Operating Characteristics of the KSTAR Superconducting TF Coil

Wooho Chung, Qiuliang Wang, Sangkwon Jeong, Cheon Seog Yoon, Hyunki Park, and Keeman Kim

***Abstract*—The Korea Superconducting Tokamak Advanced Research (KSTAR) device, a steady-state-capable advanced Tokamak, is to be built in Korea. The KSTAR device is made up of 16 toroidal field (TF) and 14 poloidal field (PF) superconducting coils. A simulation code for the transient operation of the KSTAR TF and PF coils is developed. For stable Tokamak operation, the operating characteristics of the KSTAR superconducting magnet system are studied for operation scenario. We calculated the temperature margin of superconducting cables, cryogenic flow parameters and the heat deposition in TF and PF coils. The effect of the three-dimensional heat conduction and the eddy current loss in the supporting structure and vacuum chamber of KSTAR is also included.**

***Index Terms*—PF coil, temperature margin, TF coil, tokamak.**

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. The overall tokamak configuration of the KSTAR is shown in Fig. 1 and major parameters are summarized in Table I.

Since TF and PF coils are operating in a pulsed field environment, conductors will be heated by various AC losses such as hysteresis loss, coupling loss, and eddy-current loss [1]. During the steady-state operation of the tokamak, neutron and gamma radiation heating and eddy current heating in coil cases will raise the coil temperature. The operating characteristics of the KSTAR superconducting coil system for various operating scenarios must be studied to check the temperature margin and stability margin of superconducting cables. Cryogenic flow parameters also must be determined for stable operation of the tokamak.

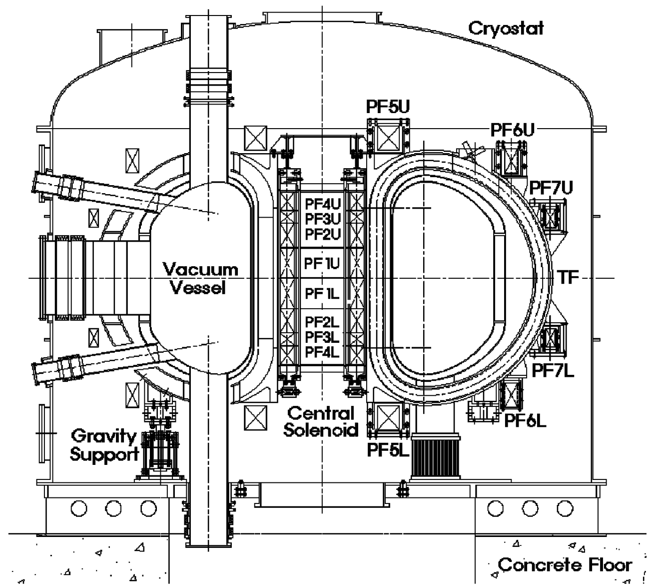

Fig. 1. KSTAR tokamak configuration.

TABLE I
Main Parameters of KSTAR

Parameters	Baseline	Upgrade
Toroidal field, B_T (T)	3.5	
Plasma current, I_P (MA)	2.0	
Major radius, R_0 (m)	1.8	
Minor radius, a(m)	0.5	
Elongation, κ_x	2.0	
Triangularity, δ_x	0.8	
Poloidal divertor nulls	2	1 & 2
Pulse length (s)	20	300
Heating power (MW)		
Neutral beam	8.0	16.0
Ion cyclotron	6.0	6.0
Lower hybrid	1.5	3.0
Electron cyclotron	0.5	1.0
Peak DD neutron source rate (s^{-1})	1.5×10^{16}	2.5×10^{16}

An advanced model for the transient operating simulation of the KSTAR TF coil system is developed. The temperature margin of the TF superconducting cable, cryogenic flow parameters and the heat deposition in TF coil system are calculated. The effect of the three-dimensional heat conduction and the eddy current loss in the KSTAR supporting structure and vacuum chamber is also included.

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W. Chung, H. Park, and K. Kim are with the Korea Basic Science Institute, Daejeon 305-380, Korea (e-mail: whchung@kbsi.re.kr).

