Design of JT-60SA cryodistribution components

Kyohei NATSUME, Kazuma FUKUI, Haruyuki MURAKAMI, Kaname KIZU, Takaaki ISONO, Kazuya HAMADA

National Institutes for Quantum and Radiological Science and Technology

= ABSTRACT =

JT-60SA is a fusion experiment tokamak device using superconducting magnets to be built in Japan. This joint international project involves Japan and Europe. In this work, we presents the design of cryodistribution components which are named main cryo-transfer line (CryoL) and valve boxes (VB).

CryoL is a vacuum heat-insulation multiple piping of which the outer diameter is 965.5 mm. It connects between the helium refrigerator system and the tokamak cryostat. All 5 supply lines and 4 return lines are installed in CryoL.

VB contains cryogenic valves and measurement devices to control the cold helium flow. Eleven VBs are installed around the tokamak cryostat asymmetrically.
Introduction of JT-60SA

JT-60SA is under construction. The plasma operation will be started in 2020.

Cryodistribution specification

<table>
<thead>
<tr>
<th>Loop No. (Component)</th>
<th>LOOP 1 (TFC)</th>
<th>LOOP 2 (PFC)</th>
<th>LOOP 3 (CP)</th>
<th>LOOP 4 (TS)</th>
<th>LOOP 5 (HTSCL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (K)</td>
<td>4.5</td>
<td>4.5</td>
<td>3.7</td>
<td>80</td>
<td>50</td>
</tr>
<tr>
<td>Pressure (MPa)</td>
<td>0.53</td>
<td>0.48</td>
<td>0.48</td>
<td>1.35</td>
<td>0.40</td>
</tr>
<tr>
<td>Flow rate (g/s)</td>
<td>876</td>
<td>960</td>
<td>270</td>
<td>404</td>
<td>30</td>
</tr>
<tr>
<td>Pressure loss (MPa)</td>
<td>0.13</td>
<td>0.08</td>
<td>0.05</td>
<td>0.15</td>
<td>0.29</td>
</tr>
<tr>
<td>Average heat load (W)</td>
<td>1794</td>
<td>1850</td>
<td>84</td>
<td>42,000</td>
<td>-</td>
</tr>
<tr>
<td>Branch Number</td>
<td>32</td>
<td>10</td>
<td>9</td>
<td>30</td>
<td>26</td>
</tr>
<tr>
<td>Cold weight (Ton)</td>
<td>434</td>
<td>257</td>
<td>-</td>
<td>96</td>
<td>-</td>
</tr>
</tbody>
</table>
= Functions of Cryodistribution =

1. Connection between the helium refrigerator and cooled components by pipes


3. Adjustment the flow rate by valves

HRS: He Refrigerator System  TF: Toroidal Field Coil  CS: Central Solenoid  EF: Equilibrium Field Coil

cryoL: Main Cryo-transfer Line  vb: Valve Box  CTB: Coil Terminal BOX  TS: Thermal Shield

Main Cryo-transfer line (CryoL) =

**Pressure Loss**

<table>
<thead>
<tr>
<th>Loop</th>
<th>Outer diameter (mm)</th>
<th>Flow rate (g/s)</th>
<th>A: (\Delta P) in CryoL (kPa)</th>
<th>B: (\Delta P) in the cryodistribution (kPa)</th>
<th>C: (\Delta P) in component (kPa)</th>
<th>Total (\Delta P) A+B+C (kPa)</th>
<th>Requirement (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loop1</td>
<td>114.3</td>
<td>876</td>
<td>0.9</td>
<td>7.4</td>
<td>118</td>
<td>126</td>
<td>(\leq 130)</td>
</tr>
<tr>
<td>Loop2</td>
<td>114.3</td>
<td>960</td>
<td>3.1</td>
<td>12.5</td>
<td>59.5</td>
<td>75</td>
<td>(\leq 80)</td>
</tr>
<tr>
<td>Loop3</td>
<td>60.5</td>
<td>270</td>
<td>2.2</td>
<td>3.3</td>
<td>37.5</td>
<td>43</td>
<td>(\leq 50)</td>
</tr>
<tr>
<td>Loop4</td>
<td>114.3</td>
<td>404</td>
<td>3.2</td>
<td>100</td>
<td>26.8</td>
<td>130</td>
<td>(\leq 150)</td>
</tr>
<tr>
<td>Loop5</td>
<td>60.5</td>
<td>21.8</td>
<td>0.3</td>
<td>18.8</td>
<td>90</td>
<td>109</td>
<td>(\leq 110)</td>
</tr>
</tbody>
</table>

