Status of helium-Cooled Plate-Type Divertor Design, CFD and Stress Analysis

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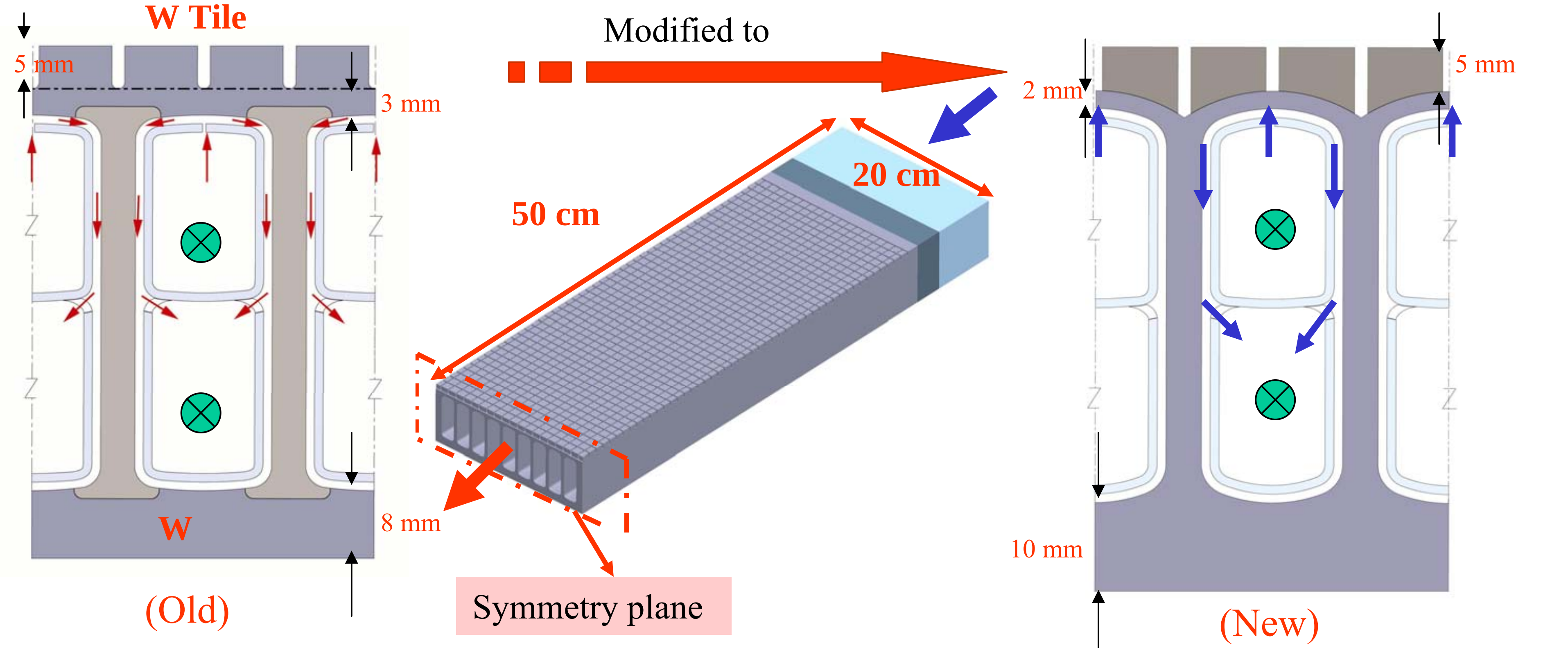
Helium-Cooled Plate-Type Divertor

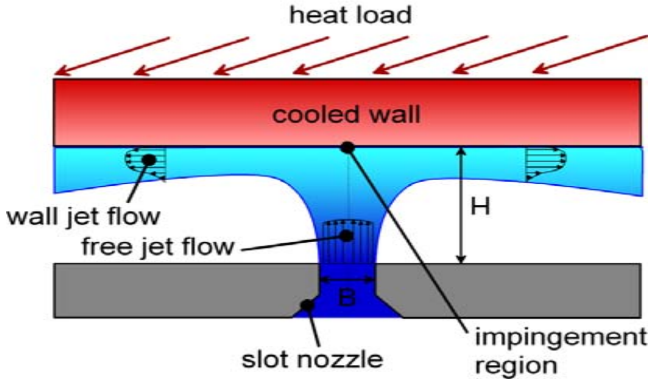


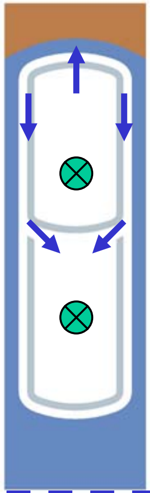
Based on initial thermo-fluid and thermo mechanical results, the configuration of the flat plate divertor has been modified:

- ✓Reducing the thickness of the front structure to reduce the maximum structure temperature
- ✓Increasing the thickness of the back plate to rise the temperature level at the back
- ✓Making the front structure (high pressure container) with a large curvature to reduce local stresses

Cooling Methods

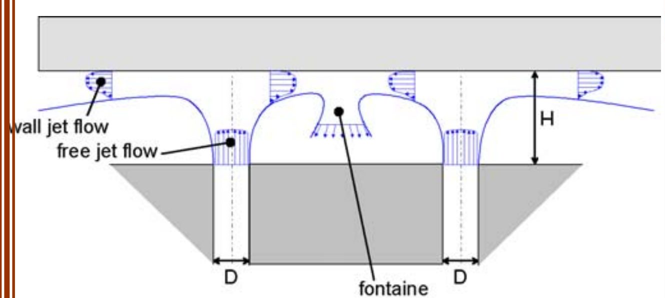
- Three Impinging jet cooling schemes are investigated to enhance heat transfer coefficient in order to meet design requirements:
  - ✓ Max. structural temperature < 1300 ^{o}C;
  - ✓ Max. structure stress <450 MPa (3Sm);
  - ✓ Ratio of the pumping power to thermal power, $P_p/P_{th} < 10\%$

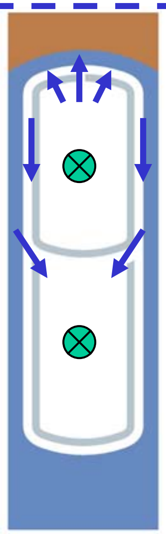




1. Slot jet

2. Slot jet with micro-channel (H~0.25 mm)





3. Multiple impinging jet arrays

CFD Thermo-fluid Model for Slot Jet Cooling

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➢Heat transfer of a single impinging jet depends on the nozzle-to-wall distance, H, width of the nozzle, D.

➢ARIES-CS reference design parameters are assumed:

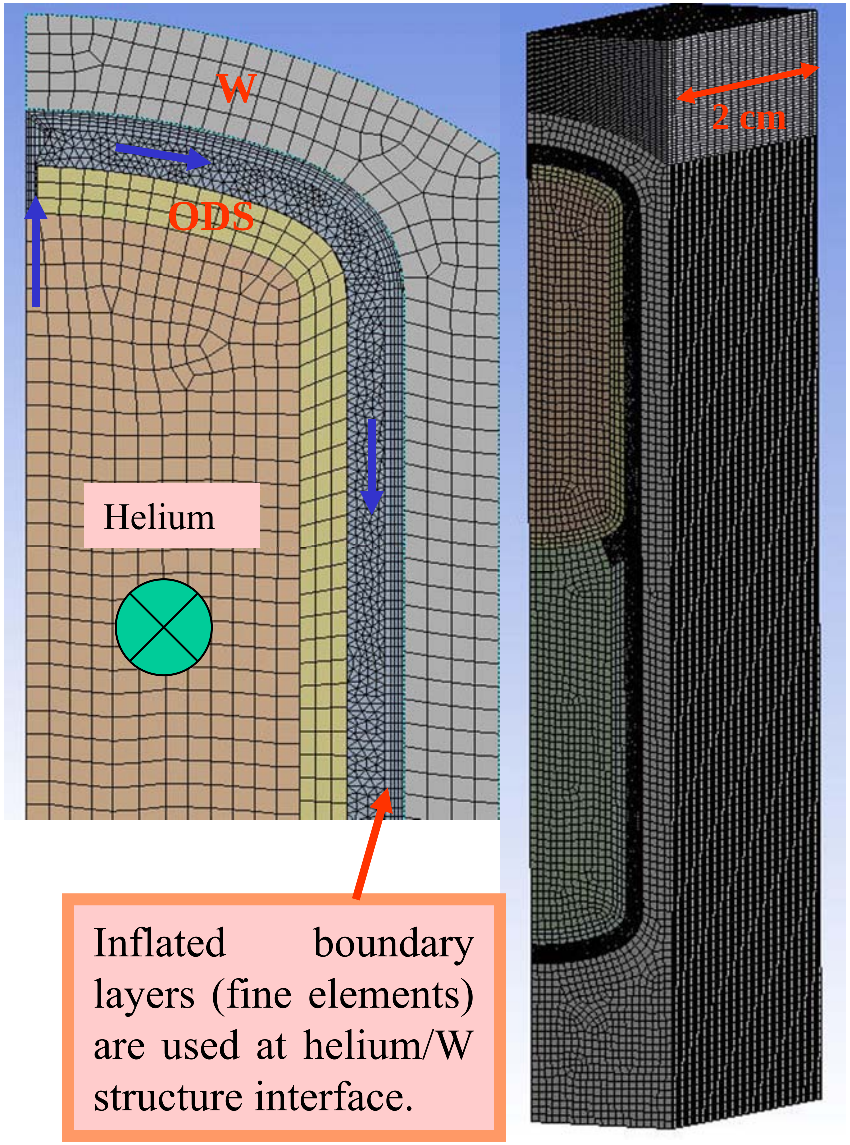
- ✓***Nozzle-to-wall distance H=1.2 mm*,***
- ✓***Nozzle width D=0.5 mm*,***
- ✓***q"=10 MW/m^2, q'''=53 MW/m^3***
- ✓***Inlet pressure=10 MPa***
- ✓***Toutlet-Tinlet=950-873 K***

**S. I. Abdel-Khalik et al., to be published in Fusion Sic.& Tech*
**T. Ihli, A.R. Raffray et al., Fusion Eng.& Des., 82 (2007)*

➢Only 2 cm plate-length (in z-direction) is simulated because huge amount of elements and computer memory are required for full length plate (~0.65 million elements for this model).

