Process optimization of helium cryo plant operation for SST-1 superconducting magnet system

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Abstract. Several plasma discharge campaigns have been carried out in steady state superconducting tokamak (SST-1). SST-1 has toroidal field (TF) and poloidal field (PF) superconducting magnet system (SCMS). The TF coils system is cooled to 4.5 - 4.8 K at 1.5 – 1.7 bar(a) under two phase flow condition using 1.3 kW helium cryo plant. Experience revealed that the PF coils demand higher pressure heads even at lower temperatures in comparison to TF coils because of its longer hydraulic path lengths. Thermal run away are observed within PF coils because of single common control valve for all PF coils in distribution system having non-uniform lengths. Thus it is routine practice to stop the cooling of PF path and continue only TF cooling at SCMS inlet temperature of ~ 14 K. In order to achieve uniform cool down, different control logic is adopted to make cryo stable system. In adopted control logic, the SCMS are cooled down to 80 K at constant inlet pressure of 9 bar(a). After authorization of turbine A/B, the SCMS inlet pressure is gradually controlled by refrigeration J-T valve to achieve stable operation window for cryo system. This paper presents process optimization for cryo plant operation for SST-1 SCMS.

1. Introduction

The steady state superconducting Tokamak (SST-1) machine consists of sixteen superconducting D-shaped Toroidal Field (TF) coils and nine circular superconducting Poloidal Field (PF) coils together with a pair of resistive PF coils inside the vacuum vessel. The NbTi/Cu based cable-in-conduit conductor (CICC) is used to wind these superconducting coils and the CICC has helium void fraction of about 40 % of the total cross-section area [1]. Each TF coil has twelve parallel coolant flow paths and each path is forty-eight meters long. The cooling schemes of the PF coils depend upon their winding scheme of either layered or double pancakes. A 1.3 kW at 4.5 K helium refrigerator cum liquefier (HRL) system has been operational to meet the SST-1 static as well as pulsed heat loads [2]. HRL have options of cooling the superconducting magnet system (SCMS) with cold circulator at high pressure 4 bar (a), 4.5 K, 300 g/s supercritical helium or 1.4 bar (a), 4.5 K, 50 g/s saturated liquid helium. Integrated fluid distribution and control system (IFDCS) distributes cold helium from HRL in to three groups namely TF SCMS, PF SCMS and case with support structure. A 10 kA rated helium vapour cooled conventional current lead (VCCL) is used between TF SCMS at 4.5 K and TF power supply at room temperature. Superconducting current feeder system (CFS) is designed to accommodate 10 pairs of current leads with associated auxiliaries. Liquid nitrogen is used to cool the

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80 K thermal shields of SST-1, CFS and IFDCS as well as pre-cooler for the purifier and cold box of HRL. We have a dedicated liquid nitrogen (LN_2) storage tanks, distribution and control system.

Several plasma discharge campaigns have been carried out in SST-1 with TF SCMS operation only. During SST-1 cool-down, we have to stop the PF SCMS cooling in order to get the cryo stable conditions to make TF magnets to superconducting state and enable current charging of the TF magnet systems. This paper describes adopted control logics and process optimization of helium plant to achieve stable operation window for SST-1 plasma experiments.

2. Description of Helium Cryogenic System

A 1.3 kW at 4.5 K helium refrigerator cum liquefier system has refrigeration capacity of 650 W at 4.5 K and liquefaction capacity of 200 L/h for the VCCLs. The HRL system is design on modified Claude cycle as shown in figure 1. The HRL has three air cooled oil lubricated screw compressor with primary oil separator, oil removal system, on-line purifier with dual beds, cold box and 2500 liters main control Dewar (MCD). The cold box has seven heat exchangers including LN_2 pre-cooling, sub-cooler Dewar with bath cooled heat exchanger, three turbines (TA, TB and TC), JT valve, cold circulator and four return valves at 4.5, 20, 80 and 300 K to low pressure stream. Turbines A and B are connected in series with each other and turbine C is a hypercritical turbine at cold end. Sub-cooler Dewar act as thermal buffer to dump the 250 W heat load of cold circulator and MCD act as thermal buffer to dump the 400 W steady state heat load of SST-1.

