Evaluation of Inductive Heating Energy of a PF Insert Coil Conductor by the Calorimetric Method (Contract Research)

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February 2009
Japan Atomic Energy Agency 日本原子力研究開発機構
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(Received December 10, 2008)

The PF Insert Coil is a single layer solenoid coil using a superconducting conductor designed for ITER, housed in a Poloidal field coil and installed in the bore of the CS Model Coil. A stability test of the conductor will be performed in a magnetic field generated by the CS Model Coil. In this test, the inductive heat of an inductive heater attached to the conductor will be applied to initiate a normal zone in the conductor. Since the conductor for the PF Insert Coil is a cable-in-conduit conductor, it is quite difficult to estimate inductive heating energy theoretically. Thus, the inductive heating energy is measured experimentally by the calorimetric method. The heating energy is in proportion to a constant multiplied by the integrated square of an applied sinusoidal current wave over the heating period. Experimental results show that the proportional constants of the conductor, cable, conduit and dummy conductor are 0.138 [J/A²s], 0.028 [J/A²s], 0.118 [J/A²s] and 0.009 [J/A²s], respectively. The first three denote not only the inductive heating but also the joule heating of the inductive heater. The final value denotes joule heating only. Therefore, subtracting the first three constants by the last one, the proportional constants of inductive heating generated in the conductor, cable and conduit are estimated to be 0.129 [J/A²s], 0.019 [J/A²s] and 0.109 [J/A²s], respectively.

Keywords: PF Insert Coil, Inductive Heater, Stability, Calorimetric Method

This work was performed at the Japan Atomic Energy Agency on a research contract with the ITER International Fusion Organization and the European Atomic Energy Agency.
PF インサート用超伝導導体の誘導加熱量の評価
（受託研究）

日本原子力研究開発機構核融合研究開発部門
ITER プロジェクトユニット

松井 邦浩、名原 啓博、布谷 嘉彦、小泉 徳潔、奥野 清

（2008 年 12 月 10 日受理）

PF インサートは、ITER の PF コイル用の超伝導導体を用いた単層ソレノイド・コイルである。PF インサートは CS モデル・コイルのポア内に挿入され、CS モデル・コイルが発生する磁場において導体の安定性試験が実施される。安定性試験では、導体に取り付けた誘導加熱ヒータから導体に熱を投入することで導体に摂乱を発生させる。しかし、PF インサートの導体は超伝導撹線とコンジットから構成されるケーブル・イン・コンジット導体であるため、導体に投入する誘導加熱量を計算で求めることは困難である。そこで、誘導加熱量の評価を熱量法により行った。誘導加熱ヒータには正弦波電流を流したため、誘導加熱量はヒータ電流の平均の時間積分に比例する。導体、撹線、コンジット及びダミー導体の誘導加熱に対する比例定数は、それぞれ、0.138 [J/A^2s]、0.028 [J/A^2s]、0.118 [J/A^2s]及び0.009 [J/A^2s]となった。ダミー導体の加熱量は導体加熱ヒータのジュール発熱によるものであるため、導体、撹線及びコンジットの誘導加熱に対する比例定数は、それぞれ、0.129 [J/A^2s]、0.019 [J/A^2s]及び0.109 [J/A^2s]と評価できた。

本報告書は、ITER 機構及び欧州原子力共同体の受託研究「PF インサート・コイル試験（TA11-106）」に基づいて実施した成果の一部である。
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Contents

1. Introduction ........................................................................................................................1
2. Parameters of the sample conductor ..............................................................................2
3. Experimental facility and methods .................................................................................3
4. Experimental results ........................................................................................................4
5. Conclusions ........................................................................................................................6
Acknowledgments ...............................................................................................................7
References .............................................................................................................................7

目次

1. はじめに ...............................................................................................................................1
2. サンプル導体の諸元 .........................................................................................................2
3. 実験装置と実験方法 ..........................................................................................................3
4. 実験結果 ..........................................................................................................................4
5. 結論 ..................................................................................................................................6
謝辞 ......................................................................................................................................7
参考文献 .............................................................................................................................7
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1. Introduction

