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Modelling of the fin type heat exchanger for the HTS current leads of W7-X and JT-60SA

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ABSTRACT

The Forschungszentrum Karlsruhe has taken over the responsibility for the design, construction and testing of the high temperature superconductor (HTS) current leads for two fusion experiments, i.e. the stellarator Wendelstein 7-X (W7-X) and the satellite tokamak JT-60SA. One important task for the design of the HTS current lead is the heat exchanger (HEX). In the current leads for W7-X and JT-60SA the HEX consists of the central conductor with meander flow fins to achieve a cross flow HEX. A design optimisation requires the knowledge of the heat transfer characteristics of the HEX. Therefore, 3D CFD simulations were performed to compute local Nusselt and Reynolds numbers. From the CFD results a 1D system code description and heat transfer correlations have been deduced. This paper describes the 3D-CFD and 1D system code as well as the results of the numerical calculations. The results were validated using experimental results of HEX mock-ups. The model was extended to the HEX covering the temperature range between 60 K and room temperature leading to a single Nusselt–Reynolds number correlation. Finally the parameters for optimised HTS current leads for W7-X and JT-60SA are presented.

1. Introduction

The stellarator Wendelstein 7-X (W7-X) [1] presently under construction at the Greifswald branch of the Max-Planck-Institute for Plasma Physics consists of 50 non-planar and 20 planar coils with a maximum conductor current of 17.6 kA. The Forschungszentrum Karlsruhe will deliver the current leads for the magnet system. In total 14 current leads are required with a nominal current of 14 kA and a maximum current of 18.2 kA [2]. A view of W7-X from underneath showing the current lead ports is presented in Fig. 1 left.

In the frame of the Broader Approach Agreement between Japan and the EU and concomitantly to the ITER project, a satellite tokamak project called JT-60SA has been launched in 2006 [3]. The magnet system of JT-60SA consists of 18 toroidal field coils (25.7 kA), 4 central solenoid modules (20 kA) and 7 poloidal field coils (20 kA) [2]. Following the commitment of the German Government to the EU, FZK shall design, construct and test the current leads. In total six leads for a maximum current of 26 kA and 20 leads with a maximum current of 20 kA, mounted in vertical, normal position are required. The plasma and basic parameters of JT-60SA are defined by the Japanese national review and the JA-EU Satellite Tokamak Working Group review considering its mission [3]. A bird's eye view is shown in Fig. 1 right.

The Forschungszentrum Karlsruhe has taken the responsibility for the design, construction and testing of the HTS current leads for W7-X and JT-60SA.

Current leads with HTS components can use commercialized HTS material because the external field is usually below 0.5 T. A large scale application for an HTS current lead (up to 13 kA) was developed for LHC [4]. A second example of such a HTS current lead has been shown by the successful construction and test of the ITER HTS current lead demonstrator (HTS–CL, 68 kA) which has been developed and built by the Forschungszentrum Karlsruhe in collaboration with the Centre Recherches en Physique des Plasmas, Switzerland in the frame of an EU Fusion Technology task [5]. The current lead consists of two main parts – first the HTS module that uses BSCOO-2223/AgAu tapes embedded in stainless steel and second the copper heat exchanger. The copper heat exchanger covers the temperature range from 65 K to room temperature and is actively cooled by 50 K He gas. The HTS module is cooled by heat conduction with a forced flow cooling of the superconducting bus bar. A clamp contact is foreseen to form the joint to the superconducting busbar that connects the current lead to the coil. This unit covers the temperature range between 4.5 K and 65 K.

The basic design developed for the ITER HTS current lead demonstrator will be used as a common base for the current leads that Forschungszentrum Karlsruhe will develop for W7-X and JT-60SA.

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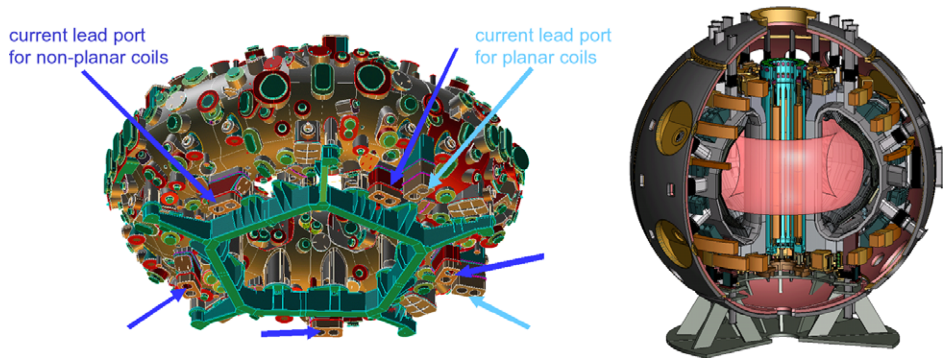

Fig. 1. Left: View of W7-X from underneath showing the current lead ports. Right: Bird's eye view of the tokamak JT-60SA.