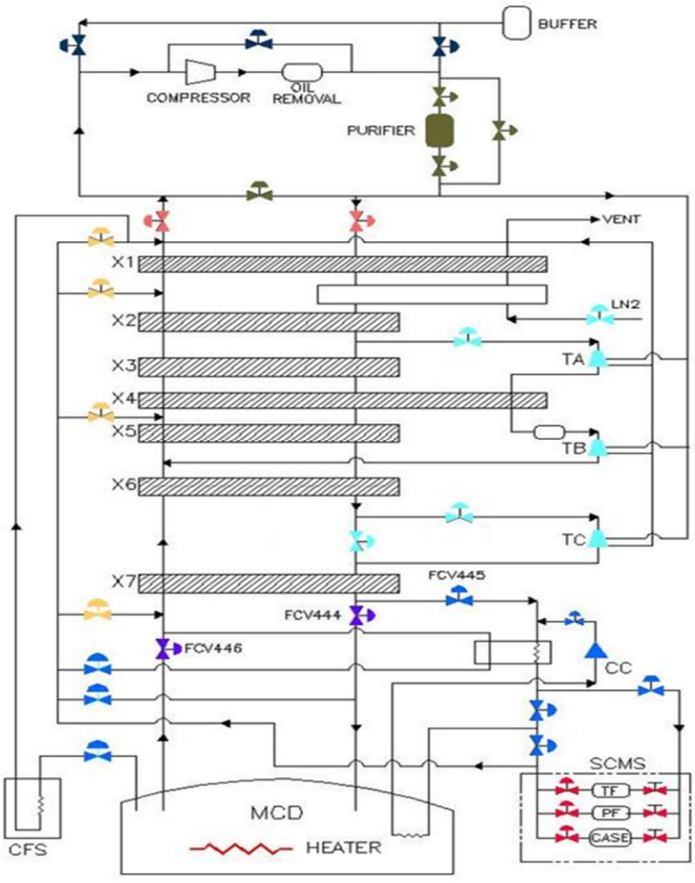

Figure 1. Process flow diagram of the HRL system with connection of SST-1 SCMS and CFS

The process is segmented into several control loops to match the operational scenarios of the HRL. The HRL has various operating modes mainly (i) air and water regeneration, (ii) cold box rinsing mode, (iii) pre-commissioning mode, (iv) double-phase mode, (v) cold circulator mode, (vi) warm-up mode and (vii) only liquefier mode. Air and water regeneration are cold box service modes, used to

regenerate 80 K / 20 K charcoal adsorbers in the high pressure (HP) stream of cold box. Cold box rinsing mode is used to purge the process lines of the cold-box by evacuating and filling with the pure helium gas. In pre-commissioning mode the on-line purifier connects to the low pressure stream between cold box and compressor suction inlet. With this arrangement the purifier adsorbs the impurities from SST-1 SCMS through adsorption process at low pressure. This process continues over days until impurities level comes to < 10 ppm. Double phase mode includes cooling down of SCMS from 300 to 4.5 K and two phase cooling of SCMS with saturated helium at 1.4 bar (a) with filling of inbuilt sub-cooler Dewar. In the cold circulator mode, the cold circulator provide 300 g/s supercritical helium at 4.5 K, 4 bar (a) and maintaining 500 mbar pressure difference across it. During a quench of the SCMS, the HRL is isolated from the SCMS in order to release the pressure at low temperature to quench recovery tank. In the warm-up mode, the HRL supplies warm helium gas using separate line with heater and control valve from compressor HP to SST-1 by maintaining 50 K temperature difference across SCMS. Only liquefier mode is used to produce liquid helium in MCD at 1.3 bar (a). In normal operation HRL operates in mix mode that is providing refrigeration power to SCMS and producing liquid helium (LHe) in MCD for current leads. The operating point varies as per requirement of SCMS.

3. Process Logics of Cool Down of SCMS

The HRL adjusts its outlet temperature in such a way that the temperature difference between maximum (T_{max}) and minimum (T_{min}) of SCMS is less than 50 K to reduce thermal stresses. Initially the LN_2 pre-cooling is used for cool down of SCMS up to 125 K of T_{max}. During this phase outlet temperature of LN_2 pre-cooling heat exchanger controls the temperature difference between T_{max} and T_{min}. After 125 K of T_{max} turbines A and B are authorised and outlet of turbine B controls the 50 K temperature difference. The control loop of inlet valve of TA and TB regulates the speed of turbines such that TB does not trip due to over speed during cool down. When temperature of MCD reaches 7 K then turbine C is authorised to provide more refrigeration power.

