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

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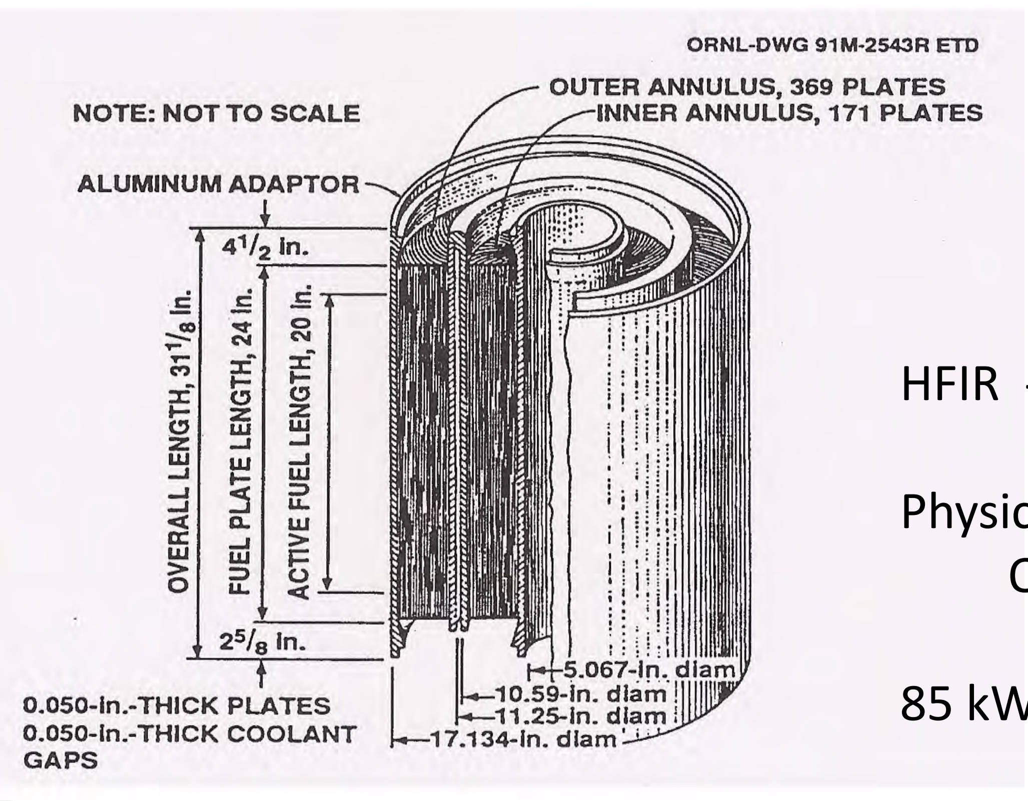
Outline of the Presentation