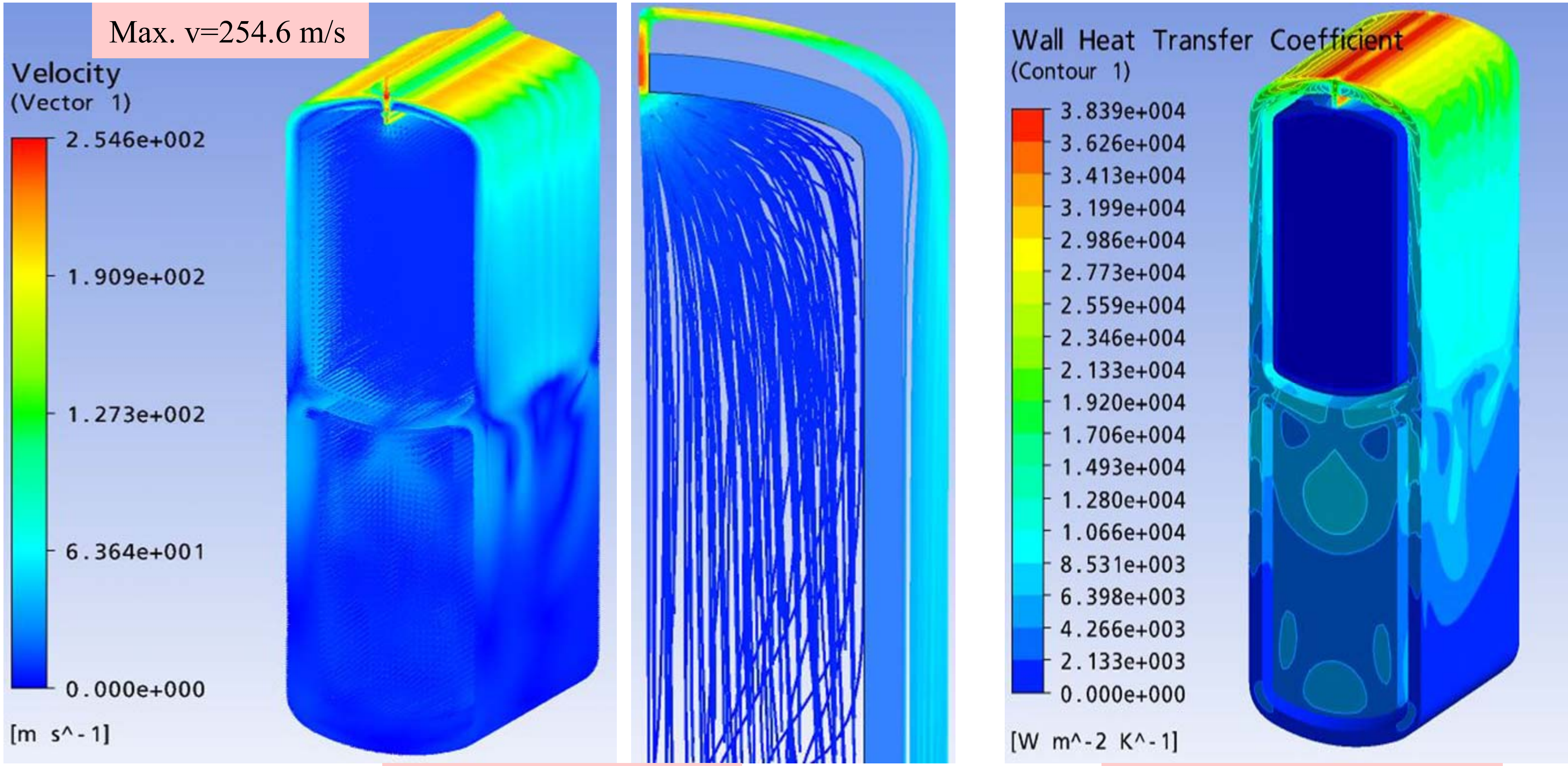
➢Standard turbulent flow model, K-epsilon is used in CFD model.

➢Rough wall is assumed. Roughness height=10 micron.



Inflated boundary layers (fine elements) are used at helium/W structure interface.

Thermo-fluid Results for Slot Jet Cooling

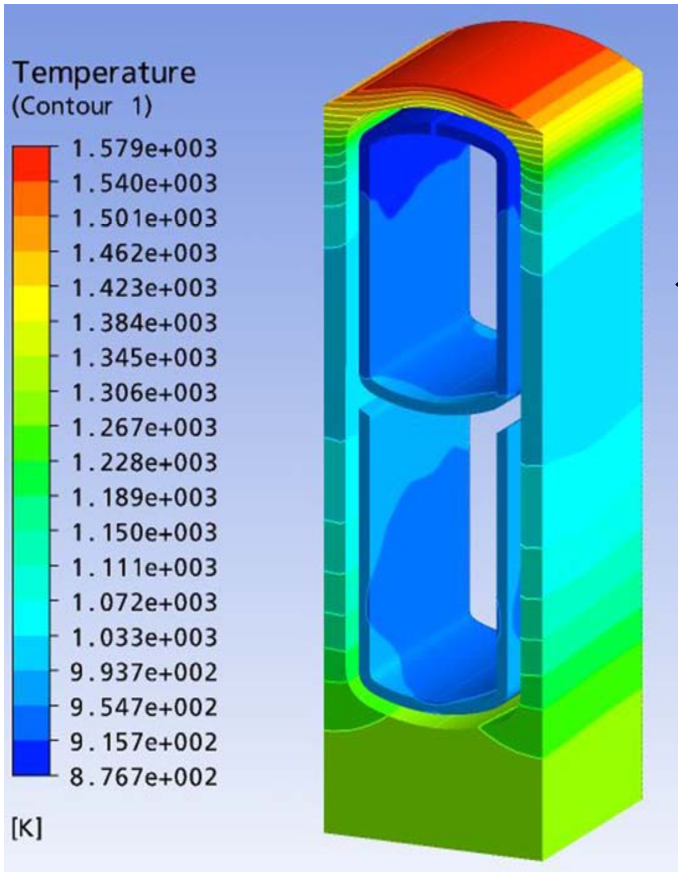


Velocity distribution

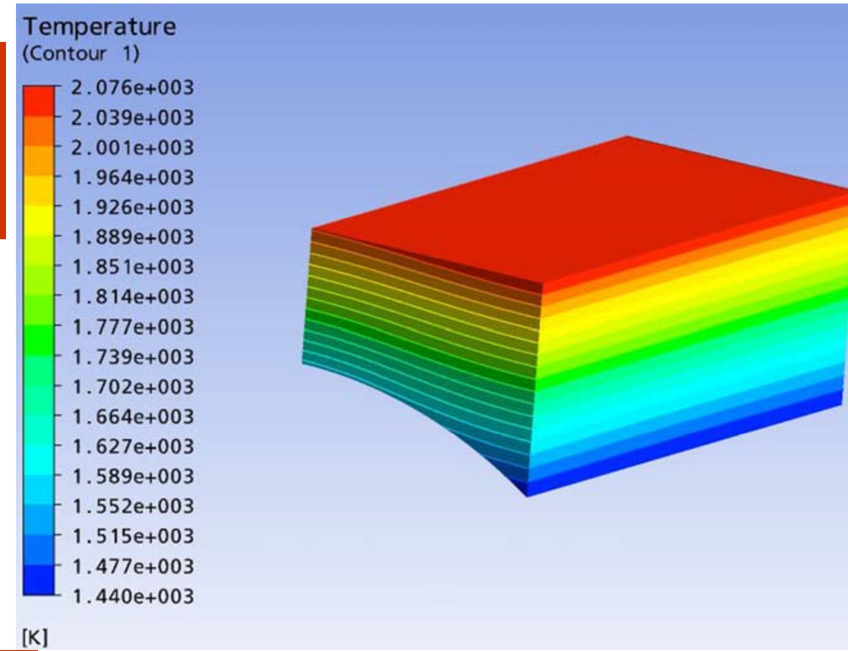
Max. h=3.84x10^4 W/m^{2}K

(Nozzle width d=0.5 mm, Jet-to-wall distance H=1.2 mm; mass flow=0.005925 kg/s)

Thermo-fluid Results for Slot Jet Cooling (Cont.)



