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Design updates and analysis of the Korean fusion demonstration reactor superconducting toroidal field magnet system

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ABSTRACT

After a conceptual design study for a steady-state Korean fusion demonstration reactor (K-DEMO) was initiated in 2012, the preliminary design of superconducting magnet system which is one of the key components of the K-DEMO has been done in 2015. The superconducting magnet system of K-DEMO has 16 Toroidal Field (TF) coils, 8 Central Solenoids (CS) modules and 12 Poloidal Field (PF) coils which use Cable-In-Conduit Conductors (CICC). For a high 7.4 T magnetic field generation at plasma center, high performance Nb3Sn based superconductor will be developed and used for TF magnet. Starting from the preliminary conceptual design, design updates of K-DEMO TF magnet is being conducted for checking engineering issues. For a validation of the magnet design, thermo-hydraulic stability and mechanical stability are being considered. In this work, the conceptual design studies for updates of K-DEMO TF magnet system is described.

1. Introduction

A preliminary Conceptual design study of the K-DEMO based on the Korean Fusion Energy Development Promotion Law (FEDPL), was started in 2012 [1] and a conceptual design study of the K-DEMO magnet system has been done in 2015 [2,3]. The superconducting magnet system of the K-DEMO contains 16 TF, 8 CS and 12 PF coils and uses internally-cooled CICCs. Two types of graded coil, a low field (LF) TF coil and a high field (HF) TF coil consist of one TF coil. The graded coil configuration of K-DEMO TF reduces superconducting strands usage and saves space for TF structure. There are 9 CICC units in one LF coil and 3 CICC units in one HF coil. The length of each LF and HF coil units are about 1030 m and 1010 m respectively. Main parameters of the K-DEMO and its TF magnet system are listed in Table 1.

After the preliminary design study of the K-DEMO magnet system, design updates of TF magnet system are being conducted to check expected engineering issues. The jacket thickness of LF CICC is increased 1 mm from previous design to enduring more force loaded to the conductor. The thickness and number of helical cooling spiral of HF CICC is changed for manufacturing feasibility. A helical spiral in previous HF CICC design was squeezed during the jacket compaction process therefore the thickness of helical spiral has been increased and double the number of helical spiral in HF CICC [4]. The sizes of TF CICCs are also modified slightly. Fig. 1 shows the up to date design of K-DEMO TF CICCs and their design parameters are listed in Table 2.

To validate and improve the design updates of K-DEMO TF magnet, analyses related with design change are underway. An electro-magnetic analysis of TF coil and static structural analysis of the TF case structure has been done as a previous step of jacket to jacket stress analysis. Before evaluating the effect of jacket thickness increment, smeared model is applied to magnetic field analysis. The results of magnetic field analysis is applied to static structural analysis of TF structure and also used to thermo-hydraulic analysis to check temperature margin of the TF coil in each winding location. Those results of magnetic field, structure and thermos hydraulic analysis are described in this paper.

2. Magnetic field analysis

A 3D model for magnetic field analysis is designed from a former TF design [2,3]. Radial build of the K-DEMO is not changed and inside of TF structure is slightly modified depending on size changes of TF CICCs. Fig. 2 is a half-cut views and it shows inside of TF magnet and an arrangement of LF and HF CICCs. The space between LF and HF coil at outboard side will be used for joints, turn transition, current leads and Helium feed-throughs [2]. Based on 2D arrangement of CICCs, 3D model of conductor is built by sweeping 2D model along D-shape of the K-DEMO. Both of the detailed CICC model and smeared model are designed. With the conductors, TF case structure, ground wrap of winding

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Table 1
Main features of the K-DEMO TF magnet system.

