Thermal Analysis of Helium-Cooled T-tube Divertor

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Objectives

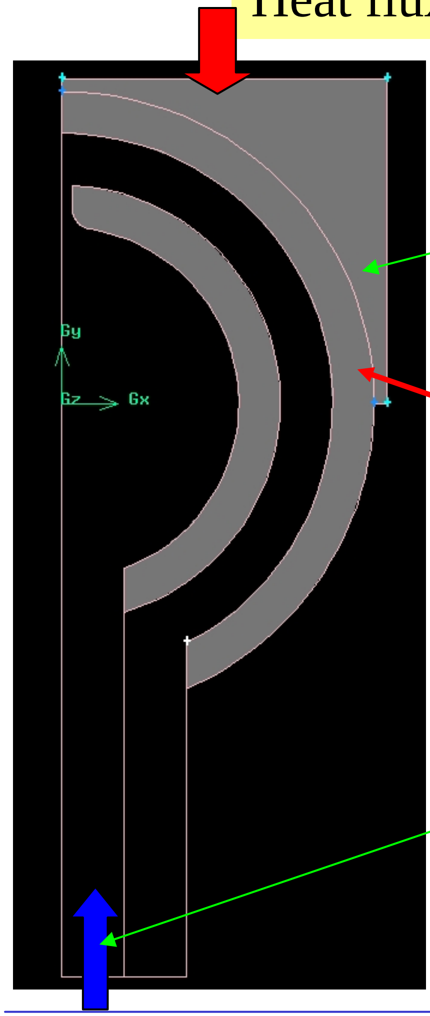
- Evaluate the thermal performance of the T-Tube, helium-cooled, divertor design at the nominal design and operating conditions
- Conduct parametric studies to assess the sensitivity of thermal performance to changes in geometry and operating conditions (due to manufacturing tolerances and/or flow mal-distribution between modules)

Overview

- **Analyses Have been performed using both a 2D- and a 3D-model to assess:**
  - Thermal performance at nominal design and operating conditions
  - 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)
  - 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

Simulation geometry (2D Model)

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



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]

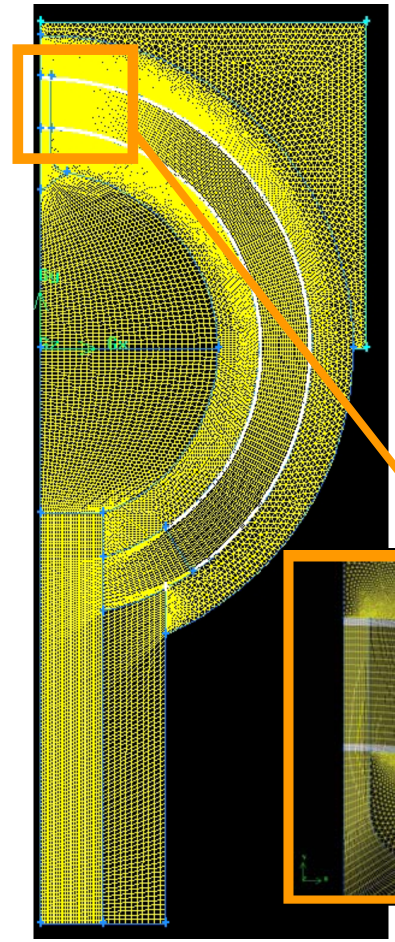
Volumetric heat generation : 53 MW/m^3

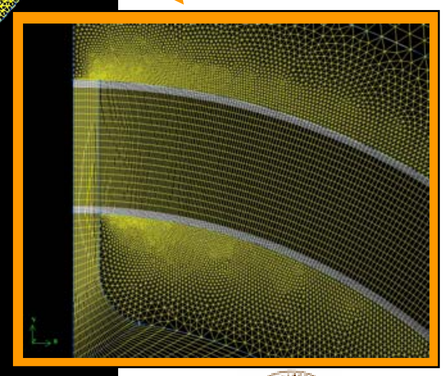
HELIUM

Mass flow rate : 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 : μ=4.5×10^{-7}(T)$^{0.67}$ [Pa·s]

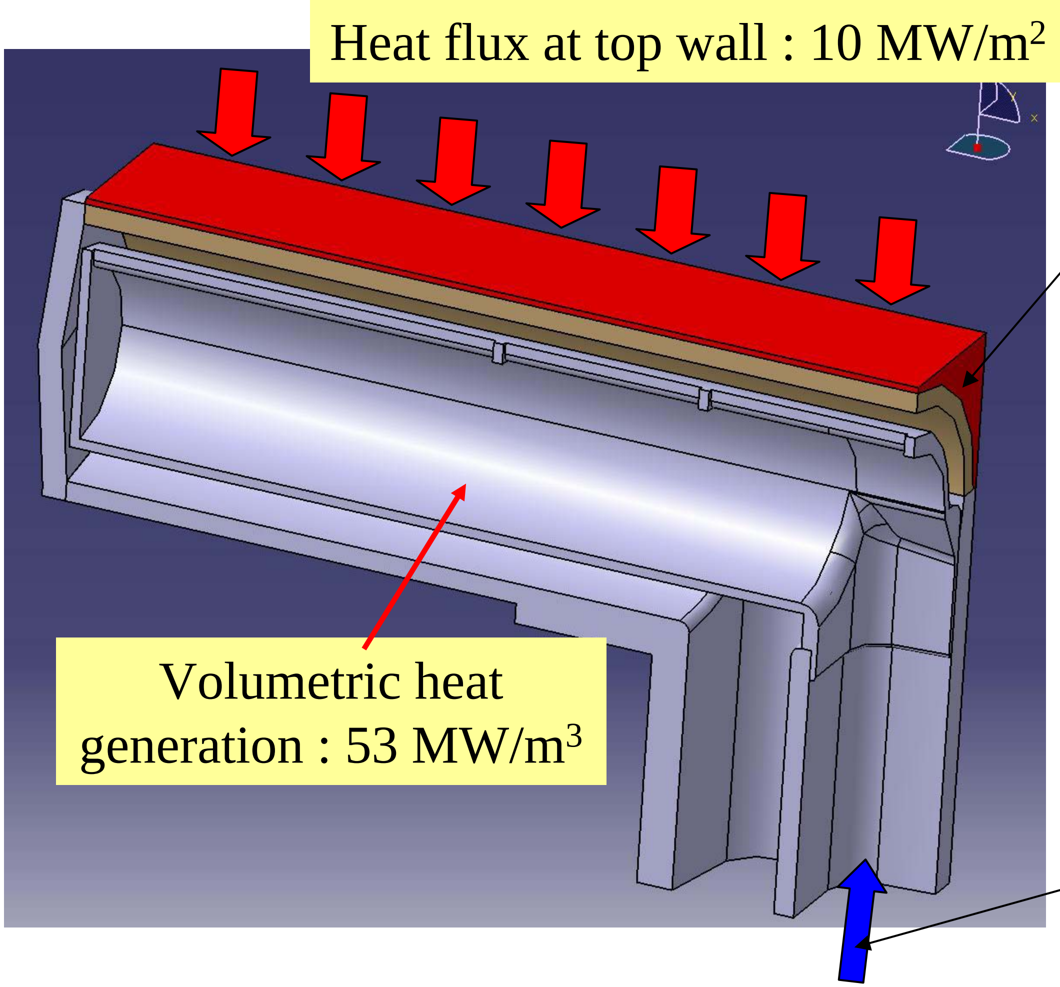
Grid Structure

35,592 cells have been used in grid generation





Simulation geometry (3D Model)



