Cryogenic heat loads analysis from SST-1 plasma experiments

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Abstract. Cryogenic heat load analysis is an important aspect for stable operation of Tokamaks employing large scale superconducting magnets. Steady State Superconducting Tokamak (SST-1) at IPR is equipped with superconducting magnets system (SCMS) comprising sixteen numbers of modified ‘D’ shaped toroidal field (TF) and nine poloidal field (PF) superconducting coils which are wound using NbTi/Cu based cable-in conduit conductor (CICC). SST-1 magnets operation has flexibility to cool either in two-phase with sub-cooling, two-phase without sub-cooling or single phase (supercritical) helium using a dedicated 1.3 kW helium refrigerator cum liquefier (HRL). Here, we report gross heat losses for integrated TF superconducting magnets of SST-1 during the plasma campaign using cryogenic helium supply/return thermodynamic data from cryoplant. Heat loads mainly comprising of steady state as well as transient loads are smoothly absorbed by SST-1 cryogenic helium plant during plasma experiments. The corresponding heat produced in the coils is totally released to the helium flowing through the TF coils, which in turn is dumped into liquid helium stored in main control Dewar. These results are very useful reference for heat loss analysis for TF as well as PF coils and provides database for future operation of SST-1 machine.

1. Introduction

The SST-1 device after successful commissioning and engineering validations of its sub-systems has achieved the first plasma in June 2013 and is now in the league of contemporary superconducting Tokamaks [1]. SST-1 has recently reached a plasma current in excess of 100 kA under a central TF field of 1.5 T. The SST-1 magnets system consists of sixteen numbers of modified ‘D’ shaped superconducting TF magnets connected electrically in series to produce the basic toroidal magnetic field and nine superconducting PF magnets together with a pair of resistive coils for plasma shaping magnetic fields. All TF and PF superconducting coils are wound using same NbTi/Cu based CICC. HRL having nominal cold power of 1.3 kW at 4.5 K caters the static as well as dynamic pulsed heat loads demand of SST-1 SCMS [2]. The SCMS is surrounded by 80 K thermal shields cooled using liquid nitrogen inside the SST-1 cryostat. Total weight of SCMS is around 40 Tons which is to be cooled by force flow supercritical helium at 4.5 K, 4 bar. Prior to assembly on SST-1 machine shell, each TF coils have been tested for its electromagnetic, thermo hydraulic and mechanical performances at rated operating currents of 10 kA [3]. SST-1 magnets system has flexibility to operate in single phase (supercritical) as well as two-phase with and without sub-cooling using HRL system. We have carried out forty such experimental campaigns which included both two-phase as well as supercritical helium operation.
In the ongoing phase of operation of SST-1 machine, circular plasma experiments are performed at toroidal magnetic field of 1.5 T at plasma centre with TF magnets system charged to ~ 4.6 kA current under double-phase cold conditions of 5 K at 1.4 – 1.65 bar (a). SST-1 cryomagnetic system has undergone various strategic changes for this phase of operation including current feeders system modification to reduce heat loads from PF current leads and divert corresponding liquefaction power to SCMS [4]. The HRL provides the cold gas at 4.1 bar (a) / 7.0 K at upstream (HP) side, which is further expanded through a J-T valve and produces cold helium vapor. The thermodynamic state points of pressure and temperature are mentioned at the inlet and outlet of the magnets system in a single phase vapor, so that mass flow rate can be known accurately. Here, we report the experimental results of gross heat loads acting on TF magnets system using helium enthalpy change data across TF magnets during entire current charging-discharging cycles for plasma experiments.

2. Helium cryogenic system for SST-1 magnet system

SST-1 HRL system for SCMS, based on modified Claude cycle with refrigeration power of 650 W at 4.5 K and 7 g/s liquefaction capacity (equivalent nominal cold power of 1.3 kW at 4.5 K) is in operation at IPR since 2003 [2, 5]. This cryoplant routinely performs controlled cool-down of SCMS from 300 K to 4.5 K, double phase (DP) mode operation and controlled warm up of SCMS. Additionally HRL absorbs pulsed heat loads (AC loss from CICC based magnets during current ramping and field changes) and other disruptions events during plasma experiments, handles abnormal conditions like quenching of superconducting magnets and emergency shutdown following safety protocols.

![Figure 1. Process flow diagram of HRL plant for SST-1 SCMS.](image)

Initial cool down of SCMS from 300 K to ~ 80 K is performed using set of heat exchangers in the cold box which utilize enthalpy of liquid nitrogen. A set of turbo expanders (T_A, T_B in series and T_C in parallel) working on isentropic expansion further cools SCMS to 4.5 K. In final
expansion, liquid helium is produced in main control Dewar (MCD) by means of Joule Thomson (JT) valve for cooling down of vapour cooled current leads for SCMS. MCD (with volume of ~ 2500 litre) also act as a thermal buffer to dump the dynamic pulsed losses of SST-1 during plasma experiments and provide uniform thermodynamic conditions into the low pressure (LP) path of HRL. Process flow diagram of HRL plant for SST-1 SCMS is depicted in figure 1.

TF, PF and case are cooled in a controlled fashion to ~ 24 K in around two weeks time from thermal stress protection point of view. Before authorizing third turbine TC, PF and 5 K case are isolated from HRL in order to mitigate hydraulic imbalance within the PF magnets system and additional heat loads on TF system by conduction cooled passive structures within the SST-1 machine. TF coils achieve cryostable conditions ~ 5 K under single phase vapor conditions within few hours once liquid helium is collected in MCD. For performing plasma experiments in SST-1, TF magnets after achieving cryo stability at ~ 5 K are charged to initiate plasma experiments.

