Thermo-Hydraulic Analysis of the KSTAR Central Solenoid Model Coil

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***Abstract*—The Korea Superconducting Tokamak Advanced Research (KSTAR) Central Solenoid Model Coil (CSMC) has been developed to validate the design of KSATR CS coil. The thermo-hydraulic characteristics were analyzed for the KSTAR CSMC. The major thermo-hydraulic parameters of the coil are AC losses, strand temperature, coolant temperature, pressure drop and temperature margin. A numerical code has been developed for the thermo-hydaulic analysis of the KSTAR CSMC according to the operating conditions. In this paper, the description of the thermo-hydraulic analysis models and analysis results of CSMC are presented. The total energy deposition due to AC losses in CSMC winding will induce a flow reversal of supercritical helium. The minimum temperature margin is estimated approximately 0.5 K. The maximum temperature in CSMC winding is about 7.6 K.**

***Index Terms*—CSMC, KSTAR, thermo-hydraulic analysis.**

I. Introduction

The KSTAR (Korea Superconducting Tokamak Advanced Research) device is a tokamak with a fully superconducting magnet system, which enables an advanced quasisteady-state operation. The major radius of the tokamak is 1.8 m and the minor radius is 0.5 m, with elongation and triangularity of 2 and 0.8, respectively. The KSTAR superconducting magnet system consists of 16 TF coils and 14 PF coils. The TF coil system provides a field of 3.5 T at the plasma center and the PF coil system is able to provide a flux swing of 17 V-sec. Both TF and PF coil systems use internally cooled superconductors [1].

A pair of central solenoid model coils (CSMC's) has been developed and will be tested in the superconducting coil test facility in the Korea Basic Science Institute (KBSI). The system for CSMC test is shown in Fig. 1. The coil was originally developed as a part of a background field magnet system for the cable-in-conduit conductor (CICC) sample test under transverse magnetic field in the order of 8 T. The conductor of the CSMC's is the same Nb_3Sn CICC as that of the KSTAR CS coils. The CSMC's have been wound in 240 turns per coil without internal joints and operated with electrical connection in series between coils. CSMC's with inner diameter 740 mm providing field up to 8 T in the 250 mm gap between two CSMC halves. These two halves of MC are almost full-scale models of KSTAR central solenoid (CS) sections. They are made from the same CICC planed to be used for the CS of KSTAR and should have the field ramp rate up to 3 T/s [2].

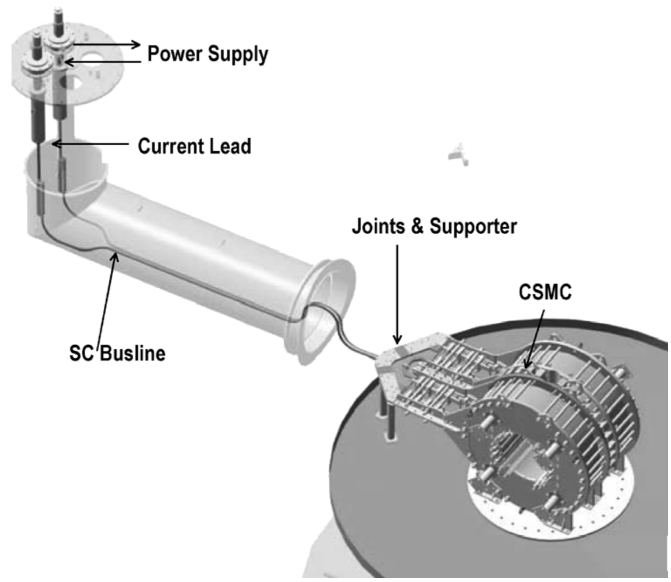

Fig. 1. System for CSMC test.

Since the CSMC's are operating in a pulsed field environment, conductors will be heated, and eddy-current loss. The operating characteristics of the CSMC for operating scenario must be studied to check the temperature margin and stability margin of superconducting cables. Cryogenic flow parameters also must be determined for stable operation.

A transient operating simulation code for the CSMC test is developed. The temperature margin of the superconducting cable, cryogenic flow parameters and the heat deposition in the CSMC are calculated by this code. The effect of three-dimensional heat conduction is considered in this code [3].

