Fusion Engineering and Design 89 (2014) 329–334

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Thermal analysis of toroidal field coil in EAST at 3.7 K

Yi Shi*, Yu Wu, Bo. Liu, Feng Long, Qiang W. Hao

The Institute of Plasma Physics of Chinese Academy of Sciences, P.O. Box 1123, Hefei, Anhui 230031, PR China

HIGHLIGHTS

- In this study, the thermal performance of toroidal field (TF) coil is studied at 3.7 K in Experimental Advanced Superconducting Tokamak device (EAST) to obtain the higher stability.
- The structure and cooling process design of TF coil and case is described and the helium temperature in the cable-in-conduit conductor (CICC) and case is evaluated during the 1.5 MA plasma disruptions.
- Then, the experimental results of TF coil cooled at 3.7 K and discharged in 10 kA are shown including the thermal loss evaluation.
- Finally, the thermal stability performance of TF coil is analyzed at 1.5 MA plasma current operations.

ARTICLE INFO

Article history:
Received 18 August 2013
Received in revised form 8 December 2013
Accepted 20 February 2014
Available online 17 April 2014

Keywords:
Thermal performance
CICC
TF coil
Cryogenics

ABSTRACT

The thermal performance of toroidal field (TF) coil is studied at 3.7 K in Experimental Advanced Superconducting Tokamak device (EAST) to obtain the higher stability for the higher plasma parameters operation. It is a good way to lower the operating temperature of TF coil to acquire the higher stability margin. This paper describes the structure and cooling process design of TF coil and case firstly. Based on the thermal load in the case, the thermal performance of the TF coil is performed at the plasma disruption state. The helium temperature in the cable-in-conduit conductor (CICC) and case is evaluated during the 1.5 MA plasma disruptions. Then, the experimental results of TF coil which has been cooled at 3.7 K and discharged in 10 kA are shown including the thermal loss evaluation. Finally, the thermal stability performance of TF coil is analyzed according to the 3.7 K experimental results and the stability prediction is performed at 1.5 MA plasma current operations.

1. Introduction

The mission of the Experimental Advanced Superconducting Tokamak (EAST) project in China is to develop a steady-state-capable advanced superconducting Tokamak, and to establish a scientific and technological basis for an attractive fusion reactor which has been building at institute of plasma and physics, the Chinese Academy of Science (ASIPP) in 2006 successfully. It will have a long pulse (60–1000 s) capability and will be able to accommodate divertor heat that makes it an attractive test for the development of advanced Tokamak operation modes. The model of EAST device is shown in Fig. 1.

The superconducting TF coil is most important system in EAST which is used to confine the plasma in the device. Its operating parameters will affect the ability of device operation directly. The main parameters of TF system required by the physical objectives are as following: major radius is 1.7 m, minor radius is 0.4 m, toroidal field of 3.5 T, and plasma current is 1.5 MA with a strongly noncircular cross-section [1].

However, in the early commissioning operation, the TF coil is always cooled at 4.5 K and operated at 8 kA which cannot discharge the better plasma configuration due to the lower magnetic field confinement. In order to obtain the higher plasma parameter, the lower operation temperature and higher operating current in TF coil are analyzed and taken to commissioning.

This paper describes the structure and cooling process design of TF coil and case firstly, after that, the thermal performance of TF case is performed and the temperature rise of helium in CICC and case is evaluated at 3.7 K. Then, the experimental results of TF coil operating at 3.7 K and thermal load evaluation are discussed. Finally, the stability performance of TF coil is analyzed and performance prediction is performed at the 14.3 kA current and 1.5 MA plasma parameter operations according to the 3.7 K experimental results.

