Fusion Engineering and Design 121 (2017) 39–42

Contents lists available at ScienceDirect

Fusion Engineering and Design

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

Consideration and research of hybrid heating method in VPI for CFETR PF coils

C. Zou, Y. Song, H. Wu*, S. Du, B. Hu, M. Shang, X. Yu, G. Shen, W. Wu, K. Lu, J. Wei

Institute of Plasma of Physics, Chinese Academy of Sciences, Hefei, 230031, China

HIGHLIGHTS

- A hybrid heating method in VPI for CFETR PF coil have been described.
- A mock-up have been design and manufactured to verify the method.
- The temperature on the coil during VPI process can satisfy the resin curing requirement.

ARTICLE INFO

Article history:
Received 21 December 2016
Received in revised form 21 May 2017
Accepted 22 May 2017

Keywords:
Hybrid heating
Vacuum pressure impregnation
PF coil
Insulation

ABSTRACT

The poloidal field (PF) coils are one of the CFETR magnet system which winding by CICC conductor. In order to meet the design requirements of demanding, the coil insulation shall be processed by vacuum pressure impregnation (VPI). After the resin impregnating the coil insulation, a subsequent high temperature cure is imposed for a relatively long period of time to fully cure the resin throughout the insulation. During the curing, the temperature must be controlled even on whole coil. All CFETR PF coil are fabricated by stacking several double-pancakes (DP), due to the complex structure, the common outer heating method can hardly satisfy the curing temperature requirement. So an inner heating which assisted by common outer heating (hybrid heating) method was researched. The experiment results shows under hybrid heating method, the curing temperature on the coil insulation can guaranteed even and the insulation quality can satisfy design requirement.

1. Introduction

China Fusion Engineering Test Reactor (CFETR) is a new tokamak reactor which under the design of China National Integration Design Group [1,2]. The Poloidal Field (PF) magnet system of CFETR consists of eight coils. Niobium-Titanium (NbTi) is used as superconducting material and cable-in-conduit conductor (CICC) type are used as a conductor. All coils are fabricated by stacking several double-pancakes wound by two-in-hand winding scheme. The outer diameters of the coils vary between 6 m and 22 m.

During the coil winding, two conductors are wound together to form a pancake layer with winding from "outside-in" in one layer, and "inside-out" on the other [3–5]. During winding process, the conductor is insulated with turn insulation which composited with five layers of half overlapped interleaved polyamide film (0.025 mm thickness) and dry fiberglass (0.25 mm thickness). In order to reinforce the bonding and accommodate the tolerance on the flatness, a 1.2 mm thickness glass fiber felt is used between conductors and the gaps are filled with glass tap or cloth to eliminate resin rich regions. After the DP winding, the DP coil will be placed in a VPI mould and impregnated with resin. Then each DP is stacked and ground wrapped to form the winding pack of the coil. When the DPs are stacked, they are separated by 4.2 mm layer of dry glass (pancake insulation) and then ground wrapped with a thickness of 8 mm interleaved dry fiberglass, polyamide film and dry fiberglass wrapped to a total of nine 50% overlapped layers. After the ground insulation, the winding pack is vacuum impregnated in a mould. Fig. 1 shows the insulation scheme.

The coil shape and quality is determined by VPI process [6,7]. When the resin injects into the mould and impregnated into the dry glass, then curing the material. The curing process is accomplished by heating the insulation material to elevated temperatures for a predetermined length of time. The elevated temperature to the material is referred to as the resin cure temperature. The magnitudes and durations of the temperatures applied during the curing process significantly affect the performance of the coil insulation

* Corresponding author.
E-mail address: hwu@ipp.ac.cn (H. Wu).

http://dx.doi.org/10.1016/j.fusengdes.2017.05.103
0920-3796/

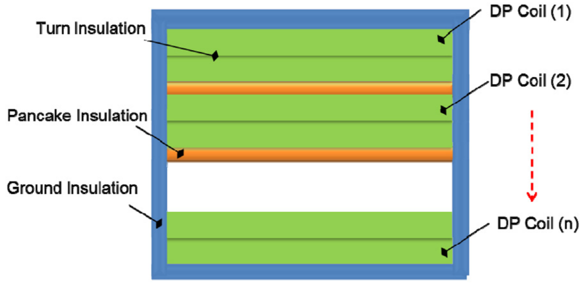

Fig. 1. Insulation layer of winding pack.

quality. Therefore, the temperature on the material must be strictly controlled referred the resin cure cycle.

The purpose of this paper is to demonstrate the heating method in VPI for CFETR PF coil, and making comparison between the internal heating and the external heating.

