Complex Geometry Creation and 2-D Turbulent Conjugate Heat Transfer Modeling

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Outline of the Presentation

• Creation of High Flux Isotope Reactor (HFIR) Fuel Plate Involute Geometry

• Data Interpolation for Use in Simulations

• Comparison of COMSOL Results with HFIR Legacy Steady State Heat Transfer Code

• Creation of a More Physically Accurate 2-D Thermal-Hydraulic Model of the HFIR
Isometric View of the HFIR Core

HFIR - Pressurized Water Reactor

Physically small reactor core
OD 34.3 in.; Height 31.1 in.

85 kW Thermal
HFIR fuel elements - heat removal requires large surface area; high surface-to-volume ratio; plate thickness and flow channels as thin as possible

154 kW heat generation per inner plate
Fuel plates are involute shaped

- Plate thickness and flow cross-sectional areas are constant in the radial direction.
- In HEU fuel plates, fuel is radically distributed to yield constant neutron flux in radial distribution.

Flow Channels are long and narrow

- Width, $W = 0.050$ in.
- Length, $L = 24$ in.
- Aspect Ratio $= W/L = 480$

ReDh $= 69,907$  \[\Rightarrow\]  Turbulent flow

- Water inlet Temperature $= 129.9 \ ^\circ F (327 \ K)$
- Inlet pressure $= 482.7$ psia $(3.233 \ MPa)$
- Core Pressure drop $= 105$ psi $(0.724 \ MPa)$
Geometry Parameterization

- The HFIR involute of circle fuel plate geometry is created as a function of the generating circle radius, \( r \), and the subtended angle, \( \theta \).

- The low enriched Uranium (LEU) fuel contour is created as a function of \( \theta \) relative to the base involute curve.

- In essence, parametric curves within parametric curves!

Reference: HFIR Drawing D-42122A
Assumptions used in the Legacy HFIR SSHTC*

- HFIR fuel plate geometry is modeled as a flat plate instead of as the involute of a circle
- Axial and span-wise (i.e. arc-length along the involute) thermal energy diffusion is suppressed in the fuel plates
- A Nusselt number correlation is used to specify a local convection coefficient
- The bulk water temperature is found using “suitable” heat balances, therefore no bulk flow of water is needed in the simulation

Comparison of HFIR SSHTC Clad Surface Heat Flux with COMSOL Results
Comparison of HFIR SSHTC Clad Surface Temperature with COMSOL Results

![Graph showing comparison of HFIR SSHTC Clad Surface Temperature with COMSOL results. The graph plots Clad Surface Temperature [K] against Axial Position [m]. The graph includes data points for both SSHTC Clad Surface Temp and COMSOL Clad Surface Temp, with a flow direction indicated.](image-url)
Two-Dimensional Conjugate Heat Transfer Capabilities of COMSOL of Interest Regarding this Study

- Conduction and convection modes of heat transfer may be simulated simultaneously.
- Laminar or turbulent convection simulation environments are available.
- Several turbulent flow models are available including the $k$-$\varepsilon$ Reynolds averaged Navier-Stokes (RANS) closure model, the low Reynolds number (LRN) $k$-$\varepsilon$ model, and the Spalart-Allmaras model.
Schematic of the 2-D Axial Slice Geometry used in COMSOL Simulations
COMSOL Relaxation of Assumptions used in the HFIR SSHTC

• Well known and established turbulence models are used to simulate fluid flow in the conduction-convection physics.
• The convection coefficient is not specified in any way, instead it is determined by the physics of the problem.
• Bulk water temperature is also determined by the physics of the problem.
• For the 2-D models, axial conduction is allowed by specifying an isotropic thermal conductivity tensor in the material properties for the fuel plate components.
• Convergence criteria was set to $1 \times 10^{-6}$ in these simulations for the primitive variables ($u$, $v$, $p$, $k$, $\varepsilon$, $T$).
Global Mass and Energy Conservation Errors as a Function of Element Number for **LowRe k-epsilon Model**

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Over all energy balances for the LowRe k-epsilon Model were shown to be mesh independent.

The maximum error is less than 0.03%
Comparison of Clad Surface Temperature Distribution Results of SSHTC and COMSOL Model
Conclusions

• Created a self-contained 2-D multi-physics model using COMSOL without the ultra-conservative assumptions used in the SSHTC

• In this model the thermal energy can now diffuse in all directions through the plate material thus lowering the temperature levels relative to the SSHTC

• A more physically realistic, “best-estimate”, clad surface temperature is obtained due to axial diffusion of the thermal energy in the plate coupled with the turbulent flow simulation
Case A energy balance check: Schematic showing boundaries used in establishing global conservation of energy between the energy leaving the clad surface and the *net convected thermal energy*
Case B energy balance check: Graphical representation of the quantities used in the relative error in the conservation of energy between the *generated thermal energy* and the *net convected thermal energy*.
Case C energy balance check: Graphical representation of the quantities used in the relative error in the conservation of energy between the *generated thermal energy* and the *energy leaving the clad surface*.