- 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

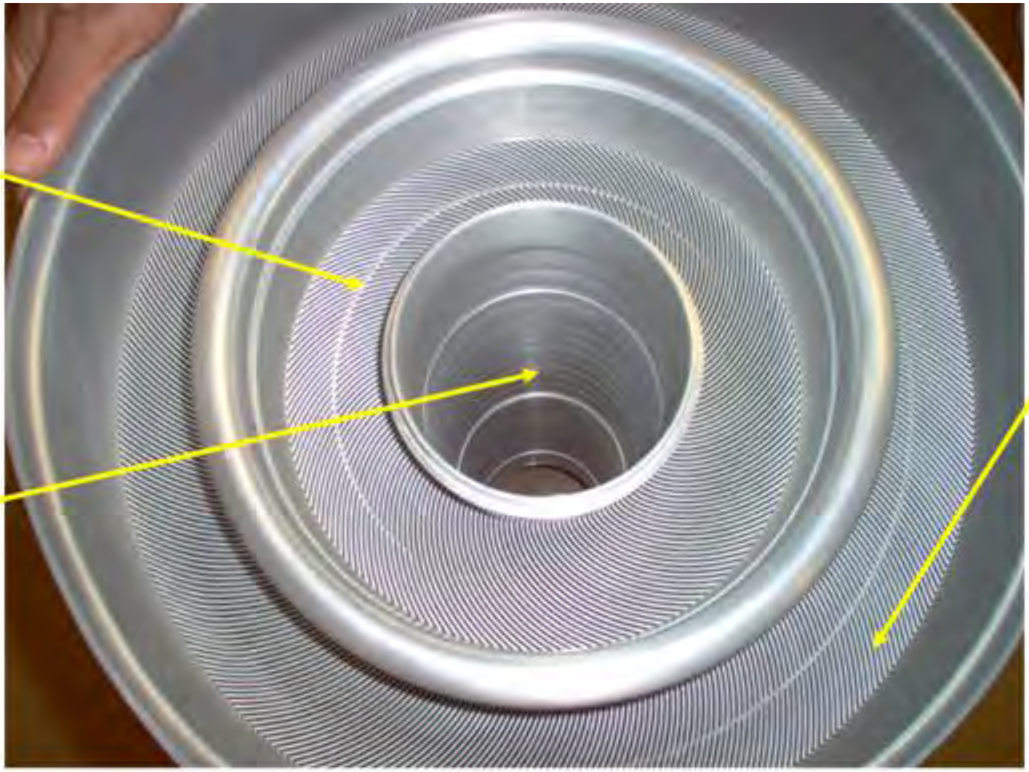


HFIR - Pressurized Water Reactor

Physically small reactor core

OD 34.3 in.; Height 31.1 in.

85 kW Thermal



171
Fuel
Plates

Flux
Trap
Region

369
Fuel
Plates

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.

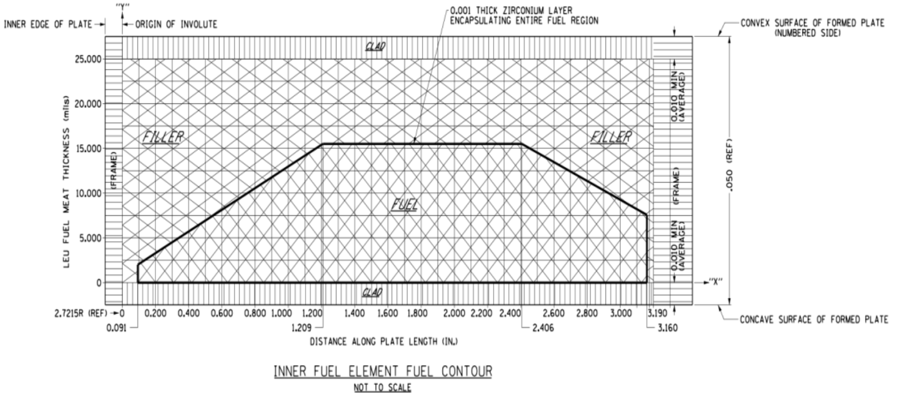
Flow Channels are long and narrow

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

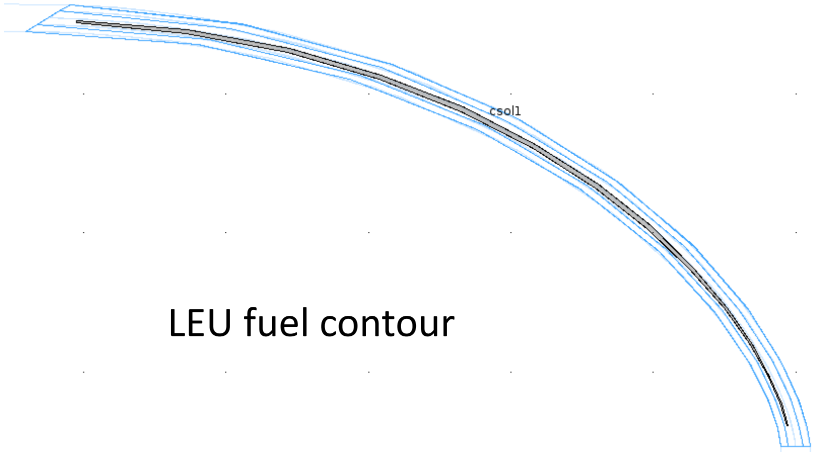
ReDh = 69,907	➔	**Turbulent flow**
Water inlet Temperature		129.9 °F (327 K)
Inlet pressure		482.7 psia (3.233 MPa)
Core Pressure drop		105 psi (0.724 MPa)

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, θ.
- The low enriched Uranium (LEU) fuel contour is created as a function of θ relative to the base involute curve.
- In essence, parametric curves within parametric curves !