2. Experimental

Based on the insulation structure of CFETR PF coil, a mock-up of coil was manufactured. Nine ITER PF5 dummy conductors were stacked together according to 3 × 3 structure. The length of mock-up is 2-m long. Before wrap the insulation, the surface of the conductor should be cleaning and sand blasting. The nine conductors were insulated with turn insulation, the stacks were separated by the 1.2 mm or 4.2 mm layer of dry-glass, finally wrapped by ground insulation.

During the curing process, the temperature inside the material must not exceed a preset maximum value at any time and the temperature distribution should be uniform. The temperature inside the material was as a function of position and time. In order to evaluate the heating method, five temperature sensors are installed inside the coil to record the temperature in different position. The position shows in Fig. 2.

The VPI mould is shown in Fig. 3. It is used to provide pressure and in order to secure the coil right shape. The mould manufactured by stainless steel. A vacuum pump system is connected to the venting port to pumping the vessel. A monitor tube is used to verify the resin level. The instrument lead is connected to data acquiring system (DCS) that used to real-time acquire the datum.

The mould is winding by several heating tapes and covered by multilayer insulation. The heating tape worked as external heating energy and controlled by model 350 temperature controller, the temperature control point for external heating is T5 temperature sensor.

The nine conductors were connected in series by cooper joints, the conductor #1 and #9 defined as input and output terminal, and connect with DC electrical power #2. This will worked as internal heating energy, and the temperature control point for inner heating is the voltage (V_{ab}) between A and B on conductor #5. Fig. 4 shows the experiment system.

The voltage between A and B cannot directly used as the feedback of inner heating. Based on the relationship between conductor temperature and its resistance [8], the equation can be created before VPI temperature control experiment. The equation can be expressed as

$$R_{AB} = V_{AB}/I = R_0\,(1 + \alpha T_{AB}) \qquad (1)$$

Where R_{AB} mean the resistance on the conductor #5 between A and B, I is the input current, T_{AB} mean the avenge temperature. The R_0 mean the resistance on room temperature. The α is the coefficient and will be calculated through testing.

The resin used for VPI consists GY282, HY918 and DY073-1. Before the resin injecting into the mould, the resin should be mixed and degassed, and maintained the temperature in 40 °C. The mould and coil need be heated to 110 °C and pumped about 12 h. Then lower the temperature to 40 °C and the vacuum pressure inside the mould to 10 Pa during injecting resin. When the monitor tube filled with resin, injection finished. Waiting several hour until the resin level on the monitor tube keep steady, then synchronize operating the inner heating and external heating system. At first, heated the coil to 90 °C and keeping 10 h for resin gelling. Then heated to 130 °C and keeping 15 h for resin curing. The temperature raise ratio should kept in 6 °C per hour. The temperature raise curve is based on the curing properties of resin.

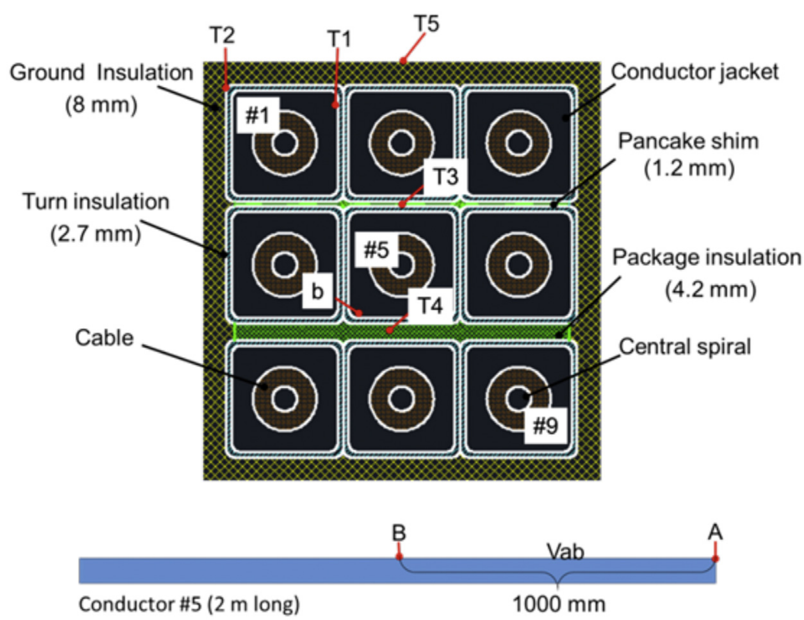

Fig. 2. Cross section of the mock-up and temperature monitor point.