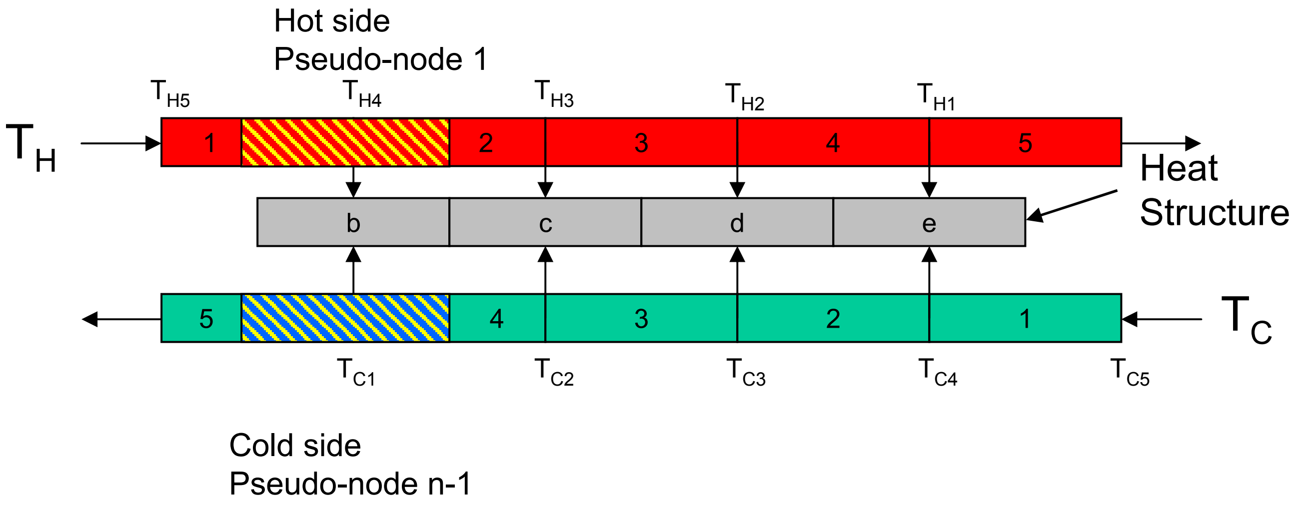
PRE-DECISIONAL - For planning and discussion purposes only

Accounting for End Volumes



- 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 ½ 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

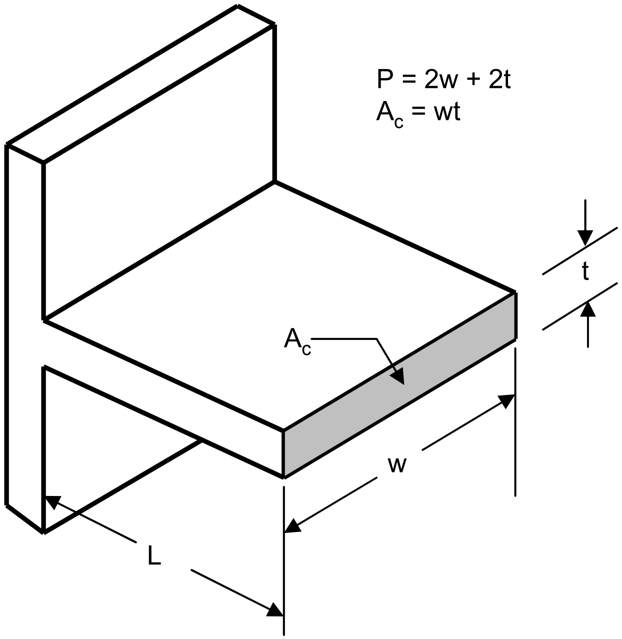
Limitations

- 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



Temperature Effectiveness:

$$\eta_0 = 1 - \frac{A_f}{A} \cdot \left(1 - \eta_f\right)$$

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.

PRE-DECISIONAL - For planning and discussion purposes only

Heat Convection Coefficient Correlations

- Two constant Nusselt Number laminar correlations available in RELAP5-3D
  - Exact solution for circular tubes (Sellars, Tribus, and Klein)