During cool down process valve FCV445, as shown in figure 1, regulates the downstream pressure of helium to maintain 50 g/s through SCMS. The control logic of valve is defined such that it operates linearly with T_{max} and maintains the compressor flow with in nominal value. The relation between maximum opening of FCV445 (FIX445_Max) and T_{max} is shown in figure 2. Simultaneously control logic checks the compressor mass flow rate looking at opening of bypass valve of compressor station. If both compressor are running fully with the bypass valve less than 1 % or FCV445 is opened more than FIX445_Max at respective T_{max} then FCV445 reduces by 2 % immediately to control overall compressor flow rate. If the bypass valve is open more than 4 % then FCV445 increases by 0.5 % at every 30 sec till it reaches FIX445_Max. During cool down the outlet pressure of TC is fixed at 9.8 – 9.9 bar (a) to provide maximum pressure before FCV445. Finally the HRL plant outlet pressure varies as per the opening of FCV445. Similarly control logic adjusts valve FCV445 with the same logic to maintain TC outlet pressure at 4.1 bar (a) during two phase operation.

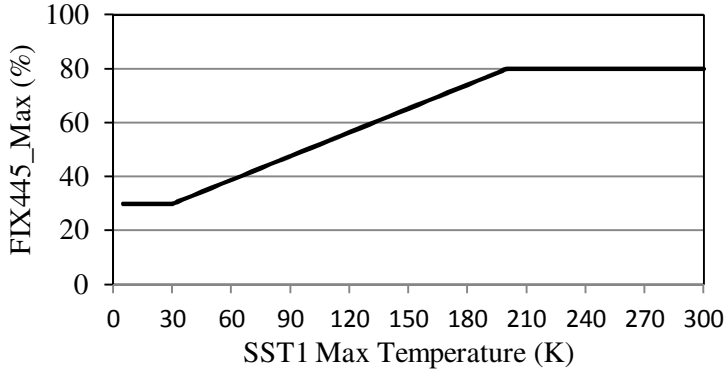

Figure 2. FCV445 is limited by FIX445_Max during cool down and FIX445_Max varies with SST-1 maximum temperature (T_{max}).

IFDCS system distributes cold helium to TF SCMS, PF SCMS and case with support structure. The three paths have individual ON / OFF valve at inlet and control valve at outlet with appropriate

instrumentation for temperature, pressure and flow. The flow in each path is regulated by outlet control valve. The TF SCMS has 16 coils and each coil have twelve parallel paths with 48 m length. The PF SCMS has 9 coils and each coil have one or more parallel paths with varying length from 67 to 130 m. The PF5 coils have longest path length and four parallel paths. While PF3 coils have eight parallel paths with varying length from 67 to 84 m. The other PF coils have average length of 113 m. There is a common cryo line with control valve for all PF coils. During SCMS cool down process the control valves of TF and PF are adjusted to allow simultaneous cool down of both SCMS. But due to large difference in their path lengths, TF cools faster than PF SCMS. Similarly individual PF coils within PF SCMS have different cool down rates. Because of this sometimes thermal run away is observed during cool-down.

4. Cool down performance before modification of FCV445 logics

The SST-1 80 K thermal shield system is cooled down with LN_2 in controlled manner and maintained uniform temperature range of 80 to 85 K across the SST-1 thermal shield and at other auxiliary cryogenic sub-systems. Simultaneously controlled cool down of TF and PF SCMS is governed by the HRL system. Initially LN_2 pre-cooling system of HRL maintains 50 K temperature difference across SCMS. The hydraulic resistance of CICC decreases as the plant outlet temperature decreases. To maintain constant flow in SCMS, the HRL outlet valve FCV445 starts decreasing at T_{max} of 200 K temperature as per control logic. Once T_{max} reaches 130 to 125 K, TA and TB are authorised. The FCV445 regulates outlet pressure of HRL to SCMS after authorisation of turbines also. Due to differences in hydraulic resistance of TF and PF SCMS, TF SCMS cool down faster than PF SCMS. We stop the cooling of PF SCMS and case circuit at ~ 30 K of PF SCMS outlet to obtain cryogenic stability in HRL for turbine C authorisation. Once temperature of MCD reaches 7 K, we authorise turbine C to produce LHe in MCD. Thereafter only TF SCMS is maintained at 4.5 K, 1.5 – 1.7 bar (a) with two phase cooling from HRL. During two phase cooling the FCV445 is manually adjusted to maintain sufficient pressure in TF SCMS. TF SCMS have been charged to 4.7 kA to get magnetic field of 1.5 T at the SST-1 major radius of 1.1 m and plasma experiments have been conducted.