* Corresponding author. Tel.: +86 0551 65593260.
E-mail address: shiyi@ipp.ac.cn (S. Yi).

http://dx.doi.org/10.1016/j.fusengdes.2014.02.040

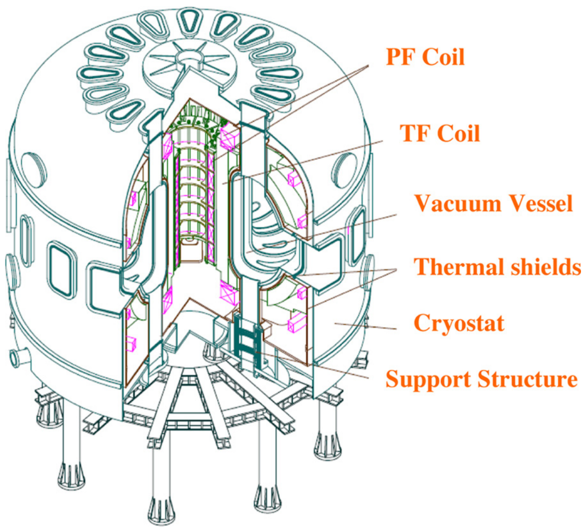

Fig. 1. The model of EAST Tokamak device.

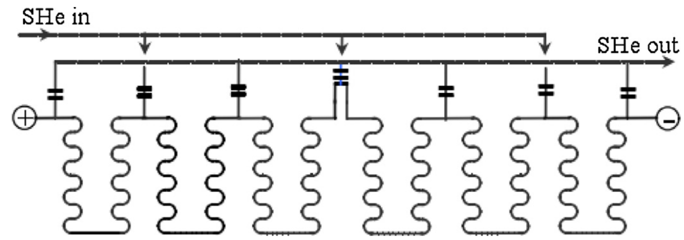

Fig. 3. The cooling flow chart of each TF coil.

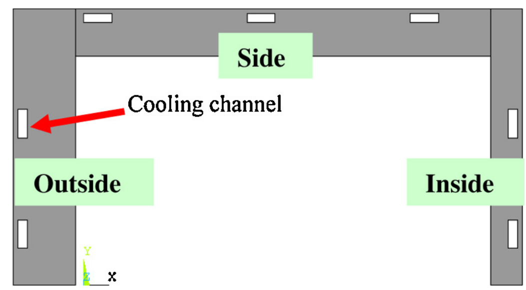

Fig. 4. The half cross-section of TF case model.

2. TF coil system in EAST

2.1. TF coil structure

The superconducting TF coil system consists of sixteen toroidal array D-shaped coil, each of the coil is made from double pancakes structure. The conductor used in the TF coils is NbTi CICC cooled by forced flow supercritical helium. The conductors are wrapped with the stainless steel case which is not only the main support structure of TF coil system, but also prevent the invasion of external heat load. Fig. 2 shows the model of the TF coil [2].

2.2. The cooling design of TF coil and case

In order to obtain the better cooling effect, the TF coil and case use the two independent cooling channels. Each TF coil has six double pancakes and each pancake has one cooling channel, so there are total six parallel cooling channels in single TF coil and the length of each cooling channel is about 200 m. Fig. 3 shows the cooling flow chart of the single TF coil which is separated by six independent cooling channels [2].

The TF case will withstand some kinds of heat load during operation, so the TF case is also cooled by supercritical helium in the cooling channels and the cross-section dimension of cooling channel is 22 mm × 8 mm shown in Fig. 4. In order to reduce the pressure loss in the cooling channel of the case, four parallel cooling channels are designed. The supercritical helium begins to flow into the outside channels and then through the side channels, finally out from the inside channels which is shown in Fig. 5.

3. Thermal evaluation of TF case in EAST

3.1. Thermal load in the case

In the normal operation of EAST, the heat loads deposited in the TF case can be divided into the steady thermal load and transient thermal load. The steady heat load includes the nuclear heat,