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]

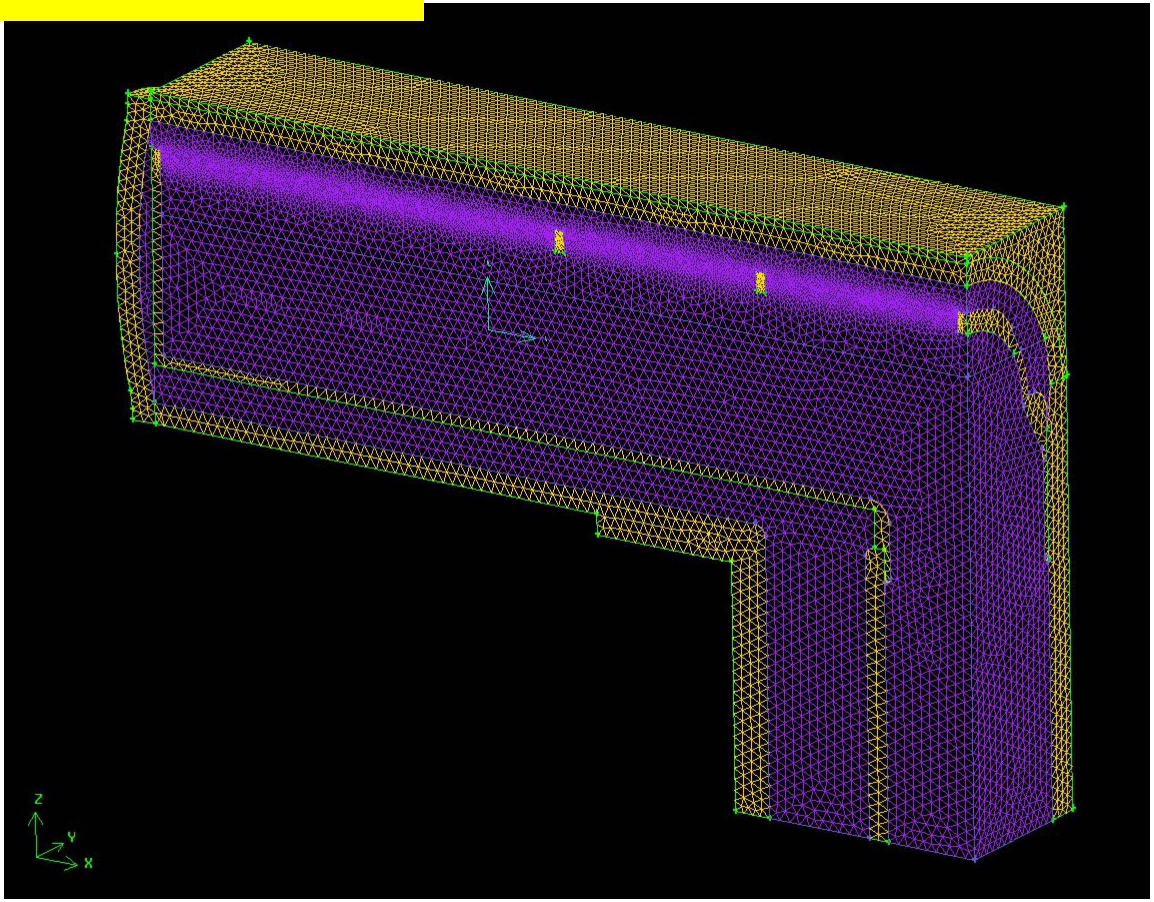
HELIUM

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 :
μ=4.5×10^{-7}(T)$^{0.67}$ [Pa·s]

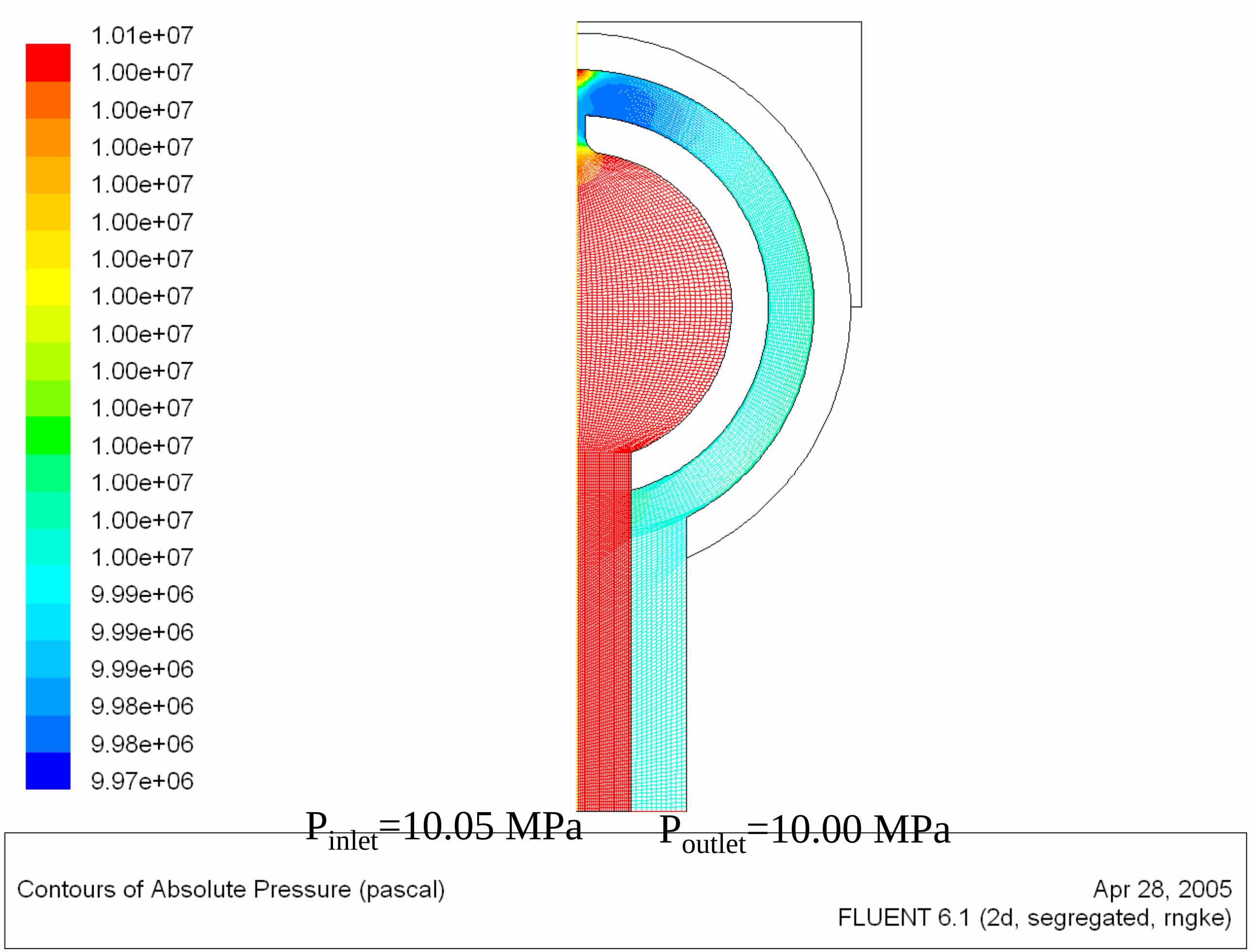
Simulation Setup (3D Model)