II. Main Design Parameters

The number of cooling channel is 8 per coil, and its distribution is shown in Fig. 2.

The parameters of the CSMC are listed in Table I. The number of CSMC is 2. The maximum operating current is 22.4 kA and the peak field at conductor and central field is 9.75 T, 8.0 T at that operating current, respectively. The parameters of CICC are

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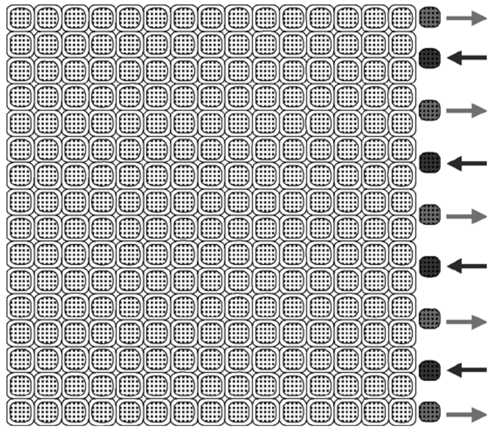

Fig. 2. Cooling channel.

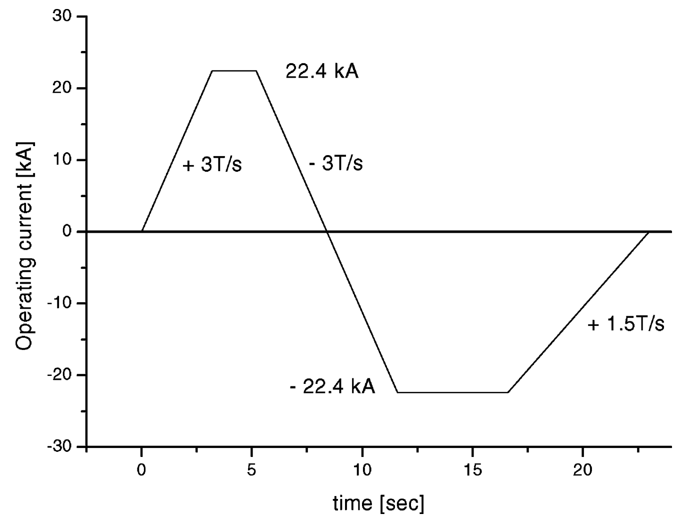

Fig. 3. Operating scenario for CSMC.

TABLE I
MAJOR PARAMETERS OF CSMC

Parameters	Value
Number of coils	2
Inner diameter [mm]	740
Outer diameter [mm]	1488
Coil height [mm]	397.9
Coil center-to-center distance [mm]	638
Number of turns per coil	240
Ground wrap thickness [mm]	7.0
Number of cooling channels	8
Operating current [kA]	22.40
Peak field at conductor [T]	9.75 at 22.4kA
Central field [T]	8.0 at 22.4kA
Expected strain [%]	-0.3
Current sharing temperature [K] (by summers correlation)	8.4 at 22.4kA
Inductance [mH]	134.39
Stored energy [MJ]	34.4
Weight of a coil [ton]	2.7

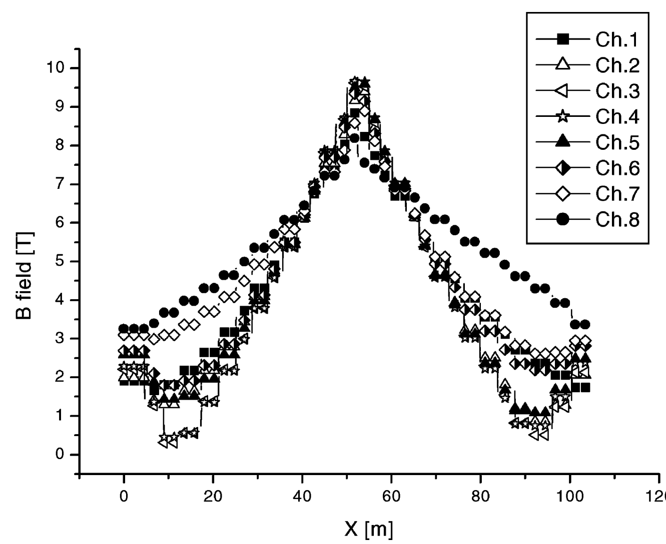

Fig. 4. Magnetic field along to cooling channel.

