Experimental Verification of Gas-Cooled T-tube Divertor Performance

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Overview

- **2D and 3D analyses have been performed to assess the thermal performance of helium-cooled T-Tube divertors.**
  - Quantified effect of changes in helium flow rate (400 g/s.m ±20%); inlet pressure (10 MPa ± 10%); Slot width (0.5 mm ± 0.1); and Jet-wall spacing (1.00 ± 0.25 mm) on thermal performance
  - Examined dependence of the calculated temperature distribution and pressure drop on the turbulence model used in the FLUENT(6.1) simulations (standard k-ε; idealized k-ε; RNG k-ε; wall enhancement; non-equilibrium wall function)

Overview (Contd.)

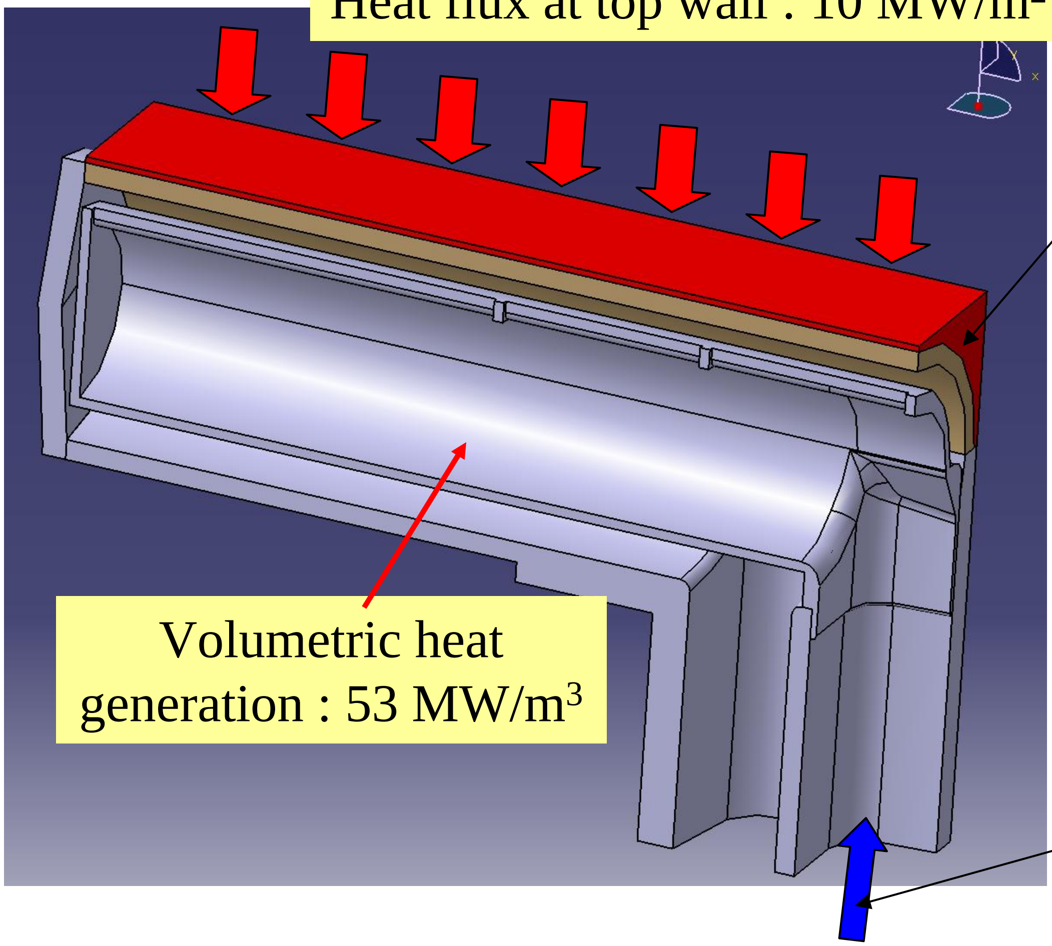
- **The numerical results indicate that:**
  - For heat fluxes up to 10 MW/m^2, the calculated temperatures at the nominal design and operating conditions are consistent with constraints dictated by material properties
  - The helium-cooled T-Tube divertor design is “robust” with respect to changes in geometry due to manufacturing tolerances, and/or mal-distribution of flow among divertor elements
  - Extremely high heat transfer coefficients (> 40 kW/m^2 K) were predicted near the stagnation point (directly opposite to the slot), thereby limiting the maximum temperatures

Objectives

- **The calculated local heat transfer coefficients (> 40 kW/m^{2}K) are "outside the experience base" for gas-cooled engineering systems. Therefore, the objectives of this investigation are:**
  - Design, construct, and instrument a test module which closely simulates the thermal-hydraulic behavior of the proposed helium-cooled T-Tube divertor
  - Experimentally measure the axial and azimuthal variations of the local heat transfer coefficient in the test module over a wide range of operating conditions
  - Perform *"a priori"* calculations to predict the wall temperature distribution and heat transfer coefficients for the test module using the same methodology used to analyze the actual T-Tube divertor performance
  - Compare the measured heat transfer coefficients with predicted values
  - Develop an experimentally-validated correlation for the local Nusselt Number for use in future design analyses of similarly-configured gas-cooled components

Simulation geometry (3D Model)