W Structure temperature distribution



W Tile temperature distribution

- The max. structure temperature is 1579 K **(~1573 K, allowable temperature)**
- Pressure drop ΔP =10.183-10=0.183 MPa
- P_p/P_{th}~8.7% **(<10%, design limit)**

CFD Thermo-fluid Model for Micro-channel Cooling

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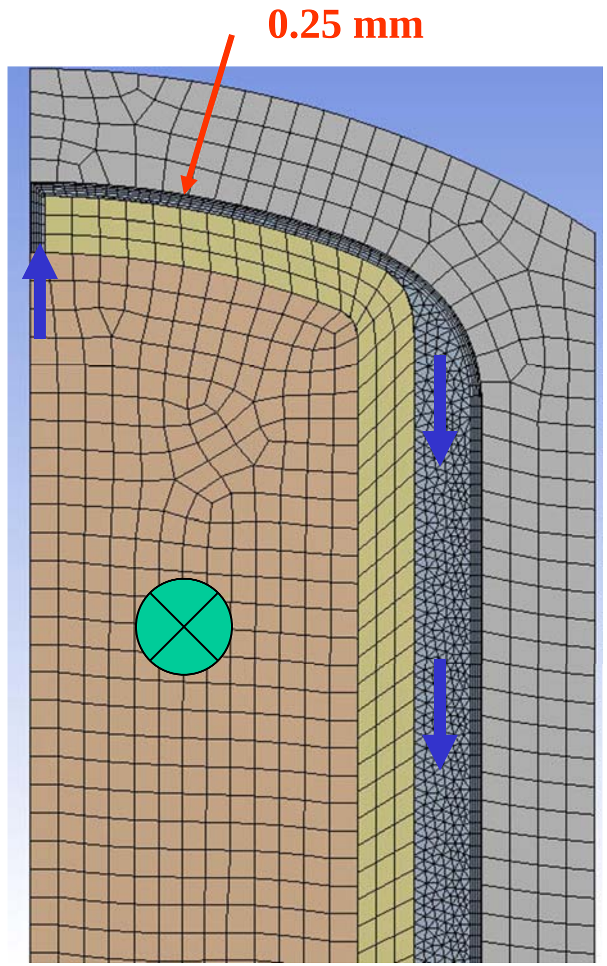
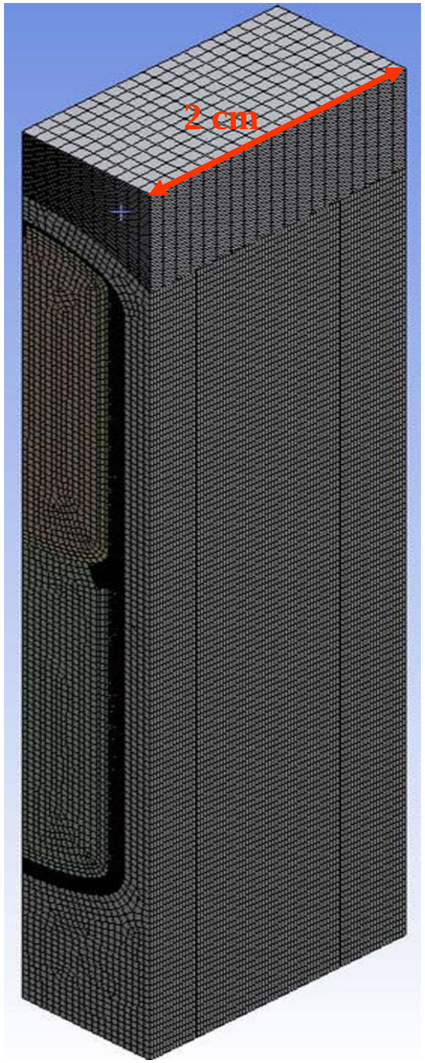
- Nozzle width d=0.5 mm, channel space H=0.25 mm
- Thermal loads and mass flow rate are the same as the slot jet cooling model.
- Standard turbulent flow model, K-epsilon is used in CFD model.
- Rough wall is assumed. Roughness height=10 micron.





Thermo-fluid Results for Micro-channel Cooling

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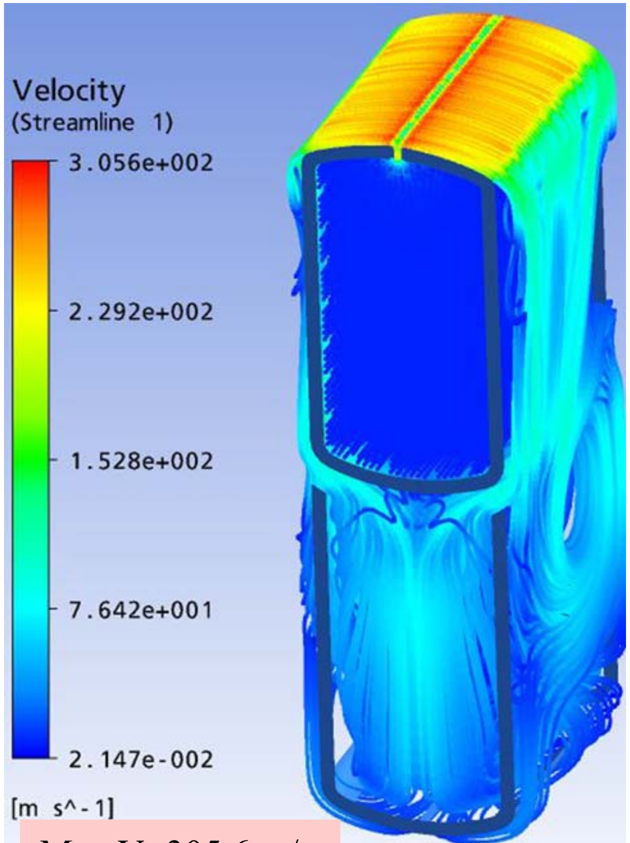

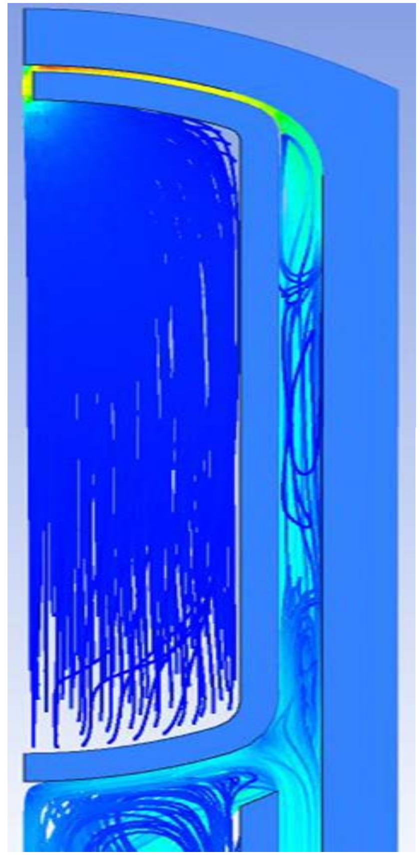

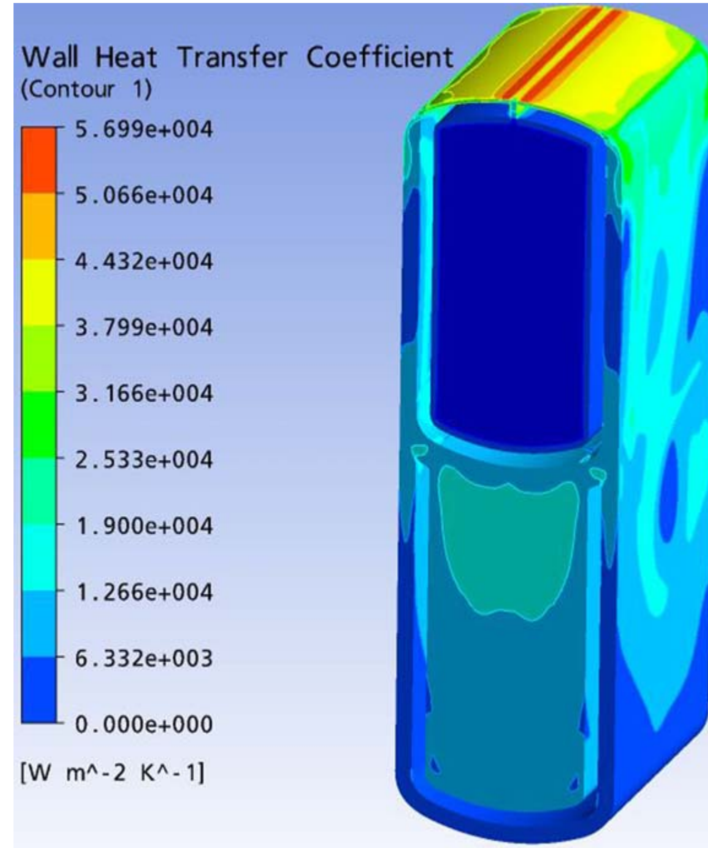

Max V=305.6 m/s

Velocity distribution

Max. h=5.7x10^4 W/m^2K

(Nozzle width d=0.5 mm, micro-channel space H=0.25 mm; mass flow=0.005925 kg/s)

Thermo-fluid Results for Micro-channel Cooling (Cont.)