HEU Inner Fuel Element Fuel Contour



LEU fuel contour

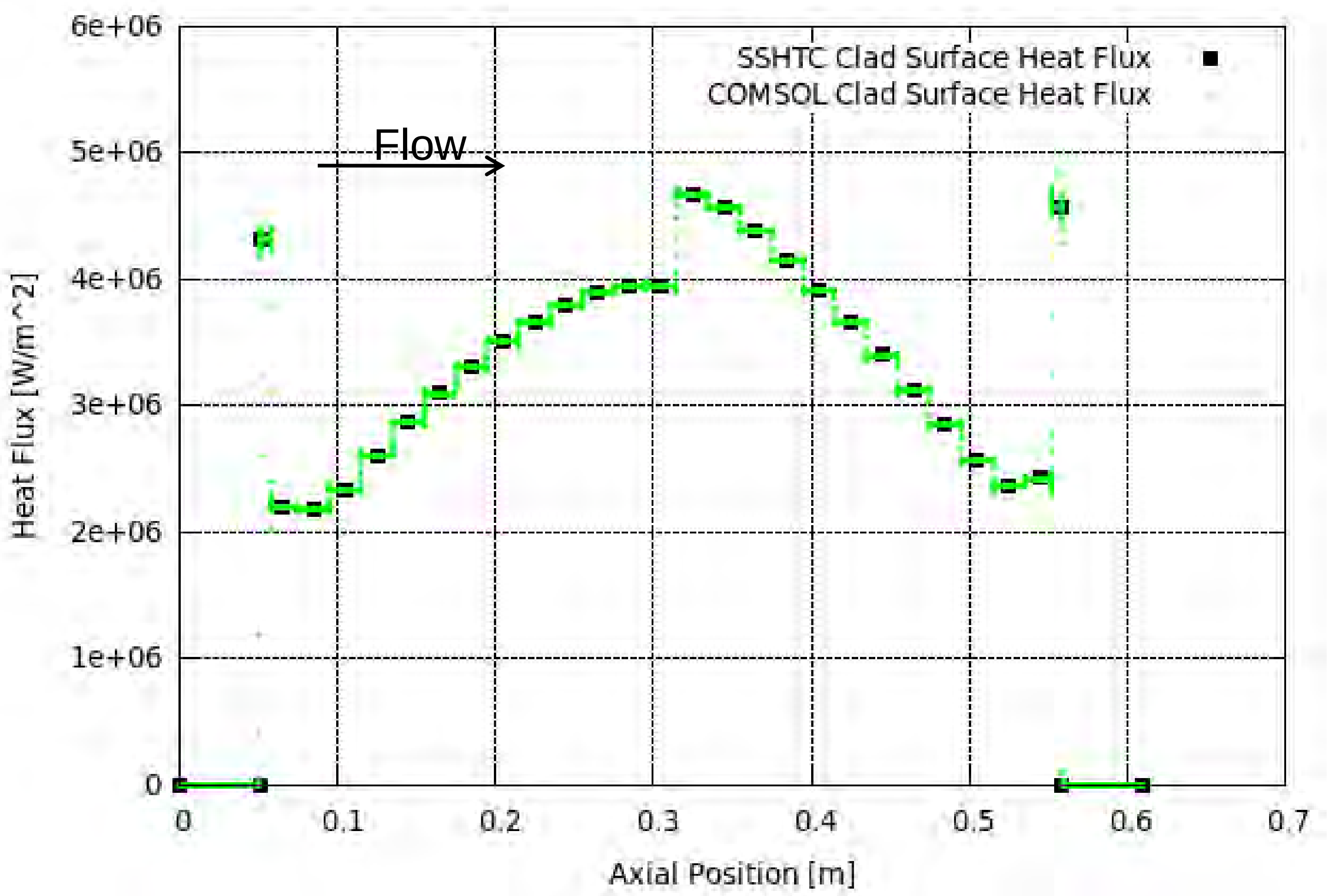
Reference: HFIR Drawing D-42122A

Assumptions used in the Legacy HFIR SSHTC*

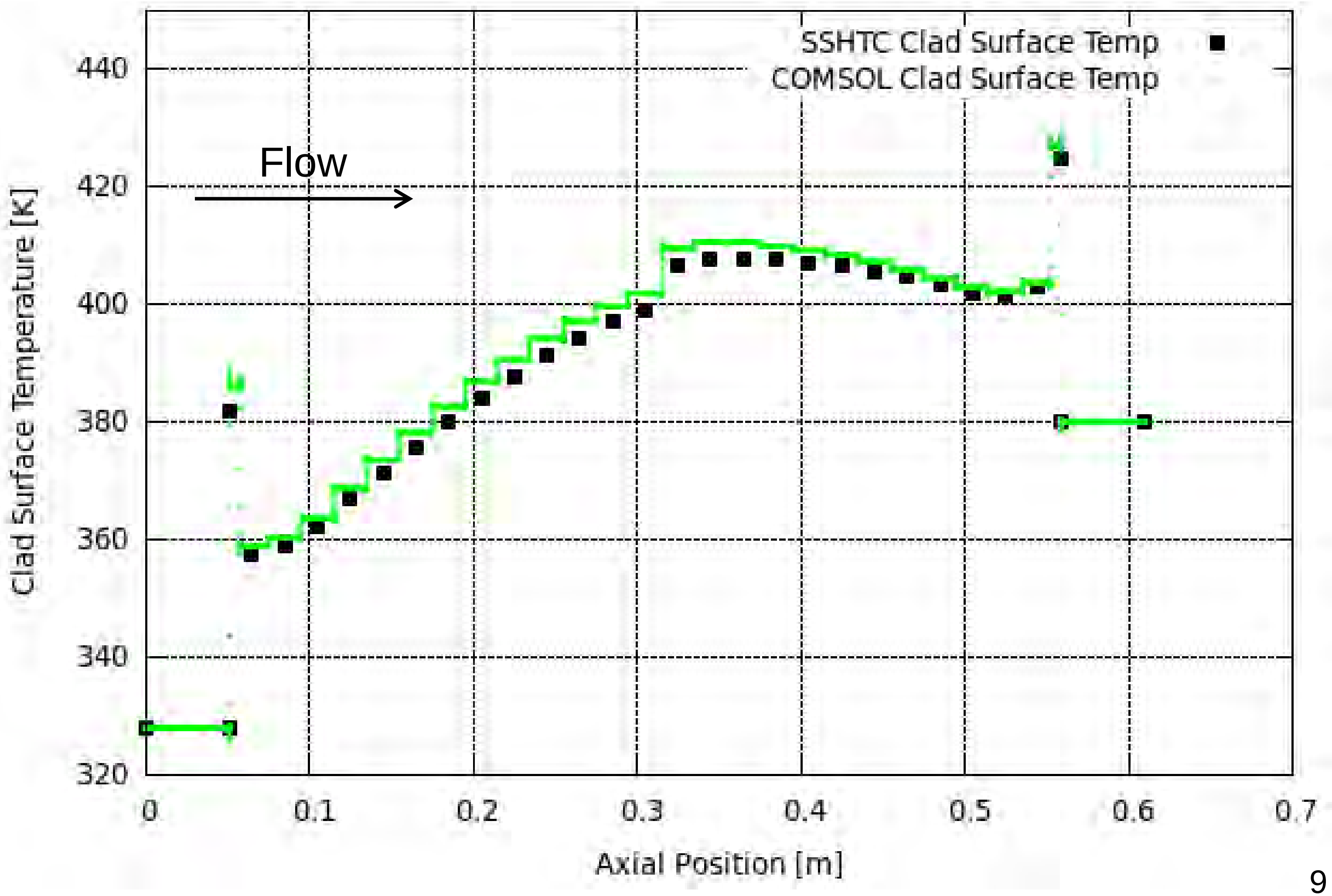
- HFIR fuel plate geometry is modeled as a flat plate instead of as the involute of a circle
- Axial and span-wise (i.e. arc-length along the involute) thermal energy diffusion is suppressed in the fuel plates
- A Nusselt number correlation is used to specify a local convection coefficient
- The bulk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

*Reference: McClain, Howard A. “*HFIR Fuel Element Steady State Heat Transfer Analysis Revised Version*” ORNL-TM-1904

Comparison of HFIR SSHTC Clad Surface Heat Flux with COMSOL Results



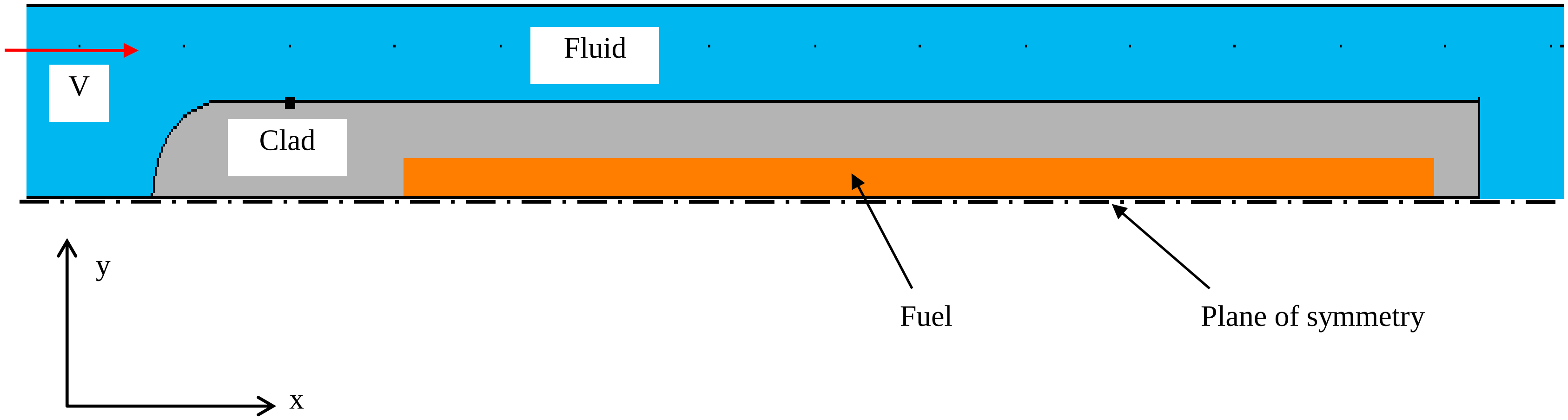
Comparison of HFIR SSHTC Clad Surface Temperature with COMSOL Results



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-ε Reynolds averaged Navier-Stokes (RANS) closure model, the low Reynolds number (LRN) k-ε 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 1×10^{-6} in these simulations for the primitive variables ($u, v, p, k, \varepsilon, T$)

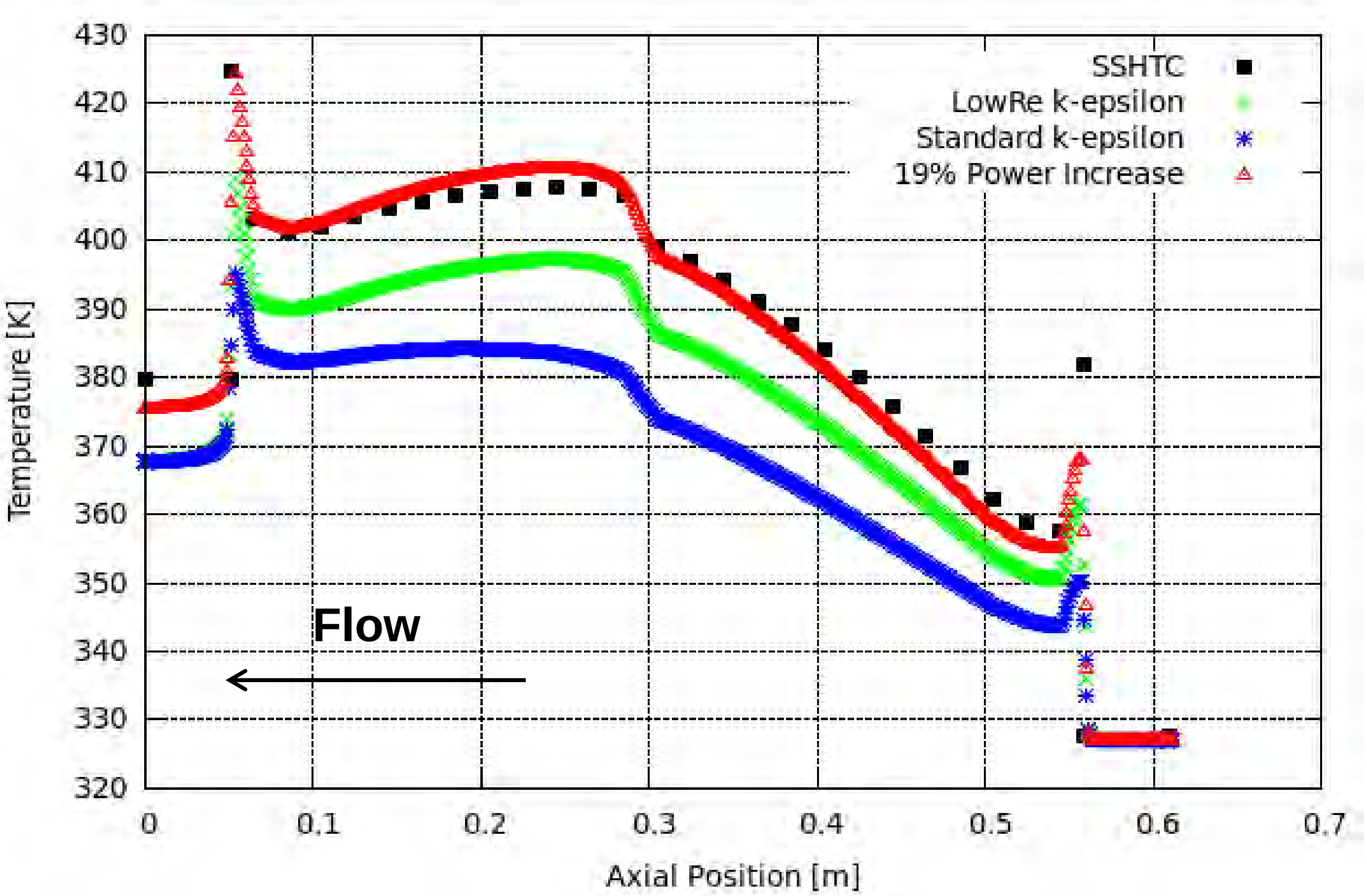
Global Mass and Energy Conservation Errors as a Function of Element Number for **LowRe k-epsilon Model**