K-DEMO parameter	
Major radius	6.8 m
Minor radius	2.1 m
Aspect ratio	3.2
Elongation	1.8
Triangularity	0.625
Field at major radius	~ 7.4 T
Plasma current	12 MA
Te	20 keV
Total heating power	150 MW
Net electric output power	400 MW
No. of coils	TF 16, CS 8, PF 12
K-DEMO TF parameters	
Mean circumference	43.6 m
Number of turns	LF 10 turns / pancake 9 double pancakes HF 5 turns / pancake 3 quadruple pancakes
CICC current	65.5 kA
Total current in coil	15.7 MA
Peak field on CICC	16 T
E.M. load	1048 kN/m

packs and Outer Intercoil Structure (OIS) are also modeled and imported to magnetic field simulation tool for converting Electro-Magnetic (EM) simulation model. Magnetostatic simulation with 65.52 kA current is solved with 1/16 rotational symmetry model. Fig. 3 shows the simulation model and calculated magnetic field distribution of the K-DEMO TF magnet. Maximum field of 17 T is at starting point of upper and lower corner of inboard side and stored energy is 8.99 GJ. CS and PF magnets are not included in the simulation.

From the result of magnetic field simulation, volume force density of winding pack is exported to structural analysis as an external load – body force density. Magnetic field along the CICC winding is also exported to thermal-hydraulic analysis for evaluating temperature margin of the conductors. Figs. 4 and 5 shows the result of magnetic field simulation, volume force density and magnetic field along conductor respectively.

3. Structural analysis

A 3D model for magnetic field analysis is also used in static structural analysis. Designed model for EM analysis is exported to the structural analysis tool and weight loads, thermal expansion, EM load from magnetic field calculation are added to the model. Weight loads of CS and PF magnet are applied on each location of the magnets and self-weight load of TF magnet is also added up to the model. Thermal expansion deformation of TF magnet is included in the model. Volume force density from EM analysis result set as an external load and mapped into the mesh of conductors in structural analysis model. 1/16 rotational symmetry is also used in structural analysis therefore only a single TF magnet was calculated. The material behavior of the model is set to linear elastic and basic stainless steel, copper alloy and insulation material is used. Effective material properties will be defined and applied in next step of analysis in near future. Contact interaction between the TF structure and winding pack is set to frictionless and it gives conservative estimation for conductor but the best case for the TF case structure [5]. Fig. 6 shows the von-Mises stress distribution and vertical deformation of the K-DEMO TF magnet. Based on this result, detailed CICC model will be built to check jacket to jacket stress for evaluating of jacket thickness change. Limit analysis of the model will be performed to investigate a margin in TF magnet structure with respect to its design load [6].

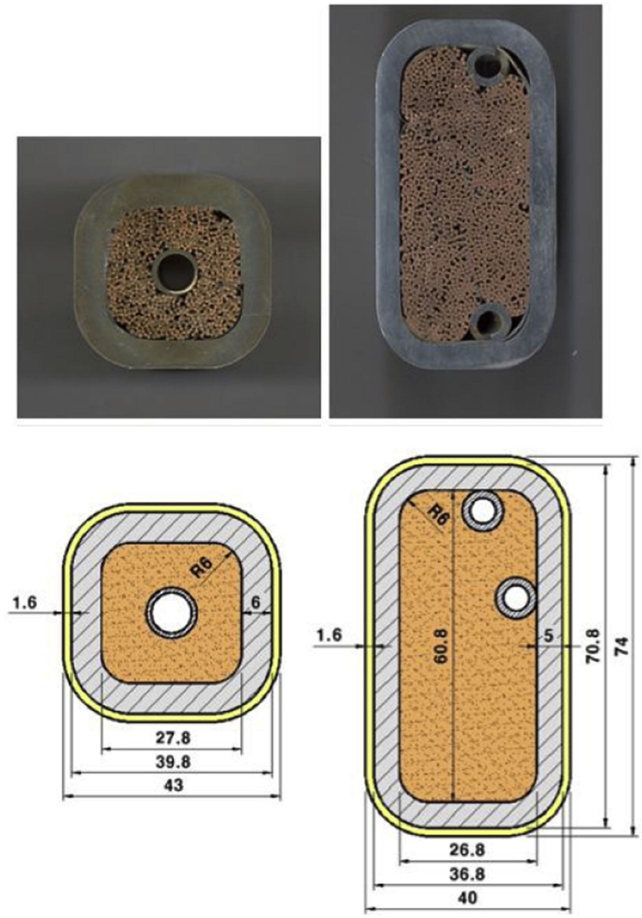

Fig. 1. Dimension of the K-DEMO CICCs in mm unit, low field TF (left), high field TF (right).