Figure 3 shows the cool down trend of HRL for campaign 7 held in February 2014. Main parameters of HRL namely outlet temperature, flow rate, FCV445, compressor flow rate and T_{max} are shown with time in figure 3. While turbines speed regulation with time is shown in figure 4. Figure 5 shows the trend of compressor flow rate, plant outlet pressure, flow rate and FCV445 with respect to T_{max}. The maximum SCMS flow rate was ~ 60 g/s at T_{max} of 200 K as well as outlet pressure and FCV445 were reducing from 200 K.

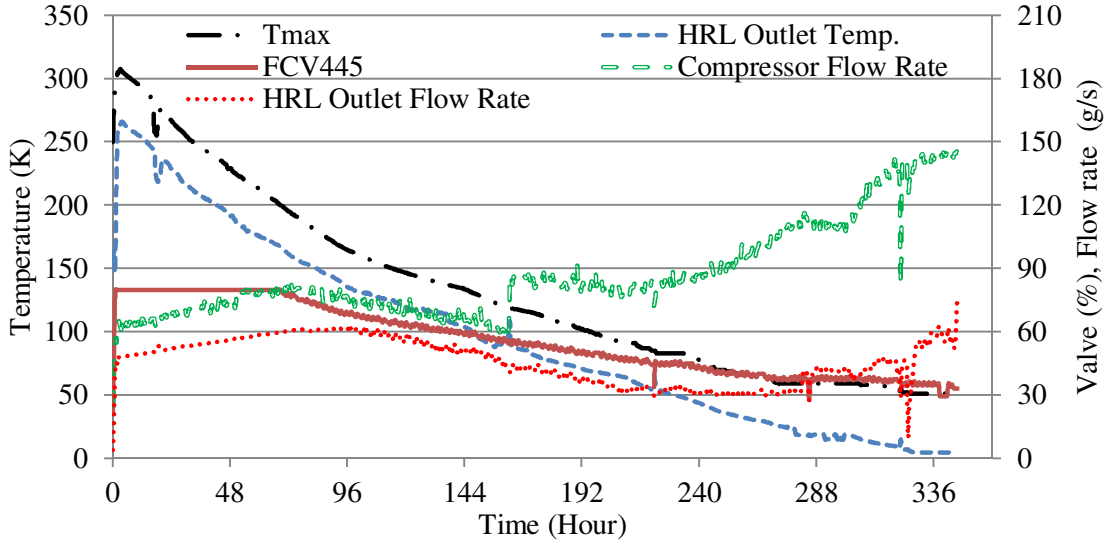

Figure 3. Cool down trend with FCV445 before control logic modification.

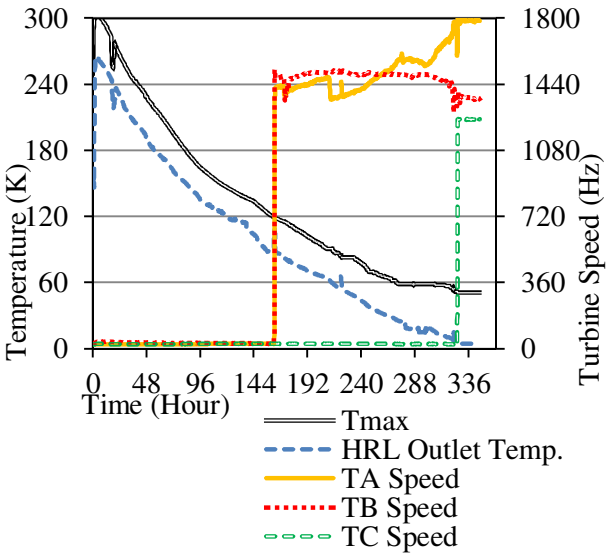

Figure 4. Turbines speed during cool down.