3. Methodology for cryogenic heat loads calculation during SST-1 plasma experiments

Energy loss in the TF magnets system can be calculated by specific heat at constant pressure method using following equation:

\[ Q = \dot{m} \cdot C_p \cdot \Delta T \]  

(1)

where \( \dot{m} \) is mass flow rate of helium in the coil, \( \Delta T \) is temperature difference between inlet and outlet helium in CICC, \( C_p \) is the specific heat of helium at constant pressure and temperature, and \( t \) is the time. The above calculation considers \( C_p \) as constant. Integrating equation (1) over \( t \) results in gross heat loads (Q) on the TF magnets system given as:

\[ Q = \int \dot{m} \cdot C_p \cdot \Delta T \, dt \]  

(2)

In our experiments \( C_p \) does not remain constant due to variation in temperature and pressure. So we use helium enthalpy to evaluate gross heat loads on TF system. Gross heat load calculations for SST-1 TF system are performed using helium enthalpy data during current charging-discharging cycles which is governed by following equation for single phase flow conditions:

\[ Q = \dot{m} \cdot \Delta h \]  

(3)

where \( \Delta h \) is the enthalpy difference between inlet and outlet helium stream in CICC. Similar method is adopted for calculating AC losses in EAST PF coil during fast discharge process [6].

In our experiment, helium mass flow rate is recorded at cryoplant outlet which supplies cold helium to TF coils during the entire current ramp-up and ramp-down cycle. Helium stream temperature and pressure are measured at the inlet and outlet of TF coils supply / return end. A simplified flow diagram for cryogenic helium through TF magnets is shown in figure 2.

![Figure 2. Schematic flow diagram for cryogenic helium through SST-1 TF magnets.](image-url)
4. Results and discussion

Using above methodology, we calculate gross heat loads on TF system for plasma experiments at maximum transport current of 4.68 kA corresponding to toroidal field ($B_T$) of 1.5 T using helium supply/return thermodynamic parameters from HRL data as shown in table 1. Current ramping rate ($dI/dt$) was kept at 5 A/s for all these shots. Helium enthalpies are known at a particular temperature and pressure from HEPAK database. Various transport current profiles and corresponding temperature and pressure profile of SST-1 TF Coils during plasma experiments at $B_T = 1.5$ T are shown in figure 3(a) – 3(d).

Average heat load for SST-1 TF system under present operational regime is ~ 275 W @ 5 K at $B_T = 1.5$ T. Taking +/- 2% error bar for mass flow meter, +/- 1% for temperature sensors and 0.1% for pressure sensors, the error bar for the calculated heat loads is +/- 3%. As the PF and Case systems are isolated from HRL at intermediate temperature of ~ 24 K, the additional heat loads other than the TF system would be a function of time. Over days, this contribution keeps increasing and after few days of operation, the heat loads even matches to available cold capacity of HRL.

![Figure 3](image_url)

Figure 3. (a) – (d) Various transport current profile and corresponding temperature & pressure profile across SST-1 TF Coils during plasma experiments at $B_T = 1.5$ T.

In the present regime of operation, outlet temperature is observed to be lower than supply helium temperature. As the operation state points corresponds to under two phase dome of T-S diagram, the outlet pressure is lesser than inlet, due to saturation point it attains the lower temperature. Secondly, the sufficient mass flow is given for cooling the TF magnets than rated one. So, contribution due to rise in temperature is negligible since heat load per path is less about 1 W per path @ 4.5 K.
Table 1: Calculated gross heat loads for SST-1 TF coils for toroidal field ($B_T$) of 1.5 T

| TF Coils charging details | Supply helium parameters | Mass flow rate (in g/s) | Return helium parameters | Enthalpy change from $\Delta h$ (J/g) | Gross load from $\Delta h$ (in W) |
|---------------------------|--------------------------|-------------------------|--------------------------|-------------------------------------|----------------------------------|
| 4.6 kA                    | $T_i = 5.5$ K, $P_i = 1.6$ bar | 61.3                    | $T_o = 4.8$ K, $P_o = 1.41$ bar | 4.59                                | 281.3 (+/-3%)                   |
| 4.6 kA                    | $T_i = 5.5$ K, $P_i = 1.62$ bar | 57.7                    | $T_o = 4.8$ K, $P_o = 1.44$ bar | 4.75                                | 274.0 (+/-3%)                   |
| 4.6 kA                    | $T_i = 5.55$ K, $P_i = 1.7$ bar | 58.9                    | $T_o = 4.9$ K, $P_o = 1.41$ bar | 4.42                                | 260.3 (+/-3%)                   |
| 4.6 kA                    | $T_i = 5.5$ K, $P_i = 1.63$ bar | 60.4                    | $T_o = 4.8$ K, $P_o = 1.44$ bar | 4.69                                | 283.3 (+/-3%)                   |

5. Summary

SST-1 TF magnets system successfully operates under single phase vapor flow conditions of 4.8 K - 5 K at 1.4 bar (a) – 1.7 bar (a) regularly for plasma experiments which is one of the unique regime of operation in case of CICC wound SCMS. Gross heat loads are estimated for integrated TF magnets of SST-1 during plasma experiments using cryogenic helium supply/return thermodynamic data from cryoplant. Average heat loads are found to be around 275 W from helium enthalpy change data for integrated TF magnets of SST-1 during plasma experiments. These heat loads include pulsed loads as well as steady state loads on TF coils and residual heat loads from passively cooled structures within the SST-1 machine. Experiments have shown that these loads are smoothly absorbed by HRL during plasma experiments. These results are very useful reference for heat loss analysis for PF coils and provides database for future operation of SST-1 machine.

Acknowledgements

The authors would like to acknowledge significant contributions by all the members of the SST-1 Mission team for their efforts to realize the plasma experiments in the SST-1 machine.

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