Thermo-structural and heat load analysis of SST-1 Superconducting coils

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Abstract

Steady-State Superconducting Tokamak-1 (SST-1) has Sixteen Toroidal field (TF) and nine superconducting poloidal field (PF) coils. TF coils are connected in series, whereas, PF coils are to be operated individually in pulse mode. TF coils are operating up to 2.5 T in steady state condition but PF coils have hydraulic as well as heat load issues. In order to operate TF coils at higher field and to understand PF coils related issues, thermos-structural and heat load analyses have been initiated using ANSYS software. In these analyses, a CATIA model is prepared for SST-1 consisting of superconducting coils, support structure, 80 K cooling system and cryostat. Meshing is done using ANSYS. Initial condition and boundary conditions for temperature, pressure and other constraints in structure are given as inputs from experimental data. Steady state thermal and static structural modules of ANSYS are used for these analysis. Structural analysis of supports, cantilever ring, TF and PF coils at cryogenic temperatures carried out. Validation of stresses and thermal contraction results compared with analytical results, design and experimental results. Using similar CATIA model, radiative heat loads on PF and TF magnet coils, conduction loads on cantilever support ring from ground supports also estimated using ANSYS software. Estimated heat loads due to residual gas conduction, radiation and conduction on various components are compared with analytically calculated and experimental results. Simulated and estimated heat loads are compared. Model preparation, meshing, boundary conditions and calculation methodologies will be discussed in this presentation.

1. INTRODUCTION

In SST-1 all 16 Toroidal field coils (TFC) and 9 Poloidal field coils (PFC) are super conducting coils of NbTi alloy. These coils are cooled using super critical liquid helium. Vertical field coils and central solenoid are water cooled copper coils. Helium liquefaction and refrigeration plant has 1.3kW rated power at 4.2K [1]. At present pressure drop and heat load on superconducting coils is very large. During plasma operations only Toroidal field coils are cooled. Few ports are not actively cooled and are at higher temperature, these ports are directly seeing 4.2K coils hence causes high radiation heat load on superconducting coils.

Radiation thermal shield at 80K temperature are used to reduce radiation heat load on low temperature magnets. These shield panels are not available at some port locations. At these places a baffled copper plate/shield is used which is conduction cooled from LN_2. Temperature of these port shields are in the range of 220-250K. It increases radiation heat load. During plasma operations of SST-1 tokamak, PFCs are not cooled and are at higher temperature (~50K). PFCs are connected to TFC through OICS, due to this TFC get conduction heat load from PFC.

In this paper radiation heat load is discussed in section2, conduction heat load is discussed in section3, thermal analysis is discussed in section4, thermal deformation in section5,

2. RADIATION HEAT LOAD

All superconducting magnets are assembled inside a cryostat. Thermal shield at 80K used to reduce radiation heat load. Emissivity of metallic surfaces increases with increase in temperature. High temperature port openings will also have high emissivity which results in higher thermal radiation. Radiation load is estimated using ANSYS software for TFCs and PFCs separately.

Total area of high temperature ports = 5.446 m^2.
PFC surface Area = 33.54 m^2
TFC surface Area = 69.54 m^2
80K thermal shield area = 101.92 m^2

Radiation heat exchange = $Q_{1-2}= \sigma(T_1^4-T_2^4)/((1-\varepsilon_1)/(A_1*\varepsilon_1) +(1-\varepsilon_2)/(A_2*\varepsilon_2)+ 1/(A_1*F_{12}))$
Where,
ε_1, ε_2 = emissivity of surfaces
A_1, A_2= surface area
T_1, T2= temperature of surfaces
F_{12}= view factor

2.1 RADIATION LOAD ON TOROIDAL FIELD COILS

Estimated radiation load on TFC, by using ANSYS software = **130 W**
Pressure drop inside cable in conduit conductor (CICI) is estimated on the basis of void fraction. Difference in Pressure drop for liquid phase and two phase flow is significantly large. As heat load on super conductor coil increases, vapour fraction in flow also increases. Hence pressure drop of the coil increases [2].