- FLUENT(6.1) has been used to solve the conservation equations (mass, momentum, and energy)
- Assumptions
  - Turbulent flow (standard k-ε with wall enhancement model)
  - compressible flow (perfect gas law)
- 707,357 tetrahedral cells are used in grid generation

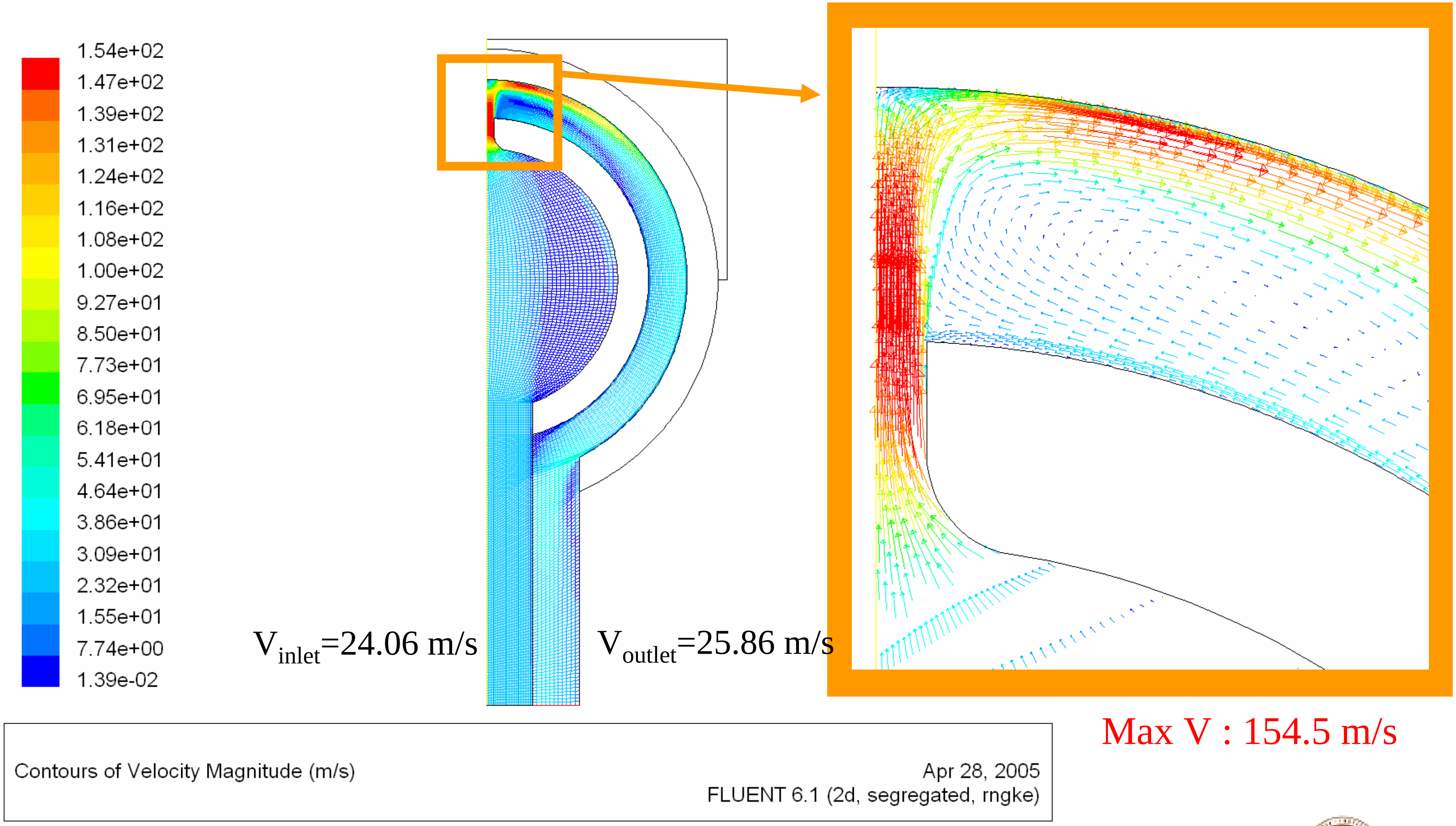
Grid Structure



2D Results – Pressure Distribution

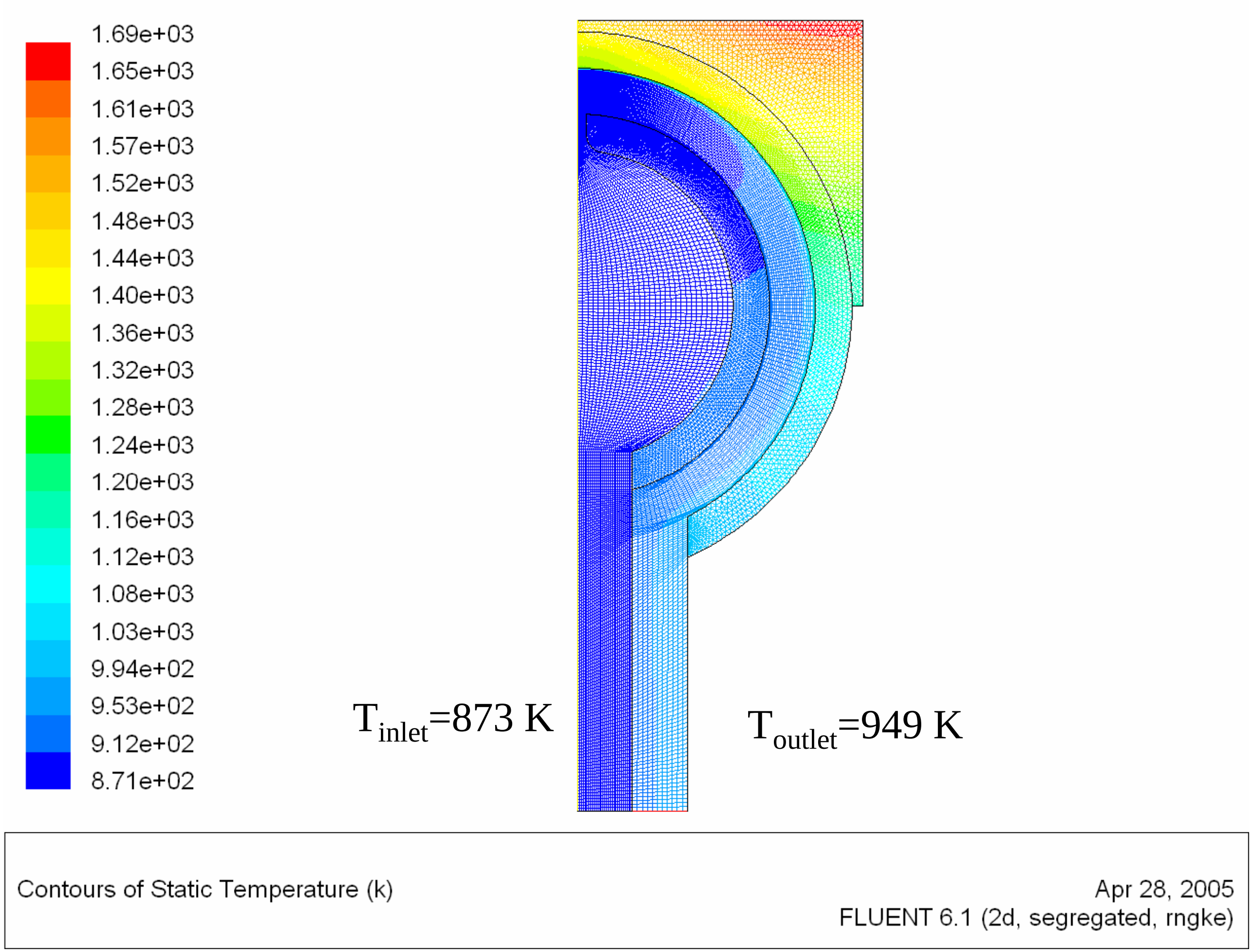


2D Results – Velocity Distribution



Max V : 154.5 m/s

2D Results – Temperature Distribution



