Heating Surge and Temperature Oscillation in KSTAR PF and TF Coils for Plasma Disruption Under Continuous Plasma Discharging Conditions

Qiuliang Wang, Keeman Kim, Hyunki Park, Wohoo Chung, C. S. Yoon, and Zengan Fen

***Abstract*—The operating characteristics in the poloidal field (PF) and toroidal field (TF) coils of KSTAR (Korean Superconducting Tokamak Advanced Research) for given operating scenarios are analyzed. In order to control the plasma shaped in KSTAR to realize the thermal nuclear fusion reaction, the operating currents in PF coils are controlled with high ramp rate with respect to time. The induced currents in the support structure and cryostat generate high eddy losses. They also produce a large hysteresis, eddy and coupling losses in superconducting PF and TF coils. The supercritical helium with high velocity through the cable-in-conduit-conductor (CICC) removes the heat load to keep the temperature of superconducting cable lower than its current sharing temperature. The maximum temperature rises in PF and TF are calculated under the continuous operating scenario. The simulation shows that the maximum temperatures in TF and PF are about 5.7 K and 5.9 K, respectively.**

***Index Terms*—CICC, fluid heat transfer, plasma discharge, Tokamak PF and TF coils system.**

I. INTRODUCTION

THE Korea Superconducting Tokamak Advanced Research (KSTAR) device, an advanced plasma, steady-state Tokamak experiment to be built in the Korea Basic Science Institute will have a superconducting magnet system, including both the toroidal field (TF) and poloidal field (PF) systems. The PF superconducting coils are operating in the fast current pulsed condition [1]. The PF and TF coils include the superconducting coils and support structure. We separate all the components into active and passive circuits. Since the currents vary relatively rapidly high frequency, the induced currents appear in the passive circuits. Due to eddy current losses in passive circuit and AC losses in the superconducting cable of CICC, the supercritical helium should remove all heat loads that are from the losses in structure and superconducting cable, environment and conductor itself. In order to check the design and operation of KSTAR in various references scenarios, the heat loads, temperature margin, cooling parameters and cooling time for continuous plasma discharge should be estimated for baseline the system on operation.

TABLE I
PF COILS DIMENSIONS—OUTSIDE GROUND WRAP

Coil	R(m)	Z(m)	R_1(m)	R_2(m)	Z_1(m)	Z_2(m)	n_{turns}
PF1, U	0.570	0.249	0.455	0.685	0.000	0.494	180
PF1, L	0.570	-0.249	0.45	0.685	-0.494	0.000	180
PF2,U	0.570	0.699	0.455	0.685	0.500	0.898	144
PF2,L	0.570	-0.699	0.455	0.685	-0.898	-0.500	144
PF3,U	0.570	1.005	0.455	0.685	0.902	1.108	72
PF3,L	0.570	-1.005	0.455	0.685	-1.108	-0.902	72
PF4,U	0.570	1.264	0.455	0.685	1.113	1.415	108
PF4,L	0.570	-1.264	0.455	0.685	-1.415	-1.113	108
PF5,U	1.085	2.295	0.910	1.260	2.096	2.494	224
PF5,L	1.085	-2.295	0.910	1.260	-2.096	-2.096	224
PF6,U	3.090	1.920	2.987	3.193	1.721	2.119	128
PF6,L	3.090	-1.920	2.987	3.193	-2.119	-1.721	128
PF7,U	3.730	0.980	3.651	3.809	0.829	1.131	72
PF7,L	3.730	-0.980	3.651	3.809	-1.131	-0.829	72

The analysis of the PF and TF coils is based on the currents, magnetic field, dimensions and thermal hydraulic analysis for the fluid. The coupling among active, passive circuits and plasma current is based on the equivalent lump circuit equations. A quasithree-dimensional model which the heat coupling terms between turns, layers, pancakes and channels are included in the equations of mass, momentum and energy conservation of supercritical helium is used to simulate the conductor temperature rise in the three-dimensional winding package. Due to the long pulse operation of PF coils for the KSTAR, the effect of the current nonuniform distribution is assumed to be small. The calculation of coupling, eddy and hysteresis losses in superconducting cable and support structure is based on an analytical model. The magnetic coupling circuit equation is solved on the basis of un-condition stable difference methods. The thermal expansion of supercritical helium is described by Navier Stoke's equation and the equation is solved by the finite element method with addition artificial viscosity [2].

