Fusion Engineering and Design xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Fusion Engineering and Design

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

Towards a multi-physic platform for fusion magnet design—Application to DEMO TF coil

Quentin Le Coz [a,*], Daniel Ciazynski [a], Benoît Lacroix [a], Sylvie Nicollet [a], François Nunio [b], Alexandre Torre [a], Roser Vallcorba [b], Louis Zani [a]

[a] CEA/IRFM, 13108 Saint-Paul-lez-Durance, France
[b] CEA/IRFU, 91191 Gif-sur-Yvette Cedex, France

HIGHLIGHTS

- Development of a coupled thermal and thermo-hydraulics simulation tool.
- Validation on the simulation of a heat exchanger.
- Application to DEMO TF coil on a burn scenario.
- Assessment of the temperature margin criterion.

ARTICLE INFO

Article history:
Received 20 September 2016
Received in revised form 10 March 2017
Accepted 14 March 2017
Available online xxx

Keywords:
Demo
Thermo-hydraulics
Code coupling
TF coil
CICC

ABSTRACT

In the framework of the EUROfusion DEMO project, studies are conducted in several European institutions for designing the tokamak magnet systems. In order to generate the high magnetic fields required for the plasma confinement and control, the reactor should be equipped with superconducting magnets, the reference design being based on Cable-In-Conduit Conductors (CICC) cooled at cryogenic temperatures by forced circulation of supercritical helium.

In order to propose a toroidal field (TF) winding pack (WP) design compatible with DEMO requirements, CEA has developed several tools addressing the different areas related to magnet dimensioning. An accurate calculation of magnetic field along the conductors is provided by the TRAPS code, and conductor design is performed by using an integrated macroscopic home design code based on simplified models accounting for superconducting properties, mechanics and thermal. This multi-physic tool gives a realistic but not assessed design. Indeed it is based on an assumed operating temperature that must be validated with an elaborate code, since it is linked with temperature margin design criterion (1.5 K).

A dedicated modelling tool was developed by coupling the THEA code for 1D thermo-hydraulics in cables and the Cast3M code for 2D transverse thermal diffusion in a limited number of coil cross-sections, enhancing the accuracy of the outputs as being a quasi-3D approach. This tool allows a better assessment of the flux exchange between WP and casing, and the modelling of inter-turn and inter-pancake thermal coupling. The coupling methodology is described, as well as its validation on the simulation of a heat exchanger. A calculation was performed on the CEA proposal for DEMO TF coil in a burn (steady state) scenario, and finally providing a realistic assessment of the temperature margin.

1. Introduction

As the EUROfusion Consortium is currently leading design activities on the DEMO fusion reactor project, studies are underway on the different magnet systems. We focus here on the TF WP for which 3 designs were issued: SPC, ENEA and CEA [1]. While different concept proposals are foreseen, the need for numerical tools for consolidated evaluations against design criteria is of first importance.

A THEA-Cast3M code coupling was developed. Firstly we present a validation of the model by comparison against a semi-analytical model, and then we use this code coupling as a refined tool for analyses of the TF design.

* Corresponding author.
E-mail addresses: Quentin.LeCoz@cea.fr, lecoz.q@gmail.com (Q. Le Coz).

http://dx.doi.org/10.1016/j.fusengdes.2017.03.076

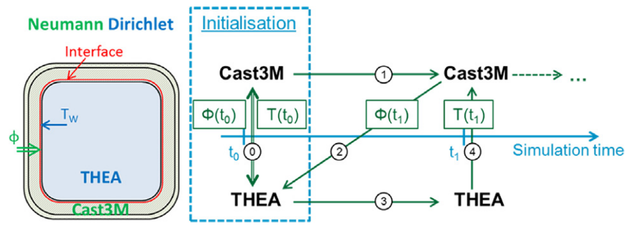

Fig. 1. Description of the coupling methodology.

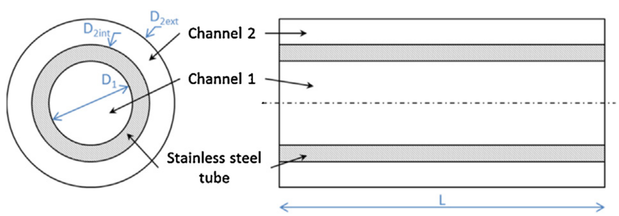

Fig. 2. Description of the coaxial heat flow exchanger.

Table 1
Main features of the heat exchanger.