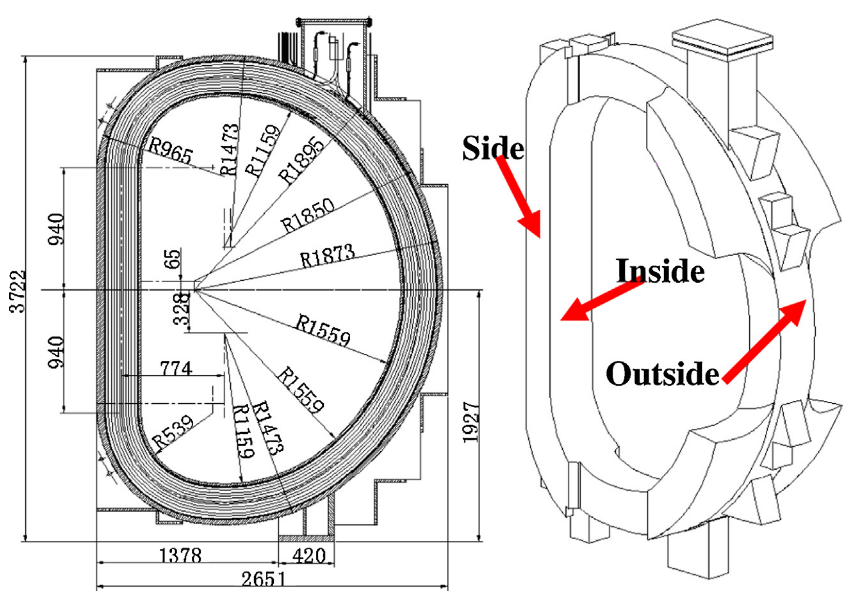

Fig. 2. The model of the TF coil.

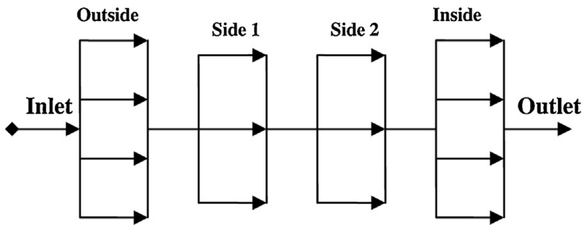

Fig. 5. The flow diagram of coolant in TF case.

radiation heat, gas convection heat and conduction heat; the transient thermal load mainly refers to the eddy current loss in the case generated by the change of magnetic field during plasma current disruption.

In EAST device, the radiation heat loss in TF case is mainly generated from 80 K shield. According to Steve–Boltzmann law, the loss can be described:

$$Q_1 = \sigma \times \varepsilon \times A \times (T_1^4 - T_2^4) \quad (1)$$

where T_1 is the shield temperature and T_2 is the TF case temperature; σ is the Steve–Boltzmann constant (5.67×10^{-8} W/(m^2 K^4)); ε is relative radiation factor between the case and shield surface which is 0.2 due to the good radiation characteristics; A is the relative radiation area.

The convection heat loss from residual gas in the ESAT vacuum is also the main heat source. The vacuum degree is generally greater than 1×10^{-5} Torr and the gap is smaller than 15 mm between the shield and the TF case, so the heat loss from residual gas convection can be described:

$$Q_2 = \alpha_0 \cdot kN_2 \cdot \left(\frac{273}{T_2}\right)^{1/2} \times (T_1 - T_2) \cdot P \cdot A_{1-1} \quad (2)$$

where α_0 is 0.6 and kN_2 is 293 W/m^2 K Torr; T_1 is the shield temperature and T_2 is the TF case temperature; P is vacuum degree and $A_{1-1}$is total of shield and case surface.

Another important heat loss is the conduction heat loss generated by supports. Based on the TF coil structure, the support bars are located in the outer vacuum and cooled by the liquid nitrogen. The top of support bars is connected by TF coil directly. The heat load can be described:

$$Q_3 = m \cdot \frac{A}{l} \cdot \int_{T_1}^{T_2} k \cdot dT \quad (3)$$

A is the cross section area of single support bar; m is the number of support bar; l is the height of support bar; k is the conduction of support material; T_1 and T_2 are the liquid nitrogen and liquid helium temperature.

The transient thermal loss mainly is the eddy current loss in the case generated by the changing of magnetic field from plasma disruption. According to Refs. [3,4], the eddy current loss in the TF case can reach to the peak value and only concentrate at the inner side of straight leg segment. In the condition of 1.5 MA plasma and 3 ms decay time constant, the maximum eddy current loss appears after plasma disruption 15 ms.

3.2. Thermal performance analysis of TF coil at 3.7 K

The TF coil cases are applied to withstand the EM force and maintain the CICC cooling environment. The cases must be cooled due to heat deposition from radiation, nuclear heating and the eddy current. The highest heat loss in the cases occurs at the plasma disruption phase.