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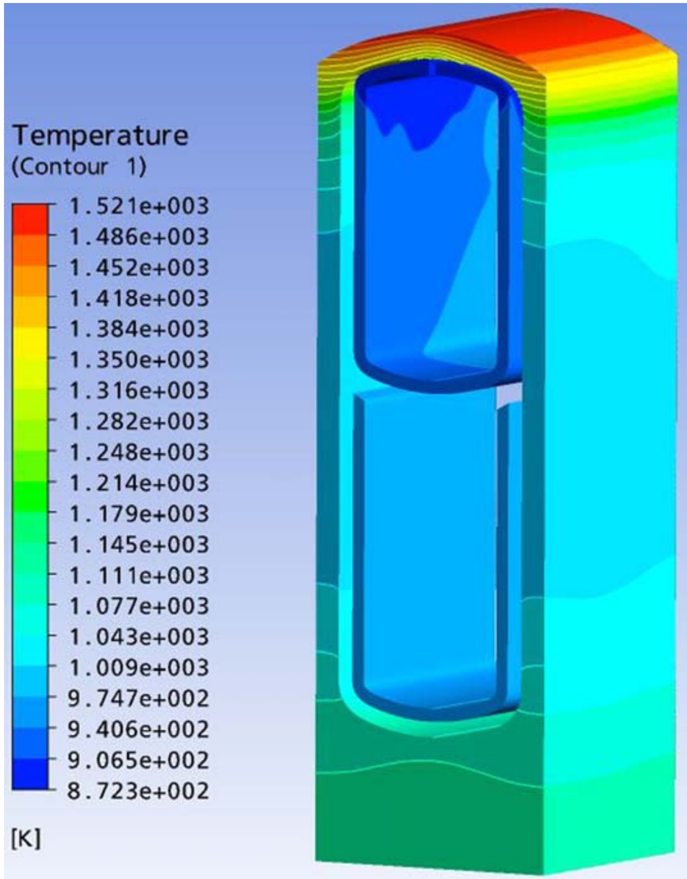
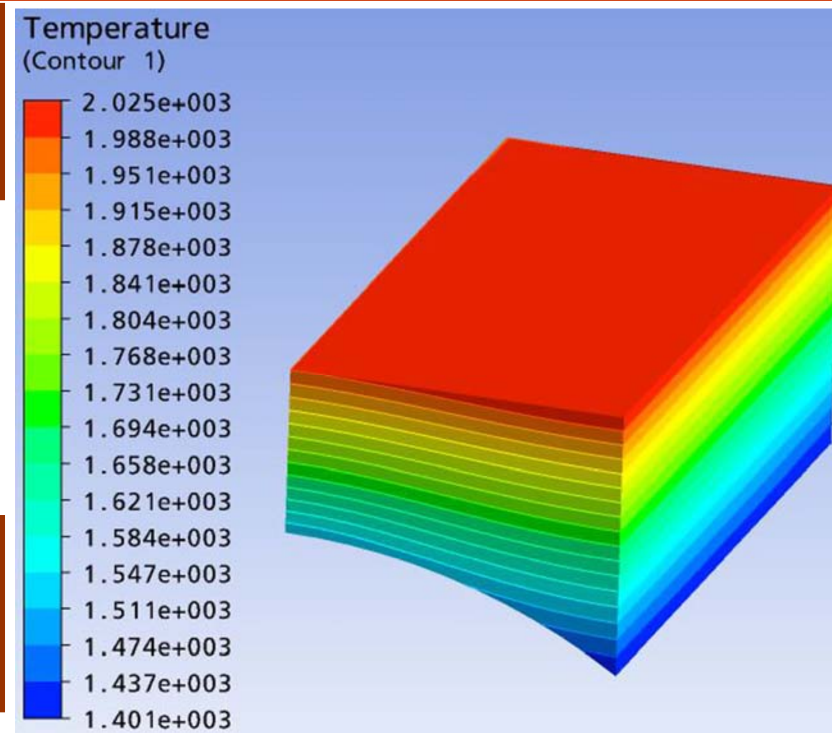


Structure temperature distribution

Coolant temperature distribution



- The max. structure temperature is 1521 K **(<1573 K, allowable temperature).**
- Pressure drop $\Delta P = 10.295-10 = 0.295$ MPa.
- P_p/P_{th}~14% **(>10% design limit)**

CFD Thermo-fluid Model for Multiple Impinging Jet Arrays

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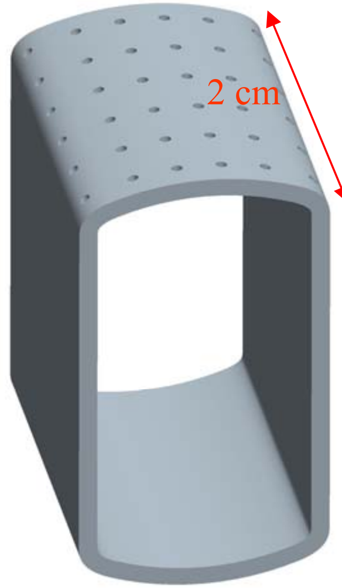
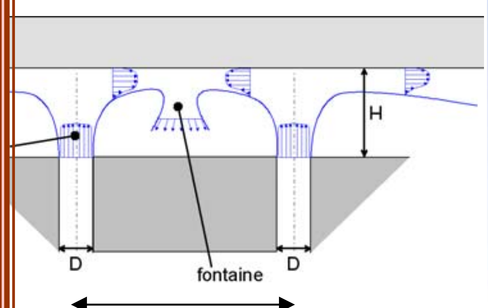
Multiple jet flow characteristics:

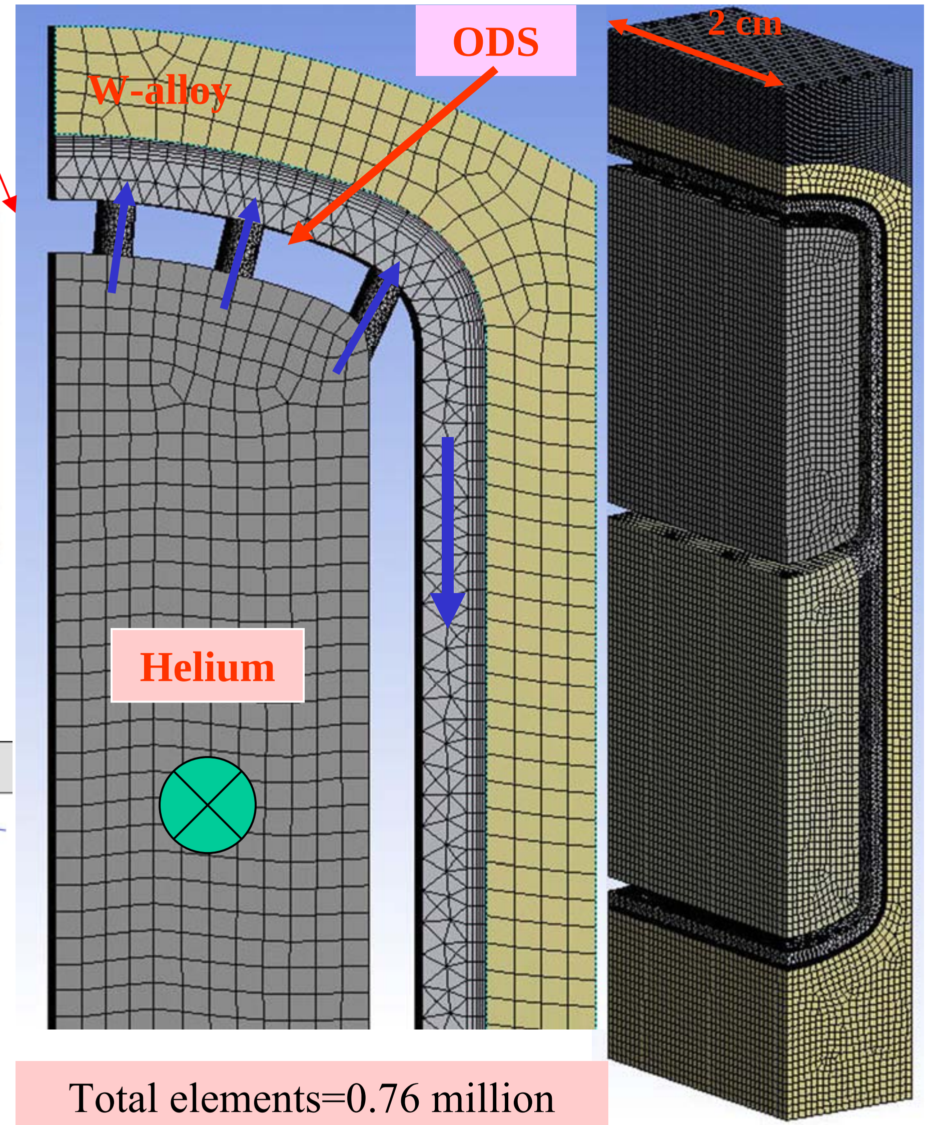
- Three flow regions as the same as a single impinging jet
- Possible interaction prior to their impingement (jet space too close, or H too large)
- Possible interaction due to collision of the wall jets
- Cross-flow for the jets on the edge of the arrays.