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

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

C. S. Yoon is with the Hannam University, Daejeon 306-791, Korea (e-mail: csyoon@hannam.ac.kr).

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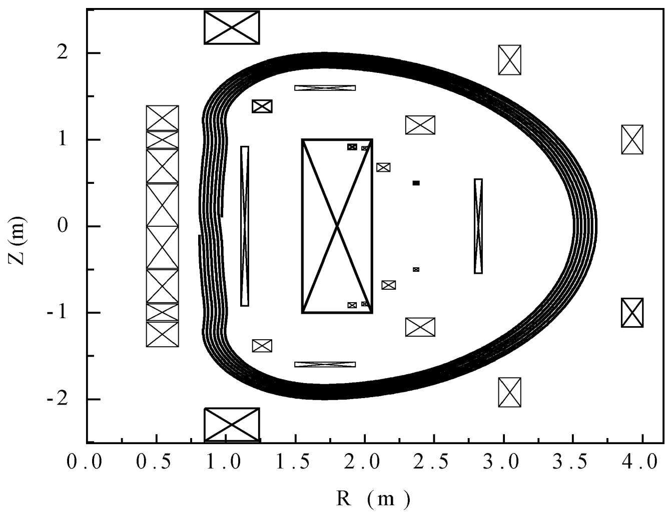

Fig. 2. Equivalent circuit model.

II. Numerical Model

An equivalent circuit model of the magnet system is considered to simulate the influence of PF coils on the operation of TF coils. We assume that the decaying time constant of the plasma current is much larger than that of the passive structure. Therefore, the variation in the current of PF coils is independent of plasma behavior and parameters. All the superconducting magnets are connected with the controlled power supply during normal operating condition with a resistivity of $10^{-23}\ \Omega\mathrm{m}$. The passive structures and field corrected coils are equivalent to the current ring with the resistivity of R. The equivalent circuit is illustrated in Fig. 2 for the KSTAR operating scenario [2].

During the variation of the current in PF magnets and plasma current, the equivalent circuit equation for the whole tokamak system is expressed as

$$\frac{\partial \psi(t)}{\partial t} + I(t)R = V(t), \tag{1}$$

where ψ represents magnetic flux. R denotes the diagonal conductor resistance matrix. I is the current in the conductor and V is the voltage applied to the PF coils. The coupled, lumped parameter circuit equation for PF coil system, support structure and plasma is solved by the linearization of coefficients in the circuit equation using the fully-implicit time stepping method. The initial condition is assumed to be $I(0) = I_0$. While the plasma current goes from 0 to $I_{\max}$ instantaneously.

The temperature of the conduit is predicted by the heat conduction equation. The coupled equations for supercritical helium, superconducting strands and conduit are expressed as (see [3] for details)

$$M\frac{\partial \psi}{\partial t} + A\frac{\partial \psi}{\partial x} + B\psi = \frac{\partial}{\partial x}\left(K\frac{\partial \psi}{\partial x}\right) + G, \tag{2}$$

where ψ represents independent variables, including density, velocity and temperature. The coefficient matrix K, is the thermal diffusion term of superconducting strands and the conduit. The coefficient matrix A, is the convection term of the supercritical helium. The coefficient matrix, B, denotes the source term with explicitly depending on the variable. The source term, G, includes the external thermal load and AC loss. The additional heat coupling term, Q_S is calculated in [3].

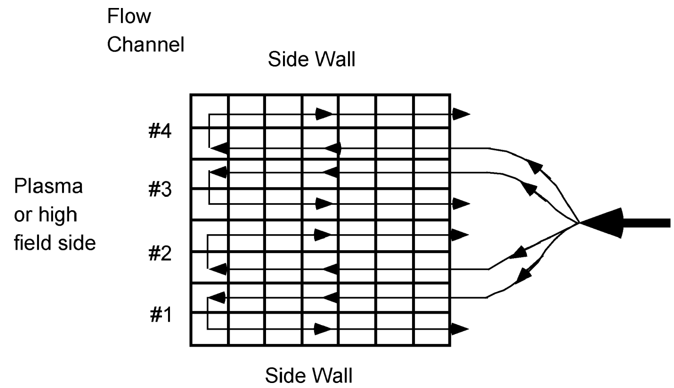

Fig. 3. Helium flow paths in the TF winding pack.

