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Conceptual design of cooling systems for the launcher and receiver mirrors of the ITER LFS-CTS diagnostic

H. Policarpo[a,*], R. Rego[b], P.B. Quental[b], R. Moutinho[b]

[a] IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Portugal
[b] Instituto Superior Técnico, Universidade de Lisboa, Portugal

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ABSTRACT

A conceptual design of a cooling system for the launcher and receiver mirrors of ITER Low Field Side (LFS) Collective Thomson Scattering (CTS) diagnostic is presented. It is motivated by the fact that these mirrors are subjected to high thermal loads, e.g., neutron fluxes, that lead to maximum temperatures above the required maximum operational temperature of 450 °C for the material (SS 316L(N)-IG). Thus, it is necessary to develop a cooling system capable of maintaining the maximum temperatures of the mirrors below 450 °C, while complying with the CTS and nuclear fusion requirements. Computer Aided Design (CAD) and Finite Element (FE) models of the mirrors with different cooling channel geometries are developed. Steady state and transient thermal Finite Element Analyses (FEA) considering different mass flow rates are conducted for the assessment of the feasible solutions. The results obtained are conclusive, i.e., the cooling requirements are verified and with one of the proposed configurations it is possible to decrease the maximum temperatures of the SS 316L(N)-IG launcher and receiver mirrors from 2307 °C and 1064 °C to 381 °C and 147 °C, respectively, which, corresponds to a maximum temperature decrease of 83% and 86%, respectively. In future works, fatigue and creep analyses shall be implemented for stress and deformation assessment of the mirrors and respective reflective surfaces.

1. Introduction

Fast ion physics and diagnostic systems, e.g., CTS, will have a relevant role in ITER (meaning “The Way” in Latin) as confined alpha particles affect plasma dynamics and the global plasma confinement. The main function of the CTS diagnostic is to diagnose the fast alpha particle population, resulting from deuterium-tritium fusion reactions, allowing for estimations of plasma temperature and density, among other parameters [1].

The ITER CTS system, illustrated in Fig. 1, is located in drawer 3 of the tokamak equatorial port 12 and in a simplified manner may be described as being equipped with a 1.0 MW 60 GHz gyrotron, that launches a microwave beam which is transmitted through a waveguide (1) and reflected by the launcher mirror (2) into the plasma. The resultant plasma reflected microwave beams are collected by the receiver mirror (3) and transmitted by waveguides (4) to the electronic data acquisition and processing units [1].

Although there exist CTS diagnostics implemented in tokamaks, e.g., JET and TEXTOR [2–4], the ITER CTS diagnostic presents some additional challenges, e.g., higher neutron flux that lead to higher thermal loads [5] and consequently may require cooling systems [6–10].

In fact, some of the ITER CTS diagnostic components namely, the launcher and receiver mirrors, are subject to high thermal loads arising from: i) direct plasma thermal radiation; ii) neutron fluxes from the nuclear fusion reaction; iii) stray radiation from the surroundings and; iv) the gyrotron microwave launcher beam (only for the launcher mirror) [5]. The resultant thermal load leads to maximum temperatures of the mirrors that exceed the maximum operational temperature of 450 °C [11] (value considered for irradiation doses up to 10 dpa and here used as the most conservative value for the analysis). Note that, it is imposed by the ITER nuclear fusion requirement (see [5]) that the material of the mirrors shall be SS 316L(N)-IG.

Hence, this work focuses on a conceptual design of the cooling systems that can maintain the temperatures of the mirrors at a maximum operational temperature < 450 °C while compiling with the CTS requirements (e.g., maximum inlet cooling fluid mass flow rate of $\dot{m} = 1.5\ \mathrm{kg\,s^{-1}}$) and ITER nuclear fusion requirements, e.g., the cooling fluid shall be water [5].

The first part of this study consists on the development of the CAD and FE models of the two mirrors. For each mirror are developed four cooling channel geometries.

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* Corresponding author.
E-mail addresses: hugo.policarpo@tecnico.ulisboa.pt, hugo.policarpo@ist.utl.pt (H. Policarpo).

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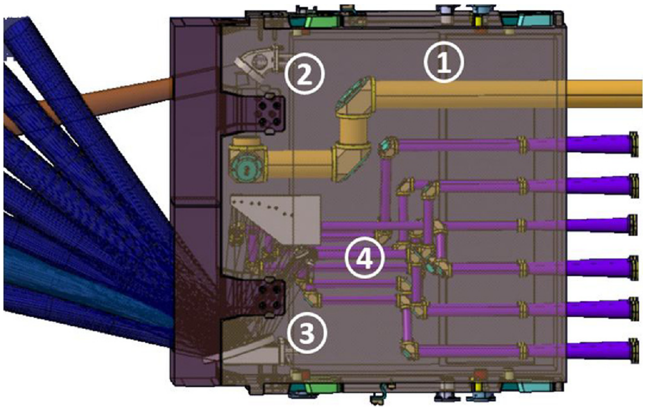

Fig. 1. Side view of the ITER LFS-CTS in which: 1 − Gyrotron beam transmission waveguide; 2 − Launcher mirror; 3 − Receiver mirror and; 4 − Reflected beams transmission waveguides.