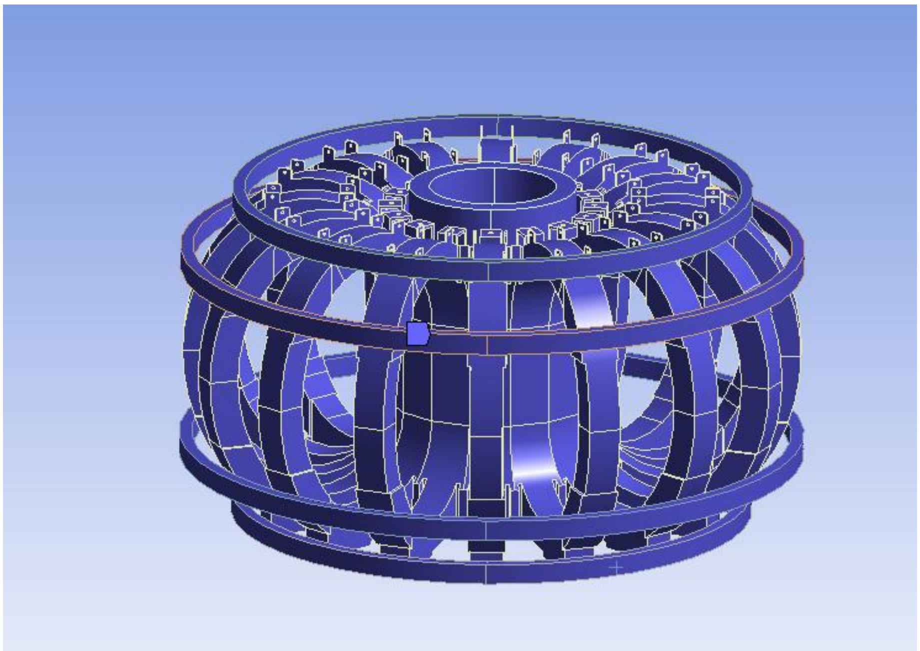

FIG.1. Schematic of Assembled TFCs and PFCs

2.2 Radiation heat load on PFC
Estimated radiation load on PF is around **100 W**
Actual Temperature of PFCs is ~50K, which is higher than 4.2K. surface of PFCs is not clean which may result in higher surface emissivity, but in our analysis we have taken emissivity as 0.1. Actual loads may have some deviation because of these assumptions.
Total radiation heat load on magnet systems is approx. **230 W**. heat load calculated from cryogenics flow parameters at inlet and outlet of magnets is estimated as **275W**[3]

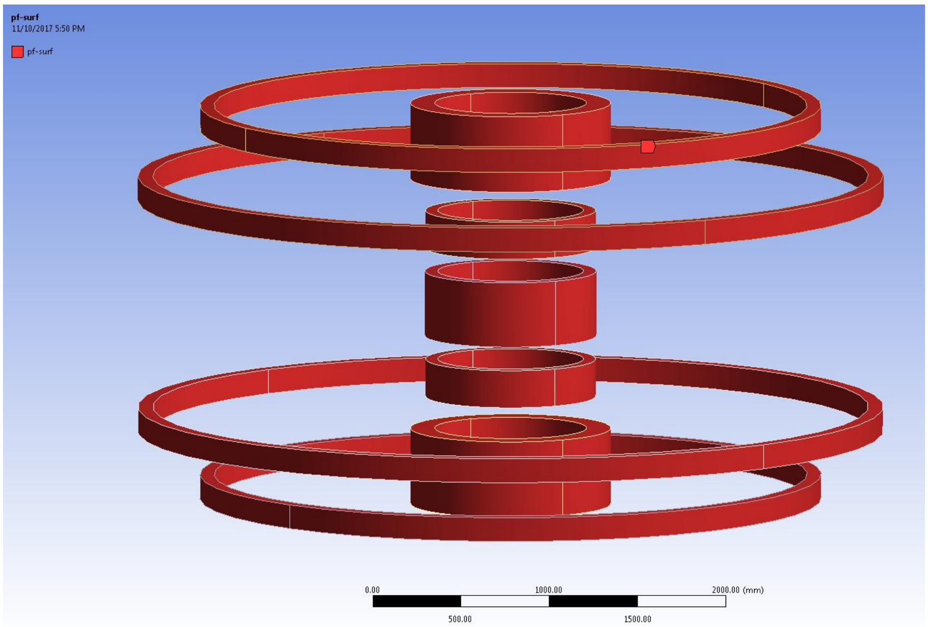

FIG.2. Schematic of PFCs of SST-1

3. CONDUCTION HEAT LOAD

Support structure of TOKAMAK is made of SS304L. One end of these supports is at 300K and another at 4.2K. At mid-point these supports are thermally anchored 80K (by using LN_2). Conduction heat load from base i.e. 300K to 80K (mid-point or thermally anchored position of support) is carried away by liquid nitrogen. Cantilever support ring of TFC get conduction heat load from 80K to 4.2K. G-10 insulating blocks are used between TFCs base and cantilever supports to reduce conduction heat load.
Total conduction heat load through supports = **272W**