2D Parametric Study
(turbulence model, mass flow rate, and inlet pressure)

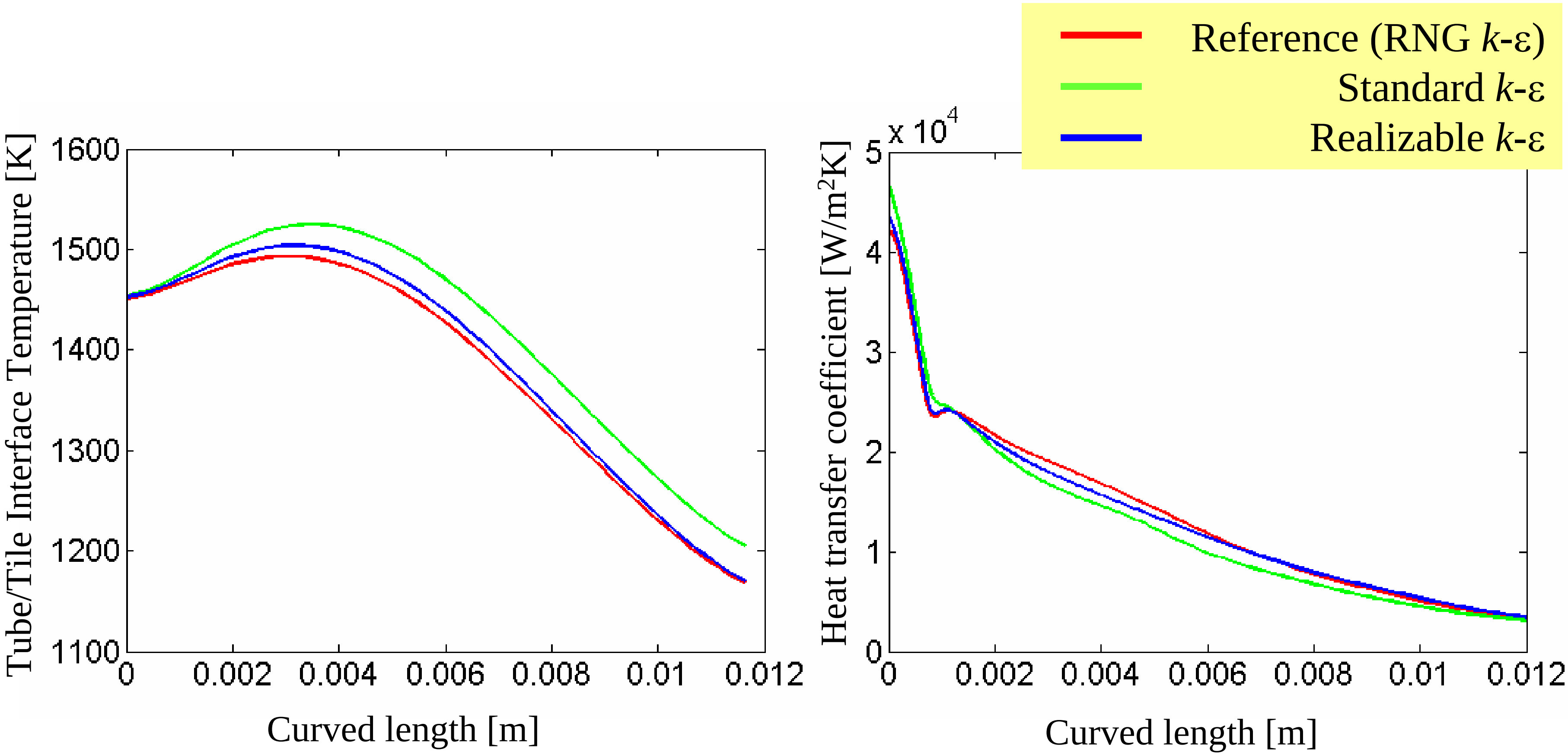
	Max Tile T [K]	Max T [K] Tube/Tile Interface	ΔP [kPa]
Reference Case (RNG k-ε, mass flow rate = 0.2 kg/s·m, P_{outlet} = 10 MPa)*	1688	1493	46.83
Standard k-ε*	1731	1525	55.75
Idealized k-ε*	1700	1504	47.38
mass flow rate 0.24 kg/s·m	1618	1423	66.34
mass flow rate 0.16 kg/s·m	1788	1594	30.67
P_{outlet}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

