Analysis of the KSTAR Central Solenoid Model Coil Experiment

W. Chung, Y. Chu, S. Lee, S. Baek, S. H. Park, J. Kim, H. Yonekawa, H. Lee, K. Park, Y. K. Oh, K. Kim, J. S. Bak, S. Jeong, and Q. Wang

***Abstract*—The Korea Superconducting Tokamak Advanced Research (KSTAR) Central Solenoid Model Coil (CSMC) was tested at the National Fusion Research Center (NFRC) to verify the design and manufacturing engineering and to ensure reliable operation. The CSMC reached 8.6 T at 20 kA DC operation successfully. We also assessed the AC loss of the CSMC by means of both a sinusoidal wave with a DC offset as well as a triangular pulse. We derived a friction factor correlation of CSMC at room temperature and at cryogenic temperature (4 $\sim$ 6 K). We also investigated the variation of the friction factor during current charging. The KSTAR PF coil simulation code was validated with inlet and outlet helium temperature, mass flow rate, and pressure drop from the experimental results. The operation temperature margin of the CS1 coil of KSTAR was calculated with the revised KSTAR PF coil simulation coil.**

***Index Terms*—AC loss, CS model coil, friction factor, KSTAR.**

I. Introduction

THE Korea Superconducting Tokamak Advanced Research (KSTAR) device is a tokamak with a fully superconducting magnet system, which enables advanced quasi-steady-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 Toroidal Field (TF) coils and 14 Poloidal Field (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].

All magnets are wound using Cable-In-Conduit Conductor (CICC) with a continuous winding scheme to eliminate internal joints [2]. The KSTAR TF magnet system consists of 16 D-shape coils, which are made of Nb_3Sn strand with an Incoloy 908 jacket. The PF magnet system is composed of 8 Central Solenoid (CS) coils (PF1-4UL) and 6 outer PF coils (PF5-7UL). Nb_3Sn Incoloy 908 CICC is also used for these coils except for PF6-7UL, which are made of NbTi strands with a stainless steel 316LN jacket.

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W. Chung is with the National Fusion Research Center, Daejeon, Korea. He is also with the Korea Advanced Institute of Science and Technology, Daejeon, Korea (e-mail: whchung@nfrc.re.kr).

Y. Chu, S. Lee, S. Baek, S. H. Park, J. Kim, H. Yonekawa, H. Lee, K. Park, Y. K. Oh, K. Kim and J. S. Bak are with the National Fusion Research Center, Daejeon, Korea.

S. Jeong is with the Korea Advanced Institute of Science and Technology, Daejeon, Korea (e-mail: skjeong@kaist.ac.kr).

Q. Wang is with the Institute of Electrical Engineering, Chinese Academy of Science, Beijing 100080, China (e-mail: qiuliang@mail.iee.ac.cn).

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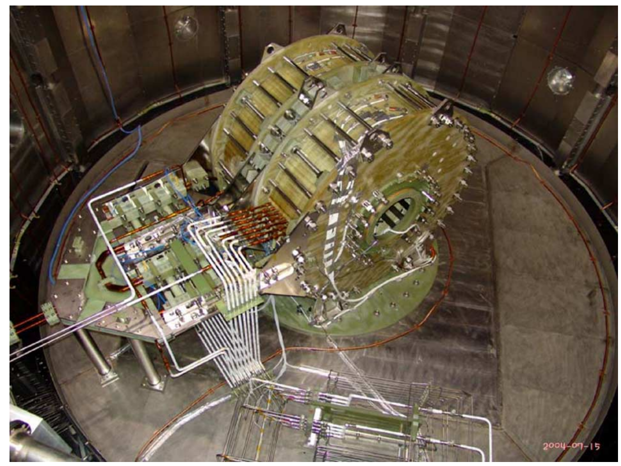

Fig. 1. KSTAR CSMC installed inside the large vacuum cryostat. The coil system consists of two split coils, MC1 and MC2.

A pair of central solenoid model coils (CSMC) have been fabricated and tested at a superconducting magnet test facility [3] to verify the design and manufacturing engineering and to ensure reliable operation after assembly. According to a reference operation scenario of the KSTAR device, the maximum magnetic field strength is 8 T and the maximum ramp rate is 12 T/s. Fig. 1 shows the CSMC installed in the large vacuum cryostat for the experiment.

