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Fusion Engineering and Design 58–59 (2001) 147–151

Fusion Engineering and Design

www.elsevier.com/locate/fusengdes

Test program preparations of the ITER toroidal field model coil (TFMC)

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Abstract

The preparative experimental and analysis work as well as the code development for testing the ITER (International Thermonuclear Experimental Reactor) TFMC, one of the large projects of the ITER research and development programme, is described. The expected critical currents of the Nb_3Sn superconducting cable are derived from the numerous short sample strand and subcable measurements. A data set of the thermo-hydraulic properties of the bundle conductor with a central channel was elaborated in experiments as an input for the thermo-hydraulic calculation codes GANDALF and MITHRANDIR combined with the hydraulic network code FLOWER. On this basis, the quench behaviour and the injection of gaseous heated helium slugs for determining the operation limits are treated. The mechanical behaviour of the test configuration was investigated by a finite element calculation. The winding type in which the conductor is embedded in radial plates has to be considered for transient voltage peaks as an electrical network. Arising over-voltages by resonance frequencies in the winding pack have to be considered for the integration of the electrical insulation system of the TFMC. Numerous sensors are installed to compare the predicted values and behaviour with the measurements. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Thermo-hydraulic properties; Finite element calculation; Superconducting toroidal field model coil; Dielectric insulation

1. Introduction

The construction and testing of the TFMC is part of the model coil task L2, which is one of the seven large R&D projects of the ITER Engineer-

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PII: S0920-3796(01)00570-1

ing Design Activity [1]. The TFMC project is the responsibility of the European Home Team. The TFMC is being constructed by the European industry consortium AGAN (ACCEL, Alstom, Ansaldo, Noell) under the direction of the European Fusion Development Agreement Close Support Unit (EFDA/CSU) at Garching, Germany, in tight collaboration with the European superconducting (sc) magnet laboratories [2]. The TFMC will be tested in the TOSKA facility of the Forschungszentrum Karlsruhe in Phase I of the test program as a single coil and in Phase II adjacent to the EURATOM LCT coil [1,3,4]. A testing program is elaborated within a working group of the sc magnet laboratories. The preparative work includes code development, accompanying experiments and calculations for getting predicted values which can be compared with the test results. The work has to be performed in the following fields: electromagnetics, thermo-hydraulics, mechanics and dielectric insulation. The TFMC is a new type of winding designed for withstanding the high forces which have to be carried by the full size coils in the ITER torus [1]. The conductor and the special coil design required the adaptation of codes and application of suitable experimental technique for getting information about the operation limits and behaviour of the coil. This contribution gives an overview about the analysis, code development and experiments performed for preparing the test of the TFMC.

2. Electromagnetics

2.1. Operation limits

These limits are determined by Summers model about the critical current dependency of Nb_3Sn strands [5]. The specific parameters needed for Summers equation were determined by a series of short sample critical current measurements on strands and sub-cables. The samples were taken from the TFMC strand production. The detailed procedure for determining the specific parameters is presented in Ref. [6].

2.2. Magnetic field calculations

Magnetic field calculations were performed in three models. The homogeneous current density distribution, closed conductor loops and conductor spiral were used for calculating the magnetic field. The first one resulted in field values which were roughly 0.6 T below the two others. Only a small difference within the calculation accuracy was found between the closed conductor loops and the spiral. The maximum field values were calculated for different test conditions (without and with LCT coil, Table 1) and for the pancakes used for injection of heated gaseous helium slugs along the joint up to the high field point of the pancake [7]. A field calculation code running on a workstation was developed for use during the experiment.

3. Thermo-hydraulics

The conductor is a ‘cable in conduit conductor’ with a central channel and a bundle region. The central channel is supported by a spiral around which the sub-cables are cabled. The different types of spirals used have some impact on the friction factor. The properties of the friction factor of both bundle and central channel region were investigated in the OTHELLO facility according to Refs. [8,9]. The winding pack contains a big fraction of structural material in the radial plates and the massive coil case. This causes eddy currents during the fast safety discharge which have to be taken into account for the quench behaviour and the relieve valve layout of the facility [10,11]. The investigation of the operation

Table 1
Maximum field values and locations in the TFMC winding

Load case		Maximum field and location	
I_{TFMC}	I_{LCT}	B_{max}	*P*ancake
80 kA	0 kA	7.80 T	DP 3.2
70 kA	16 kA	9.02 T	DP 2.2

Nomenclature: DP = double pancake; counting starts with 1 on the LCT coil side; the winding consists of five double pancakes; each double pancake contains pancake 1 and 2.

limits is foreseen by the injection of gaseous heated helium slugs in the inner pancake joints. The slugs have to enter the winding through the pancake conductor joints. A careful analysis is required to select suitable test parameters and to have the unique interpretation of the results. For this investigation, the codes GANDALF and MULTI conductor MITHRANDIR (M&M) [12], combined with the hydraulic network code FLOWER are used.

3.1. Thermo-hydraulic data set

A thermo-hydraulic data set was elaborated for double pancake DP1. The difference to the other double pancakes is very small (about 2–3%). An exception is the pressure drop which depends strongly on the type of the spiral (Showa, Cortaillod) used. The difference is about 20% in the pressure drop at 20 g/s mass flow rate [13]. The thermo-hydraulic data set is applied to the thermo-hydraulic calculations by GANDALF and M&M.