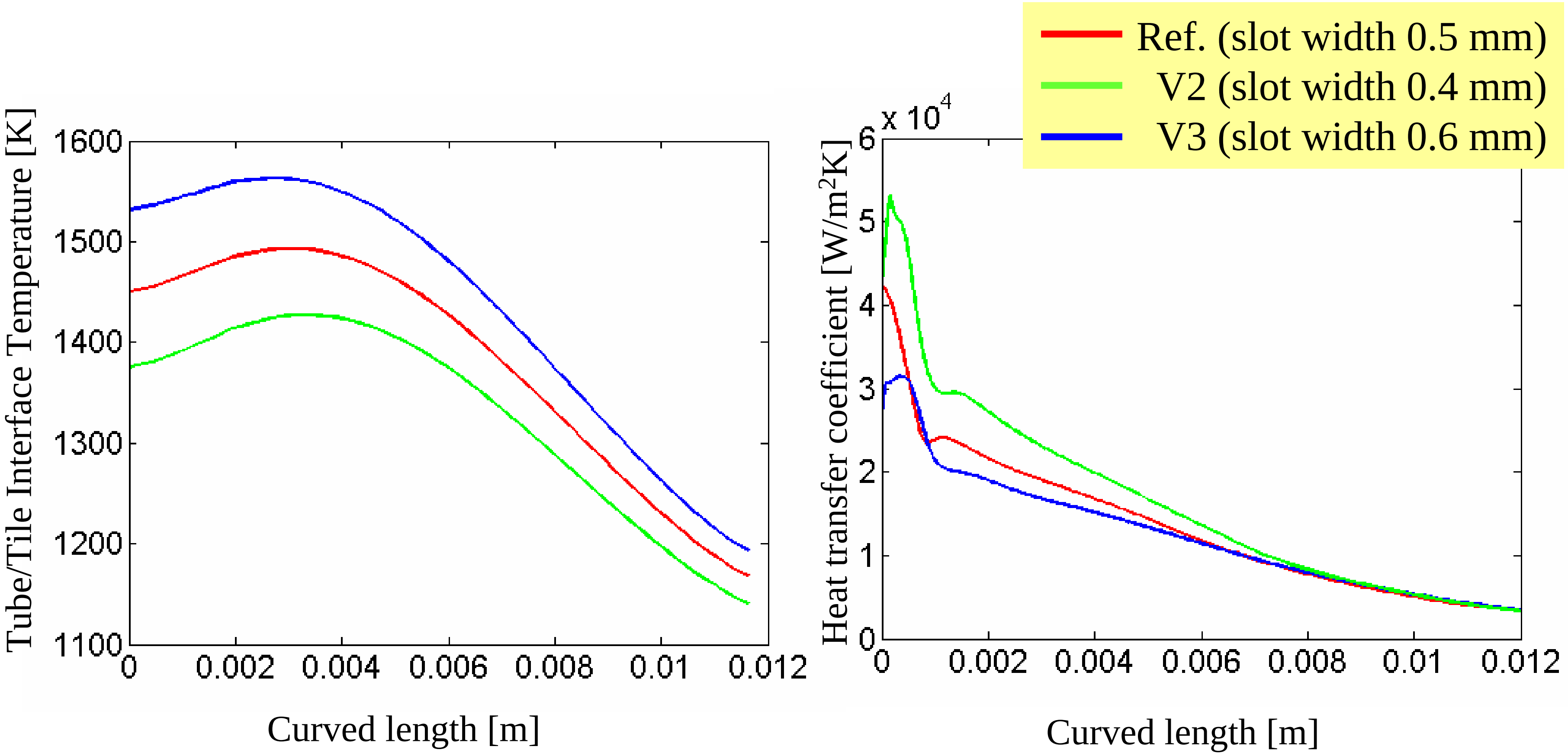
	Max Tile T [K]	Max T [K] Tube/Tile Interface	ΔP [kPa]
Reference Case (slot width = 0.5mm, jet wall spacing = 1.25mm)	1688	1493	46.83
V2 (slot width 0.4mm)	1633	1427	78.82
V3 (slot width 0.6mm)	1745	1563	31.23
V4 (jet wall spacing 1.0mm)	1695	1495	44.44
V5 (jet wall spacing 1.5mm)	1680	1491	49.69

Effect of Turbulence Model on Calculated Temperatures & Heat transfer Coefficient (2D)



* All with wall enhancement model

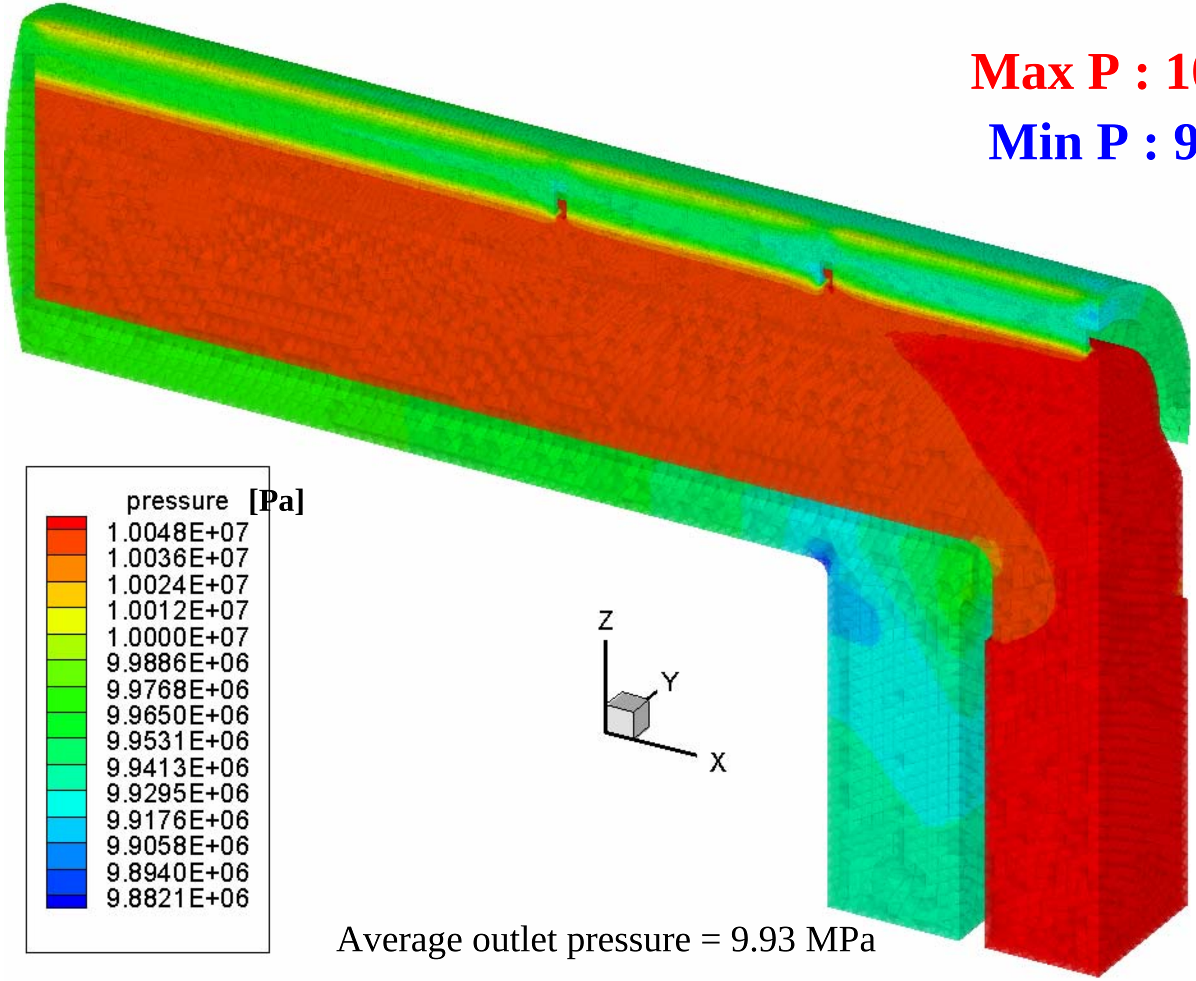
Effect of Slot Width on Calculated Temperatures & Heat transfer Coefficient (2D)



3D Results -- Pressure Distribution

Max P : 10.05 [MPa]

Min P : 9.86 [MPa]