By a simplified model, in the case of plasma current of 1.5 MA disruption at a time constant of 3 ms, the maximum eddy current heat loss dissipation on EAST TF cases will be appeared after plasma disruption 15 ms. The total heat dissipation from eddy loss in TF cases will be hundreds kilojoules within a time of several tens' millisecond [3].

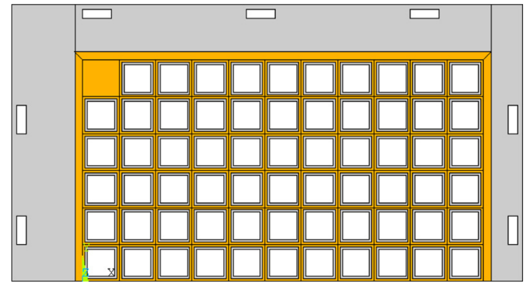

Fig. 6. The thermal simulation model of TF case.

This amount of heat dissipation will increase the case temperature up by several Kelvin and the heat would be transferred to the winding pack causing the CICC temperature to be rise and margin to be reduced.

To evaluate the heat removal rate and the influence on the winding pack of EAST TF coils, the transient thermal analysis by the ANSYS software has been done during the plasma disruption phase with two dimensional model shown in Fig. 6. The superconducting cable is not built in the model.

The supercritical helium flowing into the CICC is 3.7 K and 2.5 g/s; but the case cooling channel is 4.55 K and 2.5 g/s due to the limitation of refrigerator. In order to simplify the simulation scale, the eddy current loss is only loaded at the inner side of TF case because this region bears the most eddy current losses.

The material used for TF jacket and case is SS-316LN. The material of the ground insulation is glass epoxy. All the material properties are temperature dependent which come from Ref. [5].

Fig. 7 shows the temperature distribution of TF coil after 1.5 MA plasma disruptions 70 ms. Based on the simulation results, the helium temperature in CICC can reach the peak value after plasma disruption 70 ms and the maximum helium temperature rise is about 0.45 K. The maximum helium temperature rise in the TF case is about 11 K after disruption 11 s which is shown in Fig. 8. Table 1 shows the temperature distribution of TF coil during the different plasma current operations.

4. Experiment results of TF coil in EAST at 3.7 K

4.1. Single TF coil and case

The TF coil in EAST had been cooled at 3.7 K and taken commissioning successfully in 2012 July. Fig. 9 shows the temperature measurement results of single TF coil at seven plasma discharge

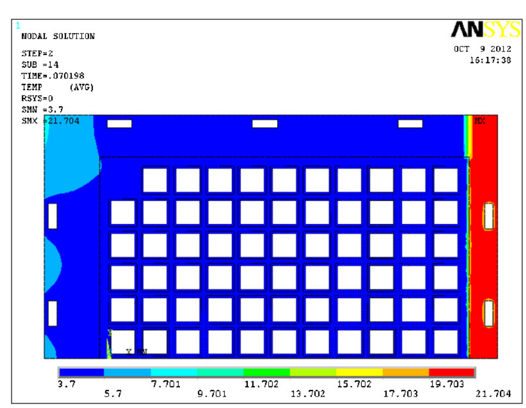

Fig. 7. The temperature distribution of TF coil after 1.5 MA plasma disruption 70 ms.

