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Electromagnetic and mechanical analysis of CFETR toroidal field coils

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HIGHLIGHTS

- A detailed design of CFETR toroidal field coils was introduced.
- Electromagnetic analyses of different current scenarios were carried out using ANSYS software.
- Static structural analysis and preliminary fatigue assessment were presented.
- These analyses provided a verification of current scheme and indicated a way to optimization.

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ABSTRACT

The toroidal field (TF) magnets of the China Fusion Engineering Test Reactor (CFETR) provide a steady magnetic field with peak value of 11.5 T. Enormous electromagnetic forces are generated on TF structures due to the high magnetic field and large current. Structural analysis of TF coils is required to investigate the feasibility of the current design scheme and to provide guidance for optimization. The design status is described and electromagnetic analyses of different current scenarios are reported. The results of the mechanical analysis show that TF structures can safely withstand the reference operational scenarios, and the fatigue life can be assumed to be infinite based on the results of this fatigue assessment.

1. Introduction

The International Thermonuclear Experimental Reactor (ITER) project is a giant step to achieving the fusion energy. With the progress made in the construction of the ITER, the conceptual design of engineering reactors for magnetic confinement fusion is moving on the way. The China Fusion Engineering Test Reactor, shorten as CFETR, is a next-generation engineering reactor between the ITER and the DEMO, currently being designed by the China National Integration Design Group [1].

For the existing tokamak machines, peak values of the toroidal field can be as high as 5 T or even higher. This indicates that TF structures will tolerate tremendous stress during operation. The Experimental Advanced Superconducting Tokamak (EAST) machine has a maximum Von Mises stress of 553 MPa while operating [2]. The peak stress on structural components of TF cases without shear keys is 570 MPa for the JT-60SA facility [3]. The conceptual design of the CFETR magnets has been accomplished [4]. A comprehensive mechanical analysis of TF coils needs to be carried out in order to verify the stability and safety of the structure.

In Section 2, we describe the design details of the CFETR TF coils. The machine is designed to achieve three plasma configurations without device upgrading. The comparison of the electromagnetic and mechanical performance of TF structures under three different plasma configurations is presented in Sections 3 and 4, respectively. Section 5 discusses a preliminary fatigue analysis based on multiaxial fatigue theory with constant principal stress direction.

2. Design description of toroidal field coils

As a general tokamak machine, the magnet system of CFETR device consists of central solenoid (CS), TF and poloidal field (PF) coils. There are two additional divertor coils (DC) in the PF magnet system, which can be used to achieve three different plasma configurations [5]. The overview structure of the CFETR magnets is shown in Fig. 1.

The TF magnets include 16 coils composed of Nb_3Sn cable-in-conduit conductor (CICC). The contour of a TF coil is a close approximation to the Princeton-D with five arcs and a straight leg, as shown in Fig. 2. All the 16 TF coils are arrayed toroidally with angular intervals of 22.5°.

Before the decommissioning of the machine, the TF coils need to withstand many million operations with high electromagnetic

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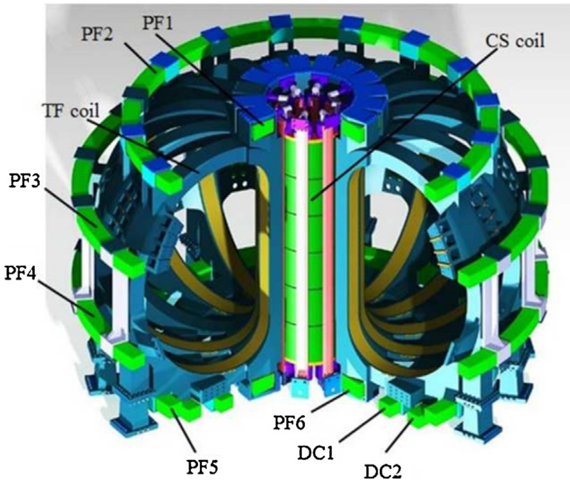

Fig. 1. Overview structure of the CFETR tokamak magnets.

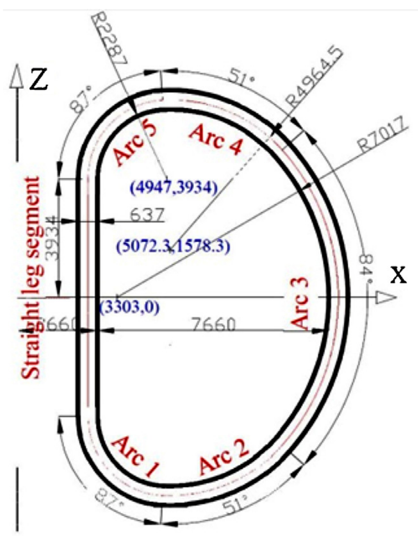

Fig. 2. The D-shaped cross-section geometry of a TF coil.