In-line

- ✓ Mass flow=0.005925 kg/s
- ✓ H=1.2 mm
- ✓ D=0.6 mm
- ✓ $A_{jet\_arrays}=A_{slot\_jet}$
- ✓ Holes/cm =18
- ✓ S/D=5.56~6
- ✓ Thermal loads are the same





CFD Results for Multiple Impinging Jet Arrays (18 Holes/cm)

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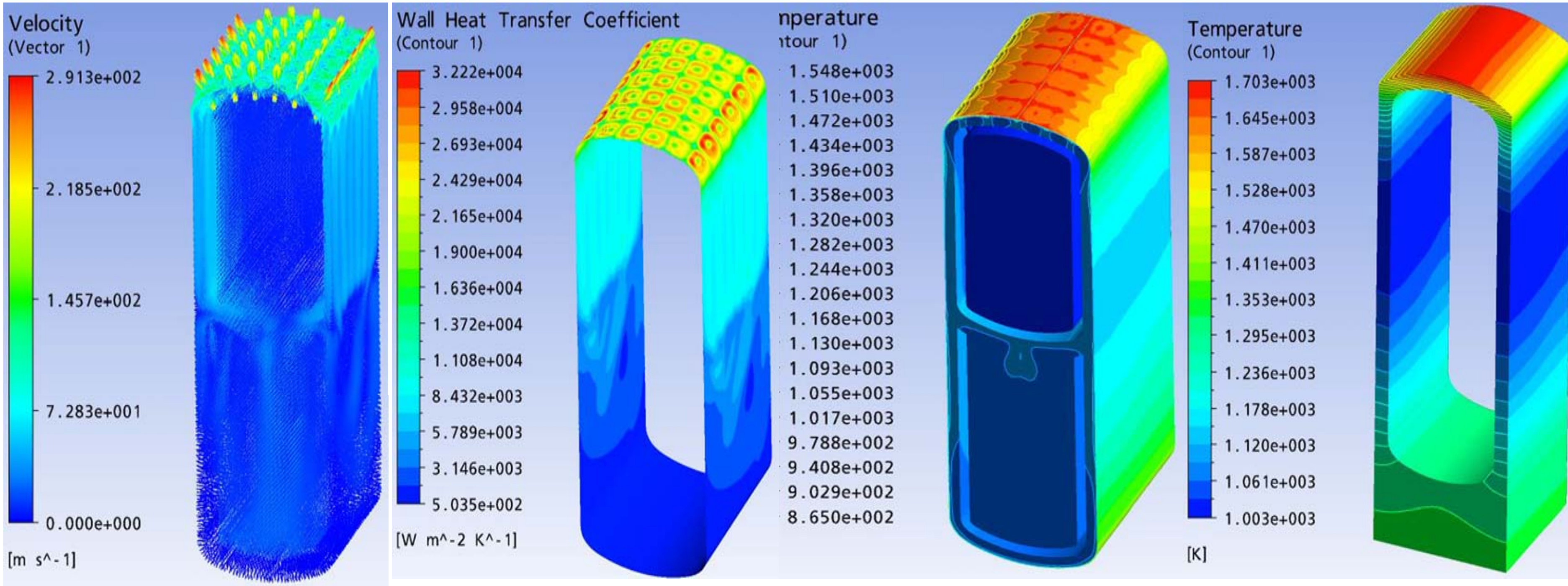

H=1.2 mm, D=0.6 mm, S/D=5.56~6

Mass flow rate=0.005925 kg/s

Max. v=291.3 m/s,

Max. local h.t.c. h=3.22x10^4 W/m^{2}K

Max. He/W interface temperature=1548 K

Max. W structure temperature=1703 K (>1573 K)

Pressure drop=10.26-10=0.26 MPa

P_p/P_{th}~12.3% (>10% design limit)

Impinging Jets Reduced to 13 Holes/cm to Increase Velocity and Heat Transfer

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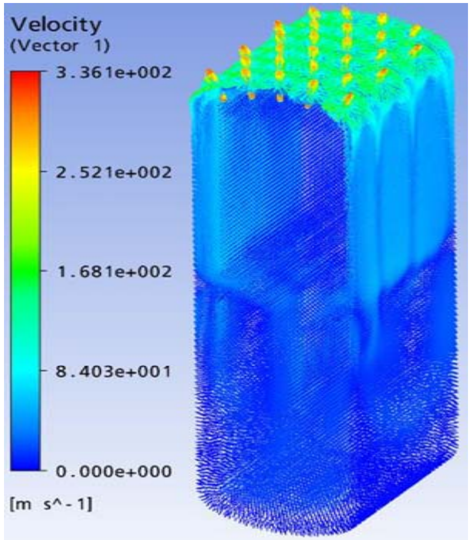

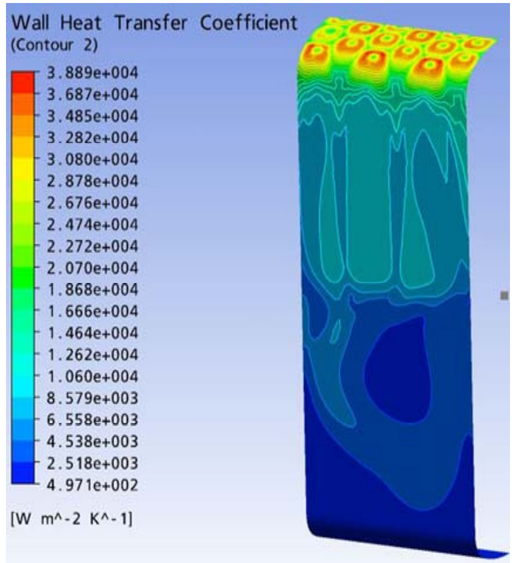

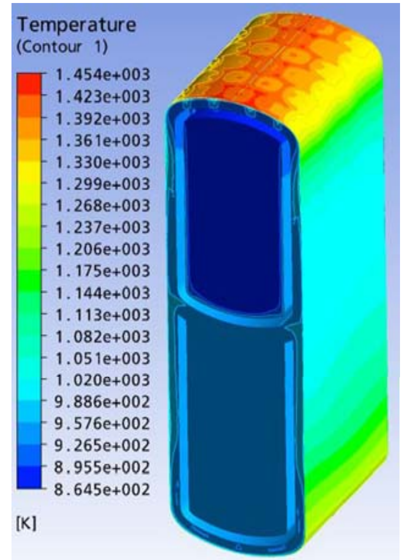

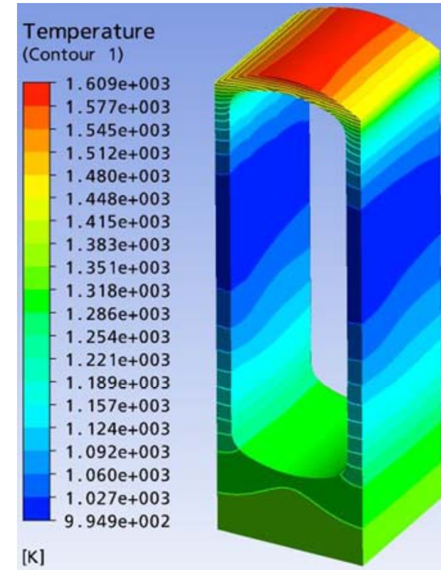

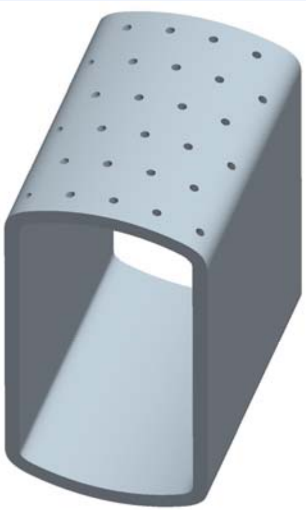

Arrangement of the Jet Arrays

H=1.2 mm, D=0.6 mm, S/D=5.56

Mass flow rate=0.005925 kg/s

Max. v=336.1 m/s,

Max. local h.t.c. h=3.89x10^{4} W/m^{2}K

Max. He/W interface temperature=1454 K

Max. W structure temperature=1609 K (>1573 K)

Pressure drop=10.441-10=0.441 MPa, P_p/P_{th}~20.9% (>10%)