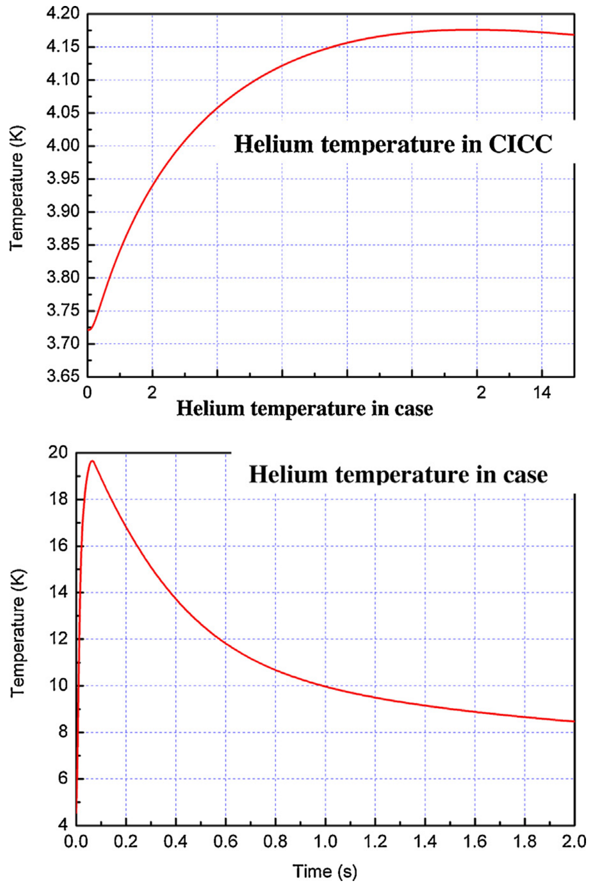

Fig. 8. The helium temperature in CICC and TF case after 1.5 MA plasma disruption.

Table 1
The temperatures rise of TF coil and case.

Plasma current	Case	He in case	He in CICC
1.5 MA			
Temp. rise (K)	17.0	11.0	0.45
Time after the disruption (s)	0.07	2.0	12.0
1.0 MA			
Temp. rise (K)	11.0	4.5	0.27
Time after the disruption (s)	0.07	0.8	8.64
0.4 MA			
Temp. rise (K)	3.35	2.0	0.06
Time after the disruption (s)	0.06	0.06	5.0

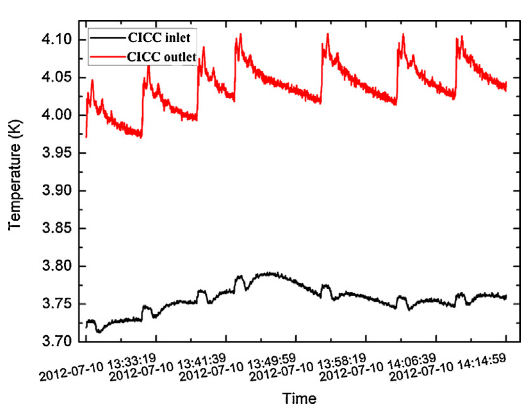

Fig. 9. Temperature measurement results of TF coil at seven plasma discharge periods.

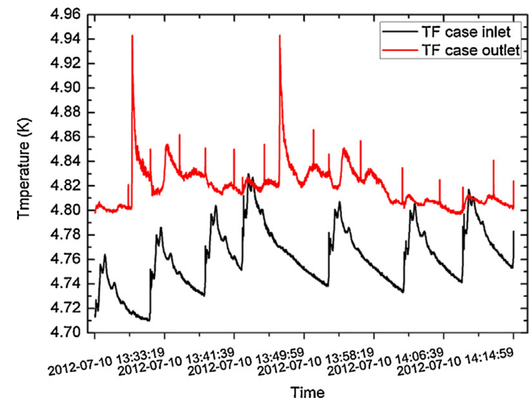

Fig. 10. Temperature measurement results of TF case during plasma discharge period.

periods when discharging at 10 kA. The 0.4 MA plasma current is obtained during the total 7 s.

The input helium temperature of TF coil is a little higher than 3.7 K. The flow rate and the output pressure are 2.0 g/s and 3 bar, respectively. The temperature difference between input and output is about 0.25 K.

Based on the measurement results in Fig. 9, the helium temperature rise in the TF coil is about 0.06 K at one plasma discharge period which is almost the same as the simulation results.

Fig. 10 is the temperature measurement results in the TF case inlet and outlet at seven plasma discharge periods. Fig. 11 shows the temperature measurement results of TF case at different locations. The flow rate and the output pressure measurement results are the same as TF coil.

Unfortunately, the helium temperature rise in the TF case measured is only about 0.14 K, but the simulation result is 2.0 K, which is the same as in the different locations. The possible reason is the lower sampling frequency (1 Hz) which cannot monitor the temperature rise quickly because the peak temperature in the case appears only 60 ms after disruption according to the simulation results, so the sampling frequency is too short. It also needs to be improved for the measurement acquisition system.