II. TEMPERATURE RISE AND HEATING IN PF COILS

The parameters of the PF for KSTAR are listed in Table I [3]. The equivalent circuit of whole KSTAR for PF and TF, plasma current and cryostat system is illustrated in Fig. 1. All the coils will be fabricated by CICC. The cryogenic cooling parameters for the superconducting coils are inlet pressure and temperature of 0.5 MPa and 5 K, outlet pressure of 0.3 MPa for PF. The parameters of CICC are listed in Table II. The operating margin of PF and TF coils system in KSTAR strongly depends on the operating scenarios for the control plasma shape. In KSTAR, the plasma is controlled by the adjustment of the variation of the op-

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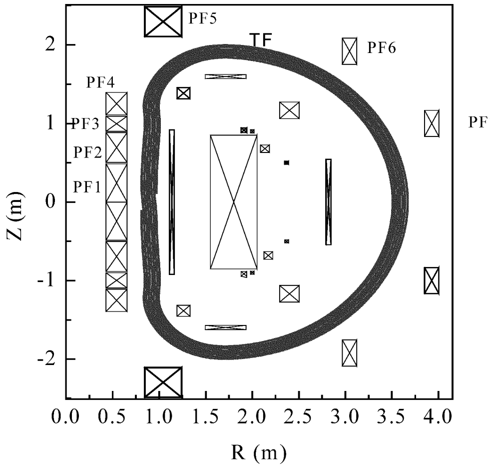

Fig. 1. Equivalent circuit model for the coupling of electromagnetic coupling.

TABLE II
TF AND PF CONDUCTOR PARAMETERS

Parameter	Units	TF	PF1-5	PF6-7
Conductor		Nb_3Sn	Nb_3Sn	NbTi
Conduit		Incoloy908	Incoloy 908	316LN
Cu/Noncu		1.5:1	1.5:1	3.5:1
$A_{conduit}$	(mm^2)	233	179.2	179.2
D_{strand}	(mm)	0.78	0.78	0.78
$n_{strands}$		486	360	360
$n_{custrands}$		162	120	120
$h_{conduit}$	(mm)	25.65	22.3	22.3
$w_{conduit}$	(mm)	25.65	22.3	22.3
$t_{conduit}$	(mm)	2.86	2.41	2.41
A_{cu}	(mm^2)	179.1	132.7	154.1
A_{noncu}	(mm^2)	65.1	48.25	26.8
A_{hecond}	(mm^2)	133	111.4	111.4
L_{strand}	(km)	3194	1625.8	1563
L_{cable}	(km)	9.86	6.78	7.33
$M_{scstrand}$	(tons)	13.4	6.844	7.5
N_{coils}		16	9	4
J_{noncu}	(A/mm^2)	540	544.2	641.8
D_{feff}	(m)	12.5	12.5	10
$E_{hyst}(\pm 3\ T)$	(mJ/cc)	250	250	200
τ (B = 0)	(ms)	60	60	60
RRR		100	100	100

erating currents with time in the PF coils. The reference scenario of KSTAR is based on the operating physical requirements.

The operating characteristics for three shots discharging of plasma are studied. The cooling time is set as 9 min. The losses in the CICC include hysteresis, coupling, cable eddy current, and jacket hysteresis. The total losses with respect to time for the continuous discharging in three shots are plotted in Fig. 2. The largest AC loss is due to coupling losses in the CICC. Hence the coupling AC losses in the superconducting cable are the main heat load, and are higher than those of hysteresis, eddy and conduit losses. The total loss for PF_{1-7} is about 272.3 kJ. All the energy should be absorbed by supercritical helium to keep the maximum temperatures of PF lower than their current sharing temperatures. The thermal hydraulic characteristics of the PF coils are 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 minimum operating temperature margin are searched for the each coil at each time step. The profiles of maximum temperatures for PF_{1-7} are plotted in Fig. 3. The highest temperature for the PF system is located at PF_1. Its value is 5.864 K. The maximum temperatures for PF6 and PF7 are about 5.07 K.