Parametric Study for Multiple Jets
(13 Holes/cm, Jet-to-wall Distance H=1.2 mm)

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	Nozzle Diameter D=0.4 mm	Nozzle Diameter D=0.6 mm	Nozzle Diameter D=0.8 mm	Nozzle Diameter D=1mm	Slot Jet D=0.5 mm
Max. Velocity [m/s]	703.4	336.1	202.2	140.5	254.6
Max Local Heat Transfer Coefficient [W/m^{2}K]	5.736×10^4	3.899×10^4	2.808×10^4	2.659×10^4	3.839×10^4
Max W/He Interface Temperature, [K]	1303	1454	1650	1677	1406
Max W Structure Temperature, [K]	1449	1609	1785	1831	1579
ΔP [Pa]	24.5×10^5	4.41×10^5	1.43×10^5	0.60×10^5	1.83×10^5
P_p/P_{th}, %	116.1	20.9	6.8	2.8	8.7

Parametric Study for Multiple Jets

(13 Holes/cm, Nozzle Diameter D=0.6 mm)

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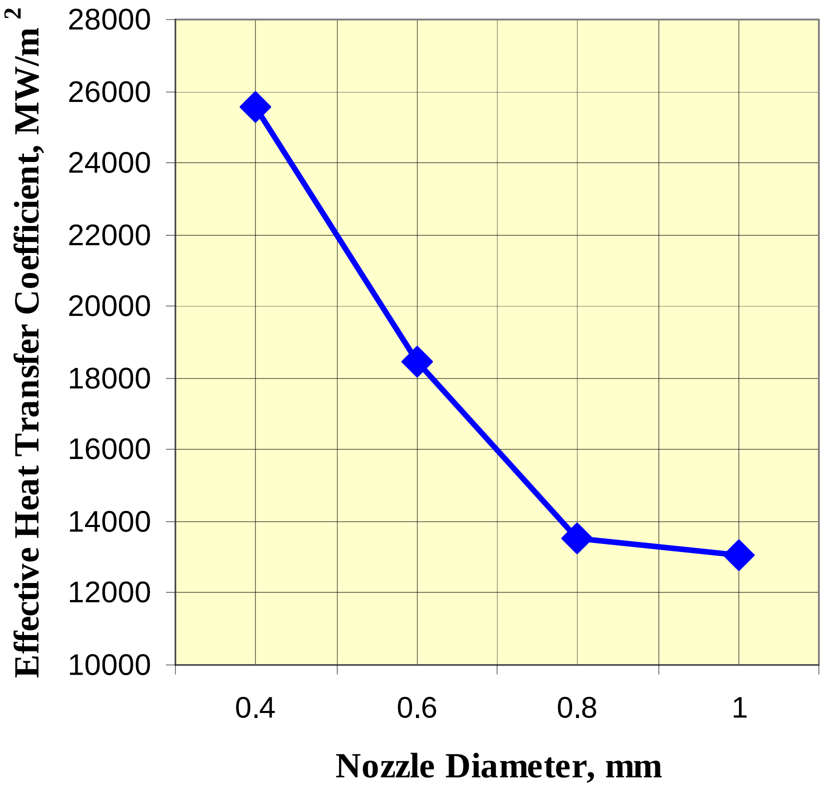
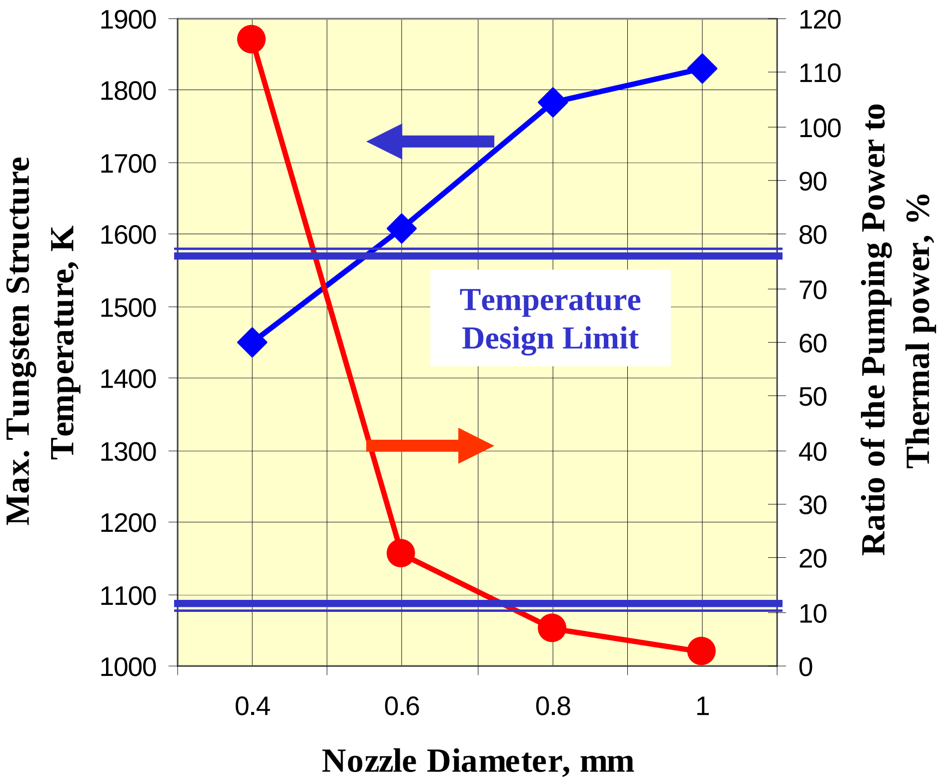
	Jet-to-Wall Space H=1.5 mm	**Jet-to-Wall Space H=1.2 mm**	**Jet-to-wall Space H=0.9 mm**	**Slot Jet H=1.2 mm D=0.5 mm**
Max. Velocity [m/s]	312.8	336.1	339.2	254.6
Max Local Heat Transfer Coefficient [W/m²K]	3.661×10^4	3.899×10^4	3.901×10^4	3.839×10^4
Max W/He Interface Temperature, [K]	1495	1454	1443	1406
Max W Structure Temperature, [K]	1650	1609	1592	1579
ΔP [Pa]	4.13×10^5	4.41×10^5	4.42×10^5	1.83×10^5
P_p/P_{th}, %	19.6	20.9	21.0	8.7

Parametric Study for Multiple Jet
(13 Holes/cm, Jet-to-wall Distance H=1.2 mm)