4.2. The heat loss analysis

The heat loss evaluation in the TF CICC and case is calculated with calorimetric method based on the enthalpy difference of output helium temperature. Fig. 12 is the enthalpy difference and heat loss distribution in single TF coil CICC at the seven plasma periods. According to the enthalpy and helium flow rate, the maximum heat

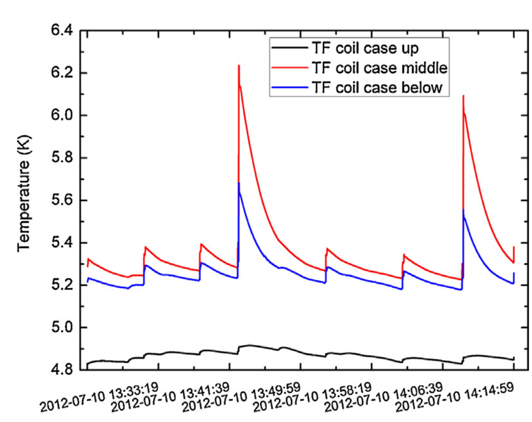

Fig. 11. Temperature measurement results of TF case at different locations.

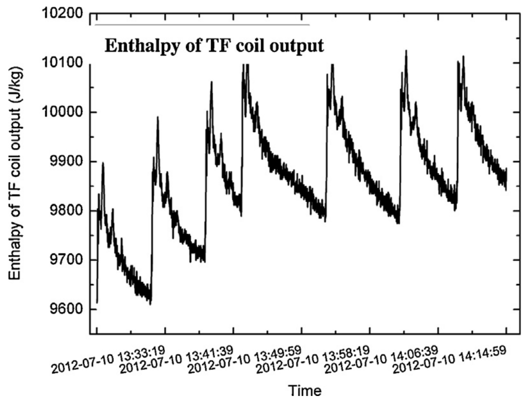

Fig. 12. Enthalpy difference of TF CICC during the plasma discharge period.

loss in single TF coil is about 3.7 W during one plasma period in which the TF coil current is 10 kA and plasma current is 0.4 MA. The energy of single TF coil is about 630 J which brings about the 10.1 kJ in all sixteen TF coils.

The enthalpy difference and heat loss distribution in TF case during several plasma periods are shown in Fig. 13. The maximum heat loss in total TF case is about 151 W when the TF coil current is 10 kA and plasma current is 0.4 MA. The energy of total TF case is about 5.13 kJ which will brings about the 320 J in single TF case.

5. Stability analysis and prediction of TF coil

5.1. Stability analysis

According to the parameter of NbTi superconducting strands of TF coil, the temperature sharing current (Tcs) is evaluated with Gandalf code depended on different operating conditions. Table 2 shows the evaluation results of Tcs. We can see that the temperature margin is about 2.38 K when the TF coil operates at 14.3 kA and 3.7 K.

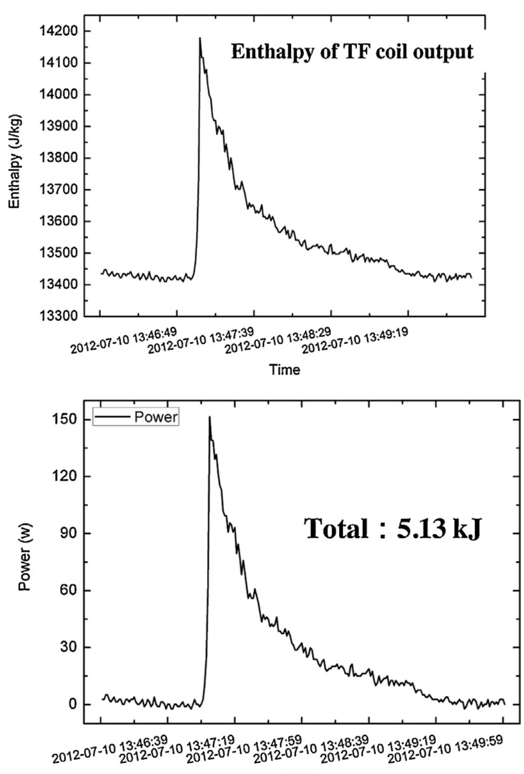

Fig. 13. Enthalpy difference and heat loss curve of total TF case during one plasma period.