4. Thermo-hydraulic analysis

The magnetic field data from EM analysis is brought into a thermos-hydraulic model and the field is applied on each CICC location proportional to ramping current [7]. The properties of superconducting strands is scaled by [8]. There are 9 cooling channels for LF TF (1 channel/double pancake) and 3 cooling channels for HF TF (1 channel/quadruple pancake). The applied current is 65.52 kA with ramp rate of 0.82 kA/s. Thus the current ramp started at 0 s and finished at 80 s. The applied current kept until 250 s. The middle of the ramping time (40 s) and 10 s after ramp up finished (90 s) is selected to check temperature margins during the ramp up and after ramp up finished. The nominal mass flow rate is set to 5 g/s and 6.5 bar of initial pressure and 4.5 K helium temperature is applied. Fig. 7 shows the calculated temperature margin of the K-DEMO TF. In LF TF, at the end of ramping (80 s) and right after the ramping end (90 s), temperature margin goes about 0.9 K below the 1 K operation margin but it can be moderated with slowing down ramp rate. After the ramping up to maximum current, temperature margin stays at ~1.5 K for LF and at ~1.9 K for HF TF (250 s).

As a changing of helical spiral scheme of HF TF, pressure drop of HF CICC will be considered in near future. If the pressure drop of one channel in HF TF is too high, the number of HF TF cooling channel

Table 2
Design parameters of K-DEMO CICCs.

Parameter	TF HF	TF LF
● Cable pattern	(3SC)×4 × 5×6 × 5 + 2 Helical Spirals	(((2SC+2Cu)×5)×6 + 7Cu)×6 + Central Spiral
No. of SC strand	1800	360
No. of copper strand	–	432
Spiral dimension (mm)	ID 5 / OD 8	ID 5 / OD 8
Void fraction (%)	29.68	27.58
● No. of turns	5	10
● No. of layers	12	18
● Nominal current (kA)	65.52	65.52
● Strand type	High Jc (> 2600 A/mm2) Nb3Sn Strand 0.82 mm diameter (~510 ton + ~320 ton)	
● Cu/non-Cu ratio	1.0	
● Insulation	1.6 mm (including Voltage Tap) (0.1 mm Kapton 400 % + 0.3 mm S glass 400 %)	
● Jacket thickness (mm)	5.0	6.0
● Twist pitch (mm)		
1 st stage	80 ± 5	80 ± 5
2nd stage	140 ± 10	140 ± 10
3rd stage	190 ± 10	190 ± 10
4th stage	245 ± 15	300 ± 15
5th stage	415 ± 20	–
● Wrapping Tape		
Sub-cable wrap thickness	0.08 mm	
Sub-cable wrap width	15 mm, 40 % coverage	
Final-cable wrap thickness	0.4 mm	
Final-cable wrap width	7 mm, 50 % coverage	

