Mesh sensitivity study and optimization of fixed support for ITER torus and cryostat cryoline

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Abstract. The torus & cryostat cryoline of ITER cryodistribution system has been designed as per the process specifications. The cryoline is an ensemble of six process pipes, thermal shield, fixed, sliding support and outer jacket. The fixed support (FS), which also acts as the anchor for the bellows, is one of the most important part of the cryoline. The FS has to withstand the static weight of pipes as well as the spring and thrust forces arising from the bellows. The FS design has been optimized for the thermal, structural and for combined loads with thermal optimization criteria; less than 8 Watt at 100 K and less than 1.5 Watt at 4.5 K. ANSYS 10.0 has been used for the analysis and CATIA V5 R16 has been used for the modelling as well as geometry optimization. In order to bring the Von-Mises stress within the acceptable limit of 115 MPa, a detailed mesh sensitivity study has been carried out along with design optimization. The iterative process of mesh refinement continued till stress convergence is achieved. The stress analysis has been carried out for optimized mesh size. The paper will present the design methodology, construction details and the results of the analysis.

1. Introduction
The ITER cryogenic system will be the next large cryogenic installation in the world to be built at Cadarache, France. The ITER cryogenic system consists of the cryoplant, cryodistribution system and the system of cryogenic lines and manifolds. Cryo-distribution system as well as cryolines and manifolds are part of in kind supply for India [1]. The design, engineering and analysis of the ITER torus and cryostat (T & C) cryoline have been done to satisfy the functional requirements. The cryoline has six process pipes, which are, 4.5 K Supercritical Helium (SHe) supply, 4.5 K SHe return, fast cool down, cold He exhaust, 80 K Gaseous Helium (GHe) supply and 100 K GHe return. The cryoline consists of straight, T, C and elbow sections and these sections contain bellows or flexible hoses, at least one fixed support and many sliding supports as per the design code guideline. The supports are important to ensure that the bellows absorbs the motion for which it is designed. The FS has to withstand the static weight of the process pipes and its content. It also acts as the anchor or fixed point for the bellows. It has to take care the spring as well as the pressure thrust forces arising from the bellows. Inadequate design fixed support causes stress that reduces the life of the bellow, cause pipe bucking and system failure. ASME B 31.3 [2], CATIA® Version 5.16 [3], HyperMesh® 8.0 [4], ANSYS® 10.0 [5] have been used as the design guideline and analysis tools.

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2. Design description

Major steps followed for the design of fixed support are represented in the flow diagram of figure 1. The model with the inside construction details of fixed support is shown in figure 2. The material of construction (MOC) and the dimension details for different components of the fixed support is shown in table 1.

![Flow diagram](image1)

**Figure 1.** Major steps in the design of fixed support.

![Construction details](image2)

**Figure 2.** Construction details of fixed support.

**Table 1.** Dimensional details of fixed support.

| Sr. No. | Component                                | Material selected       | Dimensional details (mm) |
|---------|------------------------------------------|-------------------------|--------------------------|
|         |                                          |                         | Outer | Thickness | Length |
| 1       | Outer ring                               |                         | 549   | 30        |        |
| 2       | 300 K - 100 K LCP outer                  |                         | 476   | 1.25      | 400    |
| 3       | Bridge                                   |                         | 476   | 10        |        |
| 4       | 300 K - 100 K LCP inner                  | ASTM A312/A240 304L     | 548   | 2         | 400    |
| 5       | Internal support plate                   |                         | 448   | 35        |        |
| 6       | 100 K-4.5 K LCP for DN 88.9              |                         | 101.6 | 1         | 400    |
| 7       | 100 K-4.5 K LCP for DN 42.2              |                         | 60.3  | 0.75      | 400    |

GHe supply line at 80 K and return line at 100 K are directly connected to the internal support plate of fixed support. This internal plate is linked to the outer ring at room temperature via two concentric
long pipes which is 300 K-100K Long Conduction Path (LCP). The 4.5 K SHe supply & return as well as fast cool down & cold He exhaust lines are connected to the internal support plate via an envelope which is the 100 K - 4.5 K LCP. The baseline solid model of fixed support has been generated in CATIA V5 design software.

The position and the number of support per section of cryoline have been decided based on the stress and the deformation at the anchor points. The major sources for static thermo-mechanical load on the fixed support are due to [6]

- Axial spring force of the bellows
- Axial thrust force due to internal pressure
- Moment in elbow and tee section
- Weight of process pipe and fluid

3. Analysis

The base line FE model of fixed support was imported from CATIA software. The model was meshed in HyperMesh® 8.0 by using SOLID186-3D-20 node structural solid (hexahedron) elements. The hexahedron elements are used instead of tetrahedron elements to avoid the functional error. The temperature dependent material properties of AISI 304 have been used for carrying out the thermal and structural analysis.

3.1. Mesh sensitivity study

In order to make sure that the stresses are independent of element size, the mesh sensitivity study has been carried out. The mesh sensitivity study was carried for four element sizes as listed in table 2. Only forces have been considered for the mesh sensitivity study. The mesh has to be refined globally and / or locally to improve the stress prediction in the critical regions. The mesh sensitivity analysis has been carried out for two critical locations in the high stress regions obtained during the first iterative analysis for Model A as shown in figure 3.

| Sr. No. | FE details | No of elements | Location 1 (MPa) | Location 2 (MPa) |
|---------|------------|---------------|----------------|-----------------|
| 1       | 9930       | 129.72        | 127.95         |
| 2       | 26284      | 125.93        | 124.73         |
| 3       | 28708      | 124.86        | 125.60         |
| 4       | 109763     | 125.20        | 123.30         |

Figure 4 shows the variation of von-Mises stress as a function of number of element for the fixed support. It is clear from the mesh sensitivity analysis, that the stress is independent of the mesh size beyond 28708 elements and the model with 109763 elements and 659728 nodes satisfies the requirement for capturing the results. This model has been considered for all the further analyses.