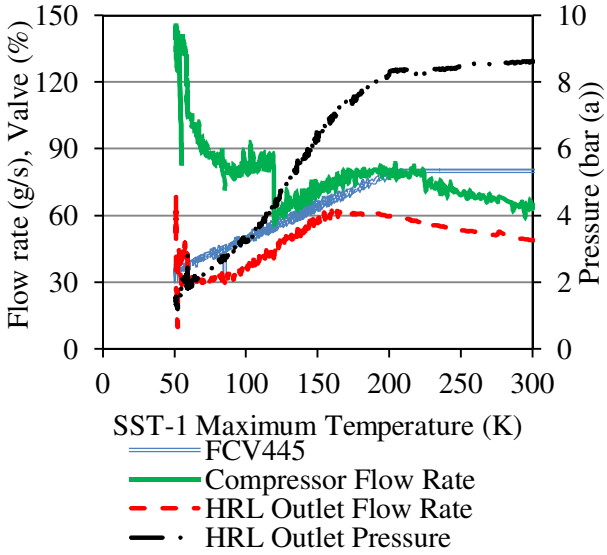

Figure 5. Plant parameters with T_{max}.

Different PF coils cooled down at different rates and PF coils with more hydraulic resistance had higher temperature than other PF coils having less hydraulic resistance. Therefore PF SCMS outlet temperature was always higher than TF SCMS and difference between both outlet temperatures increased as plant outlet approaches low temperature as shown in figure 6(a). The inlet temperature and pressure to TF and PF SCMS were same as both streams have individual ON / OFF valve and common supply header. Figure 6(a) and 6(b) show the temperature and pressure at inlet / outlet of PF and TF SCMS in IFDCS system for campaign 7. After aborting the PF cool down, gradual rise in the temperature of PF magnets was observed which results in rise in return temperature from TF SCMS as well as low yield of LHe in MCD and restricts SST-1 experimental window to few days.

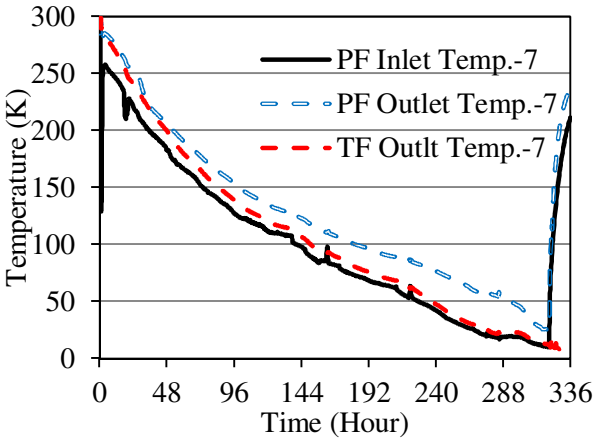

Figure 6(a). Trend of temperature for campaign 7

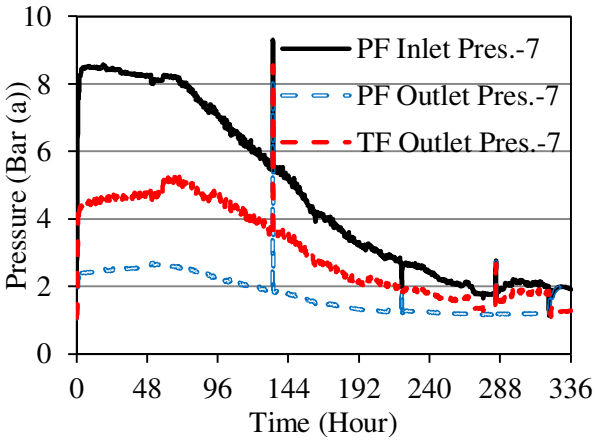

Figure 6(b). Trend of pressure for campaign 7

5. Cool down performance after modification of FCV445 logics

5.1. Implementation of FCV445 logic modification

The cooling of PF SCMS to 4.5 K is essential in order to involve PF magnets for SST-1 plasma experiments and extend the experimental window. This requires reduction of hydraulic imbalances within PF coils and requirement of more pressure head of helium from HRL to PF SCMS. The hydraulic imbalances within PF coils will be reduced by distributing the various coils in to three groups with uniform equal lengths and distribution with three separate cryo lines / control valves.