TABLE II
TF Hydraulic Parameters

Parameters	Units	Value
n_{inlets}/coil		2
$n_{channels}$/coil		4
P_{out}	(MPa)	0.3
P_{in}	(MPa)	0.5
T_{in}	(K)	4.5
Peak mass flow/channel	(g/s)	6
Peak mass flow/coil	(g/s)	24
Peak mass flow-TF system	(g/s)	384

III. Heat Source and Cooling Mechanism

The KSTAR TF coil system has 16 coils, and each coil has 8 pancakes and 7 layers. There are 4 hydraulic cooling channels in the winding pack, and each channel goes through double pancakes, making the inlet and outlet on the same side of the winding pack. The topology of the cooling channel is illustrated in Fig. 3. Cryogenic parameters of TF coils are summarized in Table II.

There are two heat sources, which are treated as external heat inputs for the analysis of TF coils. The first is the nuclear radiation term, neutron and gamma ray from the burning plasma, where the neutron source is assumed to be $3.5 \times 10^{16}\ \mathrm{n/s}$. The total nuclear heating in a single TF coil is approximately 272 W, which consists of 71 W in two side channels and 65 W in the two center channels. A uniform heat distribution along the cooling path is assumed. The second heat source is the heat conduction from TF cases. The alternating PF field during the plasma initiation, current ramp, and the time-varying field from plasma position control during the plateau induces the eddy current in the TF coil structure. Supercritical helium in the cooling channels will partly intercept the heat, while the rest of the heat will be transferred into the winding pack. The nuclear and conduction heat source with respect to time during the burning time of 300 seconds are plotted in Fig. 4.

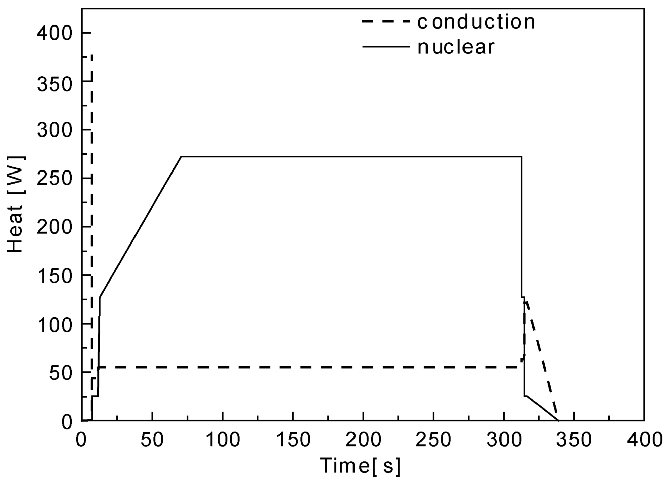

Fig. 4. The nuclear and conduction heat source versus time for burn time of 300 s.

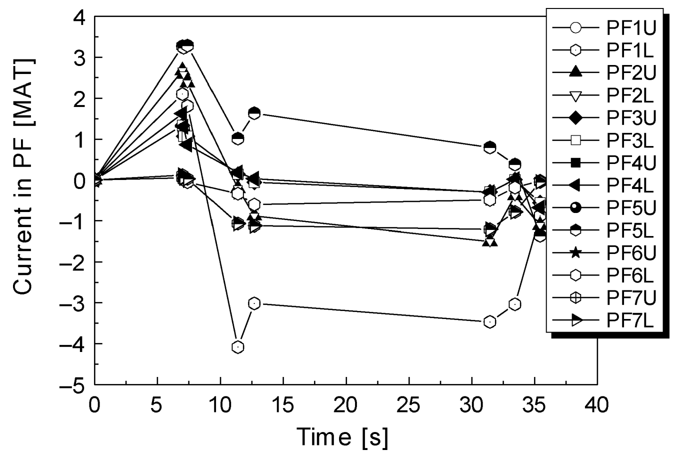

Fig. 5. PF coils ampere-turn versus time.

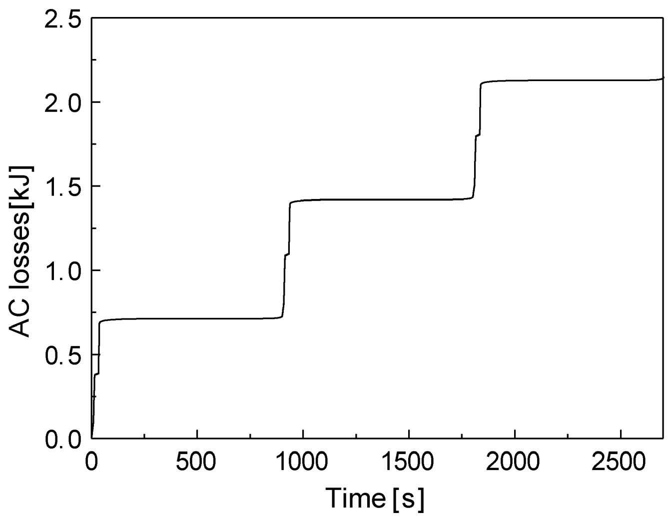

Fig. 6. Total AC losses in TF superconducting coil system.