This is possible because the W7-X current leads have similar maximum current than the PF/EF current leads of JT-60SA ands it is possible to extrapolate the design to the larger current required for the TF coils of JT-60SA.

Two heat exchanger concepts have been considered during the design phase, i.e., the perforated plate (PP) and the meander flow path fin (MF) heat exchanger. The first one was realized in the 70 kA ITER HTS current lead demonstrator [5,6] whereas the latter one is used in the 13 kA HTS current leads for the Large Hadron Collider at CERN [4]. Since in W7-X the current leads have to be installed in upside-down orientation, which means that the cold end is above and the convective flow has to be piped down against the direction of gravitational acceleration, the efficiency of the heat exchanger has to be considered with respect to a possible influence of the free convection. Experimental investigations were made using mock-ups of both heat exchanger types. No effect with regard to orientation was observed. The results are presented elsewhere [7].

The advantage of the PP-type heat exchanger is that a model for design optimisation exists at FZK which is validated in different current lead projects up to 80 kA. The disadvantage is the complex manufacturing process which is a cost issue.

The advantage of the MF-type heat exchanger is simplicity which reduces the manufacturing cost. On the other hand, no model yet exists which can be used for design optimisation. So a task has been established to find a general relation for the Nusselt number as a function of the Reynolds number which then can be used in the further optimisation. Available correlations such as Dittus-Boelter or heat transfer correlations for fully developed laminar flow are not applicable due the complex geometry which results in a complex flow structure involving recirculation and acceleration.

Fig. 2 shows the principle layout of the MF -type heat exchanger.

2. Modelling of the meander flow path fin heat exchanger

2.1. General procedure

For the investigation of the MF-type heat exchanger, the heat transfer characteristic has been studied in a 3-dimensional computational fluid dynamics (CFD) model. The CFD results are analysed and yield a parametric relation between the Nusselt number and the Reynolds number which then will be implemented in the 1-dimensional code CURLEAD [8] for further optimisation of the current lead.

For practical reasons, the procedure chosen was as follows:

1. Generation of a structured 2-dimensional mesh representing a cross-section of the current lead heat exchanger using ANSYS [9].
2. Import of this 2-dimensional mesh into the 3-dimensional code StarCD [10] where the 3-dimensional model was generated.
3. Definition of temperature dependent material and gas properties like density, thermal conductivity, and viscosity of helium and electrical resistivity of copper. The heat capacities of helium and copper as well as the thermal conductivity of copper were taken constant, since the computed Nusselt numbers are weakly affected by these variations along the current lead. The almost constant static pressure within the current lead allows neglecting the dependence of the helium properties.
4. Solution of the Navier–Stokes Equations and the energy equation employing the CFD-code StarCD yielding the local temperatures of the solid and the local temperatures, pressures and velocities of the fluid.
5. Integral analysis of CFD-data and derivation of a parametric relation between the Nusselt number and the Reynolds number. Generation of the seeked $Nu = f(Re)$ relation by least square fitting.
6. Calculation of the temperature profile in 1D exploiting the Nusselt number fit.

2.2. Short description of numerical codes used in the modelling of the MF-type heat exchanger

The flow within the current lead heat exchanger is computed employing the computational fluid dynamics (CFD) code StarCD. This code allows solving general thermohydraulic problems by selecting the appropriate models, i.e. governing equations, boundary conditions and properties.

Within the MF-type heat exchanger the flow is basically laminar, so that the governing equations are the Navier–Stokes equations coupled to the energy equation. Strong flow redistribution and acceleration due to the meandered flow path prohibits the development of substantial turbulence levels. Some test calculations employing turbulence models have shown negligible effect of turbulence on the heat transfer, so that all computations where performed assuming laminar flow. Flow velocities are much smaller than the speed of sound, i.e. the Mach number is small. Furthermore, pressure losses within the MF-type heat exchanger are small compared to the static pressure. Therefore, the static pressure is assumed constant. However, since the current leads have to bridge a temperature range from approximately 50 K to 300 K variable fluid properties must be accounted for. Within StarCD a low Mach number laminar formulation for constant static pressure and variable temperature-dependent fluid properties is selected for all simulations.

The assumed constant static pressure allows neglecting the effect of the pressure on fluid properties. This formulation speeds up simulations since acoustic phenomena are excluded. The