The PF Insert Coil is a solenoid coil using a Poloidal Field (PF) coil conductor for use in the International Thermonuclear Experimental Reactor (ITER) [1]. The PF Insert Coil was fabricated by the European Atomic Energy Community, shipped to Japan and installed in the inner bore of the Center Solenoid (CS) Model Coil at the Naka Fusion Institute of the Japan Atomic Energy Agency [2]. The objective of the test is to validate the design and evaluate the performance of the ITER PF Coil conductor. The test of the PF Insert Coil is an activity that stems from the preceding ITER cooperative phases (EDA, CTA and ITA). The PF Insert Coil conductor is a cable-in-conduit (CIC) conductor having 1440 nickel-coated NbTi strands. The conduit is made of stainless steel.

The inductive heating method is the most suitable for simulating a real perturbation in a stability experiment because the conductor can be heated directly without any time delay. However, the heat energy deposited in the conductor through inductive heating can not be estimated theoretically because of the complicated geometry of the CIC conductor. Thus, the heat energy conveyed via inductive heating is estimated experimentally.

Four samples were prepared to estimate inductive heating energy through the calorimetric method under a magnetic field of 6T, a level at which the stability experiment of the PF Insert Coil will be performed.

This report describes the estimated level of inductive heating energy of the PF Insert Coil conductor.
2. Parameters of the sample conductor

The PF Insert Coil conductor is a CIC conductor having 1440 NbTi strands and designed for use in an ITER PF coil. The strands are cabled in 5 stages. Stainless steel tape is wound around the 4th stage cable to reduce the inter-strand coupling loss and around the 5th stage cable to prevent any damage to the cable during the insertion of the cable into the conduit. There is a spiral tube in the center of the cable in order to reduce any drop in pressure of the coolant. The conduit is made of SS316LN. Major parameters of the sample conductor are shown in Table 1. Figure 1 shows a cross-sectional view of the strand.

The following samples were prepared for estimating the heating energy.
Sample #1: Conductor and inductive heater
Sample #2: Cable and inductive heater
Sample #3: Conduit and inductive heater
Sample #4: Inductive heater alone

Figure 2 shows the sample conductors, each of whose length is 175 mm.

Table 1 Major parameters of PF Insert Coil conductor

<table>
<thead>
<tr>
<th>NbTi strand</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer diameter</td>
<td>0.73 [mm]</td>
</tr>
<tr>
<td>Cu/non-Cu</td>
<td>1.41</td>
</tr>
<tr>
<td>J\text{c} at 5T, 4.2K</td>
<td>2816 [A/mm\text{2}]</td>
</tr>
<tr>
<td>I\text{c} at 5T, 4.2K</td>
<td>488.6 [A]</td>
</tr>
<tr>
<td>RRR</td>
<td>199</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cable</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cabling pattern</td>
<td>3x4x4x5x6</td>
</tr>
<tr>
<td>Number of strands</td>
<td>1440</td>
</tr>
<tr>
<td>Final cabling pitch</td>
<td>486 [mm]</td>
</tr>
<tr>
<td>Central spiral od x id</td>
<td>12 x 10 [mm]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Conductor</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Jacket material</td>
<td>SS316LN</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>50.3 [mm]</td>
</tr>
<tr>
<td>Inner diameter</td>
<td>38.3 [mm]</td>
</tr>
</tbody>
</table>
3. Experimental facility and methods

Figure 3 shows a schematic illustration of the experimental facility. The sample conductor is installed in an inner cylinder within the bore of a back-up field coil. The inner cylinder is installed in an outer cylinder because the gas Helium (GHe) vaporized during the operation of the back-up field coil and/or the heat penetration is prevented from reaching the inner cylinder. The GHe vaporized by inductive heating is collected in a chamber located above the sample conductor. Since the volume of the vaporized GHe is proportional to a decrease in the surface level of liquid Helium (LHe) in the chamber, the heat energy deposited in the sample conductor can be estimated by measuring the reduction of the LHe level in the chamber. The reduction of the LHe level is measured by a LHe level indicator in the chamber. A resistive heater is also installed in the inner cylinder to calibrate the relationship between the reduction in the LHe level in the chamber and the input energy.