Table 2
Tcs evaluation of TF CICC at 3.7 K.

Current (kA)	Magnetic field (T)	Temperature (K)	Tcs (K)
10.0	4.0	3.7	7.0
12.0	4.8	3.7	6.6
14.3	5.8	3.7	6.08

5.2. Stability performance prediction of TF coil

There are two important factors which affects the stability performance of TF coils, especially, in the plasma current disruption condition. One is the eddy current loss in the TF case which can brings the helium temperature in the CICC rise. According to the analysis model in Fig. 4, the maximum temperature rise in the CICC is about 0.45 K at the 1.5 MA plasma current disruptions from Table 1. The other factor is coupling current loss which is loaded in the CICC directly. The coupling current loss can be described as follow:

$$Q_c = \frac{2\theta}{\mu_0}\frac{d^2B_n}{dt^2} \tag{4}$$

θ is coupling time constant and the value can be taken 37 ms from the measurement results in SULTAN facility [6]. μ_0 is the vacuum permeability. The helium temperature in CICC can be performed with the Gandalf code. The maximum temperature rise in CICC is 0.63 K from the coupling current loss during 1.5 MA plasma current disruption.

So in the higher parameter case of TF coil operating at 14.3 kA and 1.5 MA plasma current disruptions, the total temperature rise in CICC is about 1.08 K which is from the eddy current loss in the TF case and coupling current loss in CICC as a simplified consideration. The residual temperature margin is 1.3 K in CICC which can be used to withstand other events except plasma disruption at 3.7 K operation in CICC.

In order to increase the stability margin for TF coil at 14.3 kA and 1.5 MA plasmas, it is better to cool the TF case at the lower temperature and increase the helium flow rate in CICC and case which can improve the thermal stability of TF coil in the actual operation effectively.

6. Summary

This paper describes the structure and cooling process of TF coil and case. The thermal performance of TF coil is simulated at 3.7 K and different plasma current discharges. Then, the operation results of TF coil at 3.7 K and 10 kA are discussed. There are some differences for temperature in the TF case between the measurement and evaluation. The possible reason is the lower sampling frequency. The heat loss of TF coil and case is evaluated with calorimetric method based on the enthalpy difference of output helium temperature.

Finally, the stability performance of TF coil is predicted at the 14.3 kA TF coil current and the 1.5 MA plasma current. The temperature margin is 2.38 K at 3.7 K operating temperature and the residual temperature margin is 1.35 K in CICC which can be used for additional thermal dissipation besides the eddy current loss in the TF case and coupling current loss in CICC. It is a good way to lower the helium temperature in TF coil and increase the helium flow rate for improving the thermal stability of TF coil in higher parameter operation.

Acknowledgements

The authors would like to acknowledge the critical discussions with Yanlang Hu about the EAST TF operation at ASIPP. We deeply thank many workers at the Superconducting Electrical Center in ASIPP for their contributions to the data acquisition system.

References

[1] P.D. Weng, The engineering design of the UT-7U Tokamak, Fusion Eng. Des. 58/59 (2001) 827–831.
[2] H. Bai, Thermodynamic Analysis and Design of the Helium Refrigeration System for HT-7U Superconducting Tokamak (doctoral dissertation), Graduate University of Chinese Academy of Sciences, 2002.
[3] B. Xiao, P. Weng, Integrated analysis of the electromagnetical thermal, fluid flow fields in a Tokamak, Fusion Eng. Des. 81 (2006) 1549–1554.
[4] D. Shijun, The eddy current analysis on the HT-7U TF coil cases, J. Hefei Univ. Technol. 23 (2000) 166–172 (in Chinese).
[5] B. Harris, Engineering Composite Materials, The Institute of Metals, London, 1999.
[6] P.D. Weng, et al., Test results and analysis of conductor short samples for UT-7U, Cryogenics 43 (2003) 165–171.