TABLE II
PARAMETERS OF THE CONDUCTOR FOR CSMC

Parameters	Units	CSMC
Conductor		Nb_3Sn
Conduit		Incoloy 908
Cu/Noncu		1.5:1
$A_{conduit}$	(mm^2)	179.2
D_{strand}	(mm)	0.78
$n_{strands}$		360
$n_{custrands}$		120
$h_{conduit}$	(mm)	22.3
$w_{conduit}$	(mm)	22.3
$t_{conduit}$	(mm)	2.41
A_{cu}	(mm^2)	132.7
A_{noncu}	(mm^2)	48.25
A_{hecond}	(mm^2)	111.4
J_{noncu}	(A/mm^2)	544.2
ntau(B=0)	(ms)	60
RRR		100

listed in Table II. Material of the conductor is Nb_3Sn, and that of conduit is Incoloy 908. Time constant of the cable, ntau, is estimated as 60 ms and RRR is above 100.

The cryogenic cooling parameters for the superconducting coils are 0.6 MPa and 5 K at the inlet, and 0.3 MPa at the outlet [4].

III. RESULTS OF ANALYSIS

The operating current scenario for CSMC test is shown in Fig. 3. The maximum current is 22.4 kA and the maximum ramp rate of the field is 3 T/s. Maximum field is 9.77 T at conductor and 8.0 T at center at 22.4 kA. Magnetic field along the cooling channel is shown in Fig. 4.

The AC losses in the CICC include hysteresis, coupling, eddy current, and jacket hysteresis. The total losses calculated for the operating scenario are shown in Fig. 5. The largest single loss is due to the coupling loss in CICC. The coupling loss in the superconducting cable is a main heat load. It is over than those of hysteresis, eddy and conduit losses. The total loss for CSMC is about 80 kJ. All the energy should be absorbed by supercritical helium to keep the maximum temperatures of CSMC lower than their current sharing temperature.

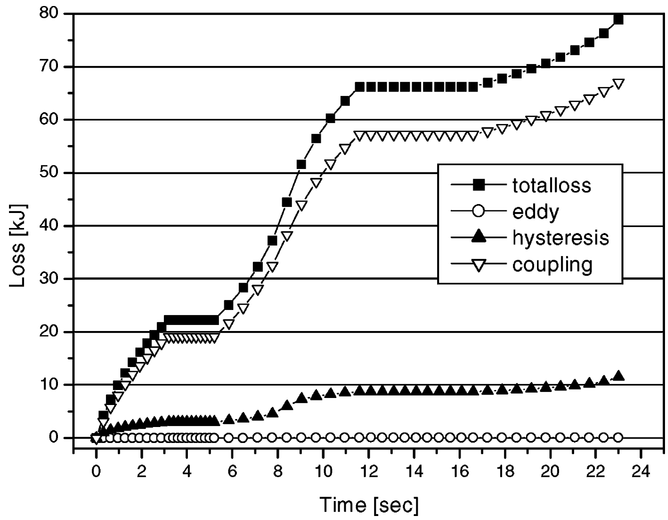

Fig. 5. AC loss of CSMC.

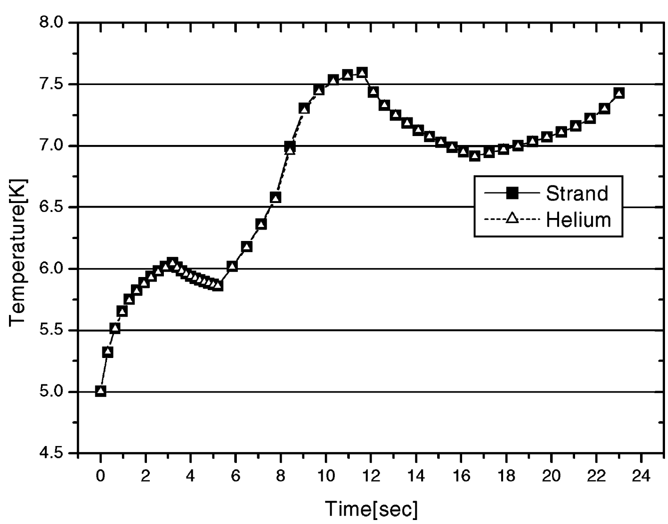

Fig. 6. Maximum temperature of CSMC.