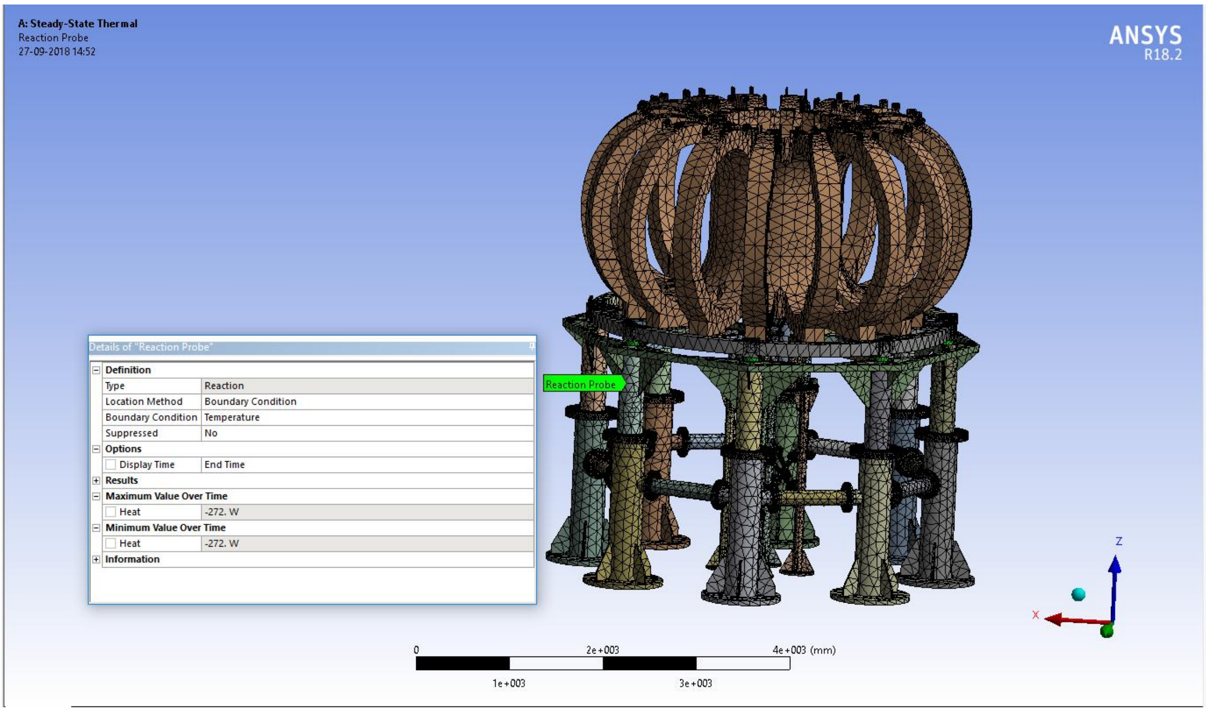

FIG 3: Meshed geometry of TFCs with support structure, conduction heat load

4. THERMAL ANALYSIS

Support ring along with TF Coil case is cooled by liquid helium. LHe flow in these sections is in two phase flow regime. Experimental data from 19th campaign of SST-1 is available. Temperature from installed temperature sensors on TF coil case and on cantilever is available. We analysed using steady state thermal analysis with Ansys software and compare our results with experimental temperature data.

Flow parameters:
Mass flow rate = 9 g/s
Pressure at inlet= 1.5 bar

Assumptions:

- Inlet Temperature is taken as 4.5 K
- 1/3rd mass flow along ring and remaining in bubble panel.
- Quality of two phase mixture at outlet is taken as 60%.
- In our analysis TF coil case temp is considered as uniform
- Cooling and radiation heat load on support ring is considered uniform.
- Position co-ordinates of temp sensors are not considered in analysis.

Cooling effect due to helium:
Cooling= 3*0.6*20 = 36 watt
Minimum temperature at TF coil outlet is achieved on 16/9/2016 at 2:00 O'clock.
All temperature data taken at that time frame and analysed.
Minimum temperature on TF casing =21.31K
Maximum temperature on TF casing =62.52K
Average of all temperature readings on TF case =43.81K
Temperature reading on cantilever are: 110.2K, 123.9K & 109.7K
Taking max TF case temp= 62.52K
Radiation Heat load= 230 watt, conduction heat load 272 W, cooling rate= 36 watt
Net heating effect= 466 watt