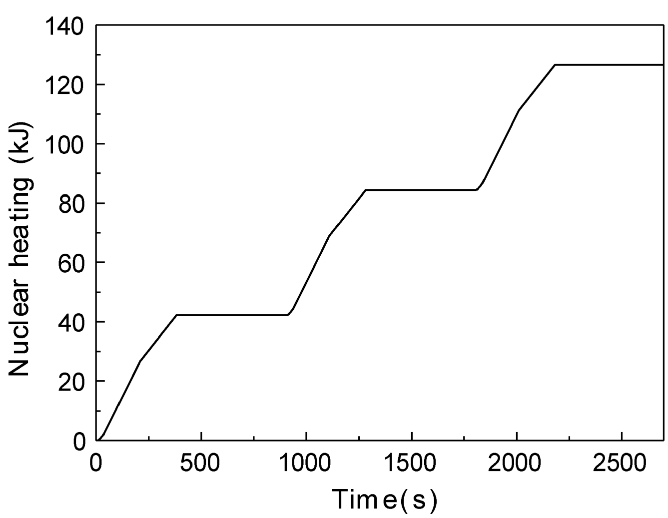

Fig. 7. Direct nuclear heat with respect to time from the fusion in burn time of 300 sec.

IV. Energy Deposition and Temperature Rise in TF Superconducting Coils

A three-dimensional transient heating and heat-removal code is developed, which self-consistently calculate AC losses, due to hysteresis, coupling, and eddy currents. Also, it includes the heat load from the external cold structure as boundary conditions. The flow model includes the flow splitting from the inlet and outlet headers.

The analysis of the TF coil system is based on a reference scenario, in which coil dimensions and parameters of the hydraulic design are specified in the facility requirement documents. The external heat load onto the winding pack from the direct nuclear heating and indirect conduction heating from the TF coil structure are deposited in CICC (cable-in-conduit conductor) and the heat load is removed by the supercritical helium. The heat from neutrons, gamma rays and eddy currents in the normal scenario and during plasma position control is transferred to the TF coil structure. Each hydraulic channel has the length of two pancakes and the inlet and outlet ports are both on the low-field side of the windings. In this simulation, the inlet pressure is fixed at 0.5 MPa, while the outlet pressure is fixed at 0.3 MPa, and the inlet temperature is fixed at 4.5 K.

During the operation, the variation of poloidal field induces AC loss in TF windings. For the given operating reference scenario, the current profile with respect to time is plotted in Fig. 5.

The instantaneous nuclear heating, AC loss and other heat flow to the TF coil system need to be considered for safe operation. AC loss of the TF coil system due to the PF coil system is as shown in Fig. 6 for the three-shots of the tokamak operation. It includes the hysteresis loss, coupling loss and eddy loss in superconducting strands and conduit.

The nuclear heat from the nuclear fusion reaction is plotted in Fig. 7, and the indirect conduction heat from the case is plotted in Fig. 8. Since the heat is deposited to the superconducting strands, the thermal balance should be carefully examined to avoid excessive temperature rise during this heating period. The temperature distribution on the side and inner channel in the TF is shown in Fig. 9. The TF coil has the peak temperature of 5.7 K, and the temperature rise is less than 1.5 K.