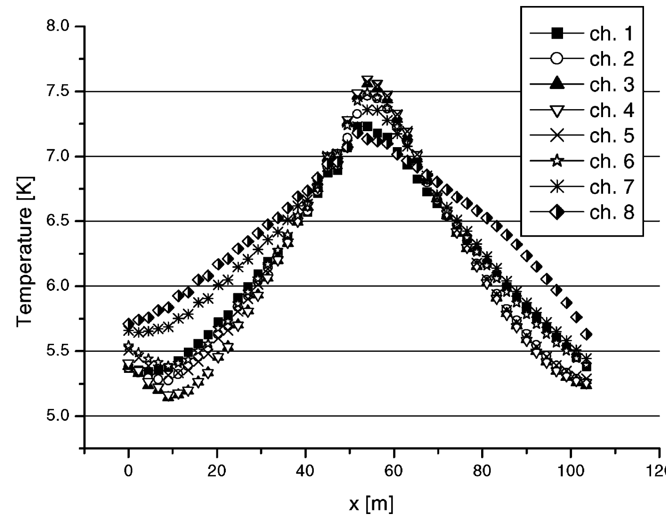

Fig. 7. Strand temperature along to cooling channel.

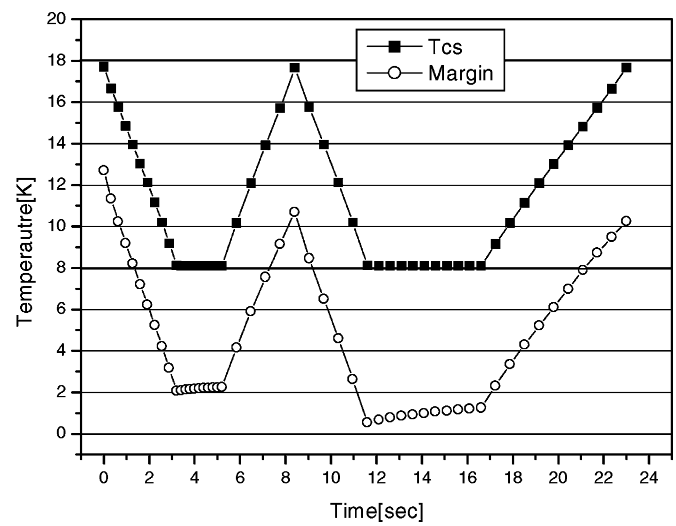

Fig. 8. Temperature margin and Tcs of CSMC.

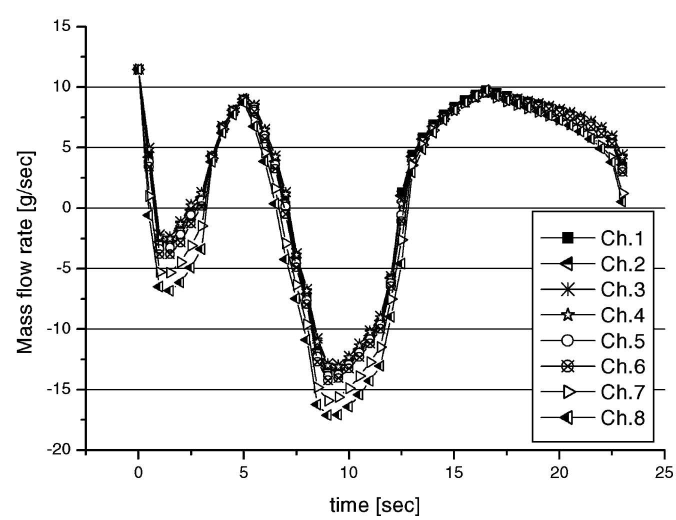

Fig. 9. Mass flow rate at inlet.

The thermal hydraulic characteristic in the CSMC is analyzed. Each hydraulic channel goes through one or two double-pancakes, making the inlet and outlet on the same side of the coil winding. Thermal diffusion through the winding pack and flow splitting through the header are also modeled. After calculating the temperatures in the conductor at every place and time, the maximum temperatures and the minimum operating temperature margin are searched for each of the coils at each time step. The profile of maximum temperatures for CSMC is shown in Fig. 6. The highest temperature is about 7.6 K.