Major parameters of the CSMC are shown in Table I [4]. The coil is composed of two coils in split-solenoid configuration as shown in Fig. 1. There are eight 105 m-length cooling channels for each coil and each channel cools two pancakes of a coil. The peak field of the system is 8.6 T and the central field is 7.1 T at 20 kA. The Current sharing temperature is 9.5 K at 8.6 T and 20 kA.

Since CSMCs are operating in a pulsed field environment, conductors will be heated by AC losses. The operating characteristics of the CSMC must be studied to check the temperature margin and stability margin of the superconducting cables. Cryogenic flow parameters also must be determined for stable operation.

II. Experimental Results

The CSMC was cooled down to the operating temperature in 9 days. The coil and structures were cooled down while

TABLE I
MAJOR PARAMETERS OF THE KSTAR CS MODEL COIL

Parameter	
Strand	
Superconductor	Nb_3Sn
Strand diameter	0.78 mm after chrome plating
Cu/non-Cu ratio	1.5
Jc (4.2 K, 12 T, 0.1 μV/cm)	> 750 A/mm^2
Hysteresis loss (±3 T, 4.2 K)	< 250 mJ/cc-nonCu
n-value	> 20
RRR	> 100
Conductor	
Conduit material	Incoloy 908
Void fraction	36.3%
Number of strands	360 (SC 240, Cu 120)
Cabling pattern	3x4x5x6
Cable twist pitch	40, 80, 145, 237 mm
Conduit dimension	22.3 (w), 22.3 (h), 2.41 (t) mm
Coil	
Number of coils	2
Inner diameter	740 mm
Outer diameter	1488 mm
Thickness	398 mm
Number of turns per coil	240 (15 x 16)
Inductance	134.4 mH
Stored energy	34.3 MJ @22.6 kA

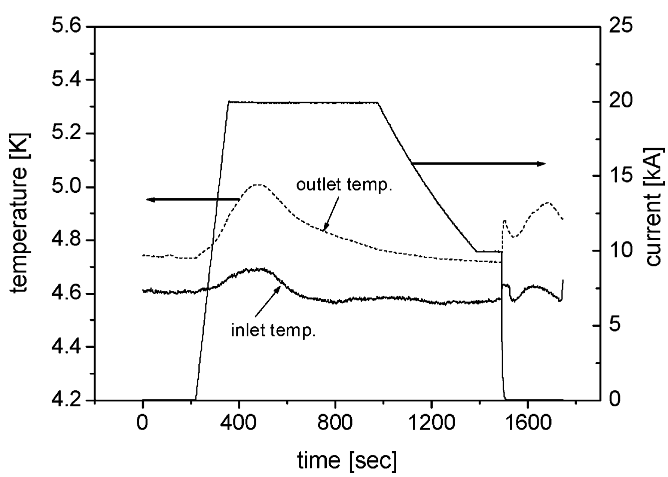

Fig. 2. Helium temperature at inlet and outlet during the DC test.

keeping the temperature difference between supply and return lines within 50 K. There was not any helium leak during the cool-down. The helium temperatures at the inlet and outlet were about 4.6 K and 4.7 K, respectively. The helium flow rate per coil was 23 g/s at a pressure drop of 0.15 MPa.

A. Current Charging Results

A current excitation test was conducted as shown in Fig. 2. We successfully charged the CSMC to 20 kA, 8.6 T in this test. The maximum temperature at the outlet was 5.0 K. The average mass flow rate of helium was 3.2 g/s for each cooling channel and pressure drop was about 0.15 MPa.

In order to estimate the AC performance of the CSMC, two kinds of waveforms were selected and analysed. One was a sinusoidal wave with a DC offset ($I_{dc} = 2, 4$ kA; $\Delta I_{ac} = 1$ kA; $f = 0.08 \sim 0.67$ Hz), and the other was a single triangular pulse ($I_{max} = 6 \sim 10$ kA; $dI/dt = 0.5 \sim 2$ kA/s). The experiment of the sinusoidal wave is shown in Fig. 3, in which