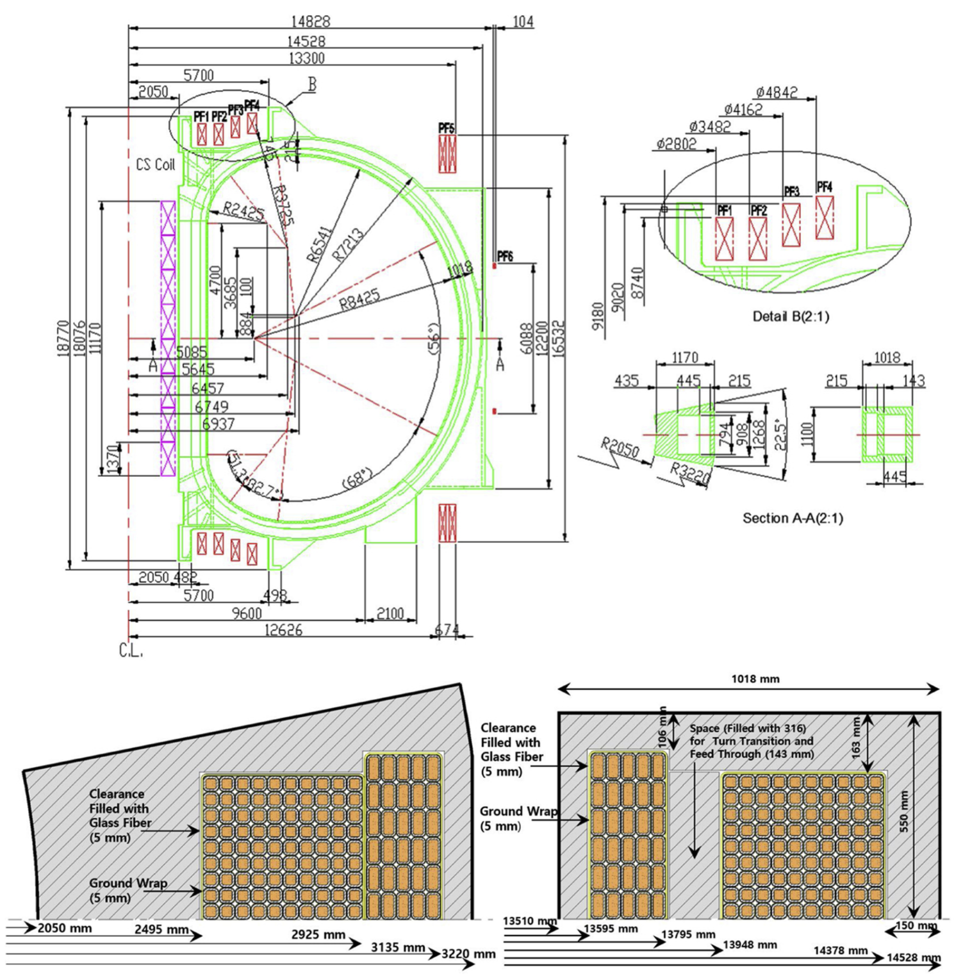

Fig. 2. Cut view of the K-DEMO TF magnet.

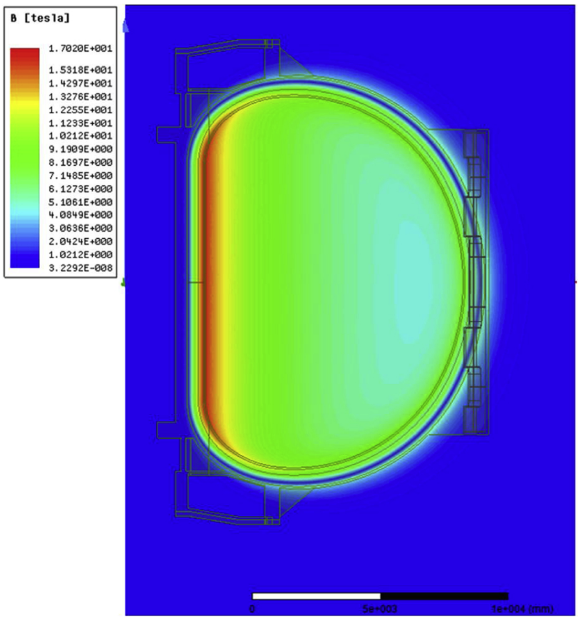

Fig. 3. Magnetic field distribution of the K-DEMO TF magnet.