3.2. Analysis of quench scenarios

For the assessment of pressure, temperature and mass flow rate increase after a quench and its effect on the facility, different quench scenarios were investigated. Parameters were the location of the quench initiation, the length of the initial normal zone, the test configuration and two delay times (1 and 2 s) after which the safety discharge starts. The quenched conductor and its hydraulic network were modelled by GANDALF/FLOWER. A relief valve with a level setting of 0.6 MPa and 2 m^3 reservoir were included in the network. Eddy current heating of the radial plates during safety discharge was considered in the model. The most serious boundary condition is the delayed safety discharge (2 s) at 80 kA coil current whereby the maximum values of pressure and temperature depend on the location and length of the initial normal zone. The hot spot temperature has the highest value of 180 K for an initial normal zone of 0.1 m in the high field region. The pressure reaches the highest value (3 MPa) for a quench of a centre turn of a pancake. A mass flow peak of 1.7 kg/s over <50 ms occurs if the whole inner turn goes normal [14]. The facility can handle the scenarios investigated. The MAGS code too was applied for quench analysis [15].

3.3. Heat slug injection analysis

The heat slug injection analysis for the investigation of the operation limits of the TFMC is being performed by three laboratories using different models:

CEA Cadarache: Joint (including heat transfer between half joints and ohmic heating) and conductor modelled, no hydraulic network.

CRPP Villigen: Joint (including ohmic heating, no heat transfer between half joints), conductor and hydraulic network modelled by GANDALF and FLOWER.

Politecnico di Torino: Joint (including heat transfer between half joints and ohmic heating) heated conductor, remaining conductors and hydraulic network modelled by MULTI conductor MITHRANDIR (M&M) and FLOWER, respectively.

Heat slug injection and Joule power in the joint: In the TFMC winding, the pancakes DP1.1 and DP1.2 are equipped with gas heaters. The applied analysis for DP1.1 showed that the Joule power generation in the joint at the mass flow of 13 g/s will quench the joint if a heat slug with minimum conductor current sharing temperature of 9.08 K is injected. For this case it was assumed that the both half joints were thermally insulated, which meant no heat flux between them. Since the conductor current sharing temperature in pancake DP1.2 is lower than that of the joint DP1.2, the conductor will quench before quenching the joint. If in both conductors DP1.1 and DP1.2 a slug is injected it is not possible to quench DP1.1 before DP1.2 as shown in Ref. [16].

GANDALF/FLOWER: The conductor is modelled by GANDALF. There are two parallel channels, bundle and hole region, with coupling between each other. Heater and joint are included in the extended conductor model with suitable adapted parameters. A parallel channel with proper adaptation of the thermo-hydraulic parameters represents the other pancakes. The external supply circuit is represented by the code FLOWER. Long linear heater ramps for different mass flow rates are applied for quenching the conductor. When only one of the ten parallel hydraulic channels is heated, instability of the cryogenic circuit occurs and the mass flow in this channels decreases (helium choking). This effect is considerably stronger at lower steady state mass flow rates. Therefore, the use of square heating pulses becomes critical because they generate thermal fronts propagating with steep gradients, i.e. quenches are initiated at the inlet of the joint regardless of the cooling conditions. Slow heater power ramp rates and high helium mass flow rates (e.g. 18 g/s) are required in DP1.1 to initiate the quench in the conductor rather than in the joint [17]. The analysis of DP1.2 is in progress.

Multi conductor MITHRANDIR-FLOWER: The MITHRANDIR code was first extended to MITHRANDIR 2.1, allowing the simultaneous treatment of joint and conductor. First validation was performed on stainless steel jacketed FSJS (Full Size Joint Sample) data [18]. An extension of the model for application of the TFMC has now been elaborated (Multi conductor MITHRANDIR; M&M). The TFMC hydraulic network model includes all pancakes (treated with M&M), the external hydraulic circuit (FLOWER), the heater and the heat exchange in the inner joint of the heated pancake. In a preliminary analysis it was shown that the relation between parameters $\mathrm{d}m/\mathrm{d}t$ and Δp is different using an ad-hoc parallel path for the remaining pancakes modelled by FLOWER or the treating each one as a separate conductor with M&M according to Ref. [19].

The current sharing temperature measurements in the TFMC are currently being investigated in detail in predictive fashion. Heat generation and heat exchange in joints is treated in Ref. [20].

Three laboratories developed the necessary tools for the analytical treatment of the heat slug injection. It is an obligation of the different laboratories to elaborate the areas of validity for their models including boundary conditions and applied codes.

4. Mechanics

Detailed results for the load case, TFMC tested as single coil were achieved by the FE model [21]. For the test configuration, TFMC with LCT coil, the results are summarised in Ref. [22].

5. Dielectric insulation

The conductor with its insulation is embedded in radial conductive plates (SS plates). The potential fixing of the plates is an indispensable item for the integration of the insulation system. Voltage transients during the switching procedure initiation of a safety discharge have to be taken into account [23]. The radial plate winding type offers the possibility to assess the electrical insulation system of such a magnet over the operation lifetime by partial discharge (PD) measurements [24].

6. Instrumentation

The TFMC and its structure are equipped with numerous sensors (voltage tap, temperature, pressure, flow rate and magnetic field sensors as well as strain gauges and displacement transducers) for protection, control and diagnostic [25].

7. Conclusions

Suitable code development and accompanying experiments were performed for the predictive analysis of the TFMC test and operation for the electromagnetic, thermo-hydraulic and mechanical properties. A key item is the determination of the operation limits of the TFMC, which is a challenging task in code development with suitable boundary conditions and an adapted experimental technique. The carefully prepared finite element analysis will deliver a first comparison with the experimental results and therefore essential properties of the radial plate winding type, which can be scaled up to the ITER full size coils. For the insulation integration, a suitable potential fixing of the radial plates is indispensable. The radial plate construction has the development potential for insulation diagnostic of the turn, radial plate and ground insulation over the lifetime of the magnet.

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