Heat flux at top wall : 10 MW/m^2



Volumetric heat generation : 53 MW/m^3

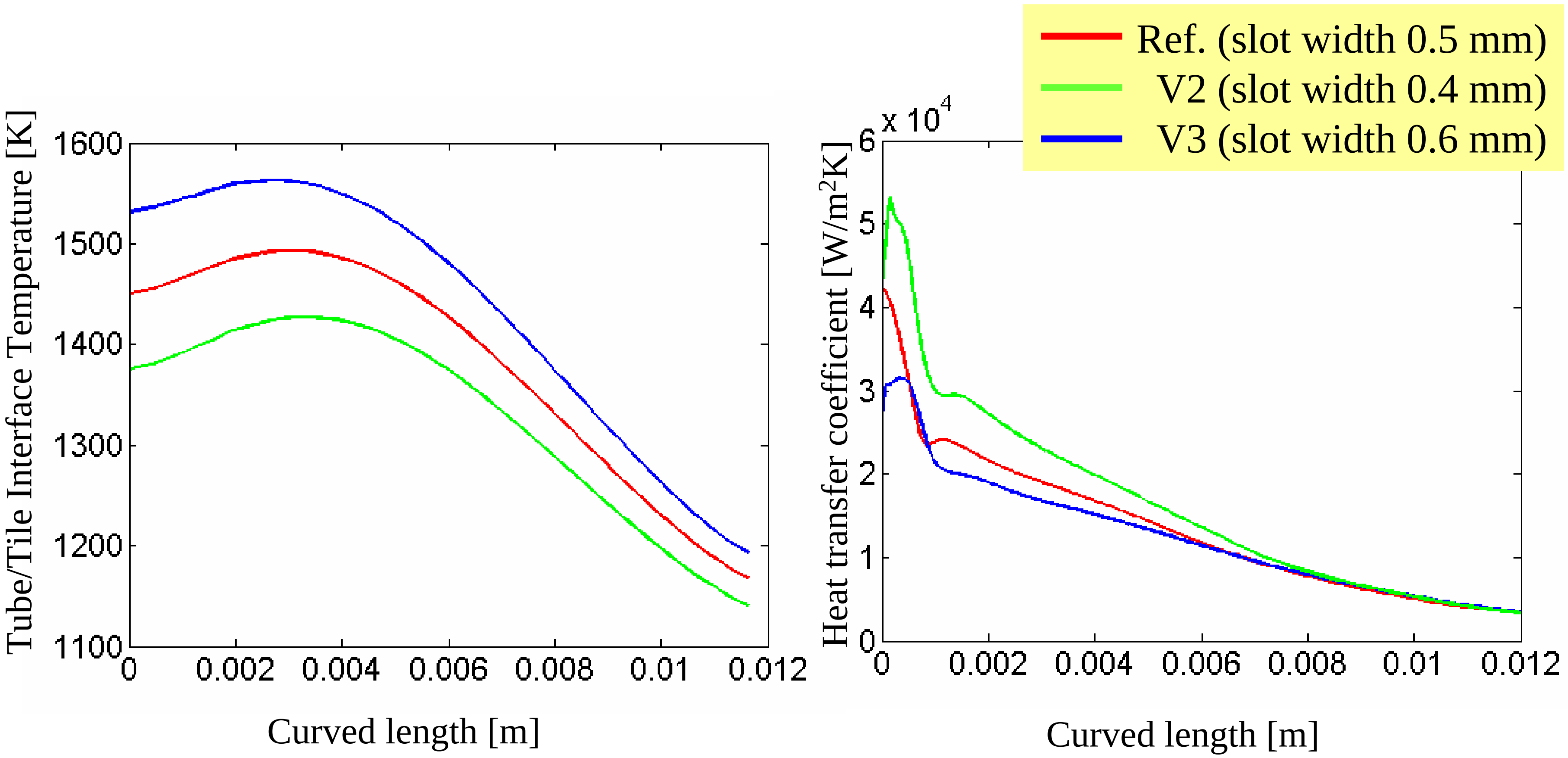
TUNGSTEN

Density : ρ=19,254 [kg/m^3]
Conductivity :
k=115-0.012×T [W/m·K]
Specific heat : c_p=138 [J/kg·K]

HELIUM

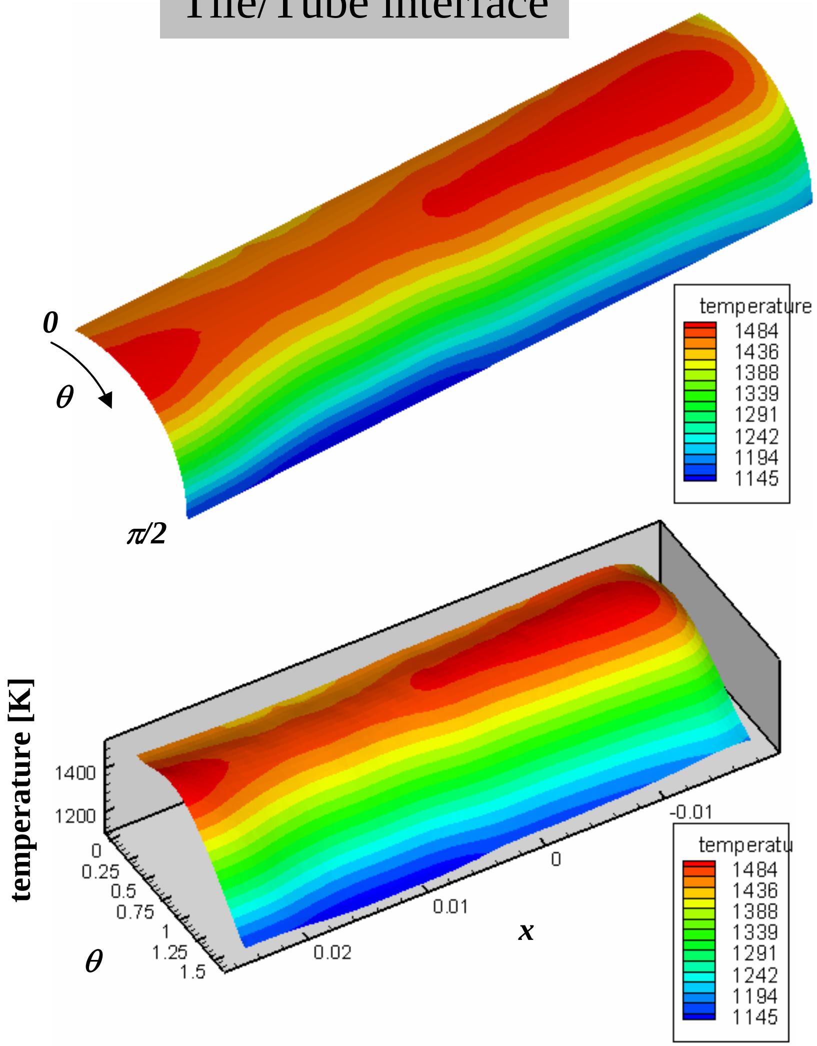
Mass flow rate : 8.5 g/s (= 0.2 kg/s.m)
Density : perfect gas law
Conductivity :
k=0.056+0.00031×T [W/m·K]
Specific heat : c_p=5,193 [J/kg·K]
Viscosity :
$\mu=4.5\times10^{-7}(T)^{0.67}$ [Pa·s]

Effect of Slot Width on Calculated Temperatures & Heat transfer Coefficient (2D)

