KSTAR 운전시나리오에 대해 초전도자석 구조물에 발생되는 줄열 및 온도분포 계산

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Calculation of Joule Heat and Temperature Distribution Generated on the Superconduction Magnet Structure for the KSTAR Operation Scenarios

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Abstract - Since the KSTAR magnet structure should be maintained at cryogenic temperature of about 4.5 K, even a small amount of heat might be a major cause of the temperature rising of the superconducting magnet structure. The Joule heating by eddy current induced on the magnet structure during the KSTAR operation was found to be a critical parameter for designing the cooling scheme of the magnet structure as well as defining the requirements of the refrigerator for the cryogenic system. Based on the Joule heating calculation, it was revealed that the bulk temperature rising of the magnet coil structure was less than 1 K. The local maximum temperature especially at the inboard leg of the TF coil structure increase as high as about 21 K for the plasma vertical disruption scenario. For the CS coil structure maximum temperature of 8.4 K was obtained from PF fast discharging scenario.

1. Introduction

The KSTAR magnet system producing the magnet field to confine and control the plasma of 2 MA during normal operation scenarios is composed of Toroidal Field (TF), Central Solenoid (CS) and Poloidal Field (PF) coil systems. TF coils producing the magnetic field of 3.5 Tesla at the plasma centre are normally under steady state operation. PF and CS coils are, however, operated in pulse mode and produce the field variation as well as eddy currents on the magnet structure [1]. The TF and CS coil structures are composed of 16 and 8 identical segments, respectively. These segments are electrically insulated each other to obstruct the eddy current induction on the structure during operation.

The Joule heating and its cumulative Joule energy by eddy current affects the structural and thermal stability of the magnet system, because it might cause a very high local temperature rising in the cryogenic magnet structure. It would require effective cooling scheme and burden the refrigerator of the cryogenic system.

In this paper, first the eddy current induced on the magnet structure for three operation periods was calculated using SPARK code [2]. Then Joule heating was estimated based on the eddy current using a developed methodology [3]. Finally the temperature distribution on the magnet structure due to Joule heat was obtained using ANSYS [4], and the results are compared.

2. Description of Joule heating calculation model

In order to calculate the eddy current and Joule heating, a model was adopted, as shown in Fig. 1. This model includes plasma facing components (PFCs) without their support structures, vacuum vessel double walls without reinforcing ribs, one TF coil structure segment and one CS coil structure segment. A TF coil structure segment includes inboard and outboard legs for the coil case and a inter-coil structure. An octant CS coil structure segment includes inner and outer shells.

3. Operation scenarios

Three operation scenarios are considered as the major concerning scenarios for the design of

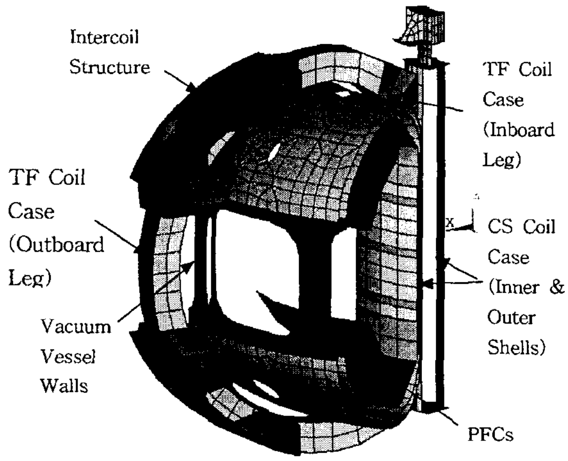

Fig. 1. A Joule heating calculation model

the KSTAR superconducting magnet system. Plasma disruption is one of the major design -driving scenarios. It releases a significant amount of thermal energy in the magnet structure [5]. PF fast discharging scenario would be necessary if abnormal condition happens in the PF coils or quench phenomena occurs in the magnet system. Finally, during the reference operation, relatively large current variation in PF coils occurs. This produces the eddy currents on the magnet structure, too [1].

4. Calculation of Joule heating

Eddy currents generated on the magnet structure were obtained using SPARK code for the defined operation scenarios. Transient Joule heating was calculated based on the eddy currents. The Joule heating on the TF and CS coil structures during plasma vertical disruption has maximum at 125 ms and 126 ms, respectively. The cumulative Joule energy at 200 ms in TF and CS coil structure segment are 20.3 kJ and 1.2 kJ, respectively.

