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Pressure drop test and analysis of Nb_3Sn superconducting magnet

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ABSTRACT

In order to test the performance of experimental advanced superconducting tokamak (EAST) central solenoid (CS) model coil, which was made by the cable-in-conduit conductor using Nb_3Sn strands and a 316 L stainless steel jacket, a cryogenic experiment system was designed. The experimental results showed that the superconducting magnet was cooled down to 5 K, which could meet the test requirements successfully. Meanwhile, we measured the pressure drop in CICC of Nb_3Sn superconducting magnet under the circulating mode of forced flow cooling which used supercritical helium as coolant compared with the result calculated by the Katheder fraction factor correlation, it showed that calculated pressure drop underestimates the experimental data. We corrected the Katheder correlation and compared with the experimental data, it proved that the corrected correlation is much more suitable for the kind of CICC of Nb_3Sn superconducting magnet.

1. Introduction

The EAST tokamak is a full superconducting tokamak. All the magnet system including toroidal field (TF) magnet system, poloidal field (PF) magnet system and CS magnet system were made of superconducting conductor [1]. The CS magnet system consists of six independent coils like the ITER CS magnet system [2]. In order to improve the EAST CS coils performance, a new Nb_3Sn superconducting model coil was manufactured.

The superconducting magnet was made by the CICC using Nb_3Sn strands and a 316 L stainless steel jacket. Fig. 1 shows the photograph of the Nb_3Sn superconducting magnet. The magnet is divided into several cooling loop including four helium inlets and three outlets as shown in Fig. 2. The main parameters of the magnet are listed in Table 1.

54 Nb_3Sn superconducting strands and 27 copper wires were used to manufacture the CICC cable. The conductor cable pattern was $(2Sc + 1Cu) \times 3 \times 3 \times 3$. All cabling was made by twisting in the same direction. Then the cable was inserted into the round 316 L stainless steel jacket. The insertion was performed by pulling the cable through the jacket. The jacket was compacted onto the cable in a single step using several sets of rollers (see Fig. 3).

As for the large-scale high field magnet, forced flow supercritical helium is a conventional cooling method for the magnet due to the direct contact between CICC and helium flow [3]. It is significant to test the relationship between the pressure drop and mass flow for keeping the supercritical helium normal flow and cooling the magnet in the fusion experiment. At present, most of the experiment for pressure drop measurement on the CICC was carried out with pressure water or nitrogen at room temperature [4–6], because of lacking of relevant cryogenic equipment, meanwhile, the cost of cryogenic experiment is very high. In this paper, the pressure drop test for the CICC of Nb_3Sn superconducting magnet is at 5 K. The test condition at low temperature is closer to the actual operation situation and it will provide a reference for the future EAST transformation.

2. Design of cryogenic experiment

The superconducting magnet was taken the means of the supercritical helium as the medium for cooling, the supercritical helium was provided by a 500 W/4.5 K refrigerator, which could provide 4.5–6 K, 2.5–5 bar, 20–40 g/s SHe for magnet or 150 L/h helium liquefying capability [7]. During the experiment, the Nb_3Sn superconducting model coil was fixed on the platform in a cryostat, and the temperature should not exceed 5 K.

Fig. 4 shows the cooling scheme for the superconducting magnet test. There were four SHe inlets and three SHe outlets in the superconducting magnet. In order to further decrease the SHe temperature, a LHe tank was installed in the cryostat to cool down SHe to about 5 K before entering into the superconducting magnet. The Venturi meters were installed in the inlet to measure SHe mass flow rate. The pressure meters and temperature sensors were installed as shown in Fig. 4.

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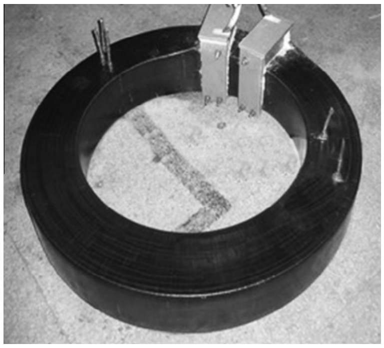

Fig. 1. Photograph of the Nb_3Sn superconducting magnet.

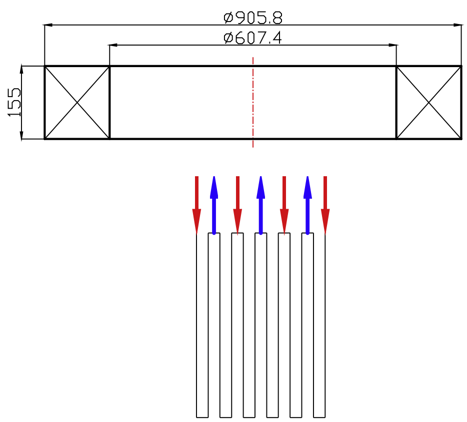

Fig. 2. The magnet cooling loop.