Recently IFDCS system is upgraded to reduce hydraulic imbalances in January 2016. Higher pressure head of helium from HRL is required to provide sufficient flow rates in PF coils having higher hydraulic resistances than TF coils. Detailed functional analysis of plant control logics concludes that the plant outlet pressure can be increased than nominal pressure head through FCV445 valve with the constraint of compressor mass flow rate. The compressor flow is divided in to four streams at cold box namely (a) turbine bearing flow, (b) turbine pre-cooling flow, (c) flow to MCD for helium liquefaction, (d) flow to SCMS circuits for refrigeration. During LN_2 pre-cooling, full compressor flow rate except turbine bearing flow and MCD flow is available to SCMS. During turbine operation at low temperature, 70 to 75 g/s helium flow rate is diverted to turbines for pre-cooling below 80 K. TA and TB are designed to operate for the feed temperature of 35 K at pressure 13 bar (a) and 15.5 K at 5.3 bar (a) with isentropic efficiencies of 76 % and 72 % respectively. So it is concluded that maximum plant outlet pressure will be given to SCMS till LN_2 pre-cooling and plant outlet pressure will be decreased gradually to maintain compressor flow rate within limit.

The FCV445 was manually operated for SCMS cool down for initial trial purpose. During cool-down, the FCV445 was opened to 80 % till turbine authorisation to provide maximum plant outlet pressure to SCMS. After TA and TB authorisation, FCV445 was decreased slowly to restrict the compressor flow rate below nominal value and allowing the simultaneous cool down of SCMS. This control philosophy was successful and provided good cryo-stability at HRL. This control philosophy also avoided thermal run-away of PF coils during re-cool down after intermediate warm-up and in the event of utility failure. During such interruption, we provide helium at higher pressure than nominal value at elevated temperature to allow simultaneous cool down of TF and PF SCMS.

Parameters in control logics are tuned such that FCV445 opens 80 % till 125 K of T_{max}. FCV445 decreased linearly with T_{max} up to 30 K after turbine authorisation. Figure 7 shows the comparison of old and new ramp profile of FCV445 with manual operation of FCV445. The HRL system is operated with manual operation of FCV445 as shown in figure 7 during campaign 15 held in November 2015. Figure 8 shows the trend of compressor flow rate, plant outlet pressure, flow rate and FCV445 with respect to T_{max} for campaign 15 and campaign 16. HRL system is operated with new control logic in automatic mode during campaign 16 held in February 2016 and has smooth regulation as shown in figure 8. The maximum SCMS flow rate was ~ 80 g/s at T_{max} of 133 K.

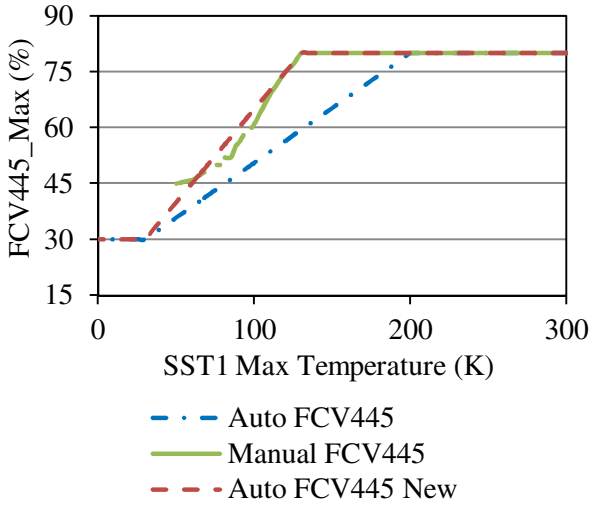

Figure 7. New control logic implementation.

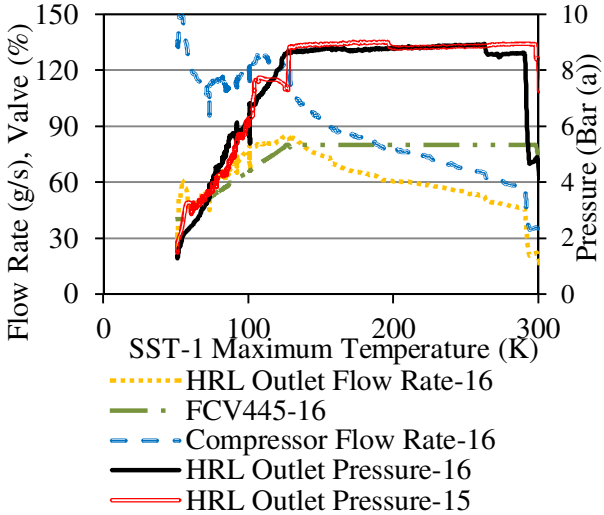

Figure 8. Plant parameters with T_{max}.