The temperature of the strand along to cooling channel is shown in Fig. 7. The hot temperature point is located at the point of maximum field region. The operating temperature margin for the CSMC is calculated. The profile of temperature margin for CSMC is shown in Fig. 8. The temperature margin is an important parameter for the operation of superconducting magnets. The minimum temperature margin is about 0.5 K. Reverse flow in the coil is possible during the operation. The inlet mass flow rate is shown in Fig. 9. After 3.2 seconds, the reverse flow occurs at the inlet of cooling channel. The maximum inlet reverse flow rate is 17 g/s.

Pressure distribution along to the cooling channel is calculated as shown in Fig. 10.

As shown in Fig. 5, the coupling loss in superconducting cable is a main heat load. In this analysis, the time constant

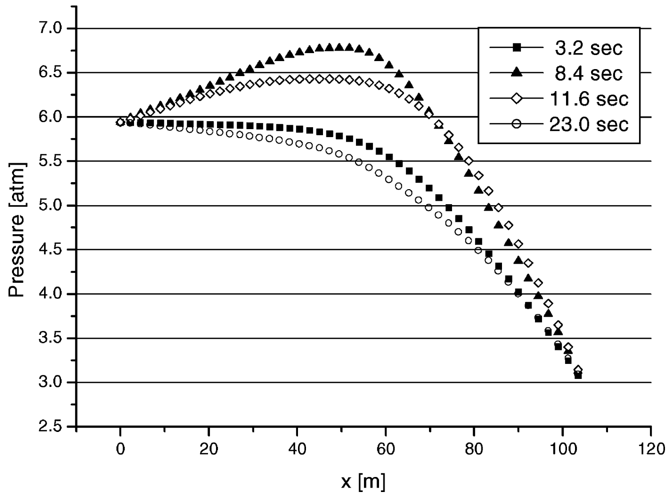

Fig. 10. Pressure distribution along the cooling channel of CSMC.

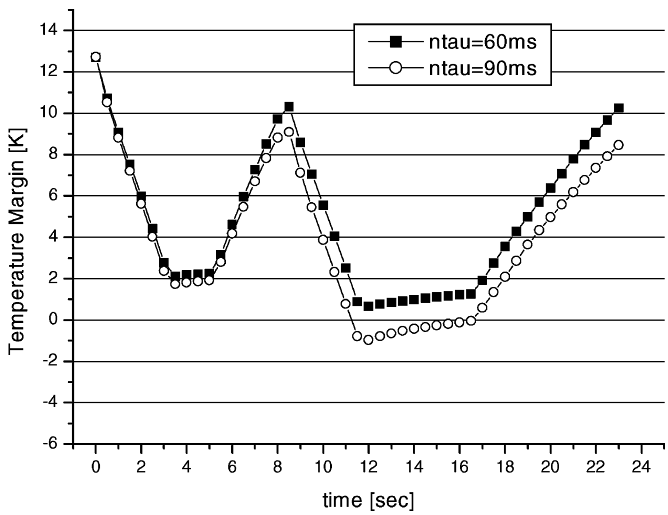

Fig. 11. The effect of time constant for coupling loss of conductor.

(ntau) for calculating coupling loss is assumed to be 60 ms. Fig. 11 shows the effect of time constant. If the time constant is over 60 ms, the temperature of strand can exceed the current sharing temperature.

IV. Conclusion

A transient operating simulation code for the CSMC test is developed, which can calculate the energy loss, operating margin, maximum temperature rise and cryogenic parameters in the superconducting coil. This simulation code considers three-dimensional thermal coupling between turn-to-turn and channel-to-channel. The model is able to confirm the main design parameters of the cooling system and operating characteristics of superconducting magnets. Analysis of the operating characteristics and the cryogenic parameters is performed for the KSTAR CSMC coil. The total energy deposition due to AC losses in CSMC winding will induce a flow reversal of supercritical helium. The minimum temperature margin is estimated approximately 0.5 K. The maximum temperature in CSMC winding is about 7.6 K. If the time constant of the cable is over 60 ms, the temperature of strand can exceed the current sharing temperature.

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