The Joule heating on the magnet structure during PF fast discharging period has maximum at 0.3 s. Once the Joule heating reaches the maximum value at 0.3 s, it decays exponentially and then almost disappears at 9 s. The cumulative Joule energy in the TF coil structure for the PF fast discharging scenario is about 65 percent of that for the disruption case. However, the energy on CS coil structure for the PF fast discharging scenario is about twice that for the disruption case. Therefore, it can be mentioned that the effect of Joule heating on the CS coil structure is more dominant in the PF fast discharging scenario than disruption case.

The Joule heating generated on the magnet structure for the reference scenario has maximum during blip period of 0.06 s. During blip period the current increase rate in PF coils are up to 3 MA/s. In the successive period up to start-of-flattop (SOF), the relatively steep increase rate of currents in PF coils results in the large eddy current and therefore relatively large Joule heating is generated. The next large current jump period is between end-of-burn (EOB) and end-of-current (EOC). Here the third largest peak of Joule heating is generated.

5. Calculation of temperature distribution

Based on the transient cumulative Joule energy the transient temperature distribution on a TF and CS coil structures was obtained using ANSYS. The maximum temperature distribution was also obtained at 200 ms, 9 s, and 60 s for vertical disruption, PF fast discharging and reference scenario, respectively, as shown in Figs. 2 through 4. For vertical disruption scenario, since the plasma moves upward the maximum Joule heating was generated in the upper local area of the inboard leg where the maximum temperature was up to 20.6 K.

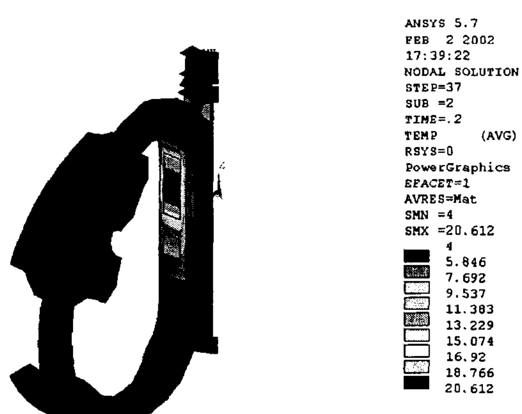

Fig. 2. Temperature distribution based on the cumulative Joule energy at 200 ms during vertical disruption

During PF fast discharging period, the eddy currents were concentrated on the interface between TF coil case and the inter-coil structure, as well as at the upper part of CS coil structure. The maximum temperatures in TF and CS coil structure increase up to 9.5 K

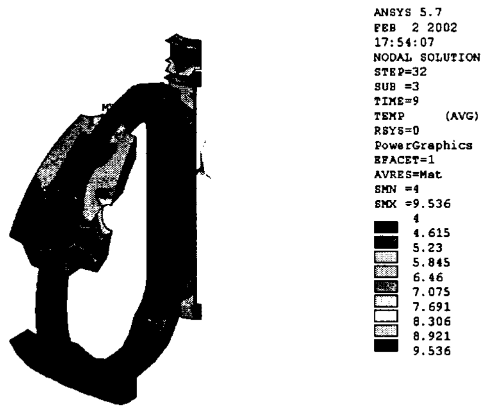

Fig. 3. Temperature distribution based on the cumulative Joule energy at 9 s during PF fast discharging

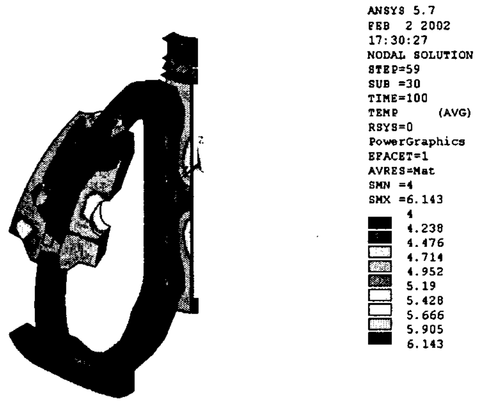

Fig. 4. Temperature distribution based on the cumulative Joule energy at 60 s during reference scenario

and 8.4 K, respectively. For the reference scenario the maximum temperature was generated in the port hole of TF inter-coil structure and the middle part of CS coil structure. This temperature is much lower than the results of the previous two operation scenarios. But the location of maximum temperature zone is different each other for all three scenarios.