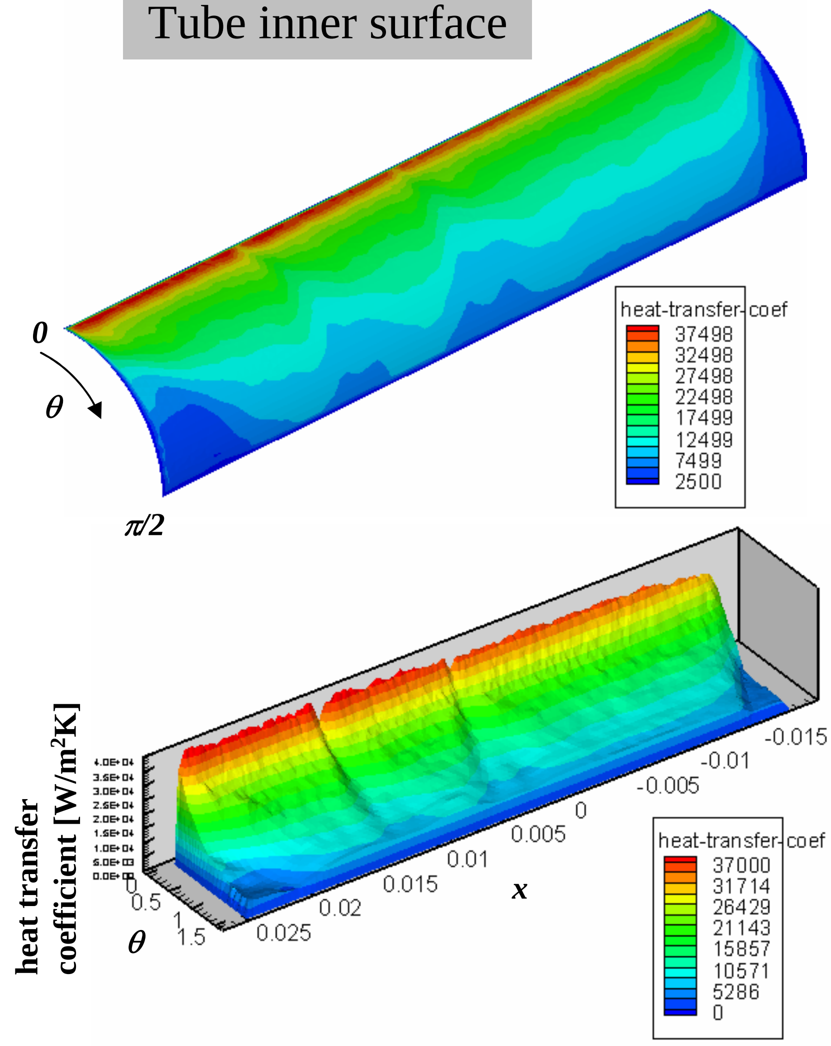


V1 : temperature and heat transfer coefficient

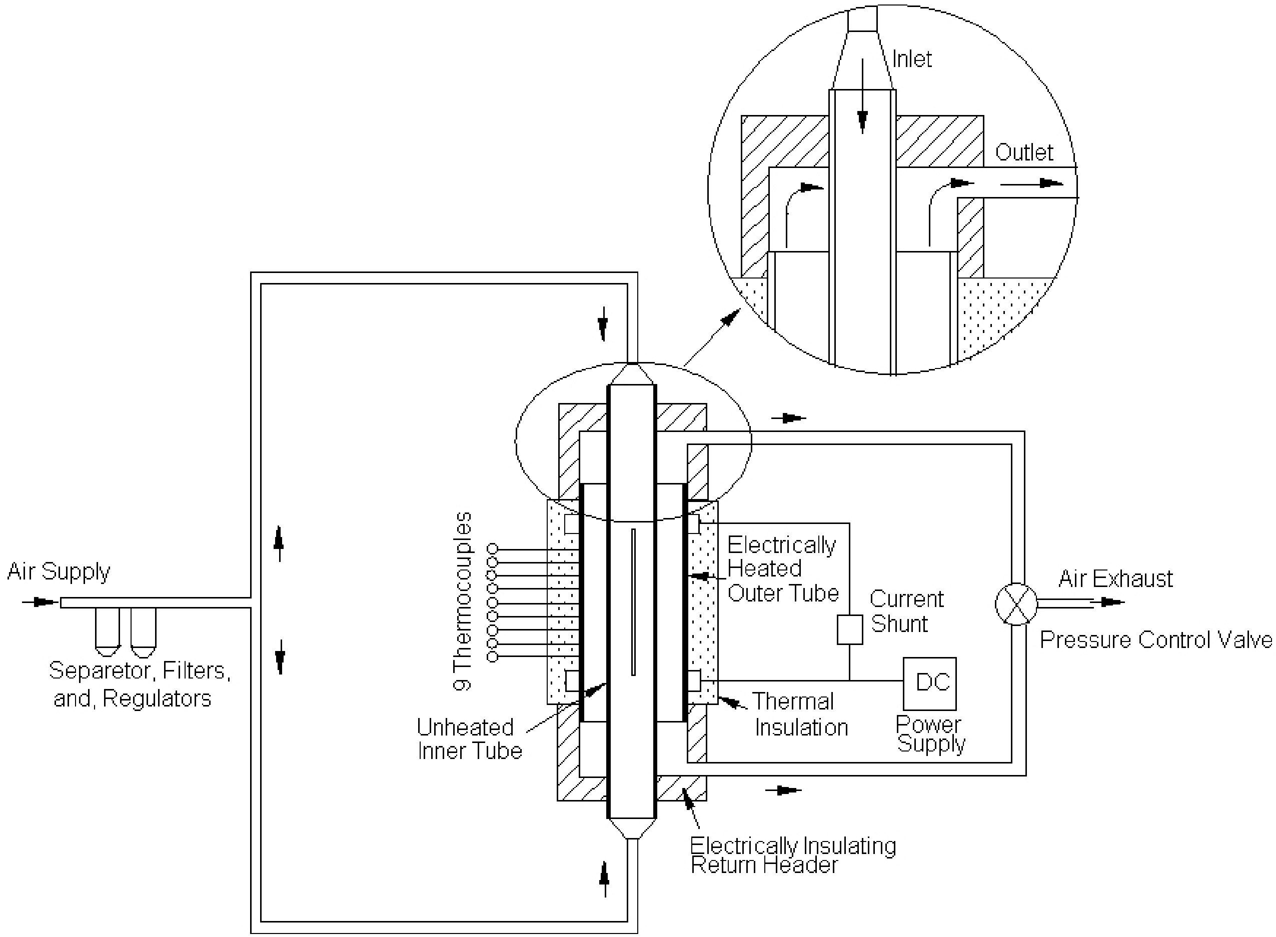
Tile/Tube interface



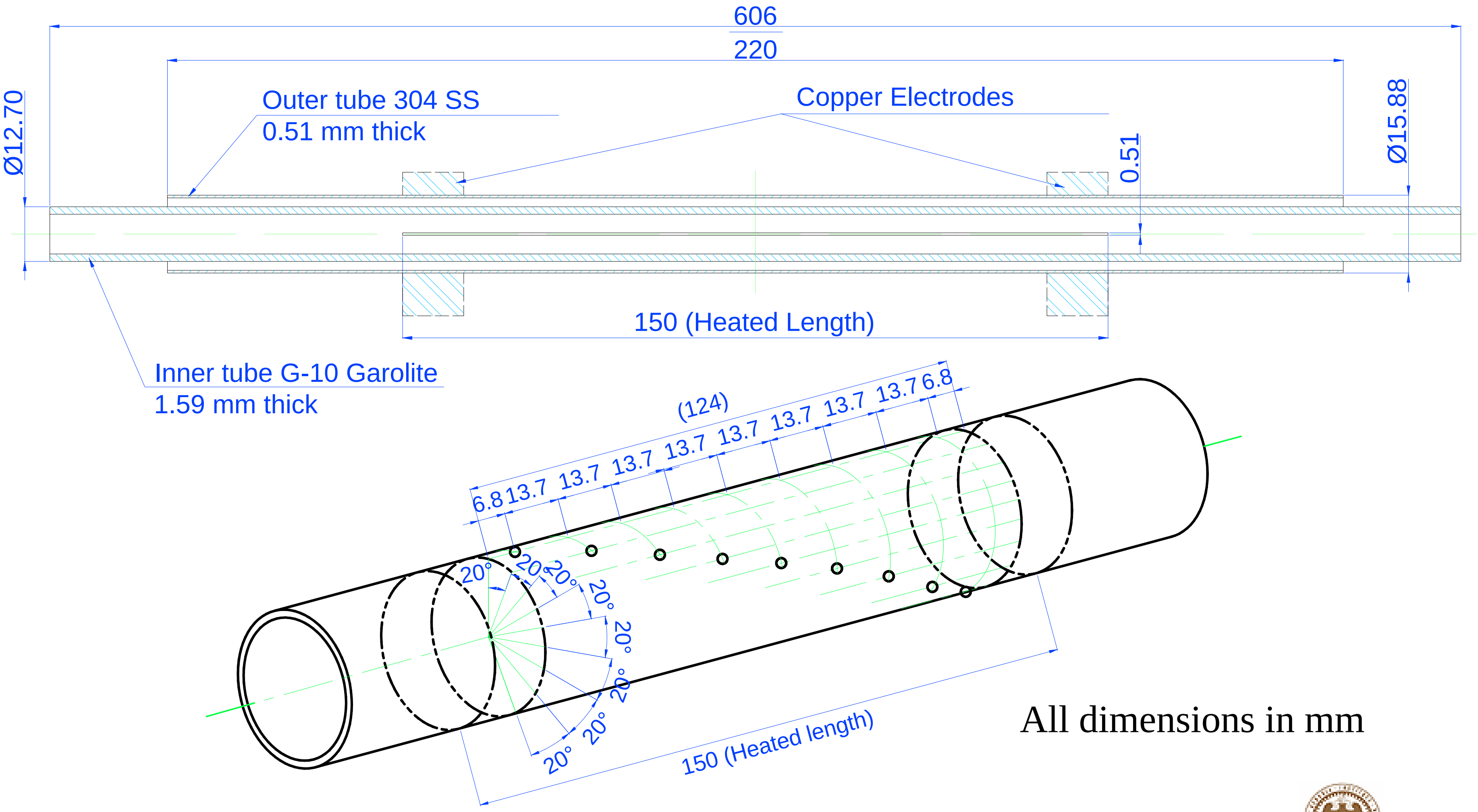
Tube inner surface



Experimental Flow Loop