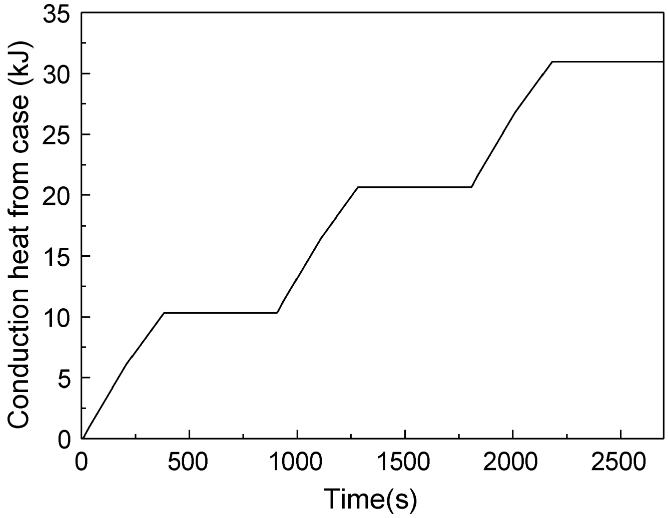

Fig. 8. Indirect nuclear heat with respect to time in burn time of 300 sec.

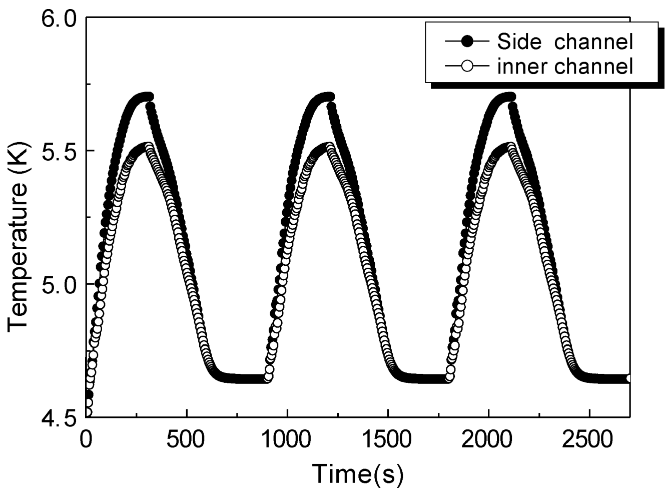

Fig. 9. Temperature of inner and side channels.

The temperature margin is an important parameter for the operation of superconducting magnets. The minimum temperature margin in the side channel is 4.9 K as is illustrated in Fig. 10. It shows that the cooling system of the TF coil is stable, in case all the losses and transient effects exist. The inlet supercritical helium is supplied by the refrigeration system, with the peak mass flow rate of 652.8 g/s for the TF system. According to simulation results, no flow reversal will be induced in the TF system during the burn time.

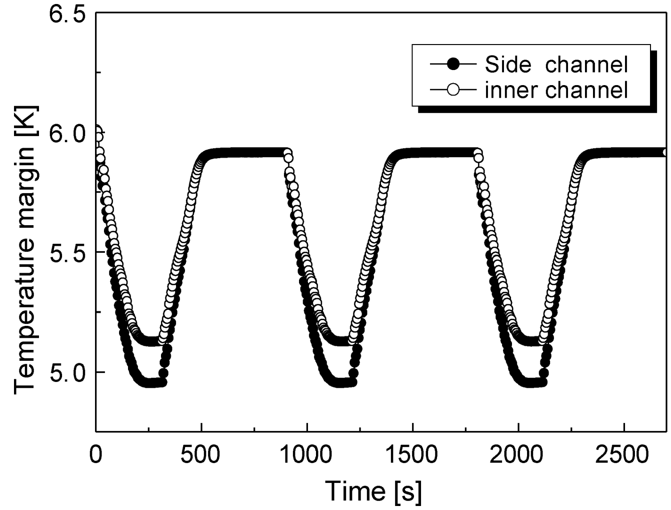

Fig. 10. Temperature margin of TF superconducting coil.

V. Conclusion

A new computational code is developed, which can calculate the energy loss, operating margin, refrigeration power, maximum temperature rise and cryogenic parameters in the TF superconducting coil. Three-dimensional thermal coupling between turn-to-turn and channel-to-channel is considered. The preliminary execution demonstrates the capability of the model for the study of the temperature and thermal flow distributions in CICC. The model is able to find main design parameters of the cooling system and operating characteristics of TF magnets. Analysis of operating characteristics and cryogenic parameters is done for the KSTAR TF coil. For the TF system, the external heat from the nuclear radiation, neutron and gamma rays dominates the cooling requirements. The AC loss and indirect conduction due to the PF field are small comparing to the nuclear heating. The total energy deposition in TF winding will not induce reversal flow of supercritical helium. The simulation results show that the maximum temperature rise in TF winding is lower than 5.7 K.

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