Table 1
Design parameters of TF coils.

Parameters	Value
Superconducting type	Nb_3Sn
Minimum piece length	1000 m
Un-reacted, Cr-plated strand diameter	0.82 ± 0.006 mm
Residual resistivity ratio of Cr-plated	>100
Cable configuration	((2sc + 1cu) × 3 × 4 × 5 + core) × 6
Copper core	3 Cu × 4
Diameter of central helium cooling pipe	8 mm
Tape around the cable	0.10 mm stainless steel
Superconducting wire/copper ratio	1.0
Number of superconducting wires	720
Void ratio	30%
Cable diameter (mm)	39.7
Conductor size (mm)	Circular 316LN ∅ 43.7

forces and other critical loadings, like the dead load, preload, thermal loads, as well as off-normal load conditions, such as seismic loads and vertical displacement events (VDEs). This necessitates strict requirements in the design of TF coils. The parameters of TF coils are shown in Table 1.

3. Electromagnetic calculation

A finite element model of the magnets, which contains 87,062 elements and 129,703 nodes, was built based on the explicit geometry of all coils. There are three scenarios of coil currents corresponding to the three different plasma configurations, which are ITER-like, Snowflake and Super-X. The ITER-like equilibrium configuration, just as the literal meaning, is quite similar to the ITER's plasma configuration, with no current in two DCs to achieve the standard *x*-point divertor configuration. The other two configurations are aiming at exploring the advanced equilibrium shapes of Snowflake and Super-X, which may reduce both steady-state and intermittent heat loads on the divertor plates to an acceptable level [6]. Magnetic shapes of the three equilibrium configurations and the corresponding current values of all coils at the equilibrium stage (the flattop stage) are shown in Fig. 3. It's evident that the currents in PF and CS coils of the three equilibrium configurations vary greatly, which will generate different magnetic field as well as different electromagnetic forces. Therefore, electromagnetic and

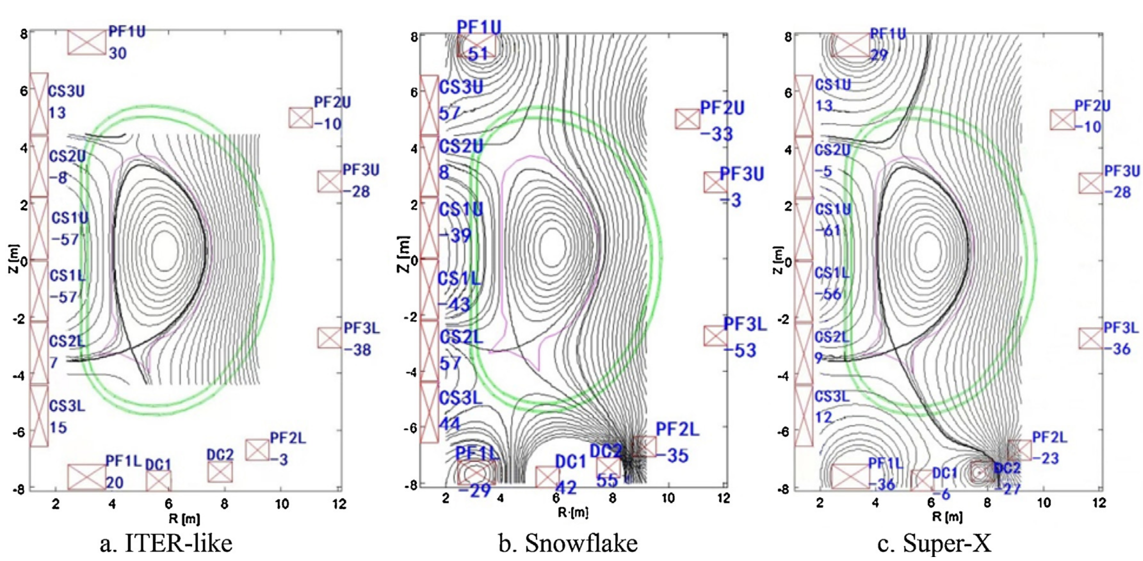

Fig. 3. Magnetic shapes of different equilibrium configurations. (Unit: kA/turn. CS coils have 396 turns while PF1 has 308 turns and other PF coils have 168 turns. Besides, all the three equilibrium configurations have a plasma current I_p = 10 MA and TF currents of 67.4 kA × 132 turns.).