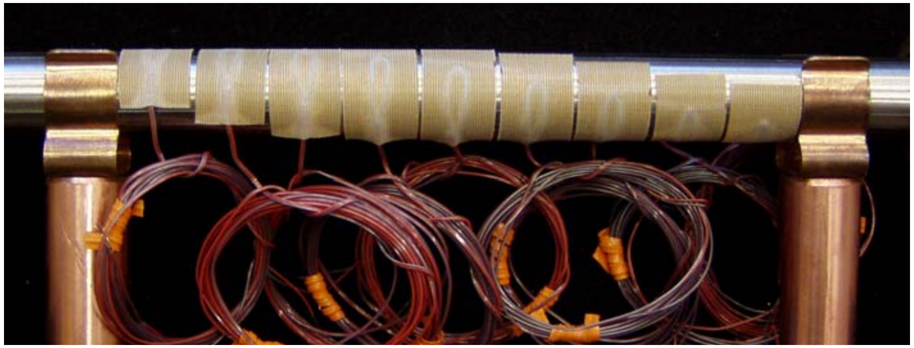


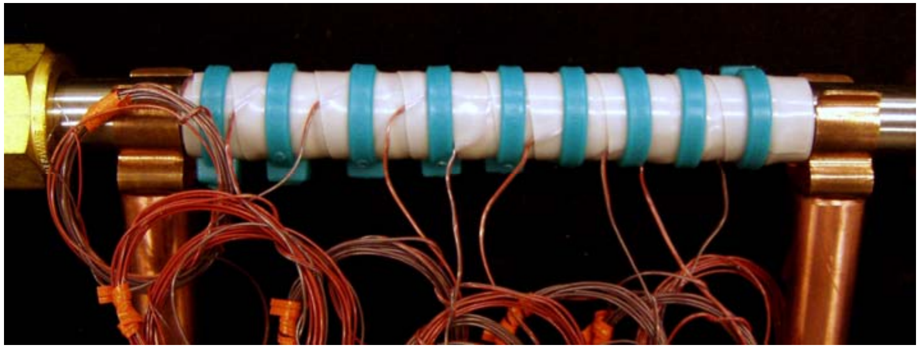
Experimental Test Section

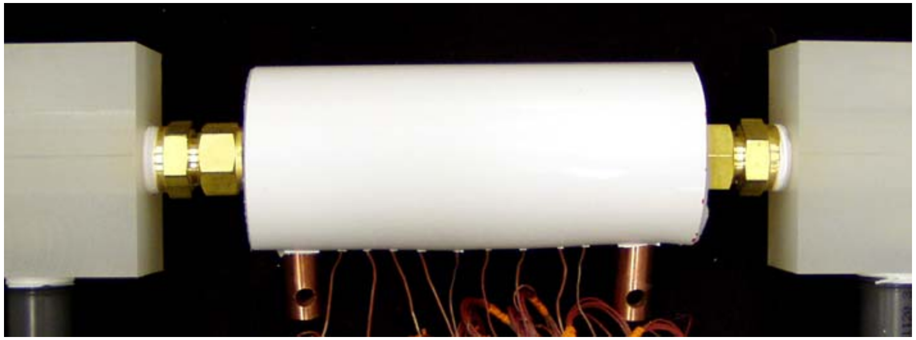


All dimensions in mm

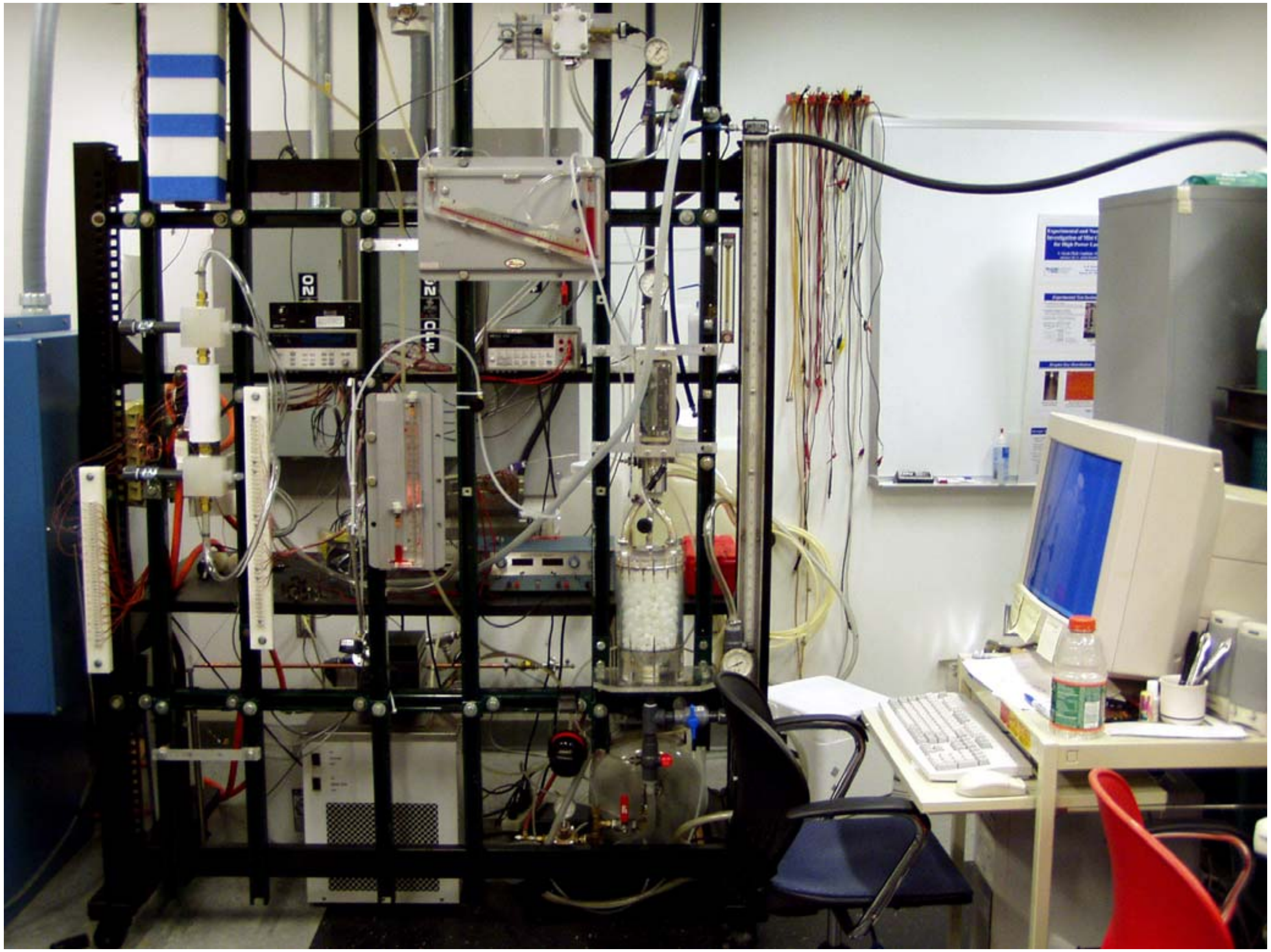
Experimental Test Section



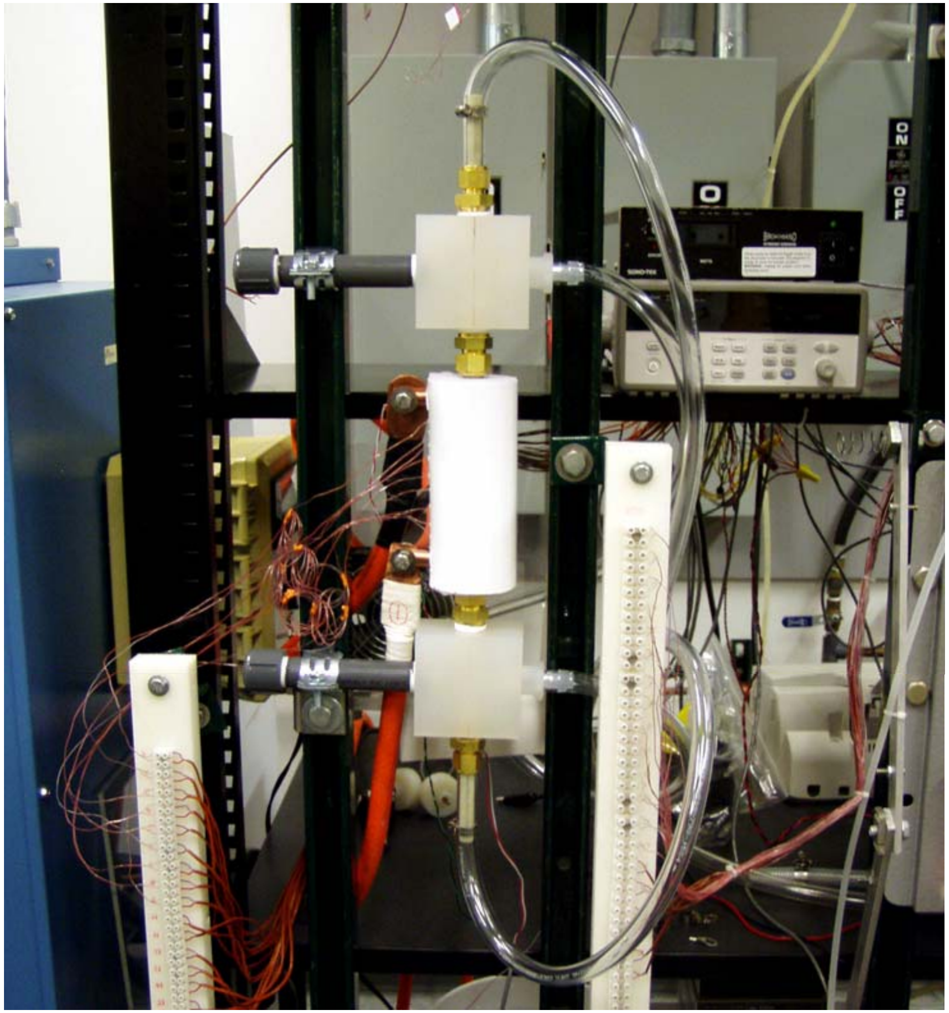