The transient temperature histories at the maximum temperature point for three operation scenarios were shown in Figs. 5 through 7. The temperature history is similar to the cumulative Joule energy profile. As an interesting result, for the reference scenario during blip period maximum tempeature was found a the top/bottom section of CS outer shell. And, over the period up to EOB the temperature at the middle section of CS outer shell is maximum. After EOC the large Joule heat is generated in TF coil structure due to plasma current variation, so the temperature in the TF coil structure became maximum.

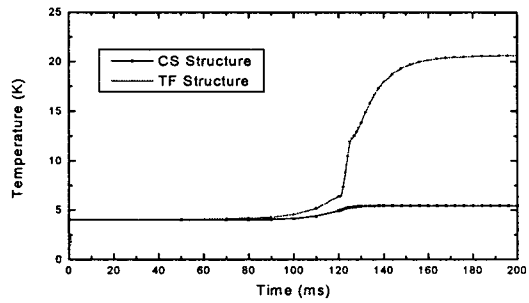

Fig. 5. Temperature history at maximum temperature points during vertical disruption

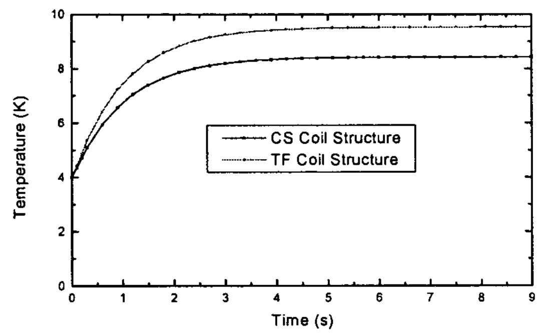

Fig. 6. Temperature history at maximum temperature points during PF fast discharging

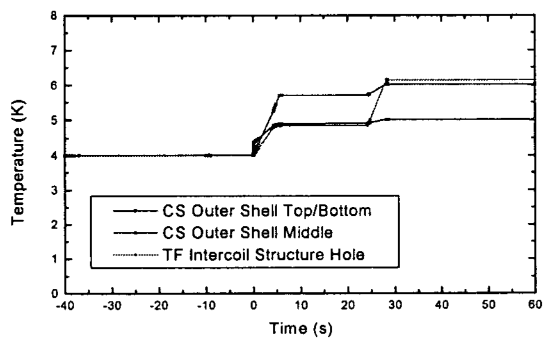

Fig. 7. Temperature history at maximum temperature points for the reference scenario

6. Comparison of the results

Maximum Joule heating, cumulative Joule energy, maximum temperature and bulk temperature increase generated on the TF and CS coil structures for three operation scenarios were obtained and summarized in Table 1. For TF coil structure the highest cumulative Joule energy was created during plasma disruption. For CS coil structure, the highest cumulative Joule energy was obtained in the PF fast discharging scenario. Therefore in order to design the cooling scheme of the TF and CS magnet structures the cumulative Joule energy of 20.3 kJ and 2.3 kJ must be considered, respectively.

7. Conclusion

The Joule heating and the cumulative Joule energy generated on the TF and CS coil structures during vertical disruption, PF fast discharging and reference scenario were calculated. The overall temperature distribution on the TF and CS coil structures was estimated based on the Joule heating. The local maximum temperature especially at the inboard leg of the TF coil structure increase as high as about 21 K for the plasma vertical disruption scenario. Maximum temperature of 8.4 K in the CS coil structure was important in the PF fast discharging rather than the disruption case. Based on the Joule heating calculation, it was revealed that the bulk temperature rising of the magnet coil structure was less than 1 K. Although the bulk temperature was negligibly small, the localized high temperature was found to be important for the design of magnet structure cooling scheme.

Table 1. Summary of maximum Joule heating, cumulative Joule energy, maximum temperature and bulk temperature increase

Operation Scenario	Plasma Vertical Disruption		PF Fast Discharging		Reference	
Coil Type	TF	CS	TF	CS	TF	CS
Max. Joule Heating, [kW]	646	80	11.6	2.3	5.1	2.5
Cumulative Joule Energy, [kJ]	20.3	1.2	13.3	2.3	7.6	1.2
Maximum Temperature, [K]	20.6	5.4	9.5	8.4	6.1	6.0
Bulk Temperature Rising, [K]	0.93	0.46	.061	1.04	0.35	0.46

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