    $$Nu = 4.36$$

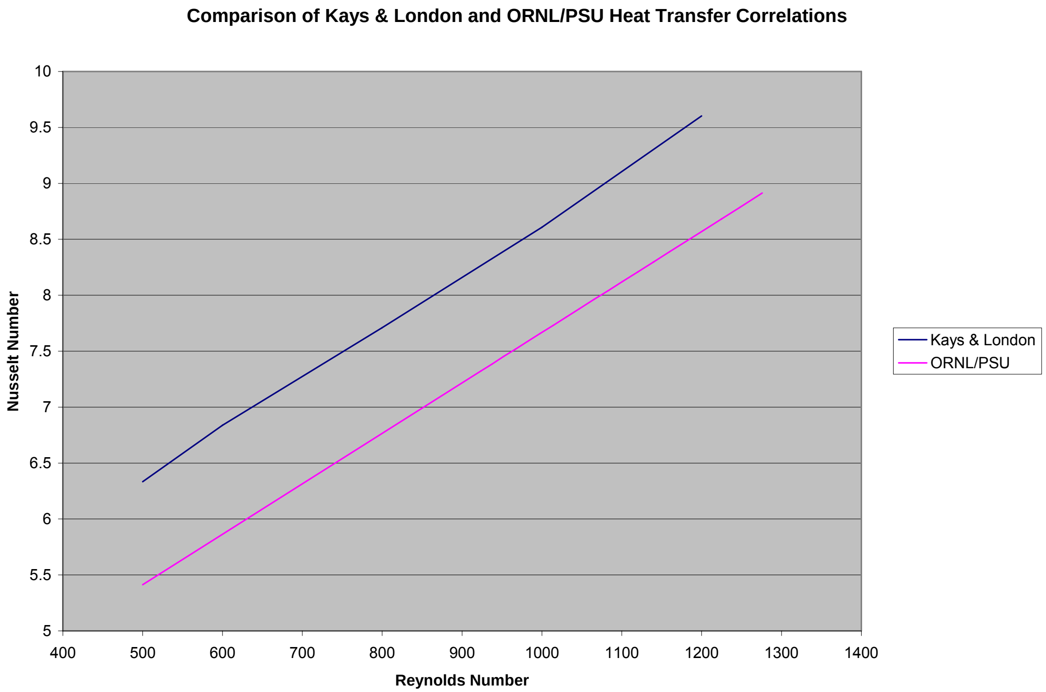
  - Exact solution for large aspect ratio flat plates (ORNL)

    $$Nu = 7.63$$

  - Flat plate solution more accurately represents the compact heat exchangers
- RELAP5-3D also has a Reynolds Number dependency relation for laminar flow (PSU)

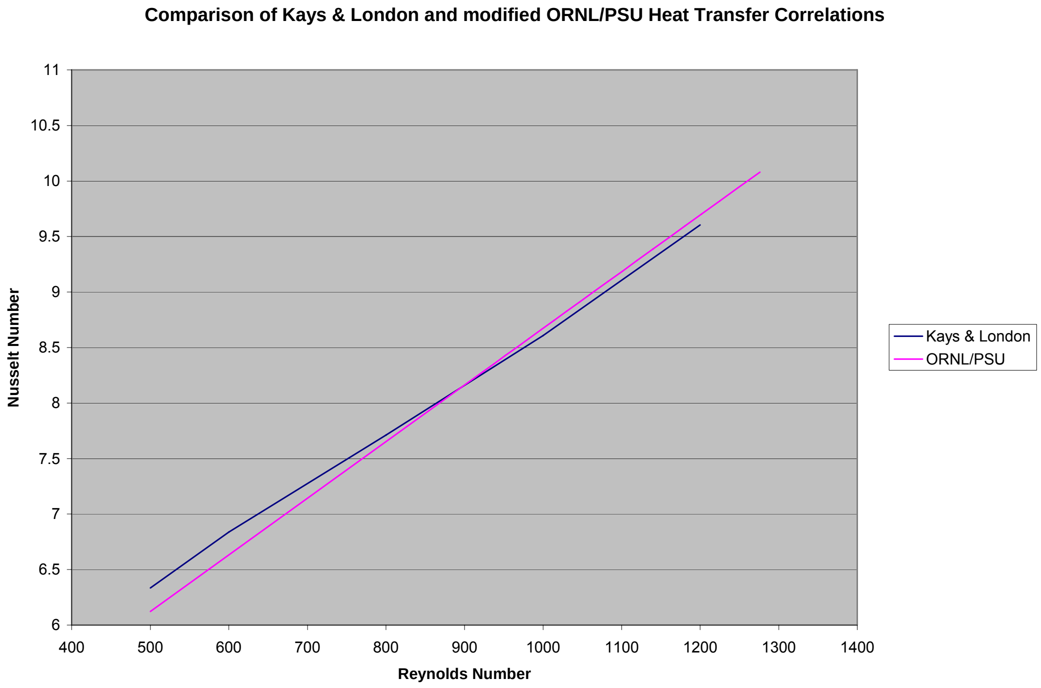
$$\mathrm{Nu}_{\mathrm{lam}}(\mathrm{Re}) = \mathrm{Nu}_{\mathrm{analytic}}\left(0.414 + 5.91 \cdot 10^{-4} \cdot \mathrm{Re}\right)$$

ORNL/PSU Correlation vs. Kays & London



- 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

PRE-DECISIONAL - For planning and discussion purposes only

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

$$Nu = \frac{hx}{k} = 0.332\,\mathrm{Re}^{\frac{1}{2}}\,\mathrm{Pr}^{\frac{1}{3}}$$

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

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

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

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

$$\boxed{\frac{\bar{h}}{h(L)} = \frac{2\left(0.332k\left(\frac{\rho u}{\mu}\right)\mathrm{Pr}^{\frac{1}{3}}\left[L^{-\frac{1}{2}}\right]\right)}{0.332k\left(\frac{\rho u}{\mu}\right)^{\frac{1}{2}} L^{-\frac{1}{2}}\,\mathrm{Pr}^{\frac{1}{3}}} = 2}$$

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

Results

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

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