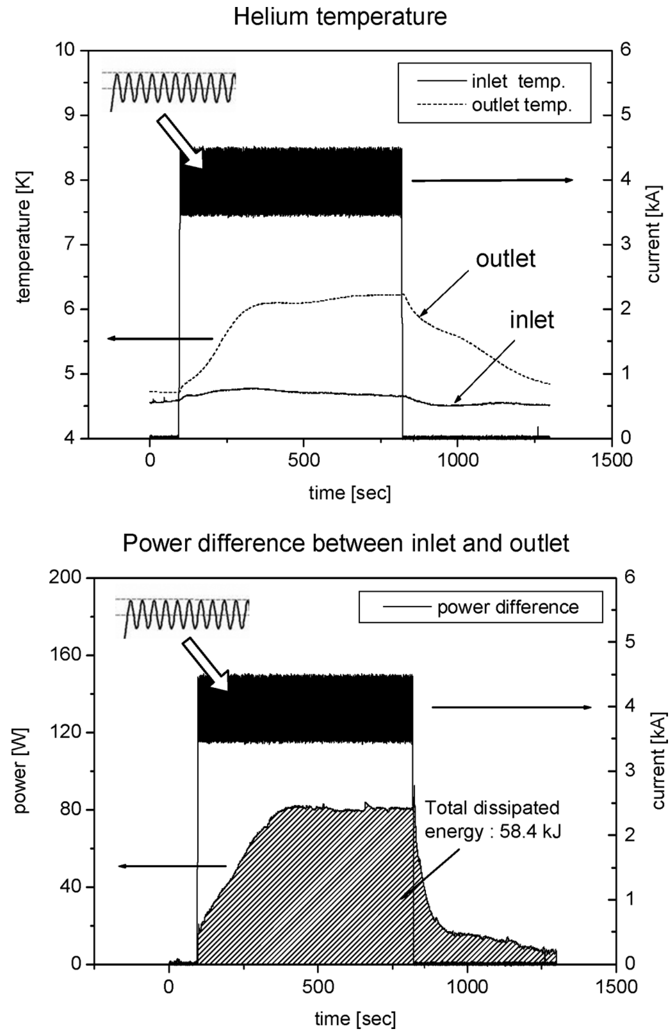

Fig. 3. Helium temperature and power dissipation of AC test.

the maximum temperature at the outlet was 6.2 K. The average mass flow rate of helium was 3.3 g/s for each cooling channel and the pressure drop was about 0.13 MPa. The total generated energy was 58.4 kJ.

B. Friction Factor of KSTAR PF CICC

The pressure drop in the KSTAR PF CICC has been measured using pressurized argon gas at room temperature to assess the friction factor. The CICC length is 5 m. The mass flow rate was measured by Mass Flow Controller (MFC) and the pressure drop was measured by a differential pressure transmitter (Fig. 4). The friction factor, f, is defined in (1). In this equation, ρ is density, A is the helium area, ΔP is the pressure drop, $\dot{m}$ is the mass flow rate, L is the CICC length, and U is the wetted perimeter.

$$f = \frac{8\rho A^3 \Delta P}{LU\dot{m}^2} \tag{1}$$

We derived the friction factor correlation of KSTAR PF CICC based on Katheder formula [5] as shown in (2).

$$f_{KSTAR,PF} = \left(\frac{1}{void\ fraction}\right)^{0.72} \times \left(0.0218 + \frac{19.5}{\mathrm{Re}^{0.758}}\right) \tag{2}$$

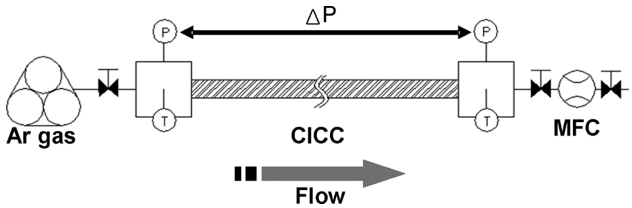

Fig. 4. Friction factor measurement system at room temperature.

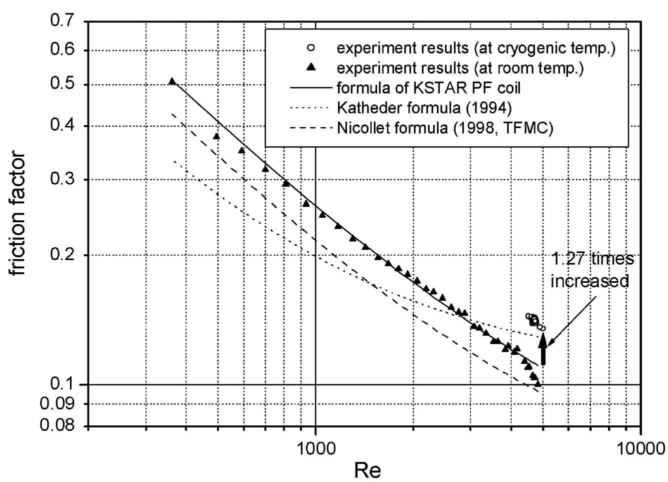

Fig. 5. Comparison of experimental results of CSMC conductor with other experimental results.

where Re is the Reynolds number.