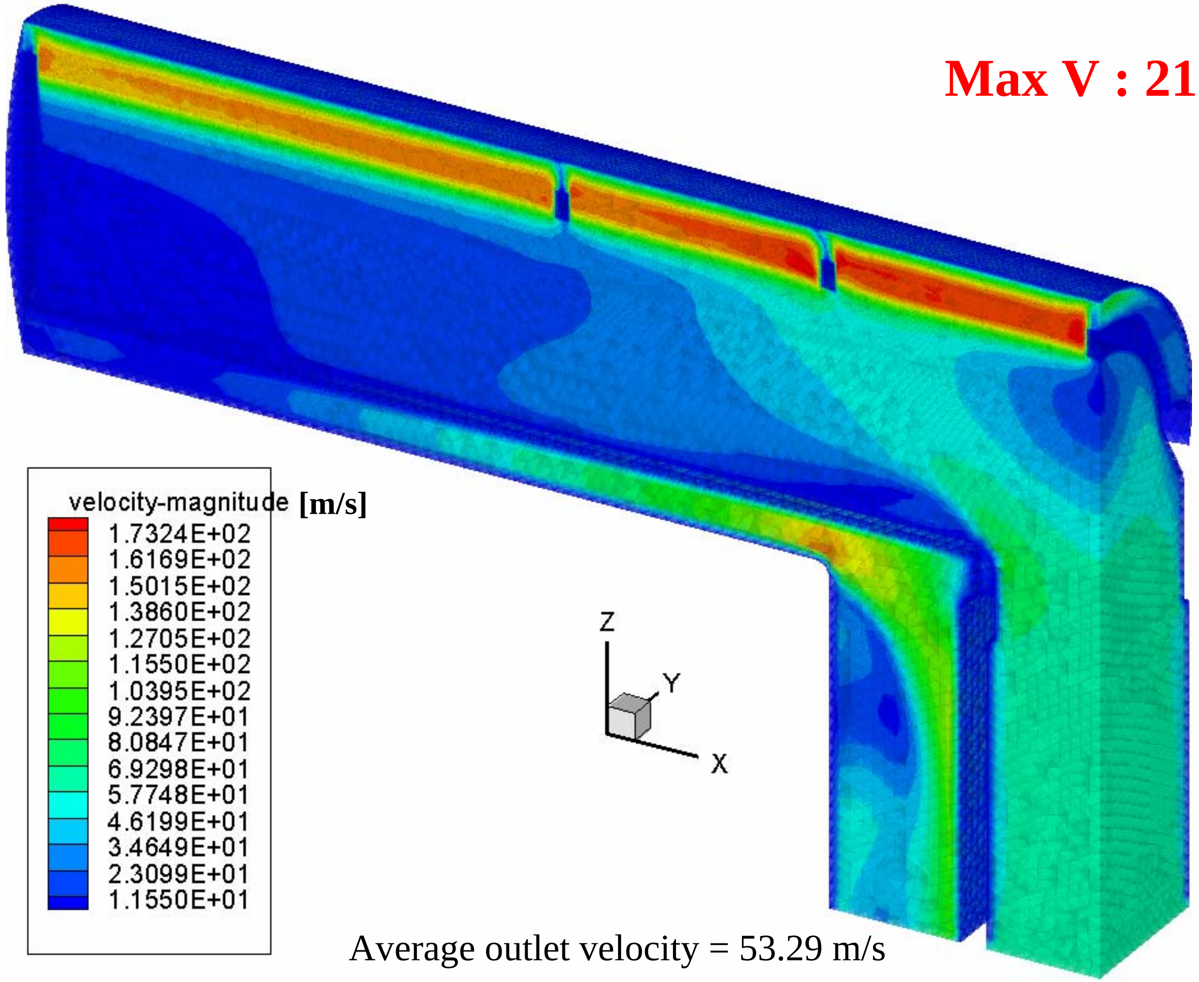


Average outlet pressure = 9.93 MPa

Average inlet Pressure = 10.04 MPa

3D Results --Velocity Distribution

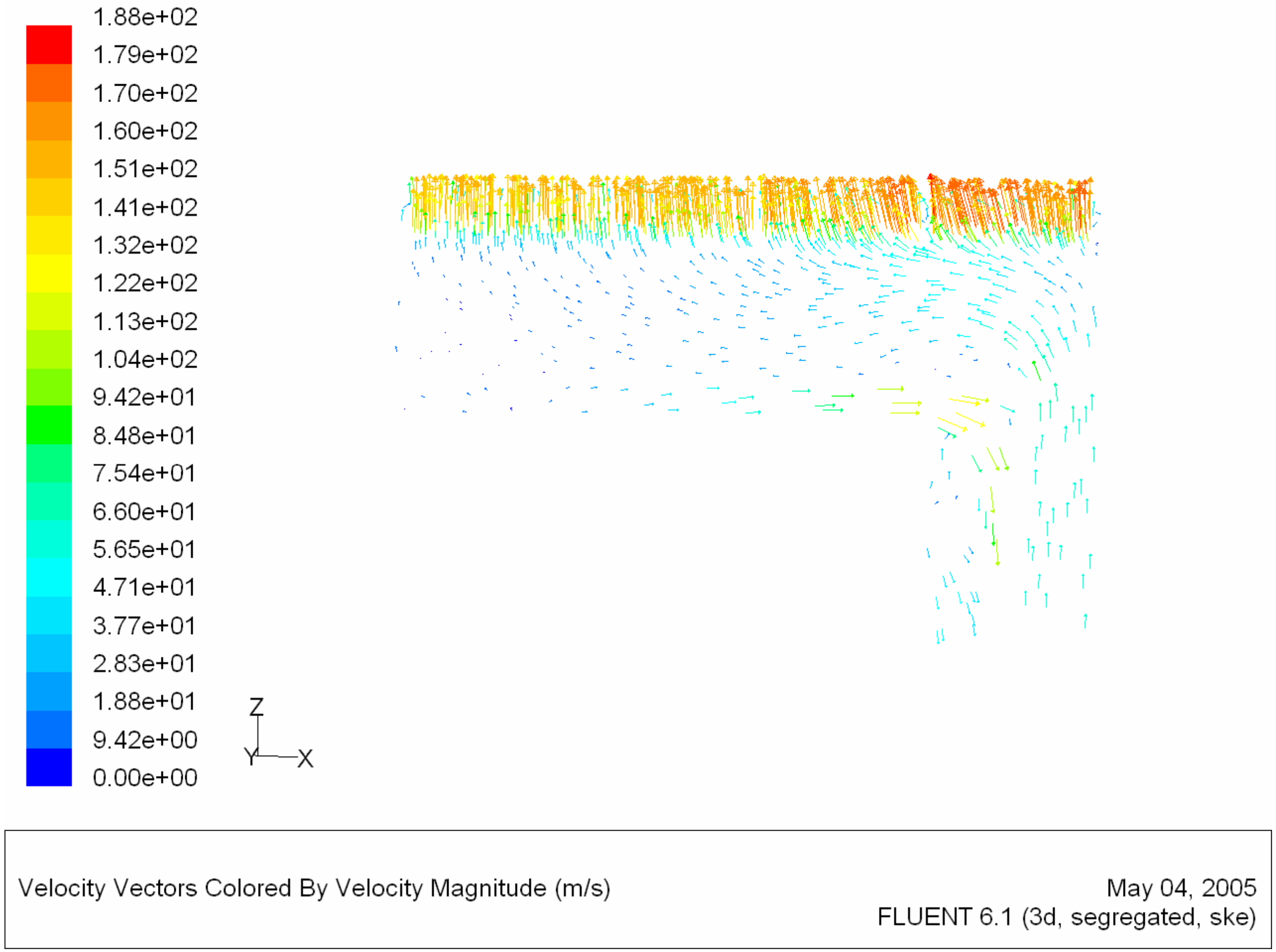
Max V : 216 [m/s]