3.2. Thermal and structural analysis

The thermal analysis has been performed to estimate the heat load from the fixed support. The structural analysis considering the forces (Fx and Fy) as well as gravity loads has been performed to estimate the stress based on the applied boundary conditions. These forces have been estimated based on pipe stress analysis of cryoline section. The manufactures data of selected bellows have been used during the pipe stress analysis. The temperature loads applied on the different pipes of the fixed support and the forces applied for the structural analysis have been summarized in table 3, shown in figure 5 (a) and (b) respectively.
**Figure 3.** Model A showing critical locations for mesh sensitivity analysis.

**Figure 4.** Variation of von-Mises stress as a function of number of elements.

**Table 3.** Temperature and forces applied on the fixed support model.

| Sr. No. | Process pipe       | Temperature (K) | Fx (N) | Fy (N) |
|---------|--------------------|-----------------|--------|--------|
| 1       | DN 42.2 supply     | 4.5             | 3542   | 35     |
| 2       | DN 42.2 return     | 4.5             | 3542   | 35     |
| 3       | DN 88.9 supply     | 4.5             | 14332  | 105    |
| 4       | DN 88.9 return     | 4.5             | 14332  | 105    |
| 5       | DN 101.6 supply    | 100             | 18179  | 419    |
| 6       | DN 101.6 return    | 100             | 18179  | 419    |
| 7       | Outer flange       | 300             | -      | -      |

**Figure 5.** (a) Thermal boundary conditions (b) Structural boundary conditions.

**4. Design optimization**

The thermal as well as structural optimization has been carried out to meet the performance criteria of the fixed support. Thermal optimization has been carried out with the following changes to meet the thermal requirement.

- 100 K - 4.5 K LCP for DN42.2 : Thickness reduced to 0.75 mm from 1 mm
100 K - 4.5 K LCP for DN88.9: Thickness reduced to 1 mm from 1.652 mm
300 K - 100 K LCP Outer: Thickness reduced to 1.25 mm from 2 mm

The structural optimization of the thermally optimized model has been carried out by incorporating the changes as shown in figure 6, to reduce the von-Mises stress within the acceptable limit of 115 MPa for the optimized Model B.

Figure 6. Changes during the structural optimization.

The maximum stress was due to bending and this was reduced by adding the stiffening ring on 300 K – 100 K LCP and introducing the hub on the 100K - 4.5 K LCP as shown in figure 6 (a) and (b) respectively. The stress near the cross stiffening ring was reduced by thickening the internal support plate by 5mm and maintaining the cross stiffeners thickness same as the plate thickness. The fillet was added to reduce the stress concentration near the corner of the cross stiffening ring. Further reduction in the stress was achieved by removing the cross stiffening ring.

5. Results
The results of the analysis, for model A (before optimization) show that, the heat load is 9.8 Watt at 100 K and 2 Watt at 4.5 K, which is higher than the acceptable limit. The maximum von-Mises stress on the fixed support is 276 MPa, which is also higher than the acceptable limit. The maximum stress was observed near the junction of thermal bridge and 300 K-100K LCP inner. The higher stress was also observed near the junction of 100 K-4.5 K LCP and internal support as well as on the internal support plate near the cross stiffening ring. The changes shown in figure 6 have been incorporated to reduce the stress on the fixed support. The results of the optimized model B (after optimization) show...
that, the heat load is 7.8 Watt at 100 K and 1.47 Watt at 4.5 K, which is within the acceptable limit. The maximum Von-Mises stress on the fixed support is 113 MPa, which is also within acceptable limit. The maximum stress is observed near the holes provide for 80K Ghe supply and return line. The maximum observed deformation is 1.51 mm. The heat flux plots and von-Mises stress profile for the final optimized model has been shown in figure 7 (a) and (b) respectively.

**Figure 6.** (a) Heat flux plot (b) von-Mises stress plot for the final optimized fixed support.

### 6. Conclusion
The design description, different analysis carried out and the results of analysis for fixed support has been presented in this paper. The mesh sensitivity analysis has been carried out. The design optimization has been carried out to meet the heat load and stress criteria. The results of the analysis confirm that the heat load at 4.5 K is 1.47 Watt and at 100 K is 7.8 Watt. The maximum von-Mises stress is 113.85 MPa. The design validation of the fixed support will be experimentally confirmed.

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### References
[1] Sarkar B, Badgujar S, Vaghela H, Shah N, Bhattacharya R and Chakrapani Ch 2007 Design, analysis and test concept for prototype cryoline of ITER *Advances in Cryogenic Engineering* **B 53** 1716-23
[2] ASME B 31.3 – Process piping
[3] CATIA® Version 5.16 by Dassault Systems
[4] HyperMesh® 8.0
[5] ANSYS® Simulation 10.0 by SAS IP, Inc
[6] Sarkar B, Badgujar S, Vaghela H, Shah N and Bhattacharya R, Serio L, Kalinin V, Chalifour M and Kim Y H 2008 Cryoline for torus and cryostat cryopumps of ITER: the engineering design pathway to be published at conference proceedings of ICEC 22