Experimental Flow Loop

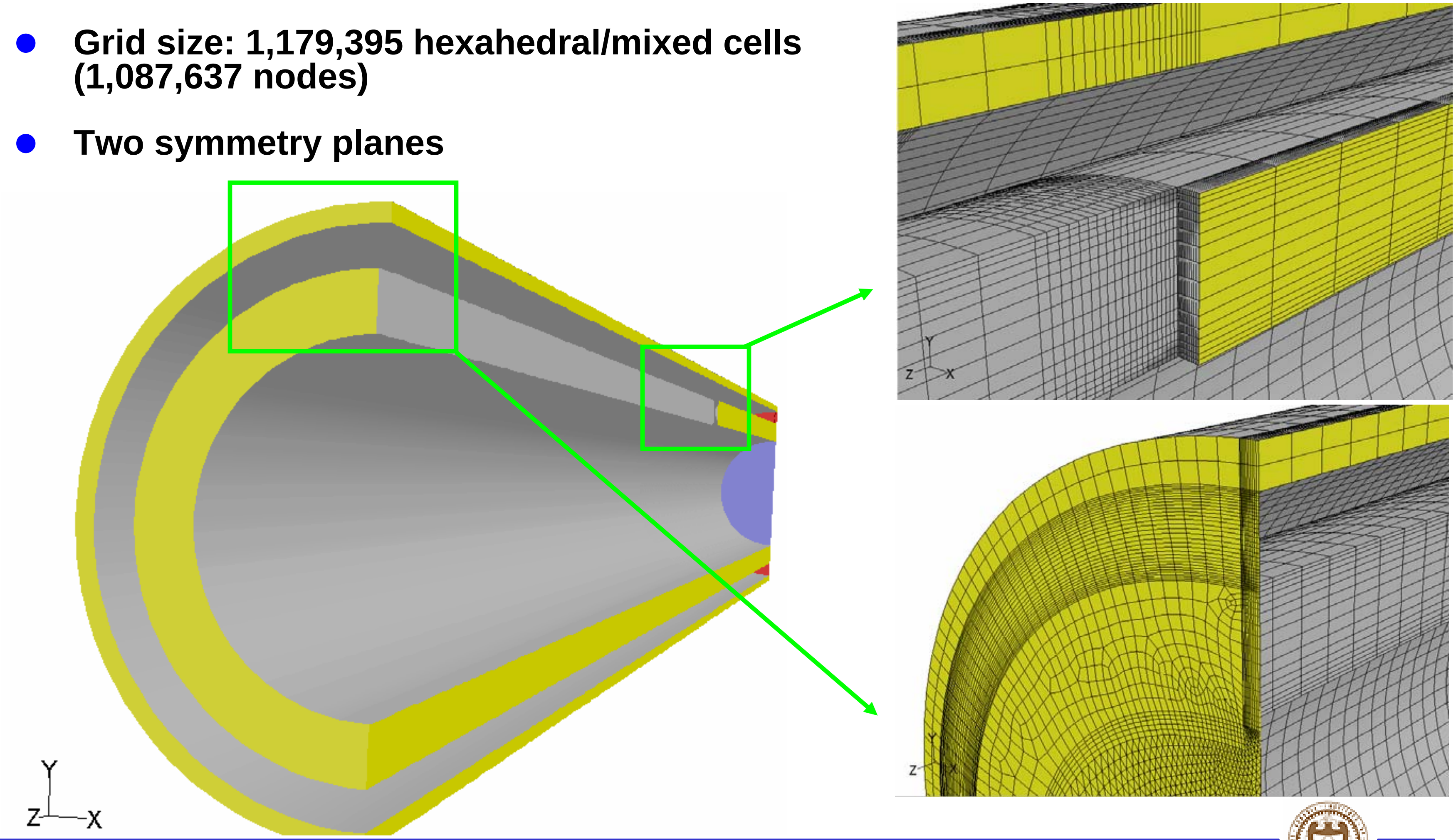


Experimental Flow Loop



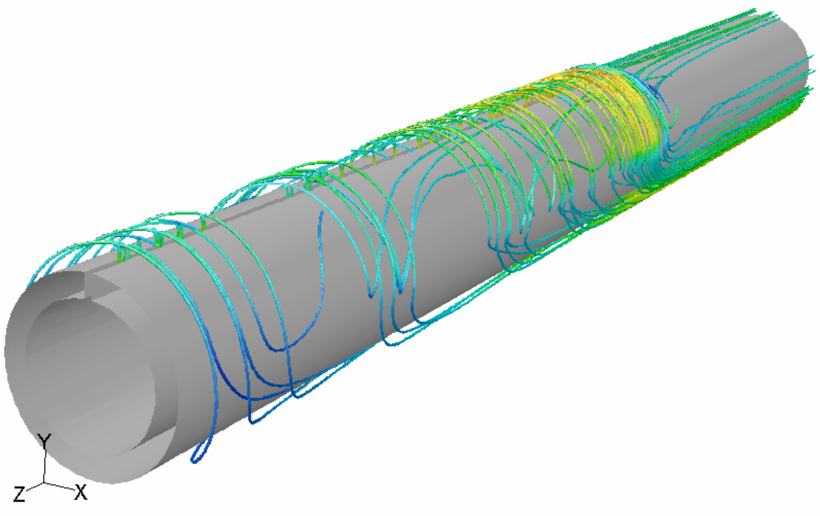
Predicted Performance - 3D Simulation

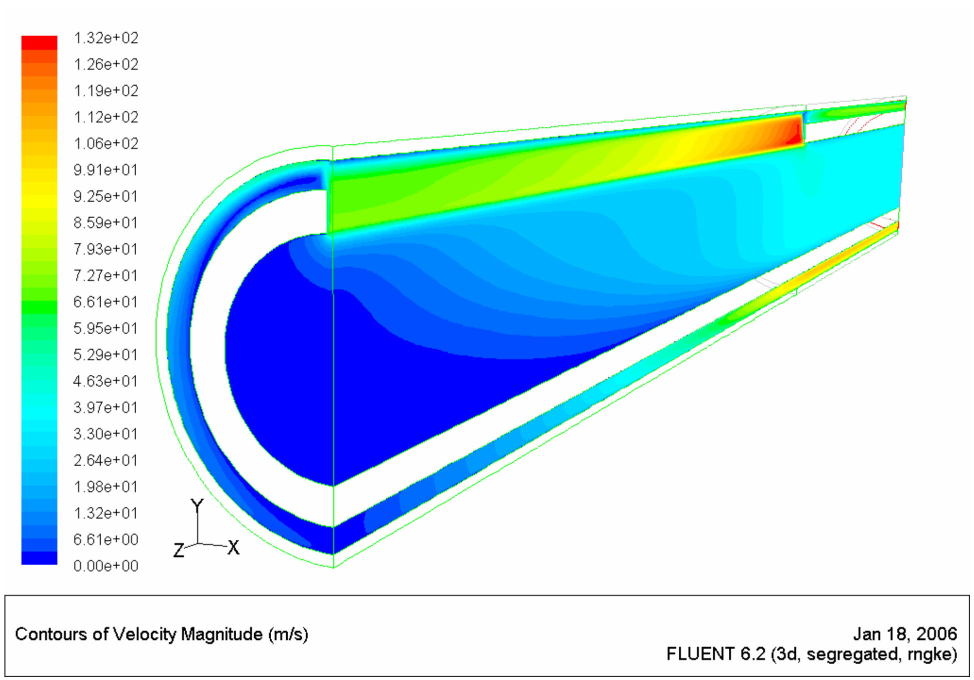