Average outlet velocity = 53.29 m/s

Average inlet velocity = 58.25 m/s

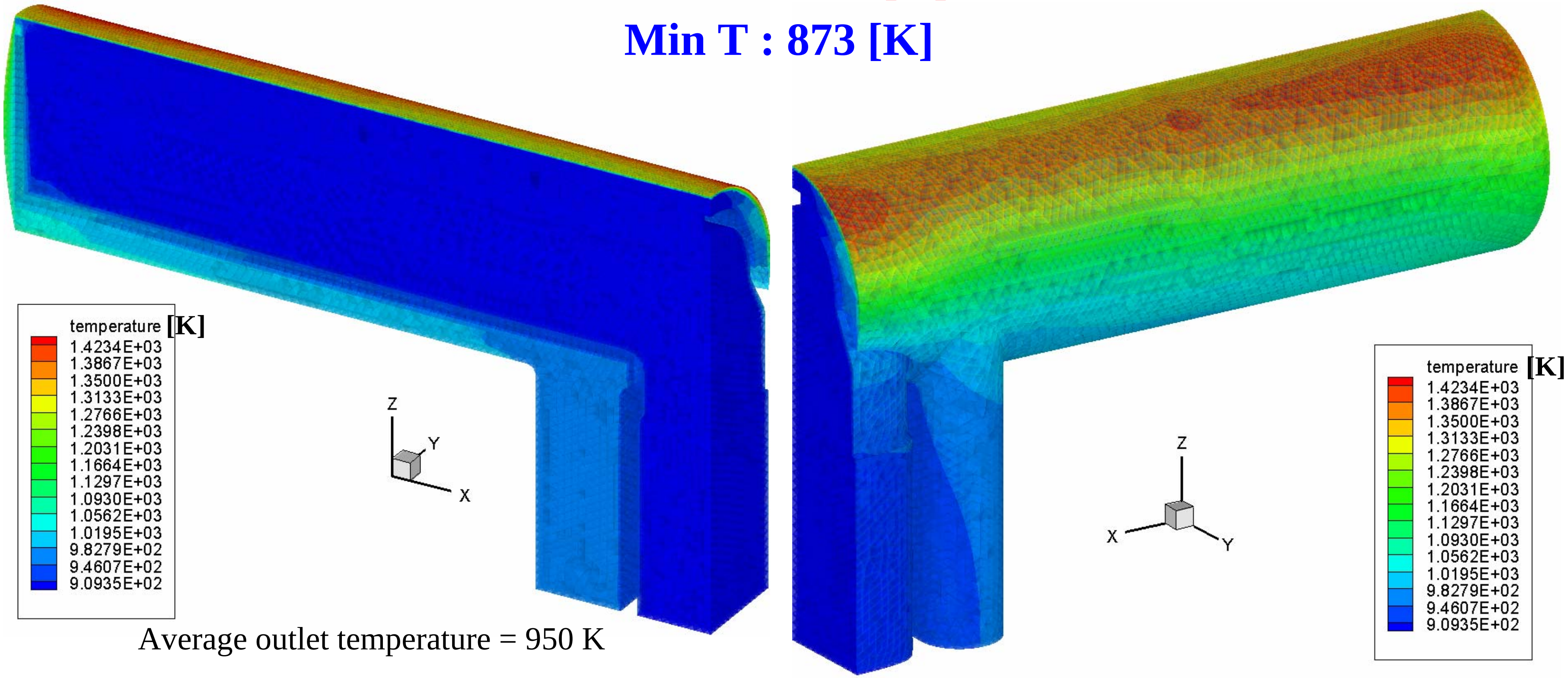
Velocity Distribution at symmetry plane



3D Results -- Coolant Temperature Distribution

Max T : 1260 [K]

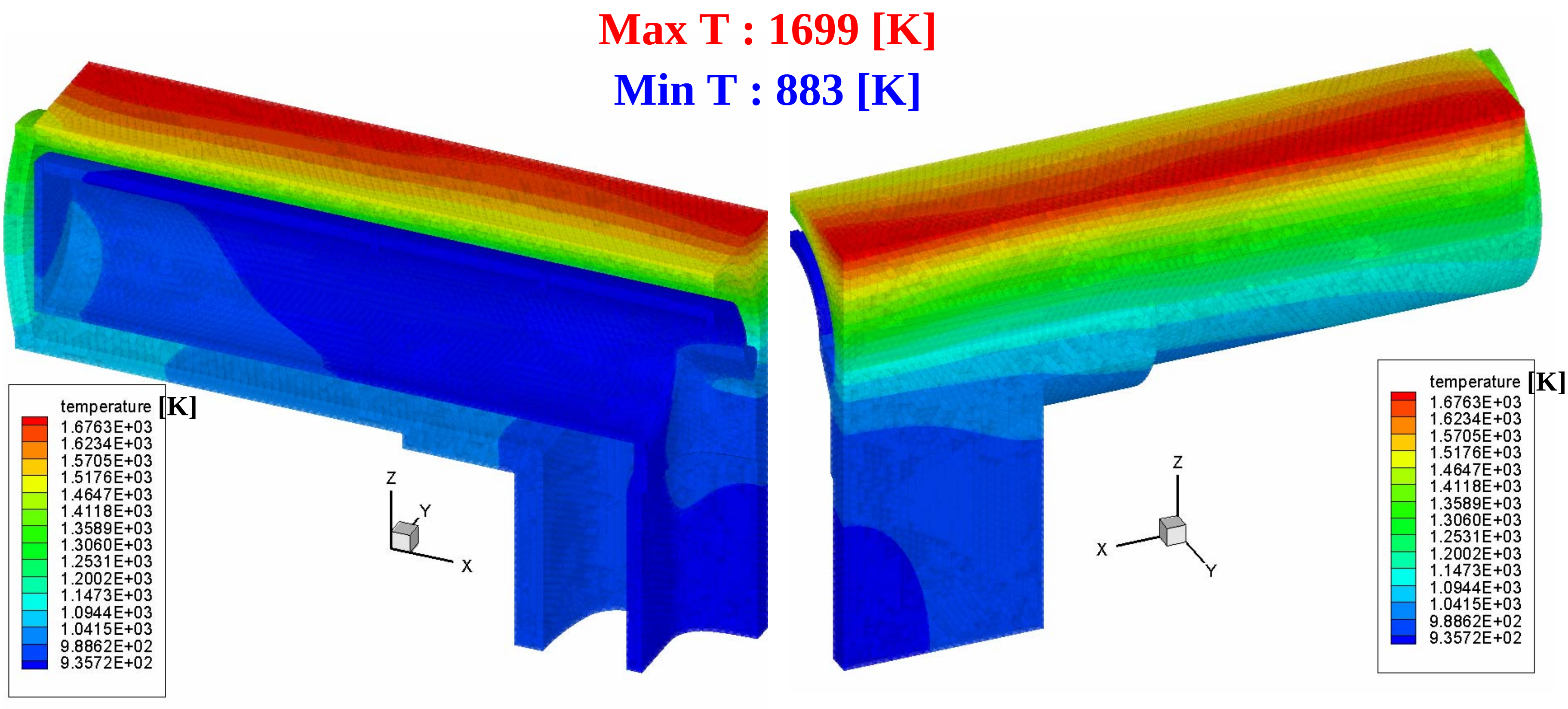
Min T : 873 [K]