The results of the CSMC experiment at cryogenic temperature ($4 \sim 6$ K) are shown in Fig. 5 [5], [6]. The friction factor of the CSMC at cryogenic temperature was 1.27 times higher than the friction factor at room temperature.

C. Effect of Current Charging on the Friction Factor

The magnetic field and current of a coil wound with CICC causes a transverse force pushing the cable to one side of the conduit. The addition of a new helium passage, which is generated by the deformation of cable, causes the helium mass flow rate to be increased during the current charging [7].

The friction factor of the CSMC is also decreased during current charging in coil as shown in Fig. 6. The friction factor is decreased by 3% at a current charging of 20 kA. This means that the mass flow rate is increased about 1.3% for a fixed pressure drop. The cross section of the flow passage may be deformed a little under the test condition, but the effect of current charging on the friction factor of CSMC was measurable but small.

D. AC Loss of the CSMC

The results and analysis of the AC losses of the CSMC were presented in [4]. The AC losses of the KSTAR CSMC have been measured by a calorimetric method. In case of the DC-biased sinusoidal wave, the measured hysteresis loss agrees with the theoretical estimation within a 15% error.

The coupling loss increases linearly with the frequency of the sine wave and ramp rate of the triangular wave. The $n\tau$ was 41.1 ms at 10 kA, where τ is the coupling current time constant of the cable, and the superconductor geometry factor n is 2 in our case [4]. Because $n\tau$ in the KSTAR magnet is designed to be less than 60 ms, it is acceptable.

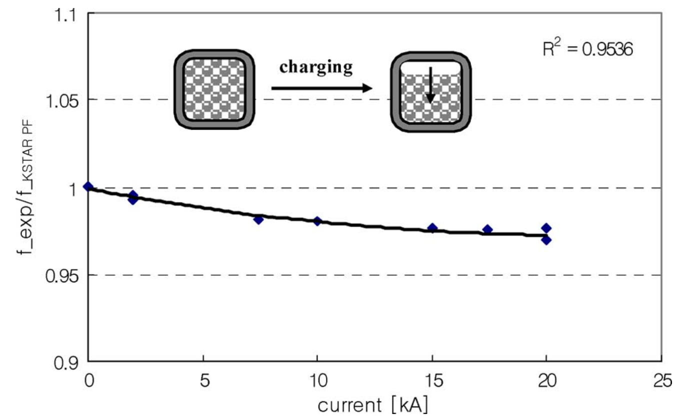

Fig. 6. Variation of friction factor ratio during charging the coil.

III. Simulation of the KSTAR Coil

We developed a KSTAR PF coil simulation code earlier [8]. The effect of three-dimensional heat conduction is considered in this code. One of the major thermal-hydraulic parameters in the simulation is the friction factor for helium flow in the CICC [9]. So, the modified friction factor and the value of the AC loss acquired in the experiment are applied in the code. The temperature of the superconducting strands and helium as well as the cryogenic flow parameters in the CSMC and CS1 coil are calculated by the code.

A. Validation of the KSTAR PF Coil Simulation Code

We compared the results of a single triangular pulse test with the computation by the code to validate the KSTAR PF coil simulation code. Fixed boundary conditions of inlet and outlet pressure and inlet temperature are applied in the calculation. The evolution of the outlet temperature is shown in Fig. 7. The calculation predicted well the temperature rise tendency and the maximum temperature at the helium outlet. The maximum helium temperatures at the outlet of experiment and from the calculation are 4.96 K and 4.95 K, respectively. The average pressure drop between the inlet and the outlet was about 1.5 bar in both cases, and the average helium mass flow rate was about 3.6 g/s in the cooling channel. The total generated energy in the experiment and in the computation were 1.0 kJ and 1.1 kJ, respectively, as shown in Fig. 8.

However the code cannot predict the initial rise of temperature and pressure of the experiment, because of the fixed boundary conditions of the code. It is possible that the boundary conditions change due to heat loads as shown in Fig. 2. So, it is necessary to consider the cooling circuit from a helium refrigerator to the coil, to predict the variation of pressure and temperature at the inlet of the cooling channel.