3. Results and discussion

3.1. Cooling procedure

The cryostat and superconducting magnet were pre-cooled by cold He gaseous with forced circulation. To avoid extra thermal stress damage to the coil, the maximum temperature difference between outlet and inlet He gas should not exceed 50 K. When the temperature was about 100 K, the liquid nitrogen (LN_2) was supplied to the LN_2 vessels and cooled the thermal shields of the cryostat. When the LHe vessel in refrigerator chamber was filled with LHe, the refrigerator mode was switched and the SHe was provided to cool down the superconducting magnet, feeder, platform, current leads and etc. It took about 50 h to cool down the system. Fig. 5 shows the Cooling down curve of the Nb_3Sn superconducting magnet.

3.2. Pressure drop

The pressure drop depends on the friction factor. The pressure drop is illustrated as follows:

Table 1
Parameters of the Nb_3Sn superconducting magnet.

Item	Parameters
Inner diameter	607.4 (mm)
Outer diameter	905.8 (mm)
Height	155 (mm)
Diameter of the strand	0.82 (mm)
Conductor type	CICC
Conductor dimensions	13.5 × 10.4 (mm^2)
Jacket material	316 (L)
Length of the conductor	285 (m)

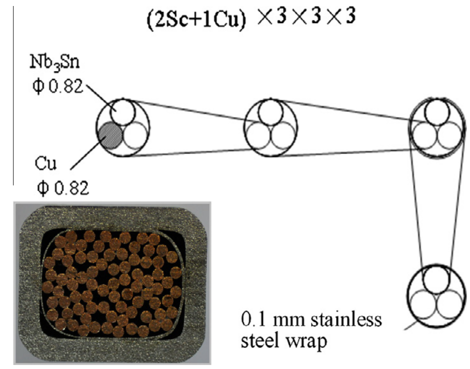

Fig. 3. Schematic diagram of CICC of the Nb_3Sn superconducting magnet.

$$\Delta P = f\frac{\rho v^2}{2D_h}L \tag{1}$$

where f is friction factor, ρ is the density of the fluid, v is the flow rate of the fluid, L is the length of pipeline, D_h is the hydraulic diameter which is expressed as follows:

$$D_h = 4A/U \tag{2}$$

A is the area took up by the fluid in the cross section of CICC, U is the wetted perimeter of the conductor which is calculated as:

$$U = n \times C_{st} + C_{in} \tag{3}$$

n is coefficient of wetted perimeter which is defined as 5/6, C_{st} is the sum of all strands cross-sectional perimeter including the Nb_3Sn strands and copper strands. C_{in} is the inner perimeter of the conduit.

Friction factor is one of the key parameters in analyzing and calculating the pressure drop in this paper. Katheder found that the friction factor is in relation between the void fraction and Reynolds number from a large number of experiments, so he gave the experimental calculated equation of the bundle region friction factor:

$$f_{Katheder} = \left(\frac{1}{V}\right)^{0.72}\left(0.051 + \frac{19.5}{\mathrm{Re}^{0.88}}\right) \tag{4}$$

where V is the void fraction of the bundle region, Re is the Reynolds number.

The Katheder correlation is well agreed in the range of 35% < void < 47% and 20 <Re < 42,000 (better agree in 1000 < Re < 10,000) [8].

The wetted perimeter and flow area of the CICC are calculated and listed in Table 2.

During the experiment, the pressure drop and the mass flow of the 40 m CICC and 55 m CICC were measured. These measurements are compared with the calculation used Katheder correlation in Fig. 6. It shows that the pressure drop measurements and calculations are consistent with the trend, the pressure drop as the mass flow increase also shows a gradually increasing trend. The error between the measurement and calculation of 40 m CICC reaches the maximum of 25.2% at the mass flow rate in 1 g/s, and the 55 m CICC is 27.2%. It exceeds the acceptable range of engineering. The friction factor calculated by Katheder correlation is much lower, so the correlation should be corrected to ensure the reliability of the calculation for this kind of CICC.

The pressure drop calculated by the corrected correlation is compared with the measurements in Fig. 7. We can see that the measured data is approximatively in correspondence with the calculated data. The error between the measurement and calculation of 55 m CICC reaches the maximum of 8.3%, and the 40 m CICC is 7.4%. The error can be accepted in engineering.