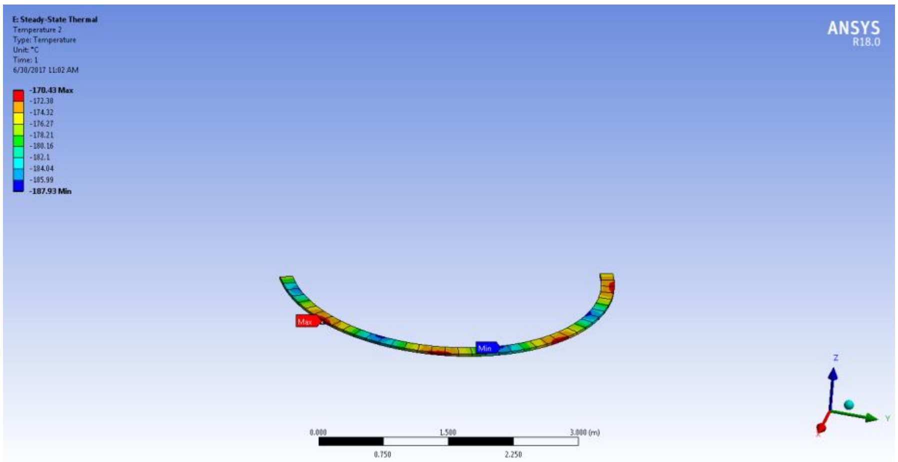

FIG 4: Temperature distribution on TFCs support ring

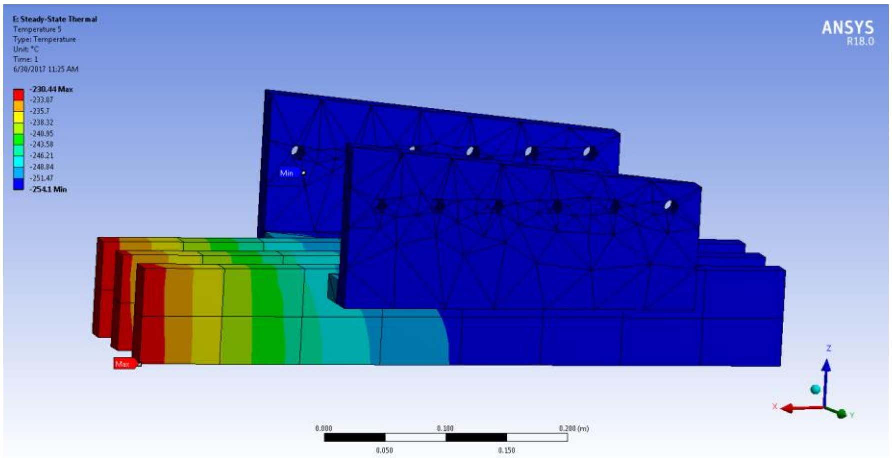

FIG 5: Temperature distribution on cantilever support

Temperature range for support ring (Ansys): 85-103 K
Temperature range for cantilever (Ansys): 19-42 K
Experimental temperature range for cantilever: 110-124 K
Temperature of support ring is higher as compared to cantilever, it is expected as support ring is getting conduction heat load from cylindrical supports while cantilever is in direct contact with low temperature TF coils. Experimental temperatures are slightly high as compared to temperatures obtained using Ansys Analysis. Possible cause of this deviation:

- Uncertainties in conduction heat load on cantilever
- Radiation heat load on cantilever is neglected
- We don't take exact location of temperature sensor that maybe the cause of small deviation.

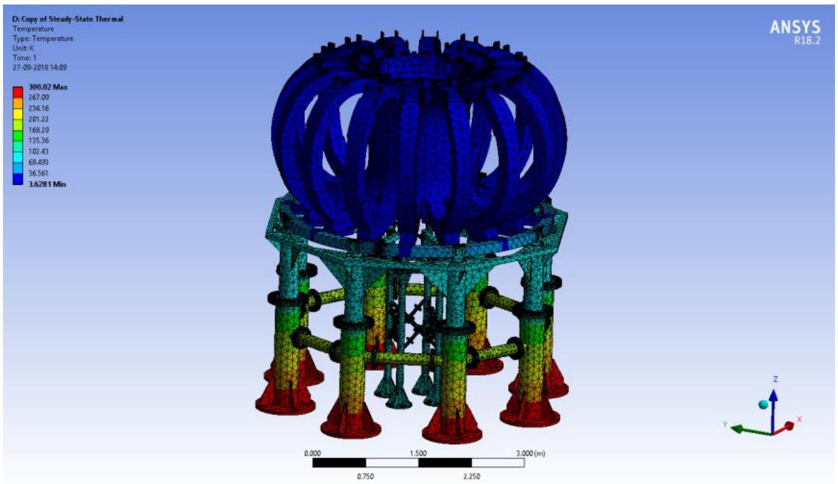

FIG 6: Temperature distribution in support structure and TF coils

5. THERMAL DEFORMATION IN STRUCTURE

5.1 **SINGLE TF COIL ANALYSIS**

Single TF coil is taken for analysis. Base of coil given fixed constraints and temperature of coil is 4.2 K. As base is fixed, there are high localised thermal stresses on these locations near coil base.