$h_{eff}=q''/(T_{\text{max at interface}}-T_{\text{ave. helium}})$

Full-length Model for Thermo-mechanical Analysis

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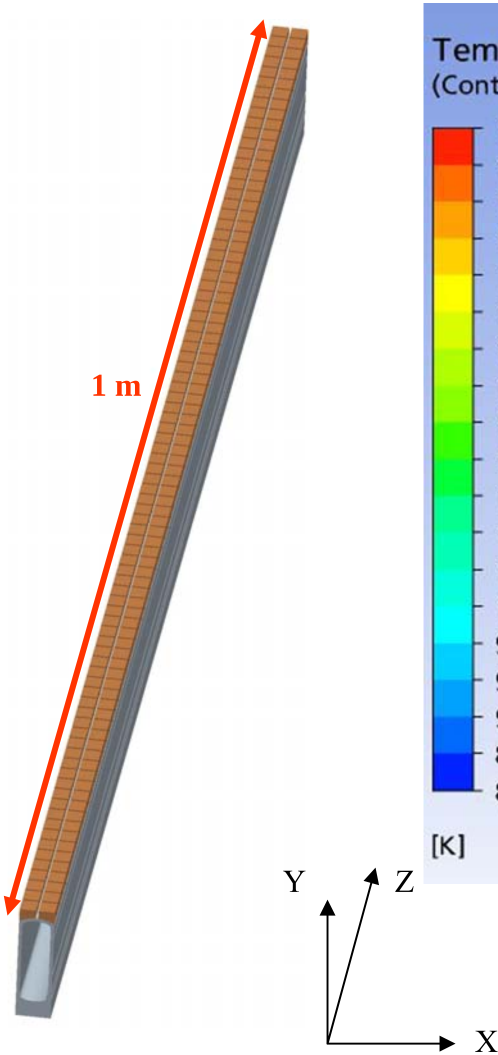
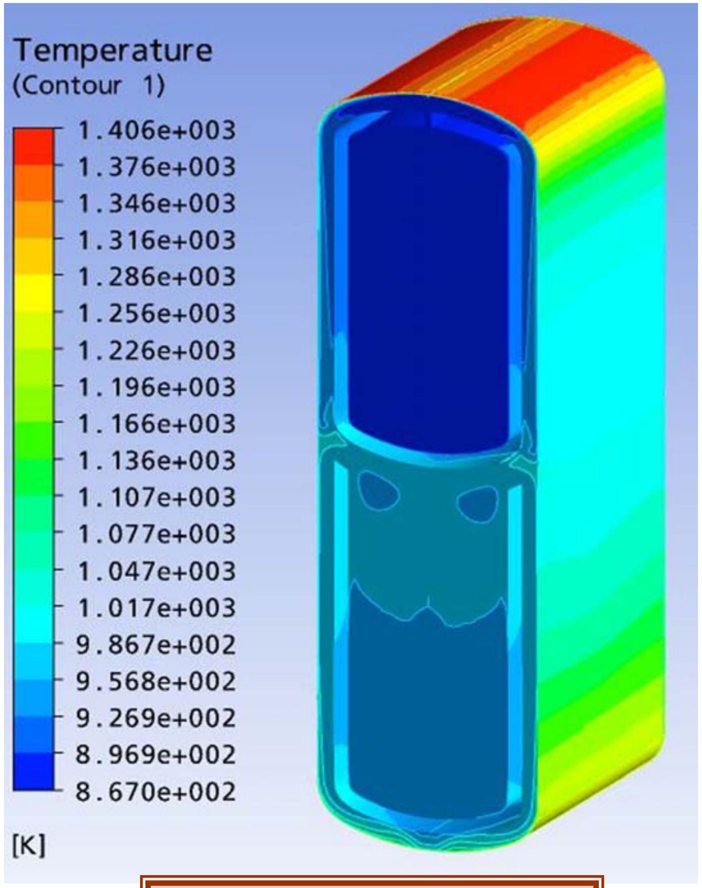
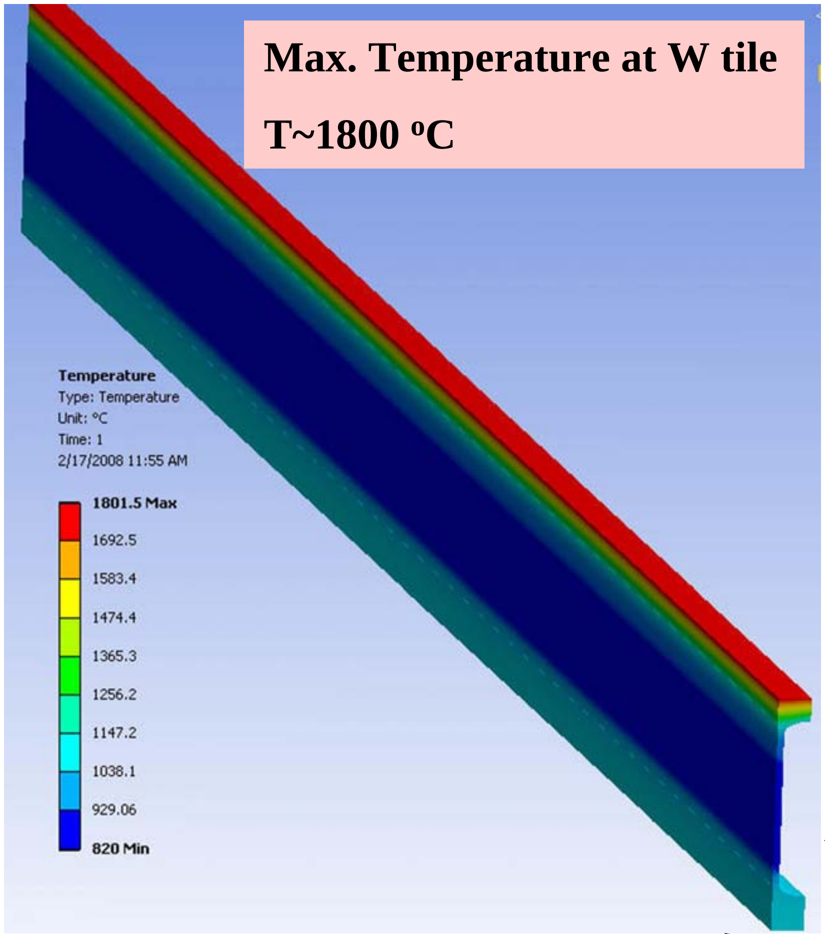
- ➢The flat plate divertor with slot jet cooling scheme is selected as the reference for stress analysis.
- ➢ODS insert manifold is excluded from thermo-mechanical model.
- ➢Temperature at the interface of the He/W is assumed to be uniform in Z-direction (CFX results) in ANSYS thermal analysis.
- ➢Two different support conditions are assumed for the thermo-mechanical simulation.
  - ✓The plate is not allowed to bend, but free to expand.
  - ✓The plate is allowed to expand and bend.

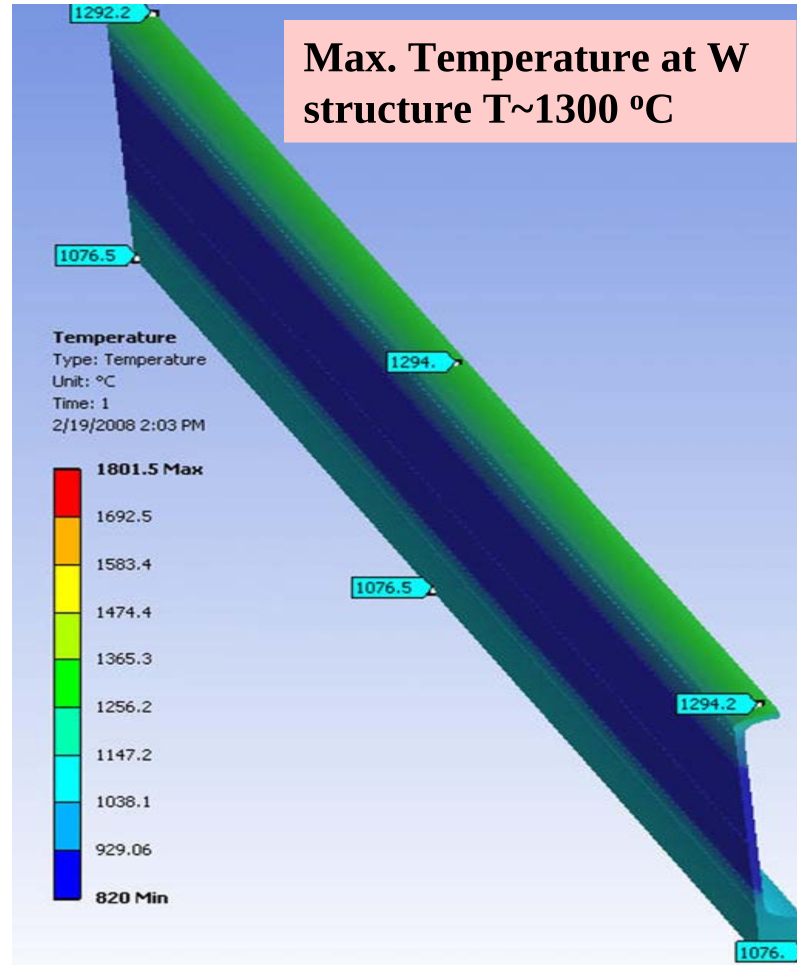


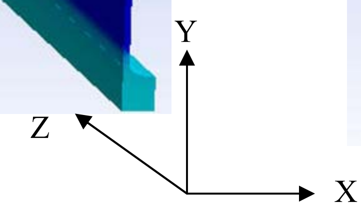


Helium Temperature distribution from CFX

Temperature Distribution from ANSYS Multi-physics







Stress and Deformation for Support Condition 1

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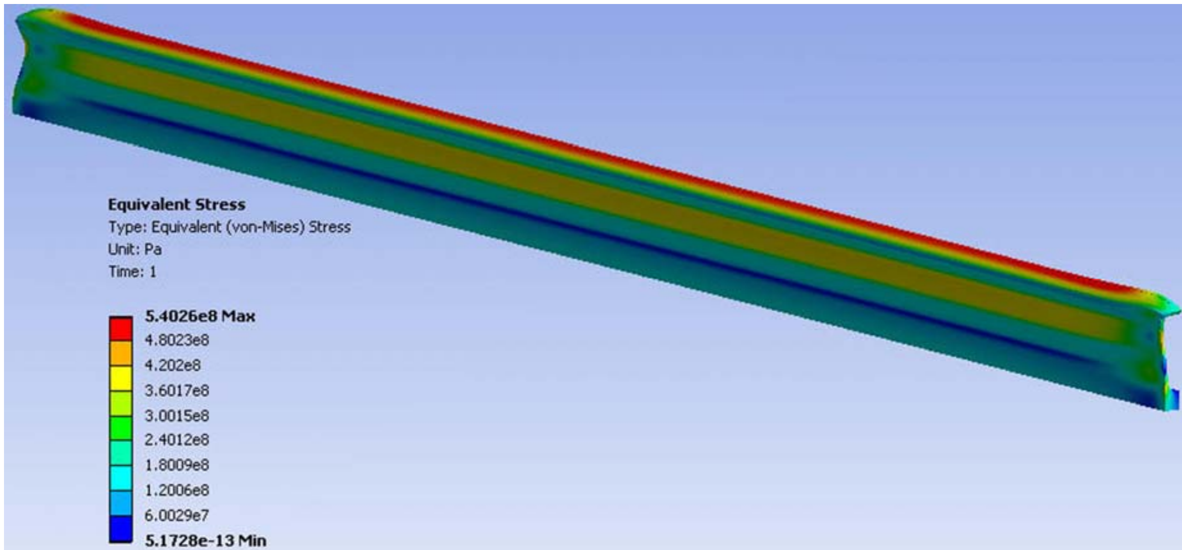
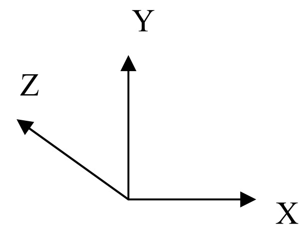