- **Grid size: 1,179,395 hexahedral/mixed cells (1,087,637 nodes)**
- **Two symmetry planes**



Predicted Performance – Flow field

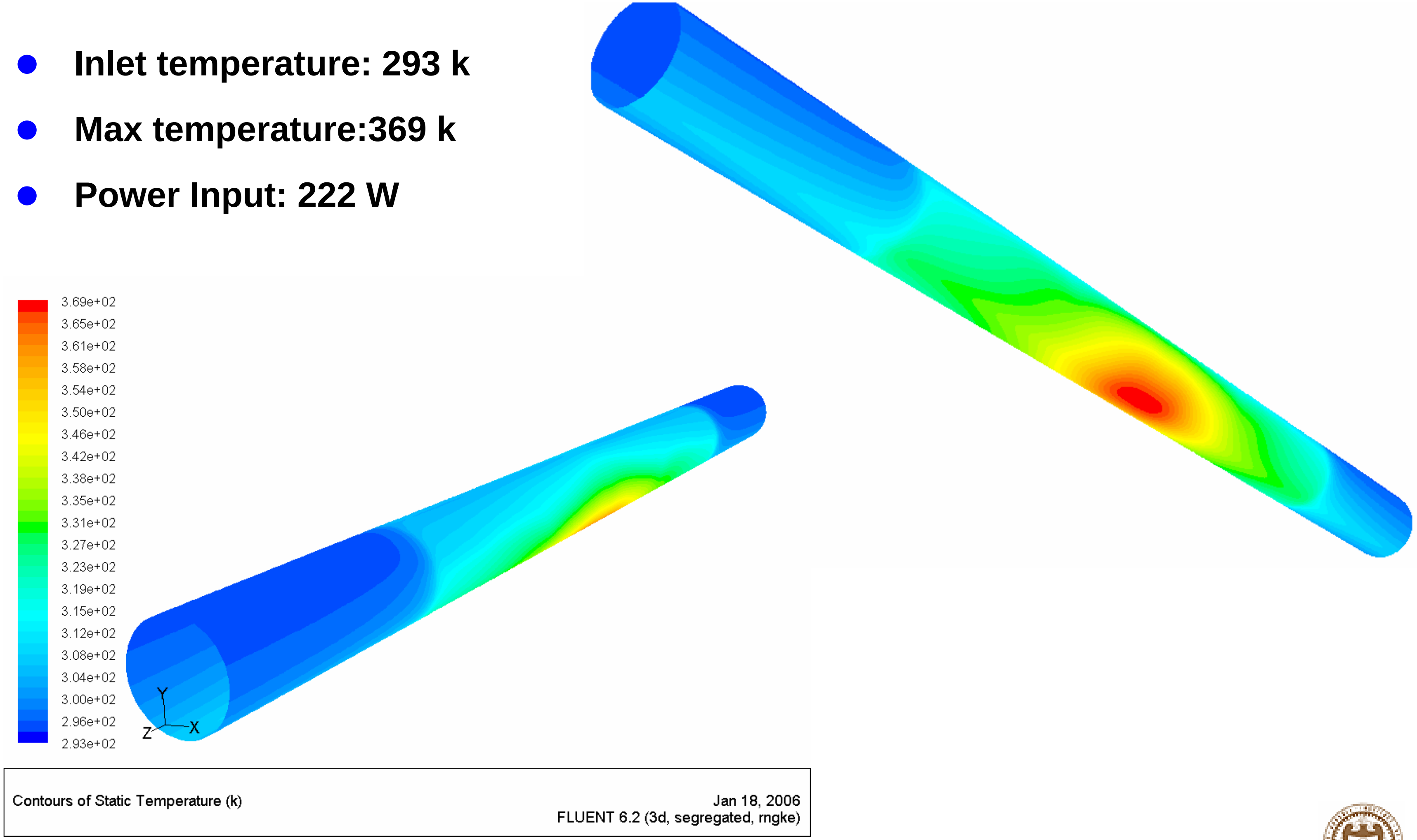
- **Max velocity: 134 m/s**
- **Operating pressure: 100 PSI (0.69 MPa)**
- **Pressure drop: 9 PSI (62053 Pa)**