5.2. Cool down results after logic modification

Figure 9 shows the cool down of TF and PF SCMS with control logic modification of FCV445 for campaign 15. Higher plant outlet helium pressure to SCMS has improved the cool down rate up to 80 K and cool down duration reduced. During the cool down the FCV445 provided higher pressure head

and mass flow rate to SCMS. The difference between outlet temperature of TF and PF SCMS remained constant and no thermal run away observed.

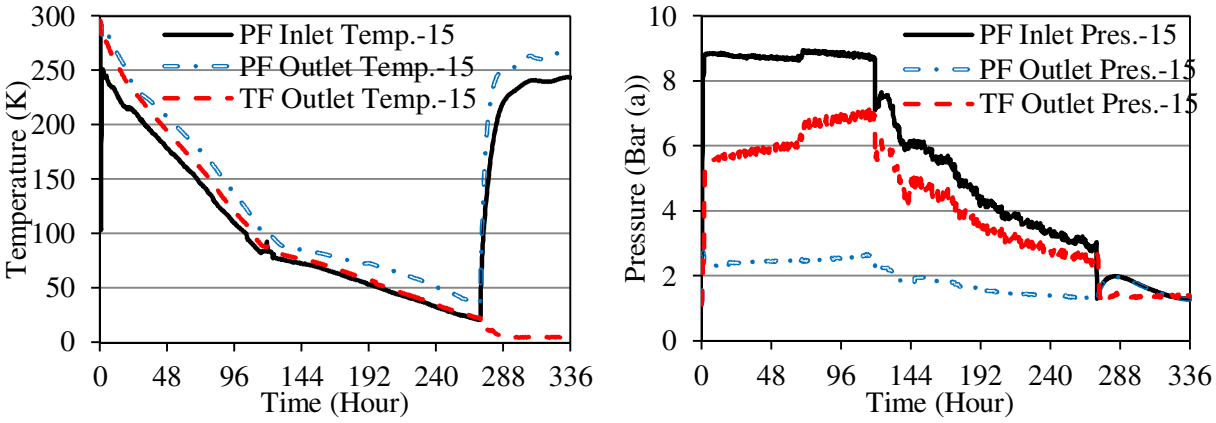

Figure 9. Trend of temperature and pressure for campaign 15 with new logics.

5.3. Comparison of cool down of PF SCMS before and after logic modification

The PF coils outlet temperatures before and after logic modification with temperature and pressure of PF SCMS cryo lines at IFDCS are shown in figure 10. During campaign 7, as shown in figure 10(a), the various PF coils had different cool down rates and thermal run away observed during cool down. During campaign 15, as shown in figure 10(b), various PF coils cooled down simultaneously and no thermal run away observed during cool down because of higher pressure head to the PF SCMS.

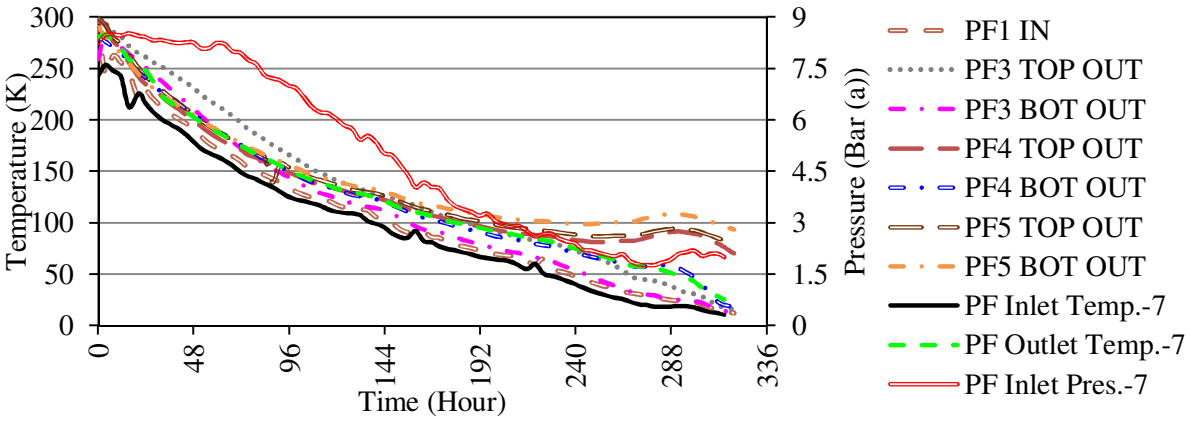

Figure 10(a). PF coils outlet temperatures before logic modification during campaign 7.

