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Development and application of a generic CFD toolkit covering the heat flows in combined solid–liquid systems with emphasis on the thermal design of HiLumi superconducting magnets

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ABSTRACT

The main objective of this work is to develop a robust multi-region numerical toolkit for the modeling of heat flows in combined solid–liquid systems. Specifically heat transfer in complex cryogenic system geometries involving super-fluid helium. The incentive originates from the need to support the design of superconductive magnets in the framework of the HiLumi-LHC project (Brüning and Rossi, 2015) [1]. The intent is, instead of solving heat flows in restricted domains, to be able to model a full magnet section in one go including all relevant construction details as accurately as possible. The toolkit was applied to the so-called MQXF quadrupole magnet design. Parametrisation studies were used to find a compromise in thermal design and electro-mechanical construction constraints. The cooling performance is evaluated in terms of temperature margin of the magnets under full steady state heat load conditions and in terms of maximal sustainable load. We also present transient response to pulse heat loads of varying duration and power and the system response to time-varying cold source temperatures.

1. Introduction

Construction-wise speaking superconducting magnets are an arrangement of solid elements immersed in liquid helium that serves as heat extraction agent. They are made of many different materials with different thermal properties, the major fraction of components being metallic. Compared to the overall object size, many parts of the magnet relevant for heat extraction are very thin e.g. the superconducting cable composition, various electrical insulation materials and quench heaters. Thermally speaking, these parts cannot, despite their small geometrical sizes, be neglected and proper inclusion in the modeling is crucial. There are a number of studies and research done to model superconducting magnets [2], but most of the work focuses on some specific part of the magnet, like the coil blocks [3], or some specific phenomenon that can occur during magnet operation, such as quench [4]. Commonly the numerical geometry is simplified to avoid a large number of different elements of the magnet. Our intent is, instead of solving heat flows in restricted domains, to be able to model a full magnet section in one go including all relevant construction details as accurately as possible. Treating the full geometry in one go should allow for better control of margin when optimizing the designs than if the optimization relies on piecing together partial solutions for restricted construction domains. For that we developed a multi-region numerical toolkit dedicated to treating heat flows in combined solid–liquid systems.

We strive for a minimal mathematical model complexity approach, only including the necessary physics required for the purpose. For example, the physics associated with the dynamics and heat transfer of super-fluid Helium (HeII). Its heat conduction capabilities are huge and it behaves as inviscid. Therefore HeII cannot be characterized as a classical liquid. We followed the state of art approach to model the dynamics of the HeII by so-called two-fluid model, where HeII is a composition of normal (viscous) fluid and inviscid fluid. The complete two-fluid model for the super-fluid helium is replaced by a simplified equation valid under the operating conditions of the magnet, i.e. absence of flow in the helium bath and in the Gorter–Mellink turbulent regime. In contrast we kept the numerical geometry as close as possible to the real geometry with its whole complexity, by including thin features such as cable insulation patterns and ground insulation. In order to do this, we developed a boundary condition to model ultra-thin resistive layers with temperature depended thermal conductivity. Attention was also paid to solid-to-liquid interface

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interactions by including the Kapitza resistance for helium interfaces. Our modeling technique speeds up the study of the influence of major and small changes of the design parameters by allowing complete simulations of the whole system cross section.

In this work we applied the model to the final focusing MQXF magnets, which form the new inner triplets of the two interaction points ATLAS and CMS in the framework of the Hi-Lumi project [1]. The Hi-Lumi project is a major upgrade of the LHC, to be done around 2020, in order to increase its luminosity (rate of collisions) by a factor of 10 beyond the original design value, taking it from $1 \times 34\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ to $7.5 \times 34\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ in ultimate luminosity. With increase in luminosity comes an increase in particle debris which dissipate energy in the final focusing magnets. Their design will have to accommodate this induced thermal load.

The magnets have one beam pipe protruding over the full length through which the accelerated particles travel. Separated from it by an annular gap, filled with static pressurized He at about 1.3 bar and 1.9–2.1 K, are the superconducting coils, usually two layers, embedded in an iron structure to maintain all the forces and to guide and shape the magnetic field. This whole, so-called cold-mass (Fig. 1) of approximately 65 cm diameter, is enclosed in a vessel, to be kept at the chosen operating temperature and supported in a vacuum insulated cryostat. The heat generated will be conducted out through the structure into the static helium towards two cold sources that will be housed in the two upper holes named "cooling channel".

For the magnet to function, current has to flow through the coil with the cable in the so-called superconducting state. For the purpose of this work it suffices to note that to maintain the coil in the superconductive state the requirement is to keep its temperature below the so-called current sharing temperature T_{cs}. The temperature margin is defined as the difference between T_{cs} and the temperature at operating conditions T_{op}. The risk for the MQXF magnets is operating with a too low temperature margin. This case study aims to characterize both the temperature margin distribution and the helium temperature distribution in the domain as well as the transient response of the system to pulse heat loads of varying duration and power and to cold source temperature fluctuations. The parameters are the luminosity, temperature of the heat exchangers, cooling passage sizes and the presence of thermal barriers like electrical insulation layers or quench protection heaters.

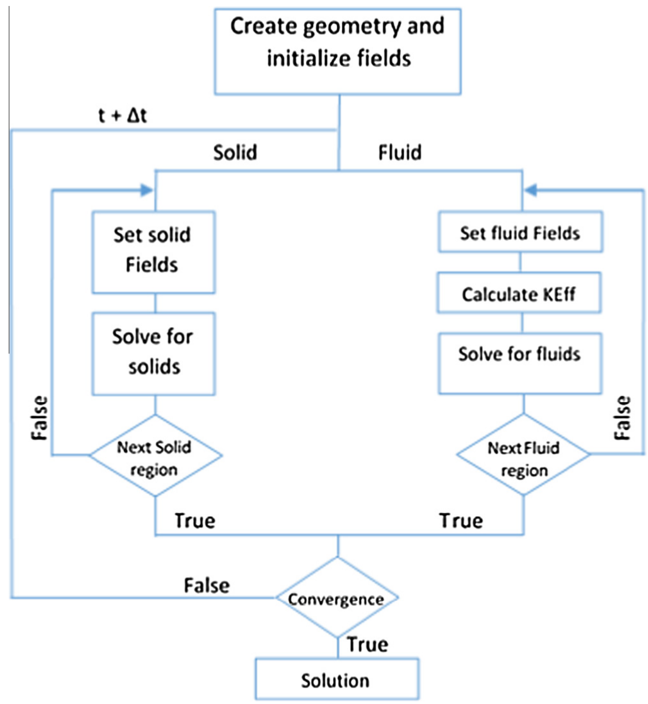

Fig. 2. Flow chart of the OpenFOAM multiregion solver.

2. Mathematical model

The main objective of the mathematical model is to solve heat transfer in complex multi-region domains where different regions are characterized by different thermal properties and different physics. Different regions can be either different types of solids or super-fluid Helium. Additionally one needs to consider very thin

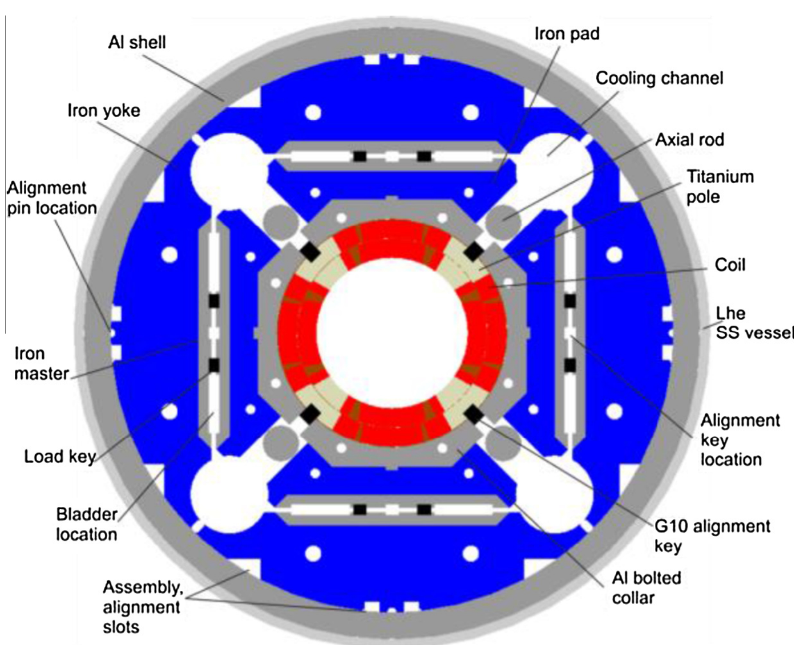

Fig. 1. A 2D cross section of the MQXF inclusive of a detailed description of the components.

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