Predicted Performance – Temperature

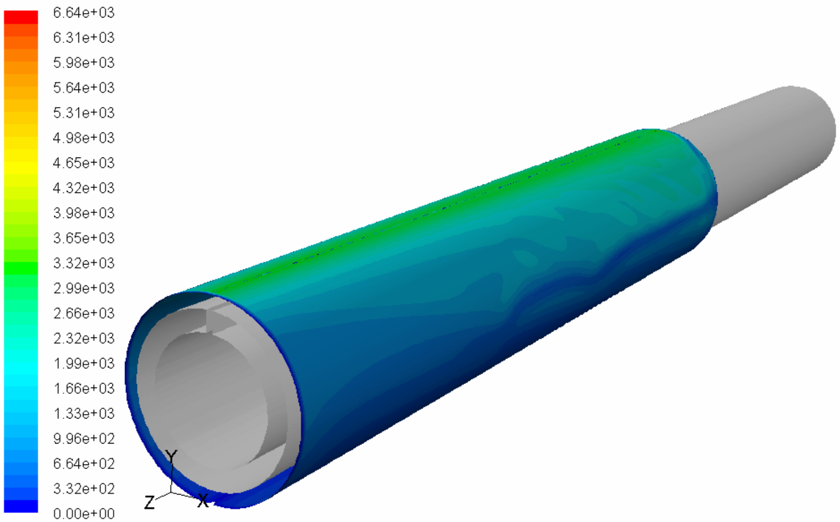
- **Inlet temperature: 293 k**
- **Max temperature:369 k**
- **Power Input: 222 W**



Predicted Performance – Heat Transfer

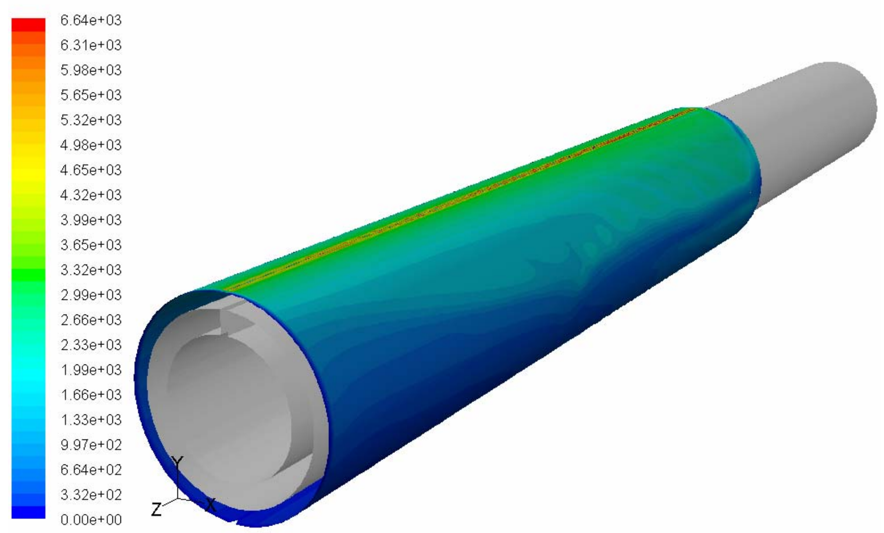
- **Max Heat Transfer Coefficient:**

  3690 w/m^{2}k (Standard Wall Functions)



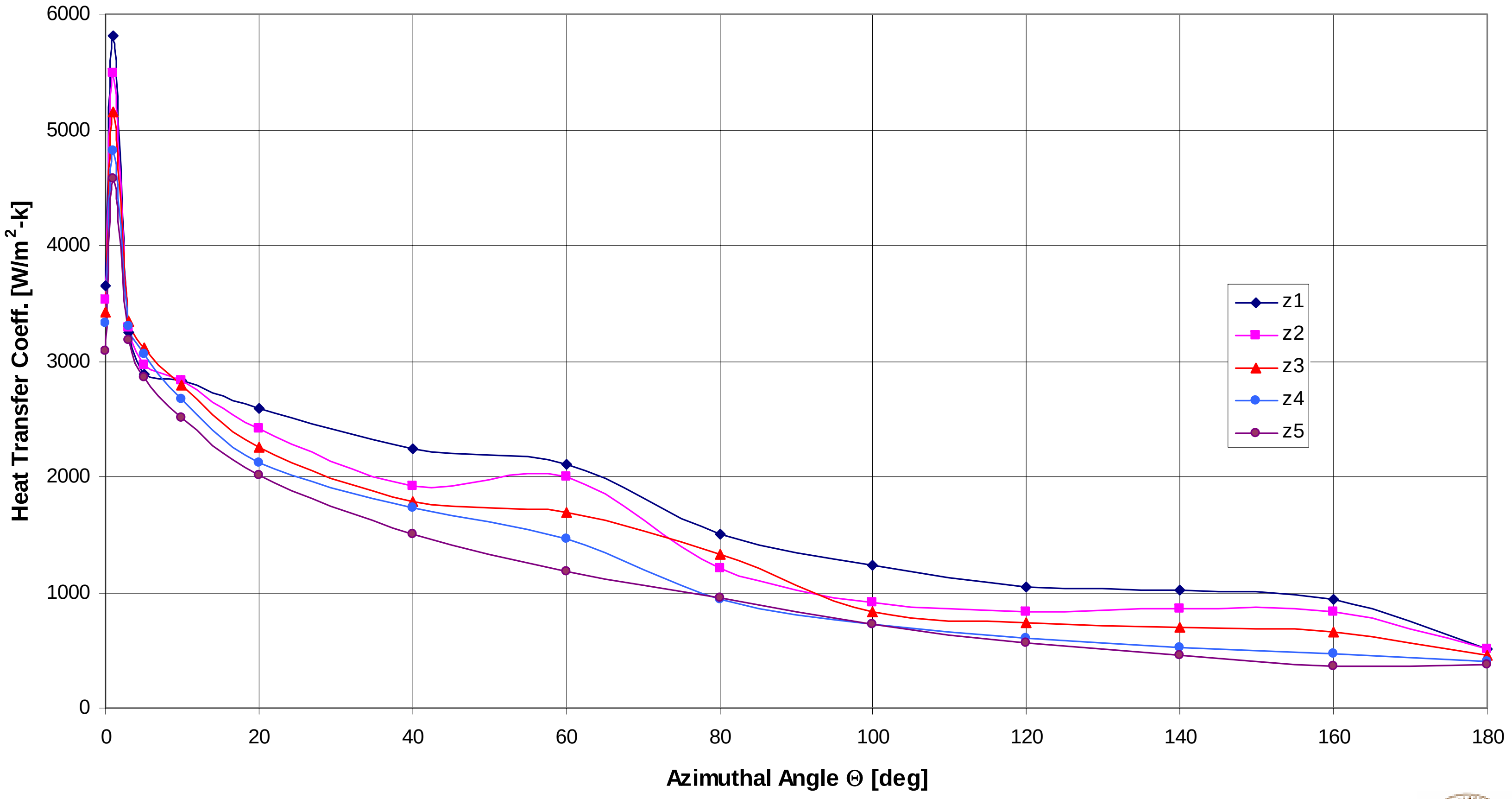
- **Max Heat Transfer Coefficient:**

  6640 w/m^{2}k (Enhanced Wall Functions)