B. Results of KSTAR CS1 Coil Simulation

The CS1 coil has the lowest temperature margin among KSTAR CS coils from the reference scenario of the KSTAR operation in a previous simulation [10]. The operating temperature margin for the CS1 coil is calculated with the code, which

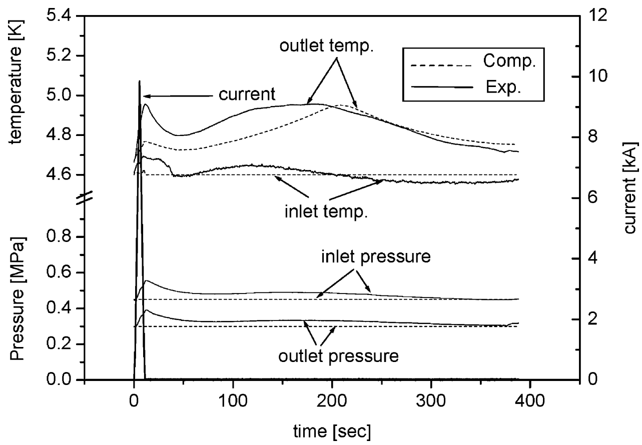

Fig. 7. Comparison of experimental temperature and pressure with those of the computation.

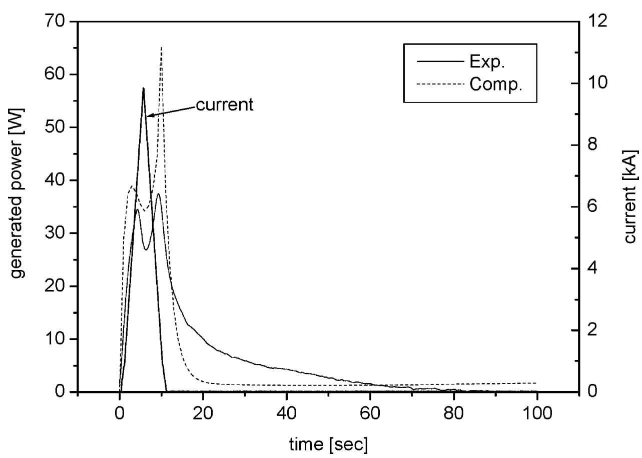

Fig. 8. Generated power of experiment and computation.

is revised in the friction factor and values of AC loss. The inlet temperature is 4.5 K. The profiles of the minimum temperature margin and the maximum strand temperature for the CS1 coil are shown in Fig. 9. The minimum temperature margin is 6.4 K and maximum strand temperature is 5.1 K.

IV. Conclusion

A pair of the CSMC has been tested to verify the design and to ensure reliable operation. We successfully charged the CSMC to 20 kA, 8.6 T in the DC test. The $n\tau$ of the CSMC was 41.1 ms and it is within the acceptable range of KSTAR.

We derived a friction factor correlation of the KSTAR PF CICC at room temperature. The friction factor of the CSMC decreases during current charging of the coil. But, the effect of current charging on the friction factor of the CSMC was negligible.

The KSTAR PF simulation code predicted well the temperature rise tendency and the maximum temperature at the helium outlet. But, it is necessary to consider the cooling circuit from a helium refrigerator to the coil, to predict the variation of pressure and temperature at the inlet of the cooling channel.

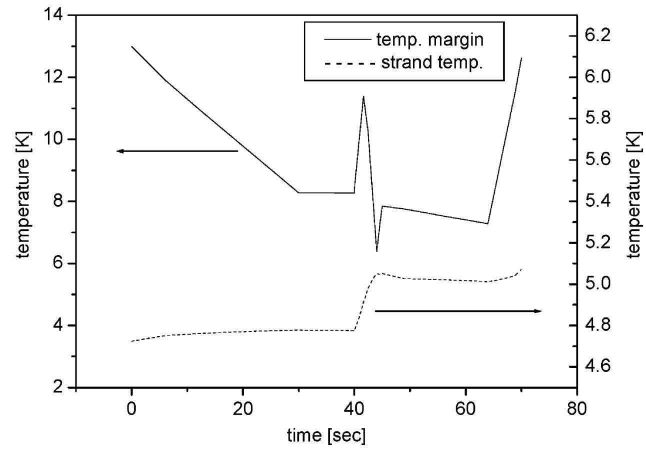

Fig. 9. Temperature margin and strand temperature of KSTAR CS1 coil in a KSTAR reference scenario.

The operating temperature margin of the CS1 coil was calculated with the revised code. The minimum temperature margin is about 6.4 K and the maximum strand temperature is 5.1 K.

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