Channel 1		Channel 2	
T_{1in} [K] =	5	T_{2in} [K] =	10
$\dot{m}_1$ [kg/s] =	0.02	$\dot{m}_2$ [kg/s] =	0.02
P_{1in} [Pa] =	$5 \cdot 10^5$	P_{2in} [Pa] =	$5 \cdot 10^5$
D_1 [m] =	0.01	D_{2int} [m] =	0.014
Dh_1 [m] =	0.01	D_{2ext} [m] =	0.02
S_1 [m^2] =	$7.85 \cdot 10^{-5}$	Dh_2 [m] =	0.006
		S_2 [m^2] =	$1.60 \cdot 10^{-4}$
L [m] = 10			

2. THEA-Cast3M code coupling

A code-coupling was developed using the THEA code [2] for 1D thermo-hydraulics in cables and casing cooling channels (CCC), and the Cast3M code [3] for 2D finite element transverse thermal diffusion in the TF cross-sections, leading to a transient quasi-3D model.

THEA and Cast3M codes feature accessible sources and thus can be customized. Both have been previously used for studies on the DEMO TF coil [4]. For that reason, it has been decided to build a tool around those codes, resulting in a tool comparable to codes such as SuperMagnet [2], VENECIA [5] or 4C [6].

The interface between the two codes is the inner surface of the conductor jacket (see Fig. 1). A thin layer of the jacket is modelled in THEA, allowing the use of a direct coupling through prescribed wall temperature (Dirichlet condition) in Cast3M, which sends back to THEA the heat fluxes (Neumann condition), data being exchanged through files. The coupling is done using a time explicit method. Cast3M is always working one step ahead so that THEA can interpolate the heat flux between two steps. The links between 1D and 2D models are given at predefined positions along the curvilinear abscissa. Linear interpolations between nodes are used in THEA to compute the data.

3. Validation: simulation of a heat exchanger

The coupling methodology was validated against a semi-analytical model on the simulation of a heat exchanger. This model was developed on VBA under Excel. We consider a coaxial flow heat exchanger (see Fig. 2). The geometry is described in Table 1. The friction factor is calculated using the smooth tube correlation and the heat transfer correlation is the Dittus-Boelter correlation. In Excel, the helium properties are imported from the CryoSoft database. The wall is made of 316LN stainless steel.

The temperatures were calculated in parallel flow (Fig. 3) and countercurrent configuration (Fig. 4). The matching plots demonstrate the consistency of the results. The relative difference is calculated with the following formula:

$$\sigma\ [\%] = 100 \left| \frac{\Delta T_{coupler}(out - in) - \Delta T_{VBA}(out - in)}{\Delta T_{VBA}(out - in)} \right|$$

The results are given in Table 2.

Table 2
Relative difference between the two models.

	Channel 1	Channel 2
Parallel flow – σ [%]	0.12	0.14
Countercurrent – σ [%]	0.18	0.07

Table 3
2015 TF WP3 reference conductor.

I_{TF}	Conductor current	111560 A
d_S	Strand diameter	1.024 mm
N_{Sc}	Number of Sc. strands	1029
N_{Cu}	Number of Cu strands	844
L_C	Cable size (square)	48.64 mm
W_{jack}	Jacket thickness	11.1 mm
N_{pk}	Number of pancakes	16
N_{tr}	Number of turns	8

Table 4
Mass flow in hydraulic circuits.

	Bundle	Spiral	CCC
$\dot{m}$ [g/s]	6.39	6.09	3.75

4. Application to DEMO TF coil

The design considered is the 2015 CEA proposal for a DEMO TF coil [7] consisting in 8 double pancakes wound in 8 turns each using CICC with Nb_3Sn strands (Table 3). CCC of a diameter of 8 mm are considered in the stainless steel casing (Fig. 5).

In a burn scenario, the conductor should satisfy a criterion of 1.5 K minimal temperature margin, defined as $\Delta T_{ma} = T_{CS} - T_{op}$, with T_{CS} the current sharing temperature and T_{op} the operating temperature.

The effective magnetic field is calculated on each pancake using the TRAPS code taking into account the contributions of TF, central solenoid and poloidal field coils, as well as the contribution from the plasma (see Fig. 6) [8].

The nuclear heating (NH) load considered on the TF is assumed to vary only in radial direction [9]:

$$P_{NH}\left[\frac{W}{m^3}\right] = 50 \cdot \exp\left(-\frac{R_{CASE}}{140}\right)$$

With R_{CASE} in mm being the radial distance from the TF case inner edge.

The hydraulic models consider an inlet temperature of 4.5 K for the conductors and the CCC. Table 4 gives the mass flow for each CCC and each CICC (bundle + spiral). The hydraulic length is of 363.86 m for the conductors and is comprised between 43 m (plasma side) and 48 m (outer side) for the CCC.

The heat transfer is calculated using the Dittus-Boelter correlation. For the friction factor correlations, the following laws were used:

$$\frac{\partial p}{\partial x} = -2\rho \frac{f}{D_h} v|v|$$

Please cite this article in press as: Q. Le Coz, et al., Towards a multi-physic platform for fusion magnet design—Application to DEMO TF coil, Fusion Eng. Des. (2017), http://dx.doi.org/10.1016/j.fusengdes.2017.03.076