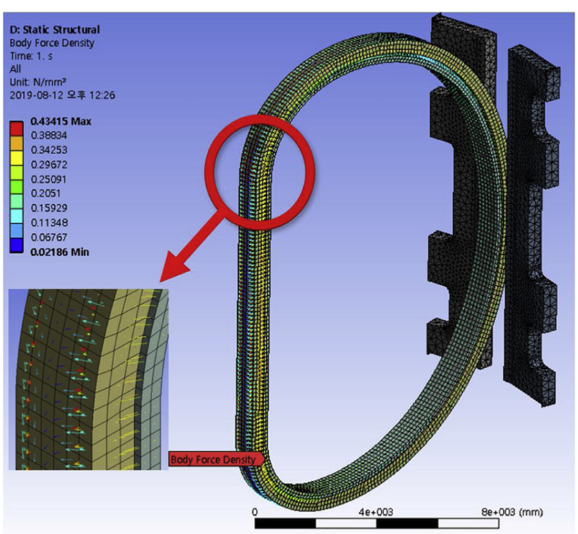

Fig. 4. Imported volume force density in structural analysis model.

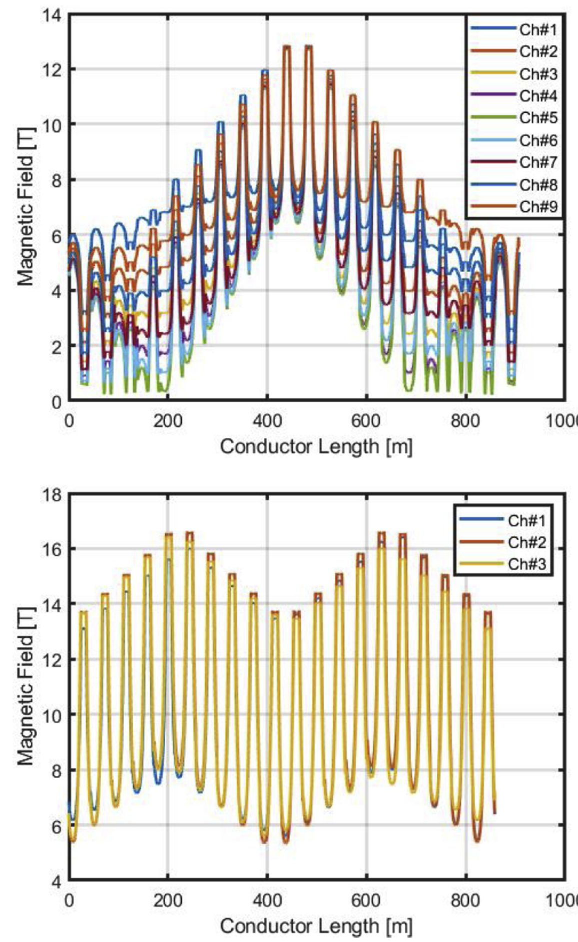

Fig. 5. Magnetic field along the CICC units of LF TF conductor (upper) and HF TF conductor (lower).