The second part of this study consists on the steady state FEA of the different mirror cooling geometries considering different mass flow rates from which the feasible solutions are selected (one for each mirror). Afterwards, transient thermal FEA of the feasible solutions are conducted considering that ITER is expected to work in 400 s pulses, with a dwell time of 1400 s between pulses [12]. Subsequently, a steady state fluid flow thermal analysis is performed to verify the pressure drop and the convection coefficient considered in the analyses.

Future works shall contemplate thermal-structural, fatigue and creep analyses for stress assessment on the mirrors and respective supports to identify and improve critical regions as well as the deformation of the reflective surfaces of the mirrors.

2. Fundaments

Within the ITER tokamak, heat transfer occurs, provided that a temperature gradient exists, in three modes: i) conduction; ii) convection and; iii) radiation.

2.1. Heat transfer modes

Conduction may be defined as the energy transfer on the form of heat in the same medium from one point to another. For a one-dimensional (1-D) isotropic medium, the heat flux q''_{cond} may be expressed by Fourier's law [13] as

$$q''_{cond} = -k\frac{\mathrm{dT}}{\mathrm{dx}}, \tag{1}$$

where T is the temperature distribution in the medium and $k = \alpha\rho c_p$ is the thermal conductivity (α is the thermal diffusivity, ρ is the mass density and c_p is the specific heat (at constant pressure) of the medium.

Regarding convection, the convective heat flux q''_{conv}, may be expressed through Newton's law of cooling [13] as

$$q''_{conv} = h(T_s - T_\infty), \tag{2}$$

where T_s and T_∞ are the surface and fluid temperatures, respectively. h is the convective coefficient that depends on the types of convection (natural or forced) and fluid flow (internal or external), among others.

For forced convection in internal flow, the Reynolds' number Re_D may be expressed [13] as

$$Re_D = \frac{\rho u_m D_h}{\mu} = \frac{\dot{m} D_h}{A\mu}, \tag{3}$$

where ρ is the material density, u_m is the mean flow velocity, μ is the viscosity of the fluid, $\dot{m}$ is the mass flow rate, A is the internal cross-section area of the channel and D_h is its characteristic hydraulic diameter that may be expressed [13] as

$$D_h = \frac{4A}{P}, \tag{4}$$

where P is the internal perimeter.

The Nusselt number Nu_D, is defined as the quotient between the heat transferred by convection and by conduction in a fluid [13]. For a circular tube characterized by uniform surface heat flux and laminar, fully developed conditions, Nu_D is a constant, independent of ReD, Pr, and axial location and may expressed as

$$Nu_D = hD_h/k. \tag{5}$$

If the flow is considered turbulent and fully developed (where $Re_D \geq 10^3$ and Pr between 0.6 and 160) then,

$$Nu_D = 0{,}023 Re_D^{4/5} Pr^n, \tag{6}$$

where, n is 0.4 if $T_s > T_m$ and 0.3 if $T_s < T_m$ and T_m is the mean fluid temperature.

Regarding radiation, if the exchange occurs between a small surface at T_s and a much larger isothermal surrounding gray or black surfaces at T_{sur}, the net rate of radiation heat transfer flux $q"_{rad}$ may be expressed as

$$q"_{rad} = \varepsilon\sigma(T_s^4 - T_{sur}^4). \tag{7}$$

where ε is the emissivity of the surface of the body ($0 \leq \varepsilon \leq 1$) and σ is the Stefan-Boltzmann constant.

When solving radiation problems recurring to computational methods, the estimation of the view factors may be performed using the hemicube method in which a surface of a three-dimensional (3-D) body that emits radiation, it is divided into N smaller two-dimensional (2-D) elements. Hence, the accuracy of the results usually depends on the resolution of the hemicube method [14].

2.2. Microwave beam power

The microwaves present in the ITER CTS system have a density distribution on the launcher mirror $P_{beam}(x, y)$ that may be expressed as

$$P_{beam}(x, y) = P_{tot}\frac{2}{\pi w_x w_y}\exp\left(-2\left(\frac{x^2}{w_x^2} + \frac{y^2}{w_y^2}\right)\right), \tag{8}$$

where w_x and w_y are the characteristic dimensions of the microwave beam with a Gaussian distribution and P_{tot} is the total power of the beam [5].

The shape of the power beam isolines are in the form of ellipses defined as

$$\left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2 = 1, \tag{9}$$

where x and y are the dimensions of the launcher mirror, in the x and y coordinates, respectively, and a and b represent the lengths of the semi-major axis and semi-minor axis, respectively, considering $a > b$ [15].

For metals, the fraction of power absorbed A_{abs} due to a normal incidence of radiation, assuming that the transmitted fraction is negligible, may be expressed [5] as

$$A_{abs} = \left(\frac{4}{Z_0}\right)\sqrt{\pi f_{Hz}\mu_0\rho_{res}}, \tag{10}$$

where Z_0 and μ_0 are the empty space impedance and permeability, respectively, f_{Hz} is the gyrotron frequency and ρ_{res} is the electrical resistivity.