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

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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 °C;
- Max. structure stress < 450 MPa (3Sm);
- Ratio of the pumping power to thermal power, \( \frac{P_p}{P_{th}} < 10\% \)

1. Slot jet

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

3. Multiple impinging jet arrays
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
- Outlet-Inlet=950-873 K

* S. I. Abdel-Khalik et al., to be published in Fusion Sic. & Tech

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.
Thermo-fluid Results for Slot Jet Cooling

Max. $v=254.6 \text{ m/s}$

Velocity distribution

Wall Heat Transfer Coefficient (Contour 1)

Max. $h=3.84 \times 10^4 \text{ W/m}^2\text{K}$

(Nozzle width $d=0.5 \text{ mm}$, Jet-to-wall distance $H=1.2 \text{ mm}$; mass flow=$0.005925 \text{ kg/s}$)
The max. structure temperature is 1579 K (~1573 K, allowable temperature)

Pressure drop $\Delta P = 10.183 - 10 = 0.183$ MPa

$P_p/P_{th} \approx 8.7\% (<10\%, \text{ design limit})$
CFD Thermo-fluid Model for Micro-channel Cooling

- 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

Max V=305.6 m/s

Velocity distribution

Max. h=5.7x10^4 W/m²K

(Nozzle width d=0.5 mm, micro-channel space H=0.25 mm; mass flow=0.005925 kg/s)
The max. structure temperature is 1521 K (<1573 K, allowable temperature).

Pressure drop $\Delta P = 10.295 - 10 = 0.295$ MPa.

$P_p/P_{th} \sim 14\%$ (>10% design limit)
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.

- Mass flow = 0.005925 kg/s
- H = 1.2 mm
- D = 0.6 mm
- \( A_{\text{jet_arrays}} = A_{\text{slot_jet}} \)
- Holes/cm = 18
- S/D = 5.56~6
- Thermal loads are the same

Total elements = 0.76 million
CFD Results for Multiple Impinging Jet Arrays (18 Holes/cm)

**Max. v=291.3 m/s,**
**Max. local h.t.c. h=3.22x10^4 W/m²K**
**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)**

H=1.2 mm, D=0.6 mm, S/D=5.56~6
Mass flow rate=0.005925 kg/s
Impinging Jets Reduced to 13 Holes/cm to Increase Velocity and Heat Transfer

Max. \( v = 336.1 \, \text{m/s} \),
Max. local h.t.c. \( h = 3.89 \times 10^4 \, \text{W/m}^2\text{K} \)
Max. He/W interface temperature=1454 K
Max. W structure temperature=1609 K (>1573 K)
Pressure drop=10.441-10=0.441 MPa, \( \frac{P_p}{P_{th}} \sim 20.9\% \) (>10%)

H=1.2 mm, D=0.6 mm, S/D=5.56
Mass flow rate=0.005925 kg/s

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

<table>
<thead>
<tr>
<th></th>
<th>Nozzle Diameter D=0.4 mm</th>
<th>Nozzle Diameter D=0.6 mm</th>
<th>Nozzle Diameter D=0.8 mm</th>
<th>Nozzle Diameter D=1mm</th>
<th>Slot Jet D=0.5 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Velocity [m/s]</td>
<td>703.4</td>
<td>336.1</td>
<td>202.2</td>
<td>140.5</td>
<td>254.6</td>
</tr>
<tr>
<td>Max Local Heat Transfer Coefficient [W/m²K]</td>
<td>5.736x10⁴</td>
<td>3.899x10⁴</td>
<td>2.808x10⁴</td>
<td>2.659x10⁴</td>
<td>3.839x10⁴</td>
</tr>
<tr>
<td>Max W/He Interface Temperature, [K]</td>
<td>1303</td>
<td>1454</td>
<td>1650</td>
<td>1677</td>
<td>1406</td>
</tr>
<tr>
<td>Max W Structure Temperature, [K]</td>
<td>1449</td>
<td>1609</td>
<td>1785</td>
<td>1831</td>
<td>1579</td>
</tr>
<tr>
<td>ΔP [Pa]</td>
<td>24.5 x 10⁵</td>
<td>4.41 x 10⁵</td>
<td>1.43 x 10⁵</td>
<td>0.60 x 10⁵</td>
<td>1.83x10⁵</td>
</tr>
<tr>
<td>P_p/P_th, %</td>
<td>116.1</td>
<td>20.9</td>
<td>6.8</td>
<td>2.8</td>
<td>8.7</td>
</tr>
<tr>
<td></td>
<td>Jet-to-Wall Space H=1.5 mm</td>
<td>Jet-to-Wall Space H=1.2 mm</td>
<td>Jet-to-wall Space H=0.9 mm</td>
<td>Slot Jet H=1.2 mm D=0.5 mm</td>
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</tr>
<tr>
<td><strong>Max. Velocity [m/s]</strong></td>
<td>312.8</td>
<td>336.1</td>
<td>339.2</td>
<td>254.6</td>
<td></td>
</tr>
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<td><strong>Max Local Heat Transfer Coefficient [W/m²K]</strong></td>
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<td></td>
</tr>
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<td><strong>Max W/He Interface Temperature, [K]</strong></td>
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<td>1406</td>
<td></td>
</tr>
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<td><strong>Max W Structure Temperature, [K]</strong></td>
<td>1650</td>
<td>1609</td>
<td>1592</td>
<td>1579</td>
<td></td>
</tr>
<tr>
<td><strong>ΔP [Pa]</strong></td>
<td>4.13 x 10⁵</td>
<td>4.41 x 10⁵</td>
<td>4.42 x 10⁵</td>
<td>1.83x10⁵</td>
<td></td>
</tr>
<tr>
<td><strong>P_p/P_th, %</strong></td>
<td>19.6</td>
<td>20.9</td>
<td>21.0</td>
<td>8.7</td>
<td></td>
</tr>
</tbody>
</table>
Parametric Study for Multiple Jet (13 Holes/cm, Jet-to-wall Distance H=1.2 mm)

\[ h_{\text{eff}} = \frac{q'}{(T_{\text{max at interface}} - T_{\text{ave. helium}})} \]
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.
Temperature Distribution from ANSYS Multi-physics

Max. Temperature at W tile
T~1800 °C

Max. Temperature at W structure T~1300 °C
Stress and Deformation for Support Condition 1

Max. von-Mises Stress
\[ \sigma \approx 540 \text{ MPa} \]

Max. Thermal Deformation
\[ \delta \approx 0.54 \text{ mm} \]
Stress and Deformation for Support Condition 2

Max. von-Mises Stress
\[ \sigma \approx 651 \text{ MPa} \]

Max. Thermal Deformation
\[ \delta \approx 1.25 \text{ mm} \]
Summary

- 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/m².

- **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 (~3.7x10⁴ W/m²K)
  - ✓ Pumping power, Ok
  - ✓ W Temperature, Ok
  - ✓ Stress, Ok
  - ✓ 75,000~110,000 T-tubes for one plant (for divertor area: 100~150 m²)

- **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 (~3.9x10⁴ W/m²K)
  - ✓ Pumping power, Ok
  - ✓ W Structure temperature, Ok
  - ✓ Stress, > the 3Sm (450 MPa)
  - ✓ 500~750 flat plates for one plant (for divertor area:100~150 m²)

- 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