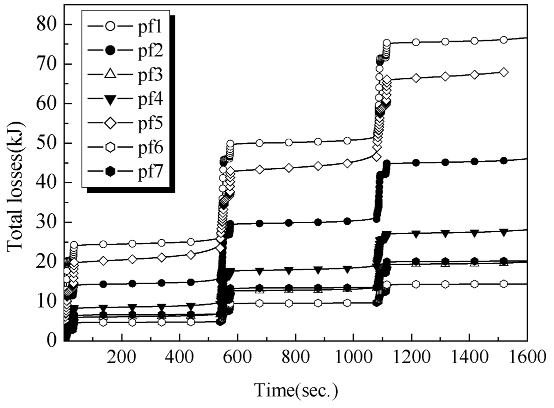

Fig. 2. Total AC losses for continuous discharging of three shots with respect to time.

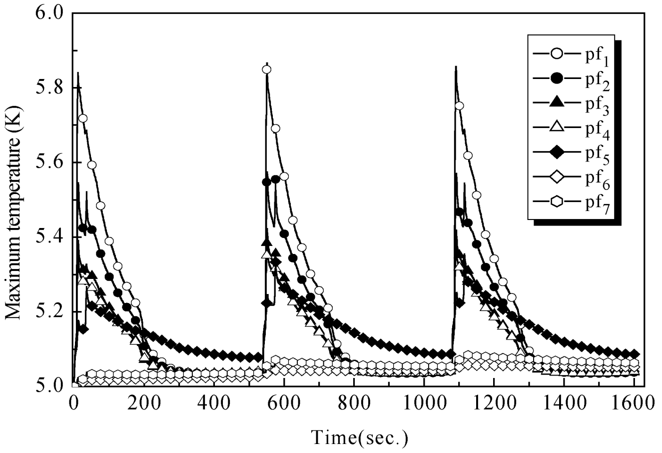

Fig. 3. Maximum temperatures in PF1-7 with respect to time for continuous operation of three shots.

The operating temperature margin for the PF is simulated. The profiles of temperature margin for PF1-7 are shown in Fig. 4. The minimum temperature margin is located at PF_1, its value is about 4.63 K. The minimum temperatures for NbTi coils of PF6 and 7 are 3.95 and 3.0 K, respectively. The outlet mass flow rate versus time is shown in Fig. 5. The maximum outlet helium mass flow rate is over than 22.5 g/s.

III. THERMAL ANALYSIS IN TF COILS

The KSTAR TF 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. There are two heat sources that are treated as external heat input for the analysis. The first is the nuclear radiation, neutron and gamma from the burning plasmas. The total nuclear heating in single coils is about 272 W with 71 W in two side channels and 65 W in the two center channels. The same heat distribution function along the cooling path is assumed. The second

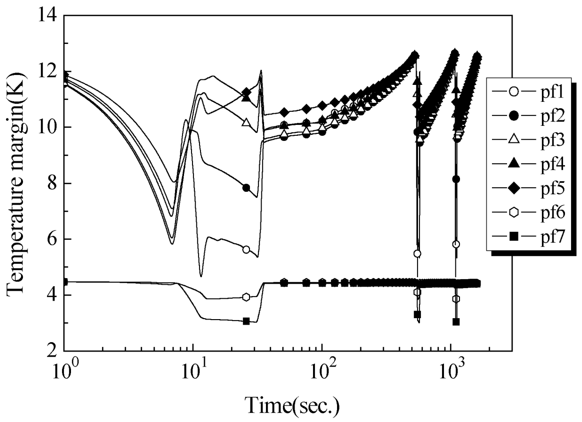

Fig. 4. Temperature margins for PF1-7 for continuous operation of three shots.

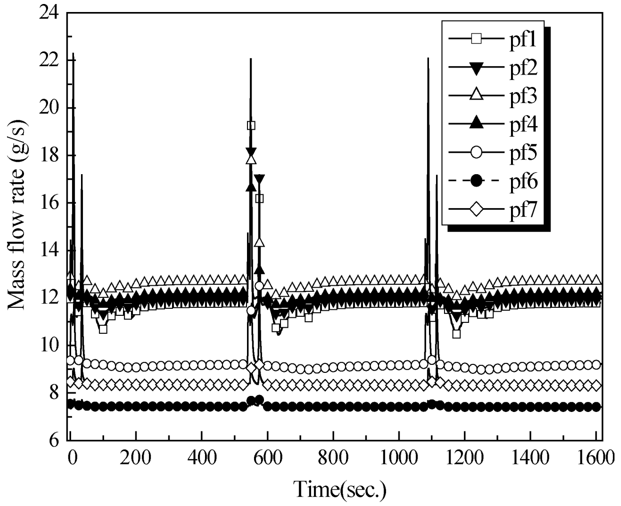

Fig. 5. Outlet mass flow rate for PF1-7 for continuous operation of three shots.