**Design Requirement: main factors**
- Pressure loss derived from HRS specification
- Mechanical soundness toward seismic event and thermal contraction
- Heat load: conduction and radiation
Mechanical strength of outer pipe for seismic event

**Condition of FEM analysis for the outer pipe**
- Dead weight: total ~17 ton
- Outer pressure: 0.1 MPa
- Contraction of bellows due to vacuum
- Enforced displacement of interface
- Seismic force

<table>
<thead>
<tr>
<th>Enforced displacement</th>
<th>horizontal</th>
<th>vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interface of support stage</td>
<td>9 mm</td>
<td>-</td>
</tr>
<tr>
<td>Interface of tokamak cryostat</td>
<td>5 mm</td>
<td>– 5 mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Seismic force</th>
<th>horizontal</th>
<th>vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static load</td>
<td>0.4 G</td>
<td>-</td>
</tr>
</tbody>
</table>

Obtained results by FEM analysis
- Displacement of the outer pipe
- Stress on the outer pipe

**Allowable stress of SS304**: 205 MPa
(Japanese law about high pressure gas safety)

The stress on outer pipe is reduced by inserting bellows between CyOL and the tokamak cryostat.

FEM analysis of Inner pipes is conducted using obtained displacement results of the outer pipe as boundary conditions.
The support structure or pipe might be broken, if the excess stress is induced by thermal contraction.

[Ordinary solution]
- Inserting flexible tube
- Inserting crank pipe

[JT-60SA solution]
- Using 3 support types properly
  (We named them guide, anchor, and vertical support.)
**Analysis result of FEM for inner pipes**

Condition of FEM analysis for inner pipes
- Dead weight: ~400 kg
- Inner pressure: 2.0 MPa (Safety valve open threshold)
- Displacements of the outer pipe
- Seismic force

Obtained results by FEM analysis
- Displacement of inner pipes
- Stress on inner pipes

**Example**: Stress and displacement of Loop 2 Supply pipe in CryoL

The stress on inner pipe can be managed by using 3 different types of support structure.
Heat load sources

- **Conduction**
  - Pipe support
    - Adopted thin epoxy legs and plates
  - Vacuum Partition
    - Extended conduction path by sheaths

- **Radiation**
  - Covered pipes and the thermal shield by multi-layer insulator (MLI)

The total heat load to 4 K, 50 K, and 80 K are estimated by summing calculation results of all conduction paths and the radiation using the Stefan–Boltzmann formula of two concentric cylinders.

<table>
<thead>
<tr>
<th>Conduction path</th>
<th>Path A</th>
<th>Path B</th>
<th>4 K</th>
<th>50 K</th>
<th>80 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross section: $S$ (mm$^2$)</td>
<td>745</td>
<td>745</td>
<td>91.6 W</td>
<td>5.5 W</td>
<td>393 W</td>
</tr>
<tr>
<td>Length: $L$ (mm)</td>
<td>374</td>
<td>48</td>
<td>97 W</td>
<td>9 W</td>
<td>434 W</td>
</tr>
<tr>
<td>Thermal conductivity Integral $80K \rightarrow 4.2K$ : $\lambda$ (W/m)</td>
<td>19.6</td>
<td>19.6</td>
<td>0.039</td>
<td>0.304</td>
<td></td>
</tr>
</tbody>
</table>
**Valve box (VB)** - Measurement and adjustment coolant flow -

**VB vessel**
- 1.4 m diameter
- 2.0 m height
- 1.2 ton weight

**Satisfaction of requirement in the pressure loss, heat load, and mechanical strength are also confirmed by similar methods to CryoL.**

**Orifice plate**

The flow rate is obtained by measuring the pressure in front of and behind an orifice plate.

Lead pipes for the pressure measurement are connected to vacuum feedthroughs on the tokamak cryostat.

**Cryogenic valve**

Remote control valves are operated pneumatically. These valves are installed in VBs and controls coolant helium flow.

Safety valves are connected inlet and outlet side of each coolant loop for cooled components [2].

**Thermometer**

Two resistive thermometer devices which are made of carbon ceramics (TVO) are installed on each lines in VBs.

They are inserted with Apiezon N grease in holes of a copper block which is attached on the pipe surface by brazing [1].
= Conclusion =

Design of all cryodistribution components of JT-60SA has been completed. Calculated pressure loss, heat load, and mechanical strength are satisfied requirements.

- Inner pipes of main cryo-transfer line are able to withstand toward the force due to the thermal contraction and the seismic event by managing support positions and shapes.

- TVO sensors and orifice plates are installed in valve boxes to measure the temperature and the flow rate of coolant in pipes.

Reference: