Thermal-hydraulic analysis of Cable-In-Conduit Superconductor: A CFD approach

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Abstract. Superconducting (SC) magnets with Cable in Conduit Superconductor (CICSC) winding, cooled by helium at 4 K temperature are employed for many applications which require high magnetic field and high current densities. The construction of CICSC aims to maintain superconductivity state by optimization of various parameters, i.e., thermal stability, ratio of normal conductor to superconductor material, mechanical strength, low hydraulic impedance, current density, magnetic field, etc. The cryogenic thermal stability of the CICSC is of prime importance for the safe, stable and reliable operation of SC magnets. The prediction of thermal and hydraulic behaviour of CICSC in large SC magnets is difficult due to the complex geometry, variation of fluid properties, various heat in-flux incidences over the long length of CICSC and a complex heat transport phenomenon. Here we present a CFD approach for the thermal hydraulic analysis of a typical CICSC applying the porous media analogy and discuss the suitability for a wider range of operational scenario at higher Reynolds number and for various geometries.

1. Introduction

The use of superconducting (SC) magnets in various applications, namely, Magnetic Resonance Imaging (MRI), Nuclear Magnetic Resonance (NMR), magnetic confinement of hot plasma, particle accelerator, thermonuclear fusion and mass spectrometry, is inevitable due to the fact that very high current densities, less noisy and high magnetic field can be achieved with the superconductors [1–4]. Where the normal resistive conductor can produce up to 1 Tesla field with a consumption of significant electrical power, the SC can produce above 9 Tesla magnetic field with very less electrical power input. The state of superconductivity is achieved when SC magnets are cooled at temperature lower than critical temperature which is 10 K for Niobium-Titanium (NbTi) superconductor and 18 K for Niobium-Tin (Nb3Sn) superconductor. However, the state of superconductivity also depends on the magnetic field and current density as shown in Figure 1.

The SC magnets are prone to return to normal conductor in local region, called the quench phenomenon. In order to maintain superconductivity, three parameters are the boundaries, i.e., the magnetic field, the temperature and the current. Among the three parameters, temperature boundary is very unstable due to the fact that SC magnets contains huge magnetic and mechanical energy which can be easily converted to heat and upset the thermal equilibrium and raise the temperature above its critical temperature. Thus proper stability of the SC magnets is achieved by proper cryogenic cooling of SC magnets which overcomes Joule heating and keeps the conductor in superconducting state. Therefore, careful studies
must be carried out to ensure proper cooling of the CICSC despite heat generation, local pressurization and very long path for the cooling.

Figure 1. The magnetic field vs. critical current for a Superconductor

Typical CICSC for the SC magnets can be up to few hundred meters long. The cryogenic cooling of the CICSC is done by the forced flow of the cryogen, e.g. supercritical helium (SHe) at 5 K temperature level. The cryogen flows along the strands of SC cables which carries the electrical current. A brief overview of the CICSC construction has been presented with the brief literature review of the thermal-hydraulic analysis. A typical CICSC sample has been analysed with porous media analogy and the results compared with experimental data. The overall approach of the CFD analysis presented with the results obtained.

2. Construction of SC magnets

Practically SC magnets are made from tiny multi filamentary wire made of superconducting material with a mixture of normal conductor, like copper, as a stabilizing agent. The SC strands are paired and twisted to make a cable, e.g., a twisting of strands in a pattern 3×3×4×5×6 will make a cable with 1080 strands. The cables are encased in a jacket, normally made of steel or aluminium, to give mechanical strength. The cryogenic cooling fluid passes through the voids between the SC strands. Sometime a central hole is provided as coolant passages. Typical cross-sections of such Cable in Conduit Conductor (CICSC) is shown in the Figure 2.

Figure 2. Cross-section of CICSC; Type-(a) Square without central hole Type-(b) Square with central hole and Type- (c) Round with central hole and Type-(d) Square jacket, circular strands without central hole
The first mock sample is of 3.3 m long single channel CICSC with parameters as shown in Table 1 has been analysed using the CFD approach.

### TABLE I
CICC SAMPLE PARAMETERS

| PARAMETERS                  | VALUE                  |
|-----------------------------|------------------------|
| NO. OF STRAND               | 180                    |
| STRAND DIA                  | 0.80 mm +/- 0.01 mm    |
| STRAND AREA                 | 90.48 sq. mm           |
| CONDUIT AREA                | 123.21 sq.mm           |
| CORNER RADIUS AREA          | 1.93 sq.mm             |
| FLOW AREA                   | 30.80 sq.mm            |
| VOID                        | 0.25                   |
| WETTED PERIMETER            | 500.38 mm              |
| HYD. DIA.                   | 0.25 mm                |
| LENGTH                      | 3.727 M                |
| NO. OF STRAND               | 180                    |

3. **Thermo-hydraulic studies in CICSC**

CICSC functions as electrical superconductors for SC magnet at the same time continuously cooled by helium at 4 K temperature and provide flow channel for the coolant. Heat transfer and fluid flow studies though the complex geometry of the CICSC necessary to predict the conductor cooling, quench behaviour and to ensure stability as well as effective cold source requirement at 4 K temperature.

The thermo-hydraulic characteristics of type-(d) CICSC have been analysed for Wendelstein 7-X magnet by Cheng [5] as well as Cheng and Lehmann [6] and they proposed friction factor with empirical coefficient. The pressure drop evaluated was 3 times higher than the equivalent smooth tube. However, proposed correlation of friction factor does not mention the effect of void fraction, which is important parameter for the pressure drop. In the same experimental set-up, the transverse heater transfer coefficient proposed which is modified form of Dittus-Boelter correlation. Katheder [7] proposed friction factor based on standard formula used for pebble beds for type-(a) and type-(d) CICSC, which takes into account the void fraction in the CICSC. Katheder proposed an optimum operating regime for CICSC from the first principle and suggested that for a typical CICSC geometry the optimum pressure is between 6 and 7 bar. Katheder’s work was pioneering for CICSC and referred subsequently by many authors.

ITER Central Solenoid Model Coil (CSMC) test results were presented by Hamada et al. [8]. CSMC has type-(c) conductor and therefore two different pressure drop correlations were applied, one for bundled region and the other for central hole region as per ITER design criteria. Bottura et al. [9] proposed transverse heat transfer coefficient for CICSC with central hole – type (c). They further distinguished the bundle region; strands wrapped with steel band and without steel wrap. The method is based on the temperature measurement in time and space during pulsed heat load condition. Similar method for the prediction of heat transfer utilized by Renard et al. [10] and proposed heater transfer coefficient for type (c) CICSC. Marinucci et al. [11,12] proposed approximate analysis to obtain mass flow rates in bundled region and central hole region, to predict the friction factor coefficient and concluded that the friction factor is 0.7 times the Katheder’s [7] correlation. A method of transient temperature measurement at various locations was employed to estimate heat transfer coefficient. New term ‘effective thermal conductivity k_eff’ proposed by Claudio Marinucci et al. [11] for ITER CICSC, type-(c). Lewandowska and Bagnasco proposed friction factor correlation based on various data of CICSC with an analogy of porous media [13]. The flow distribution and heat transfer coefficient between the central heat and the bundle region in the ITER TF conductor was determined based on a direct heat and mass transfer analysis of the temperature measurements at steady states by Lewandowska and Malinowski [14]. The mass and heat transfer between central channel and bundle region were studied with mass and energy balance method by Zanino et al.[15]. A CFD based analysis approach was adopted and reported by Sekhar [16–19].
4. Method for CFD analysis
A scaled model (1:1) of the coil sample, of parameters shown in Table 1, has been modelled in ANSYS CFX® with total 923418 number of nodes and 895152 elements. Meshing has been refined in near wall region with maximum aspect ratio 102 and maximum skewness 0.53. The complete model has been defined as two domains, fluid domain at the inlet and outlet for 60 mm of length and in between as porous domain as shown in Figure 3. The bundled region defined with the porous model which consider both a generalization of the Navier-Stokes equations and of Darcy’s law (equation 1) commonly used for flows in porous regions.

\[ \frac{\Delta P}{L} = \frac{\mu}{\alpha} V_s + \frac{\rho}{\beta} V_s^2 \]  

Where, ΔP is pressure drop across the CICSC length L, \( \mu \) and \( \rho \) are the dynamic viscosity and the density of the fluid respectively. \( V_s \) is a superficial velocity. \( 1/\alpha \) is permeability and \( 1/\beta \) is a loss coefficient. The term \( \mu/\alpha \), as a linear coefficient and \( \rho/\beta \), as a quadratic coefficient of the superficial velocity obtained from the velocity - pressure gradient curve from the experiment, as shown in Figure 4 and incorporated in the CFD simulation set-up.

![Figure 3](image.png)

Figure 3. (a) Model of CICSC (b) Meshed model (c) close view of the cross section.

![Figure 4](image.png)

Figure 4. Measured pressure drop as a function of velocity.
5. Results and Discussion
The simulation model prepared in parallel to the experiments utilizes the viscous (1/α) and inertial coefficient (1/β) from the first experimental data. Full range of Re has not been obtained from the CFD simulation at this stage due to uncertainty involvement in the measurements. Figure 5 shows the pressure drop results with reference pressure as 3.2 bara. Velocity variations as expected with an average velocity of 3.6 m/s whereas highest velocity up to 12 m/s is limited to very local region near bends. Density variation along the length of CICSC attributes to the compressible fluid and is very close to the predicted values and consistent with the pressure variation.

6. Conclusion
The thermal-hydraulic study of the CICSC is very critical for the SC magnet application since the improper cooling will lead to the loss of superconductivity. The pressure drop through the CICSC is also important parameter to decide the pumping capacity for the forced flow circulator of the cryogens through the CICSC. A short sample CICSC has been modelled and analysed in Computational Fluid Dynamics (CFD) simulation platform, defining as porous media of the bundled region to cover a wide range of various thermo-hydraulic and geometrical parameters involved in the test sample. A comparison of the analytical results and the CFD simulation results shows the average velocity of 3.6 m/s in the CFD analysis matches with the calculated superficial velocity. The pressure drop obtained from the CFD results shown ~50% higher value than the theoretically calculated value which is to be further investigated with the inertial and viscous loss coefficient defined from the room temperature pressure drop measurement with limited range of Re, up to 200. The inertial and viscous loss coefficient will be further verified with extensive test with higher Re; which can be obtained by pressure drop measurement at cryogenic temperature, e.g., liquid nitrogen temperature level at 77 K.

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