heat source is the conduction heat from the TF case. The pulsed PF field during the initiation and plasma current ramp-up and ramp-down period, and the time-varying field from plasma position control during the plateau would conduce eddy currents in the TF cold structure, which heat up the structure. Some of the heat will be intercepted by the cooling channels in the TF cold structure, and some conducts into the winding packet. The nuclear and conduction heat versus time are plotted in Fig. 6.

Instantaneous nuclear heating, AC losses and other heat flow of the TF superconducting magnet assembly are of concern for safe operation of cryogenically cooled superconducting coils. The AC losses from the PF coils in TF with respect to time are plotted in Fig. 7 for the three plasma discharge cycles conditions, including the hysteresis, coupling, eddy losses in the superconducting strands and eddy losses in the conduit. The supercritical liquid helium maintains the coil temperature around 4.5 K. It is important to assess any extra heat loading to the magnet structure, such as the nuclear heating and AC losses, which will require a higher refrigeration capability for TF magnet cooling. The nuclear heat from the fusion is plotted in Fig. 8, and the indirect conduction heat from the case changes with the time, it is plotted in Fig. 9. The total heat included the AC losses, nuclear and conduction is removed by supercritical helium.

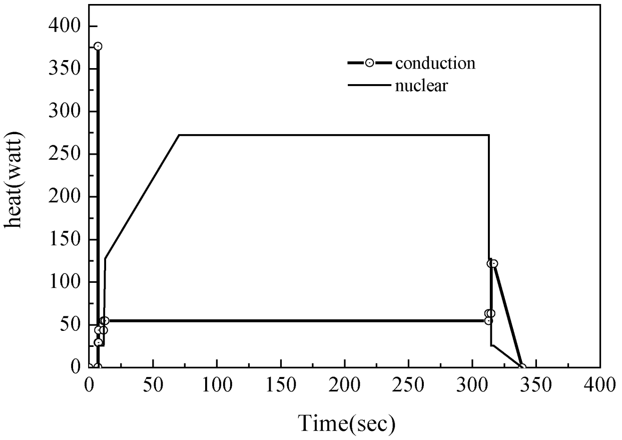

Fig. 6. Heat versus time for the nuclear and conduction for burn time of 300 sec.

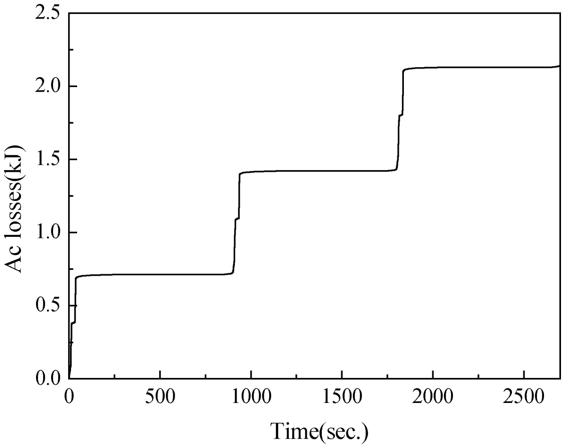

Fig. 7. Total AC losses in TF winding from the PF current variation with time.

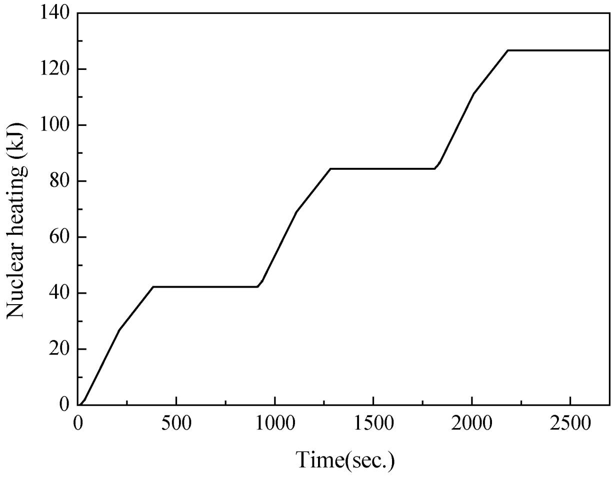

Fig. 8. Direct nuclear heat versus time from the fusion in burn time of 300 sec.