Current to the inductive heater, $I_h$ [A], the inductive heating energy, $E_h$ [J] and the heat energy
from the resistive heater, $E_{hr}$ [J], are represented by,

$$I_h = I_{hp} \sin(2\pi ft) \quad (1)$$

$$E_h = C \int_0^{t_h} I_h^2 \, dt = \frac{C I_{hp}^2 t_h}{2} \quad (2)$$

$$E_{hr} = \int_0^{t_h} I_{hr} V_{hr} \, dt \quad (3)$$

Where $I_{hp}$ [A] and $f$ [Hz] are the amplitude and frequency of the inductive heater’s current, $t_h$ [s] is the heating period, and $I_{hr}$ [A] and $V_{hr}$ [V] are the measured current and voltage of the resistive heater, respectively. The purpose of this experiment is to estimate the proportional constant, $C$ [J/A^2s], in eq. (2).

The sample conductor is subjected to a magnetic field of 6 T generated by a back-up field coil. The heating period and frequency of the inductive heater’s current were 40 ms and 1 kHz, respectively.

4. Experimental results

Figure 4 indicates the calibration results of the relationship between the heat energy from the resistive heater and the reduction in the LHe level. Using these calibrations and the measured relationship between the LHe level reduction and the heating factor, the relationship between the inductive heating energy and the heating factor may be obtained.

Figure 5 shows the findings. Inductive heating energy proportionally increases as a function of the heating factor for each sample conductor. From these results, the following equations are
obtained.

(1) For the conductor and inductive heater,

\[ E_s = 0.138 \int I_h^2 dt \]  

(4)

(2) For the cable and inductive heater,

\[ E_s = 0.028 \int I_h^2 dt \]  

(5)

(3) For the conduit and inductive heater,

\[ E_s = 0.118 \int I_h^2 dt \]  

(6)

(4) For the inductive heater alone,

\[ E_s = 0.009 \int I_h^2 dt \]  

(7)

These inductive heating energies include not only inductive heat but also joule heat from the inductive heater. Therefore, the inductive heat energy deposited in the conductor, cable and conduit are calculated by subtracting the joule heat of the inductive heater, with the following results:

(1) For the conductor,

\[ E_s = 0.129 \int I_h^2 dt \]  

(8)

(2) For the cable,

\[ E_s = 0.019 \int I_h^2 dt \]  

(9)

(3) For the conduit,

\[ E_s = 0.109 \int I_h^2 dt \]  

(10)

From these results, the proportional constants for the conductor, cable and conduit were calculated to be 0.129 \([J/A^2s]\), 0.019 \([J/A^2s]\) and 0.109 \([J/A^2s]\), respectively.
Fig. 4 Relationship between the heat energy from the resistive heater and the reduction in the LHe level

Fig. 5 Inductive heating energy as a function of the heating factor

5. Conclusions

The inductive heating energy of the PF Insert Coil was estimated in a magnetic field of 6 T through the calorimetric method. The heating energy deposited in the conductor, cable and conduit was individually calculated. The proportional constants for the conductor, cable and conduit are 0.129 [J/A²s], 0.019 [J/A²s] and 0.109 [J/A²s], respectively.
Acknowledgments

The authors would like to thank Drs. T. Tsunematsu and R. Yoshino for their encouragement and support during this work. Thanks also should be given to all staff members of the ITER Superconducting Technology Group in the Japan Atomic Energy Agency.

References


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国際単位系（SI）

表1：SI基本単位

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<td>m</td>
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</tr>
<tr>
<td>質量</td>
<td>kg</td>
<td>kg</td>
<td>kg</td>
<td>質量</td>
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<tr>
<td>時間</td>
<td>s</td>
<td>s</td>
<td>s</td>
<td>時間</td>
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<tr>
<td>電流密度</td>
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<td>A/m²</td>
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<tr>
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<td>cd</td>
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注意：この表は国際単位系（SI）の基本単位を示しています。各単位の記号と定義、およびその変換関係を示しています。
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