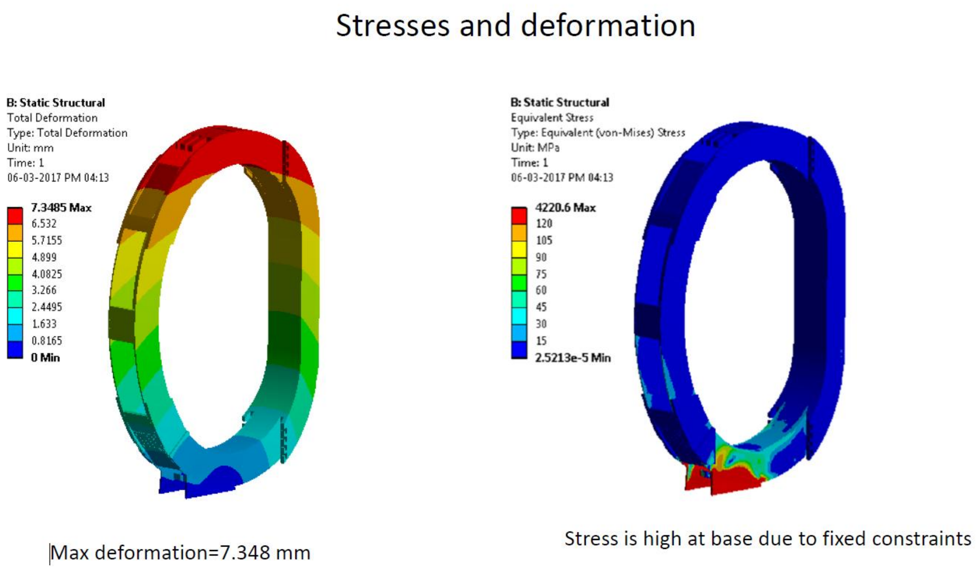

FIG 7: Thermal stress and deformation in a single TF coil

5.2 THERMAL DEFORMATION IN COMPLETE STRUCTURE

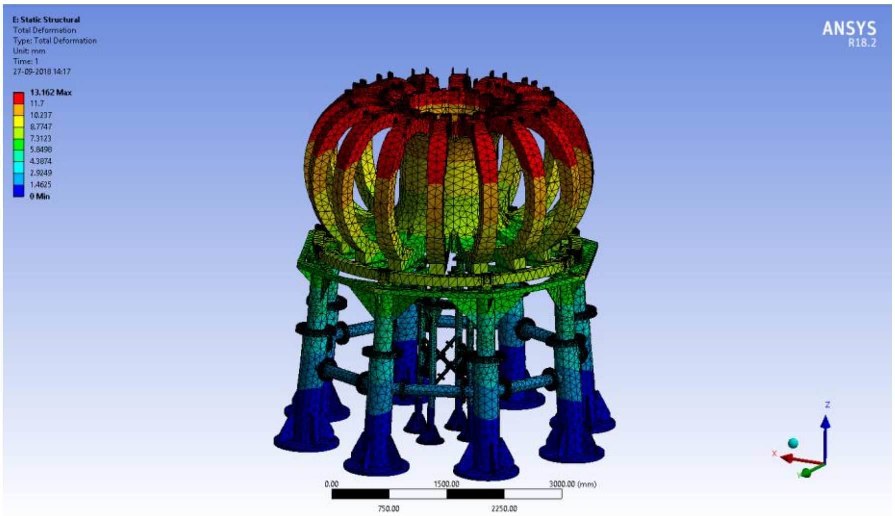

FIG 8: Thermal stress and deformation in support structure and TF coils

SUMMARY AND CONCLUSION

Heat loads on superconducting coils are large. Due to high heat loads pressure drop inside TFCs and PFCs are high. Performance of SST-1 tokamak cannot be realised fully until we validate the performance of PFCs. Radiation heat load on superconducting magnets increased due to absence of thermal shield on few ports. This need to be fixed. Thermal deformation is 13.2 mm which is within permissible limit. In future we need to analyse conduction heat load from PFCs to TFCs. Total heat load due to conduction and radiation 500W approx.

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