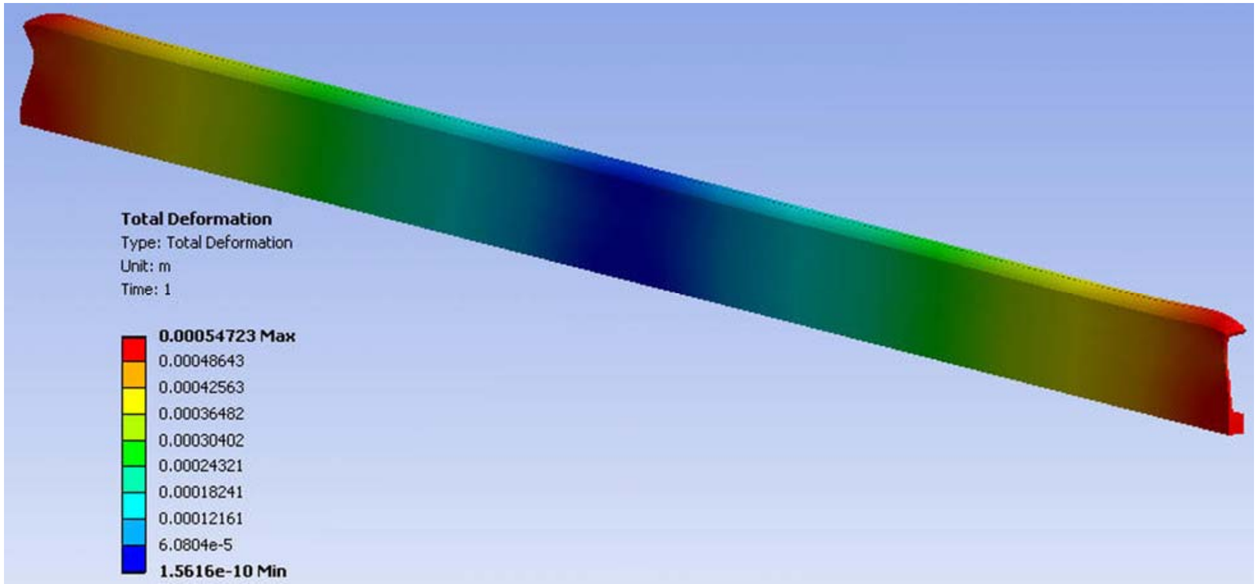
Max. von-Mises Stress

σ~ 540 MPa

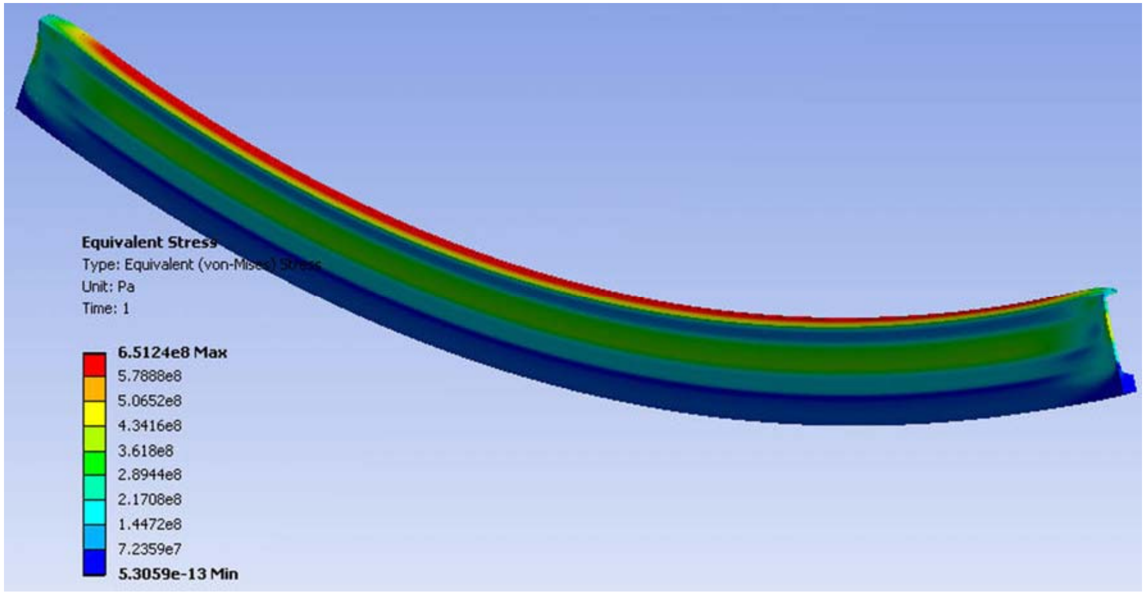


Max. Thermal Deformation

δ~0.54 mm

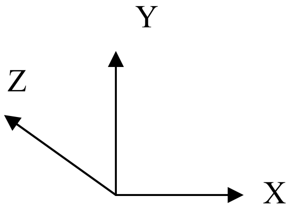


Stress and Deformation for Support Condition 2



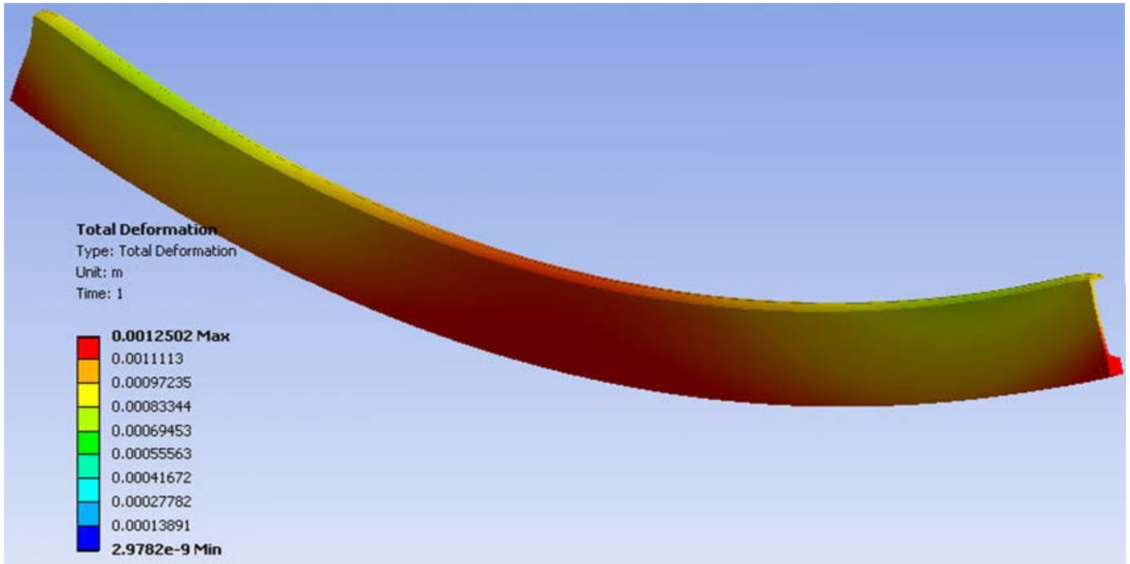
Max. von-Mises Stress

σ~ 651 MPa



Max. Thermal Deformation

δ~1.25 mm



Summary

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- Thermo-fluid and thermo-mechanical analyses have been performed for the helium-cooled flat plate and T-tube divertor concepts with heat loads up to 10 MW/m^2.

- ***T-tube Divertor Concept*** with the slot jet cooling has been considered as reference design of the ARIES-CS stellarator power plant and it will also be suited for tokamak power plant. The thermo-fluid and thermo-mechanical results are re-produced by CFX and Workbench.
  - ✓Heat transfer, High (~3.7×10^4 W/m^2K)
  - ✓Pumping power, Ok
  - ✓W Temperature, Ok
  - ✓Stress, Ok
  - ✓75,000~110,000 T-tubes for one plant (for divertor area: 100~150 m^2)

- ***Flat Plate Divertor Concept*** with the slot jet, the micro-channel and the multiple jet arrays have been investigated. The thermo-mechanical analysis have been performed only for the flat plate divertor with the slot jet cooling scheme.
  - ✓Heat transfer, high (~3.9×10^4 W/m^2K)
  - ✓Pumping power, Ok
  - ✓W Structure temperature, Ok
  - ✓Stress, > the 3Sm (450 MPa)
  - ✓500~750 flat plates for one plant (for divertor area:100~150 m^2)
  - ❖**Further to look into the multiple jets to see if the performance could be improved**
  - ❖**Further to look into the flat plate divertor concept to see if it is possible to improve the design to reduce the thermal stress**