Element #	A Relative Energy Error: Clad Surface to Net Energy Convection [%]	B Relative Energy Error: Generation to Net Energy Convection [%]	C Relative Energy Error: Clad Surface to Generation [%]	Relative Mass Error: Inlet to Outlet [%]
69532	6.4845E-01	7.5700E-02	5.7649E-01	0.0000E+00
75112	2.1490E-01	9.9050E-02	3.1463E-01	0.0000E+00
80332	1.7475E-02	4.0785E-02	2.3306E-02	0.0000E+00
85552	5.2390E-02	1.7475E-02	6.9902E-02	0.0000E+00
91132	5.8245E-03	1.7475E-02	1.1650E-02	0.0000E+00
96352	2.3302E-02	1.7475E-02	5.8251E-03	0.0000E+00
101932	4.0785E-02	1.7475E-02	2.3301E-02	0.0000E+00
107152	3.4957E-02	1.7475E-02	1.7475E-02	0.0000E+00
112372	3.4957E-02	1.7475E-02	1.7475E-02	0.0000E+00
117952	3.4957E-02	1.7475E-02	1.7475E-02	0.0000E+00

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



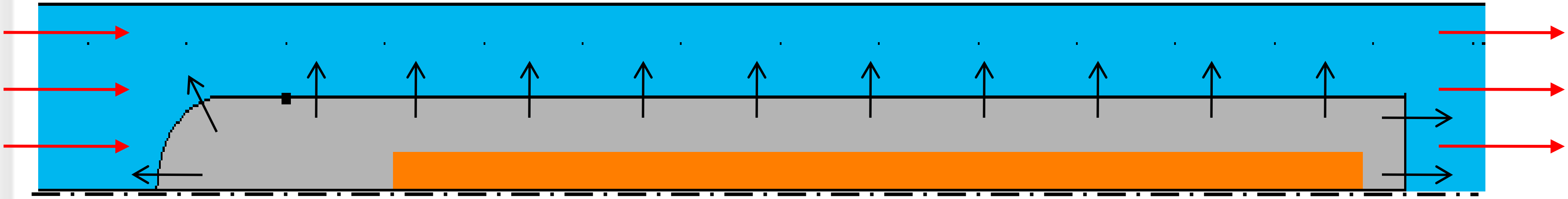
Conclusions

- 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

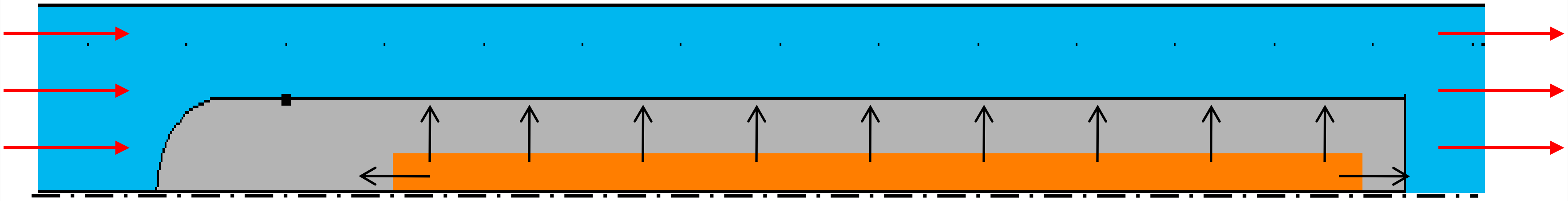
Questions

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*