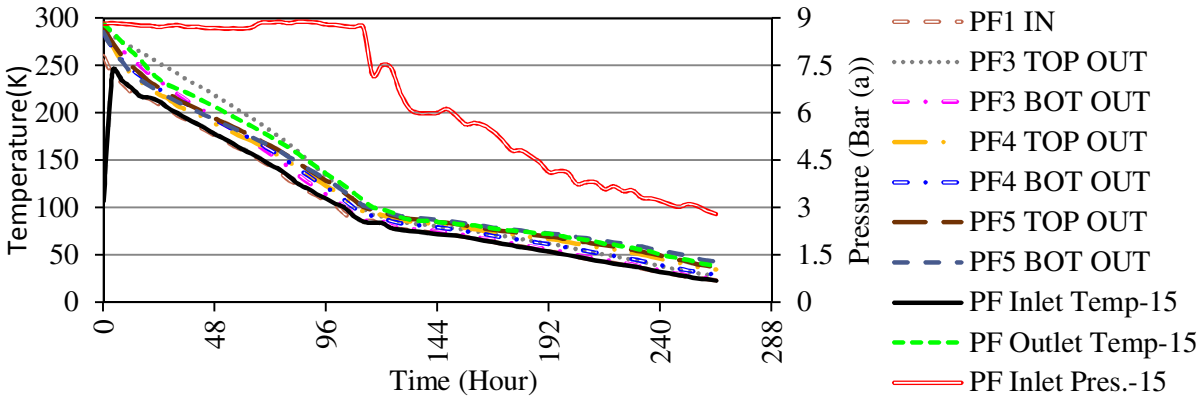

Figure 10(b). PF coils outlet temperatures after logic modification during campaign 15.

6. Protocols adopted for SST-1 Plasma Campaigns

We have faced the problems related to hardware and process during SST-1 operation [4]. Based on the operational experience we have implemented following standard protocols and procedure for reliable operation of HRL.

i. Conditioning of SCMS circuit by purging / evacuation and HRL pre-commissioning mode, if SCMS hydraulics is opened for repair or maintenance.
ii. Regeneration of purifier and conditioning of cold box (# 3 cycles of alternate air/water regeneration and rinsing).
iii. TA-TB pressure drop test with HRL in pure liquefier mode.
iv. SCMS cool down with HRL, if pressure drop test is successful else reconditioning of cold box.
v. On successful cool down of TF SCMS, TF is charged and plasma experiment begins.
vi. Intermediate warm-up (IWU) or full warm up mode is initiated on the basis of condition of HRL and SST-1 for immediate plasma experiment.

Intermediate warm-up is a special mode, in which either only TF SCMS or both TF and PF SCMS are warmed up to elevated temperature and then re-cool down from elevated temperature with HRL.

7. Conclusion

The SST-1 TF SCMS are cooled to 4.5 K, 1.5 – 1.7 bar (a) with two phase helium from 1.3 kW HRL system. The higher pressure head requirement for PF SCMS cool down is demonstrated using HRL with constraint of compressor mass flow rate and cold power. The process optimization related to control valve FCV445 is successfully implemented and tested. Higher pressure head in PF paths eliminated the thermal run-away at low temperature for common control valve distribution system for non-uniform path lengths of PF SCMS. The process optimization of FCV445 valve is extremely helpful during intermediate warm-up where PF SCMS are re-cooling down from elevated temperature with higher pressure head. Recently the hydraulic imbalances within PF SCMS are addressed by providing three cryo lines with dedicated control valves in the IFDCS system. The results are presented in other paper in the same conference.

Acknowledgements

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References

[1] Pradhan S et al, “First Plasma Experiments in SST-1”, APFA (2013) at South Korea
[2] Tanna V et al, “Recent Progress and Development of Cryogenic system towards the refurbishment of SST-1”, Proc. of 24th International Cryogenic Engineering Conference, May 2012, pp. 619-623
[3] Patel R et al, “Cool down experience with the SST-1 helium cryogenics system before and after current feeders system modification”, Proc. of 25th International Cryogenic Engineering Conference, Physics Procedia (2015), pp. 170-175
[4] Mahesuriya G et al, “Operational and Troubleshooting Experiences in the SST-1 Cryogenic System”, Advances in Cryogenic Engineering, June 2013, Vol-1573-59B, pp. 1645-1651