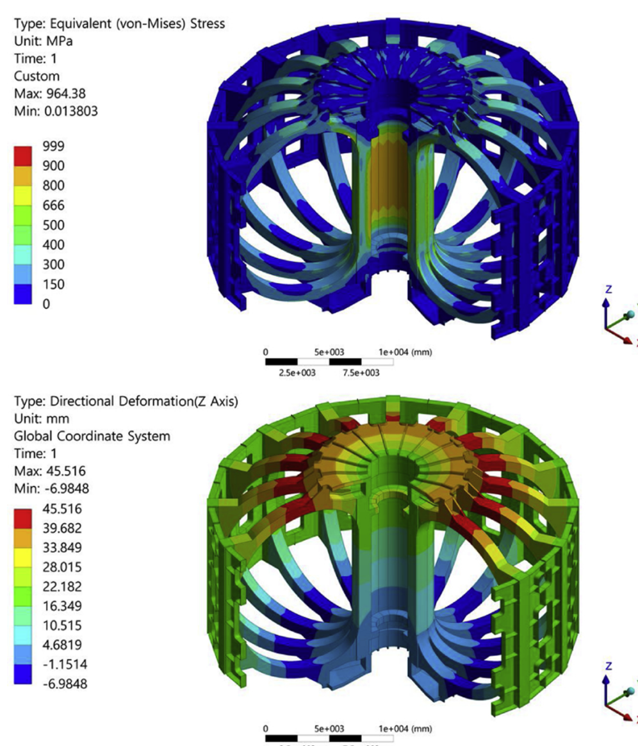

Fig. 6. Von-Mises stress distribution (upper) and vertical deformation of the K-DEMO TF magnet.

will be increased from 3 to 6 by put one cooling channel per double pancake instead of one channel per quadruple pancake. Space in between LF and HF winding pack is prepared for additional helium feed-throughs.

5. Summary

Design updates of the K-DEMO superconducting TF magnet has been carried out in 2018 [3]. For a validation of the updates, EM, structural and TH analysis are being conducted. Modified TF CICC array generate adequate magnetic field for plasma. From the EM analysis, force and magnetic field data are delivered to structural and thermos-hydraulic analysis and applied. Structural analysis with smeared model is performed as a previous step of detailed CICC model. Effective material property and detailed CICC model will be applied in next step. In TH analysis, TF CICC satisfy 1 K temperature margin for stable operation.

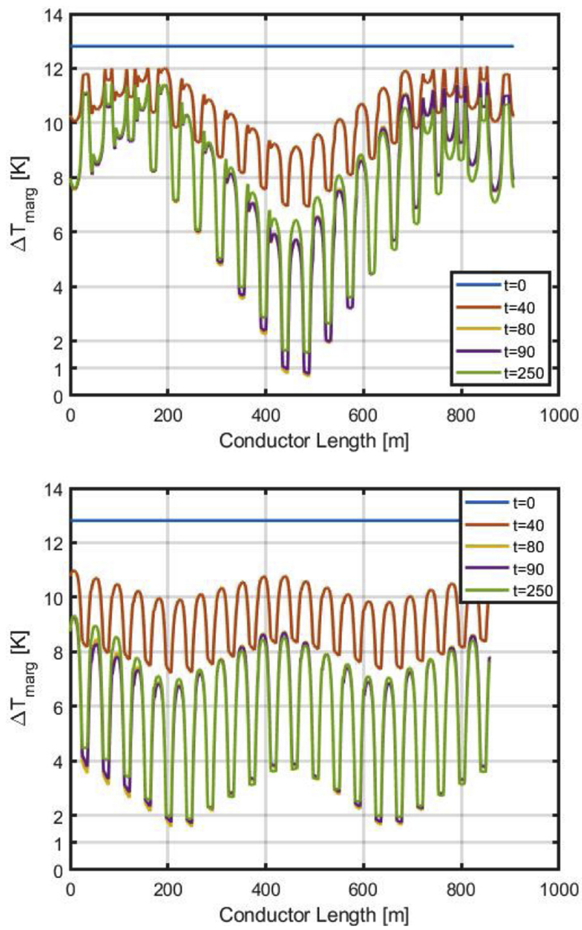

Fig. 7. Temperature margin of the K-DEMO LF TF conductor (upper) and HF TF conductor (lower).

CRediT authorship contribution statement

Hyun Wook Kim: Writing - original draft, Formal analysis, Visualization. **Sangjun Oh:** Resources, Validation. **Hyun Jung Lee:** Resources, Validation, Formal analysis, Investigation. **Yong Chu:** Resources, Validation, Investigation. **Sungjin Kwon:** Resources, Formal analysis, Investigation. **Hong-Tack Kim:** Resources. **Keeman Kim:** Conceptualization, Methodology, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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