Average outlet temperature = 950 K

Average inlet temperature = 873 K

3D Results -- Temperature Distribution of solid structure



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

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

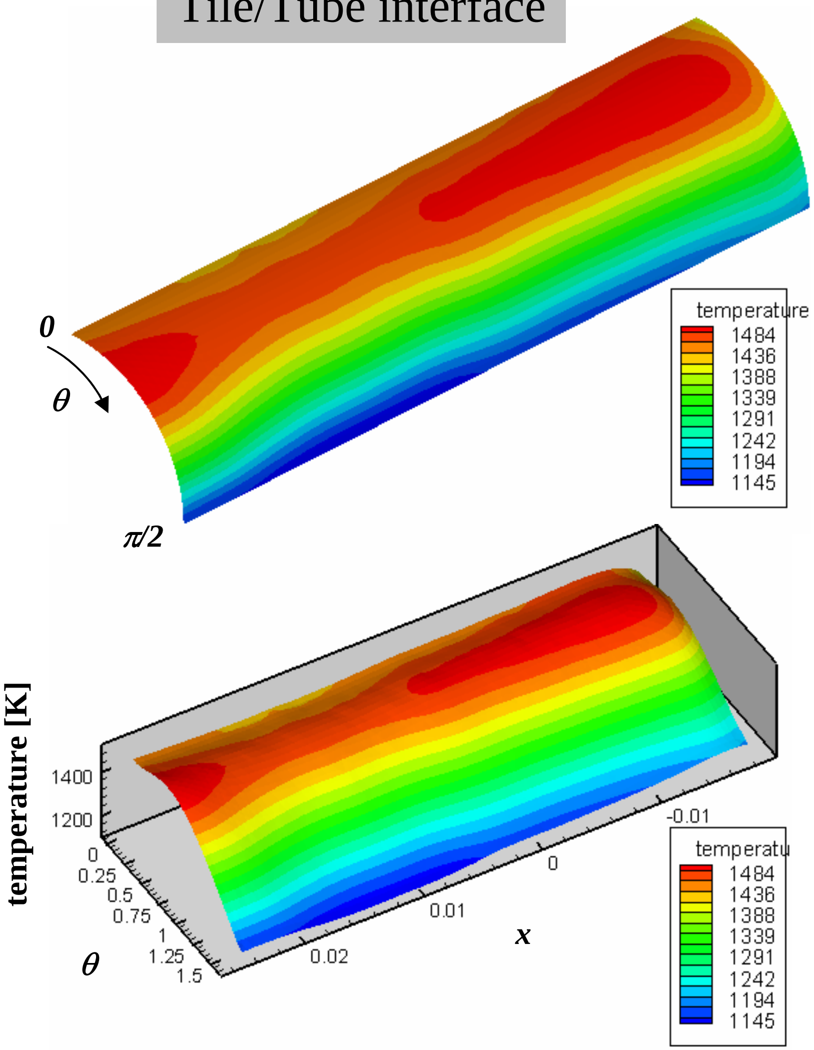
3D Parametric study
(slot width and jet-wall spacing)

	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}

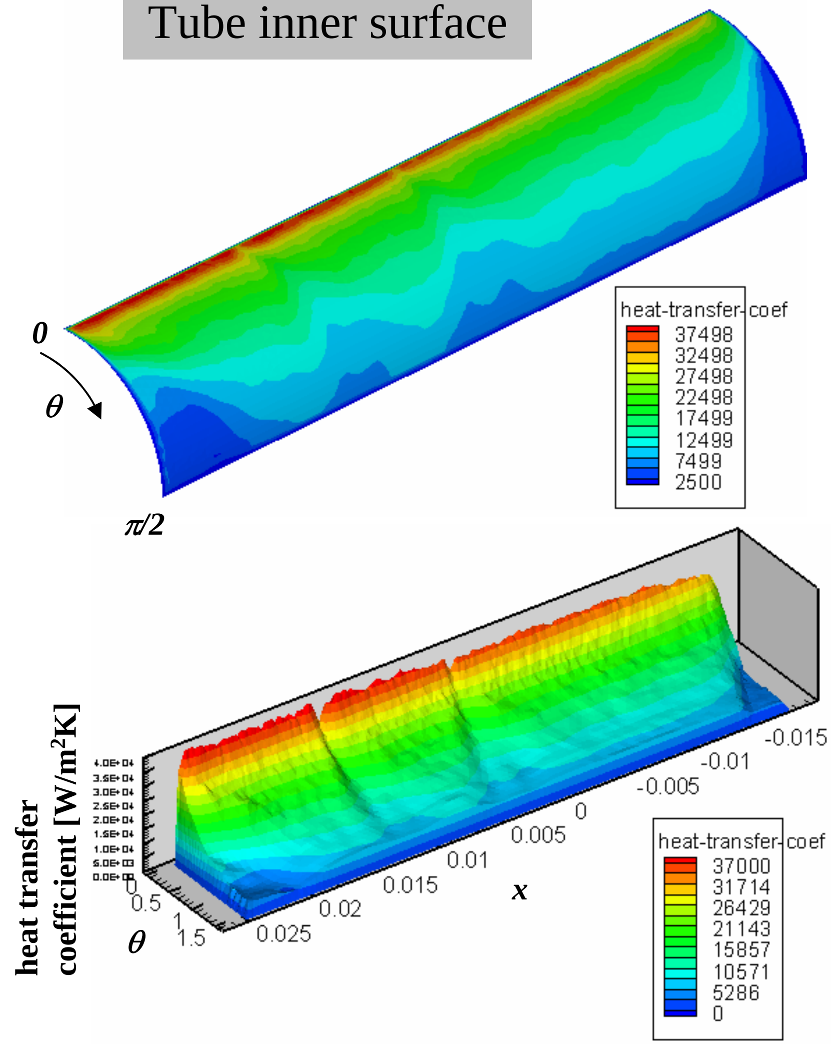
* All use std. k-ε, w/wall enhancement

V1 : temperature and heat transfer coefficient

Tile/Tube interface



Tube inner surface



Conclusions

- **Numerous analyses have been performed. The results indicate that:**
  - Maximum calculated temperatures at nominal design and operating conditions are consistent with constraints dictated by material properties
  - Sensitivity studies indicate that the proposed 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