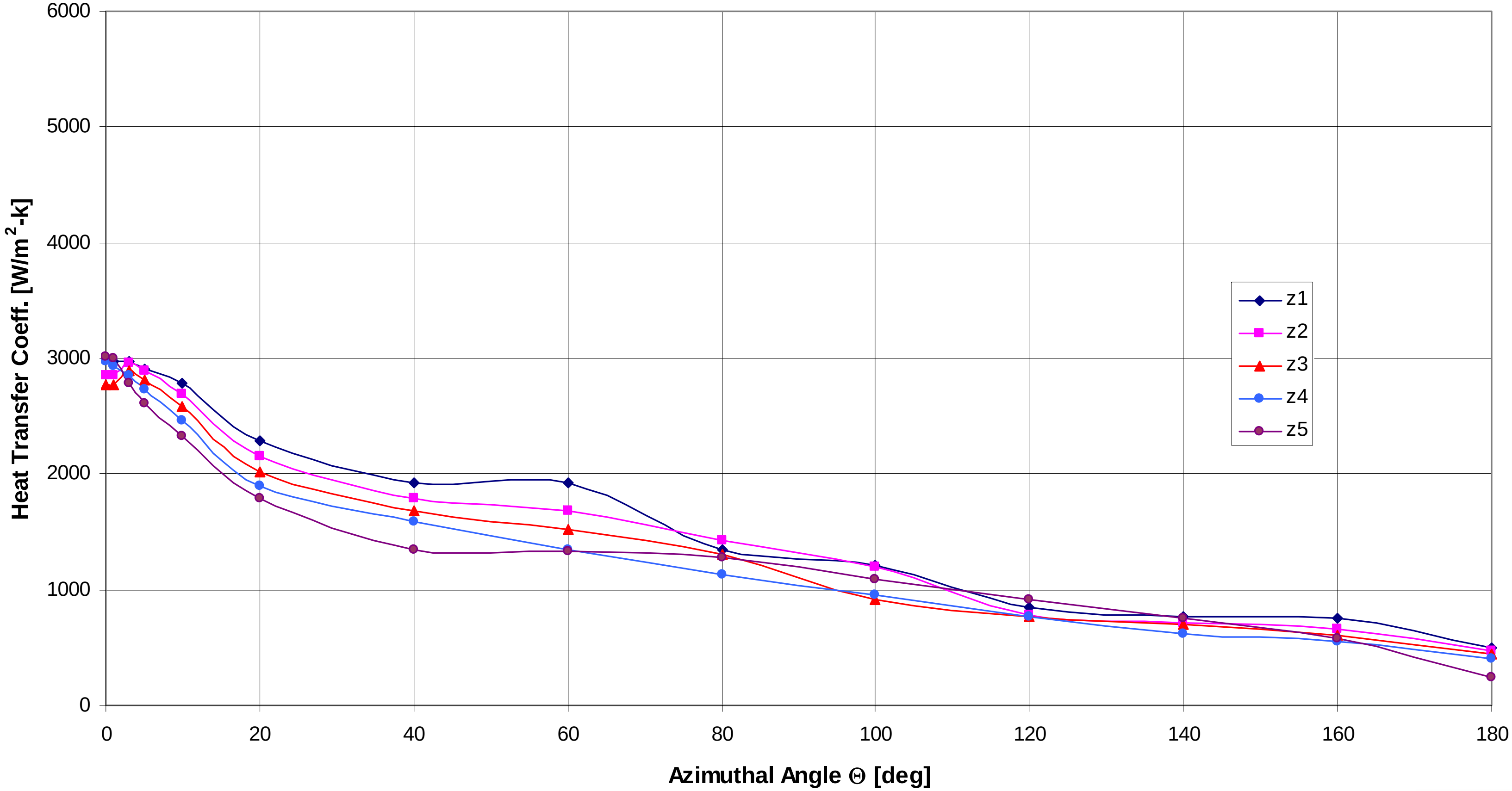
Predicted Performance – Heat Transfer

- **Surface Heat Transfer Coefficient, Enhanced Wall Functions**



Predicted Performance – Heat Transfer

- **Surface Heat Transfer Coefficient, Standard Wall Functions**



The Path Forward

- **Experiments will be conducted for different gas flow rates, exit pressures, and power input levels.**
  - **Test conditions will be selected to closely match the expected non-dimensional parameter ranges for the proposed helium-cooled T-Tube divertor**
  - **Preliminary experiments will be conducted using air as the coolant**
  - **Power levels will be selected so that the temperature differences are significantly higher than the measurement uncertainty**
  - **For each set of test conditions, the experiment will be repeated numerous times by incrementally rotating the inner tube (with slit) relative to the outer tube (fixed) to determine the azimuthal variations of the heat transfer coefficient at each of the nine axially-instrumented locations.**

Extra Slides

3D Parametric Study
(turbulence model)

	Max Tile T [K]	Max T [K] Tube/Tile Interface	ΔP [Pa]
2D Reference (RNG k-ε, w/wall enhancement)	1688	1493	0.47×10^5
2D Reference (Std. k-ε, w/wall enhancement)	1731	1525	0.55×10^5
3D Reference (V1) (Std. k-ε, w/wall enhancement)	1699	1523	1.06×10^5
3D Reference (V1) (RNG k-ε, w/wall enhancement)	1726	1583	1.12×10^5
3D Reference (V1) (Std. k-ε, w/o wall enhancement)	1723	1558	1.22×10^5
3D Reference (V1) (Std. k-ε, w/non-equil. wall fn.)	1762	1587	1.07×10^5

2D Parametric Study

(turbulence model, mass flow rate, and inlet pressure)

	Max Tile T [K]	Max T [K] Tube/Tile Interface	ΔP [kPa]
Reference Case (RNG k-ε, mass flow rate = 0.2 kg/s·m, P_{outlet} = 10 MPa)*	1688	1493	46.83
Standard k-ε*	1731	1525	55.75
Idealized k-ε*	1700	1504	47.38
mass flow rate 0.24 kg/s·m	1618	1423	66.34
mass flow rate 0.16 kg/s·m	1788	1594	30.67
P_{outlet} = 9 MPa	1688	1493	52.06
P_{outlet} = 11 MPa	1689	1493	42.56

* All with wall enhancement model

2D Parametric study
(slot width and jet-wall spacing)

	Max Tile T [K]	Max T [K] Tube/Tile Interface	ΔP [kPa]
Reference Case (slot width = 0.5mm, jet wall spacing = 1.25mm)	1688	1493	46.83
V2 (slot width 0.4mm)	1633	1427	78.82
V3 (slot width 0.6mm)	1745	1563	31.23
V4 (jet wall spacing 1.0mm)	1695	1495	44.44
V5 (jet wall spacing 1.5mm)	1680	1491	49.69

3D Parametric Study
(mass flow rate, and inlet pressure)

	Max Tile T [K]	Max T [K] Tube/Tile Interface	ΔP [Pa]
3D Reference (V1)	1699	1523	1.06×10^5
mass flow rate=7.0 g/s (V1A)	1782	1607	0.76×10^5
mass flow rate=10.0 g/s (V1B)	1646	1466	1.55×10^5
P_{outlet} = 9 MPa (V1C)	1701	1523	1.07×10^5
P_{outlet} = 11 MPa (V1D)	1719	1543	1.07×10^5

* All use std. k-ε, w/wall enhancement

3D Parametric study
(slot width and jet-wall spacing)

	Max Tile T [K]	**Max T [K] Tube/Tile Interface**	**ΔP [Pa]**
3D Reference (V1) (slot width=0.5mm, jet-wall spacing=1.25mm)	1699	1523	1.06×10^5
V2 (slot width=0.4mm)	1621	1452	1.67×10^5
V3 (slot width=0.6mm)	1720	1545	0.86×10^5
V4 (jet-wall spacing =1.0mm)	1728	1557	0.89×10^5
V5 (jet-wall spacing= 1.5mm)	1716	1545	0.90×10^5
V6 (revised geometry)	1762	1608	1.17×10^5

* All use std. k-ε, w/wall enhancement