Since the heat is generated in the superconducting magnet, the thermal balance is needed. Otherwise, the temperature of superconducting strands rises during this period. The temperature distribution in the TF for the side and inner channel with respect to time is illustrated in Fig. 10. The TF coils have a peak temperature of 5.7 K, and temperature ratcheting is less than 0.15 K.

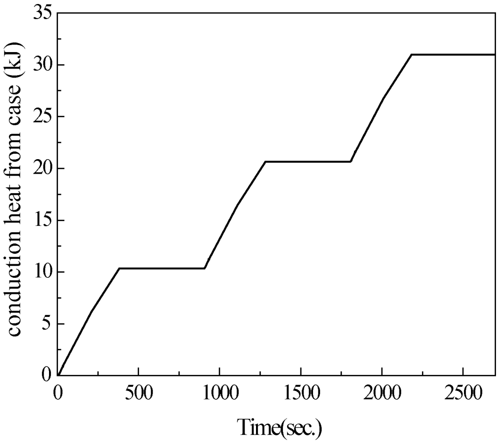

Fig. 9. Indirect nuclear heat versus time in burn time of 300 sec.

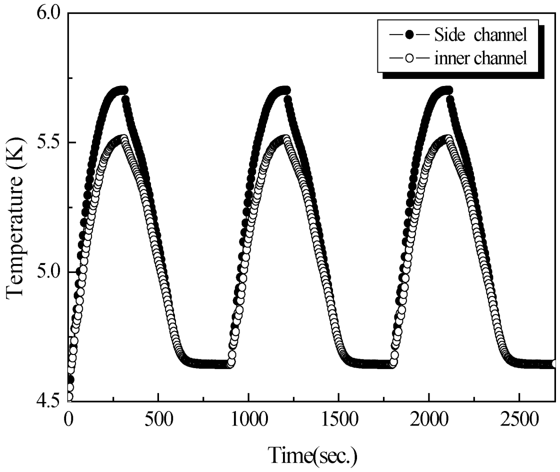

Fig. 10. Temperature with respect to time for inner and side channels.

The margin of temperature is an important parameters for superconducting magnet operation. Since all TF allowables can be met out to 6.0 K, this demonstrates the feasibility of the conceptual design. The minimum temperature margin in the coil is plotted in Fig. 11. The minimum temperature margin in the side channel is 5.7 K. This study demonstrates that cooling of the TF system to less than 4.9 K is feasible, even when all losses and transient effects are considered self-consistently. However, the design of the cooling system is probably optimized.

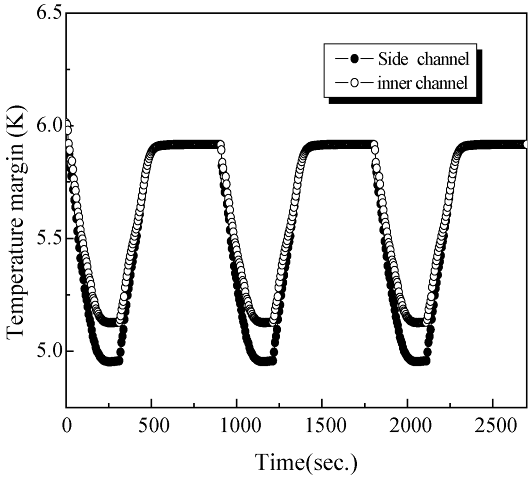

Fig. 11. Temperature margin in TF winding versus time in the three-shots.

IV. CONCLUSION

The analysis of the operating characteristics and cryogenic parameters has been done for the KSTAR TF and PF coils. For the TF system, the external heat from the nuclear radiation, neutron and gamma, dominates the cooling requirements. The AC losses and indirect conduction due to the PF field are small compared with the nuclear heat. The total energy deposition in the TF winding can not induce the reversal flow for supercritical helium. It is more useful for the stable operation of CICC. The simulation shows that the maximum temperature in the TF winding is lower than 5.7 K. The results show that the PF_1 has a minimum temperature margin of about 4.63 K and the temperature margin of PF_6 and PF_7 are about 3.95 and 3.0 K, respectively.

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