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CFD analysis of a regular sector of the ITER vacuum vessel. Part II: Thermal-hydraulic effects of the nuclear heat load

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ABSTRACT

The 3D Computational Fluid Dynamic (CFD) steady state analysis of the regular sector #5 of the ITER vacuum vessel (VV) is presented in these two companion papers using the commercial software ANSYS-FLUENT®. The pure hydraulic analysis, concentrating on flow field and pressure drop, is presented in Part I. This Part II focuses on the thermal-hydraulic analysis of the effects of the nuclear heat load. Being the VV classified as safety important component, an accurate thermal-hydraulic analysis is mandatory to assess the capability of the water coolant to adequately remove the nuclear heat load on the VV. Based on the recent re-evaluation of the nuclear heat load, the steady state conjugate heat transfer problem is solved in both the solid and fluid domains. Hot spots turn out to be located on the surface of the inter-modular keys and blanket support housings, with the computed peak temperature in the sector reaching ~290 °C. The computed temperature of the wetted surfaces is well below the coolant saturation temperature and the temperature increase of the water coolant at the outlet of the sector is of only a few °C. In the high nuclear heat load regions the computed heat transfer coefficient typically stays above the 500 W/m^2 K target.

1. Introduction

The ITER vacuum vessel (VV) will be located inside the cryostat and it will house the in-vessel components, providing a high quality vacuum for the plasma and the first confinement barrier [1,2]. The VV is a double-wall structure where the volume between the inner and outer shells is designed to allow the circulation of the cooling water through a complicated structure including the in-wall shielding (IWS) made of borated stainless steel plates.

The VV is partitioned in 9 sectors, each occupying 40°, with three bands of ports located on the outboard side. Each sector is actively cooled by pressurized sub-cooled water at 100 °C and 0.9 MPa, entering from dedicated piping on the lower port, bifurcating and flowing both in the inboard and in the outboard side through the space left open between inner and outer shell as well as in other auxiliary structures, see below, before joining again and being routed through the upper port frame to an exit pipe. Here only half (20°) of the sector will be considered, see Fig. 1, assuming symmetry around the poloidal plane bisecting the central equatorial port.

In Part I of this paper [3], we presented a detailed *hydraulic* analysis of the VV RS #5, considering only the fluid portion of the domain and ignoring the thermal load of nuclear origin which acts on the VV during the operation of the machine. Here we address the steady-state conjugate heat transfer problem, including the VV solid structure and concentrating on the thermal-hydraulic effects of the recently re-calculated nuclear heat load.

As discussed in [3], previous published CFD work on the ITER VV [4,5], was based on the design status in 2006 and did not include several of the important features of the VV like the Inter-Modular Keys (IMKs), the Blanket Support Housings (BSHs) or the Triangular Support (TrS).

2. Model

As in [3], the Reynolds-Averaged Navier–Stokes (RANS) model with SST k-ω [6] turbulence closure was chosen to compute the steady-state flow field in the VV. Now the energy equation is also solved, both in the water coolant and in the solid structures, determining the temperature distribution in the two sub-domains. The

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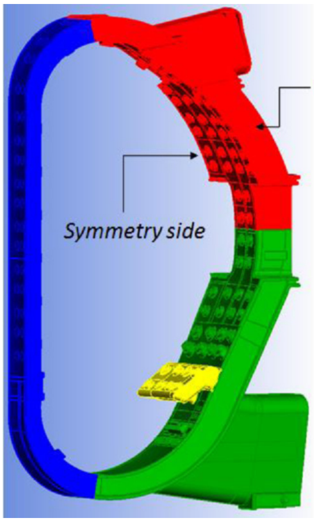

Fig. 1. Schematic view of (half) of the VV regular sector #5, ~11.5 m tall. The three segments constituting the sector are highlighted: inboard (Inb) in blue, outboard bottom (OB) with the lower port and the two half equatorial ports in green, outboard top (OT) with the two half equatorial ports and the upper port in red. The triangular support (TrS) is also shown, in yellow. The original 40° sector is bisected leaving a "symmetry side". On the side facing the reader the field joints (FJ) are located, connecting this sector to the neighbouring sector. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

energy balance of the coolant is coupled to the flow field through the advective contribution to the energy flux, while the thermal coupling between fluid and structures is achieved by enforcing the continuity of temperature and heat flux at the interface (wall). Therefore, the heat transfer coefficient (HTC) between coolant and wall is an output (not an input) of our calculation. Finally, the temperature feeds back on the flow field both through the effect of buoyancy and through temperature-dependent thermo-physical properties.

The software packages adopted for the present analysis are the same as in [3], except a more recent version of ANSYS ICEM [7], 14.5, was used for the smoothing of the grids.

3. Computational solid domain

The RS #5 can be divided into different segments, see Fig. 1, including the inboard (Inb) segment, the two outboard, bottom (OB) and top (OT) segments, and the Triangular Support (TrS) structure.

The solid domain retained for the thermal-hydraulic analysis can be split in two parts: the IWS and the rest, which will be called "skeleton" below. The IWS and the skeleton domains are shown in Figs. 2 and 3 for the case of the Inb and OT segment, respectively. The TrS solid domain is shown in Fig. 4.

In Fig. 2a, the location of the toroidal ribs, which constitute as seen in [3] an obstacle for the fluid flow in the Inb segment, is clearly visible, while in Fig. 2b several details of the skeleton included in our modelling (like divertor rails, IMKs, BSHs and centering keys) are highlighted. In Fig. 3a, the space left empty for the internal poloidal ribs is highlighted together with IMK #9.

For the TrS, no IWS is foreseen in the cavity occupied by the fluid. As opposed to the rest of the VV skeleton, which is made of stainless steel, the TrS is made also of copper, as shown in Fig. 4.

4. Mesh generation in the solids

The mesh is generated by ICEM using the Octree algorithm. As in the case of the fluid domain, the mesh was separately generated

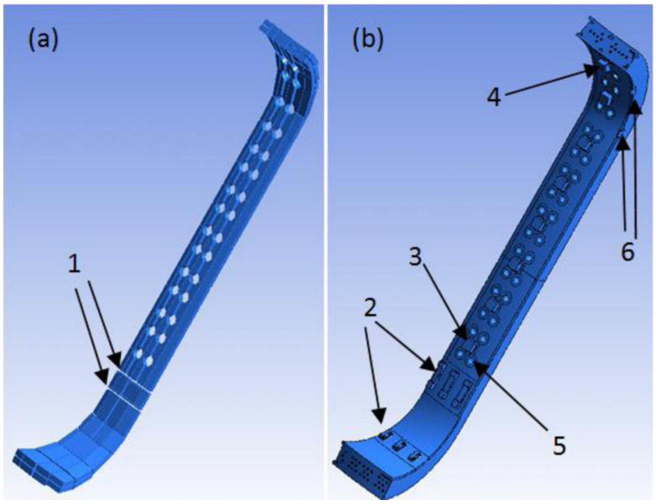

Fig. 2. Inb solid domain: (a) IWS, with empty space left by the toroidal ribs (marked with "1"). (b) Skeleton with divertor rails (marked with "2"), IMKs #1 (marked with "3") to #8 (marked with "4"), blanket support housings (marked with "5") and centering keys (marked with "6").

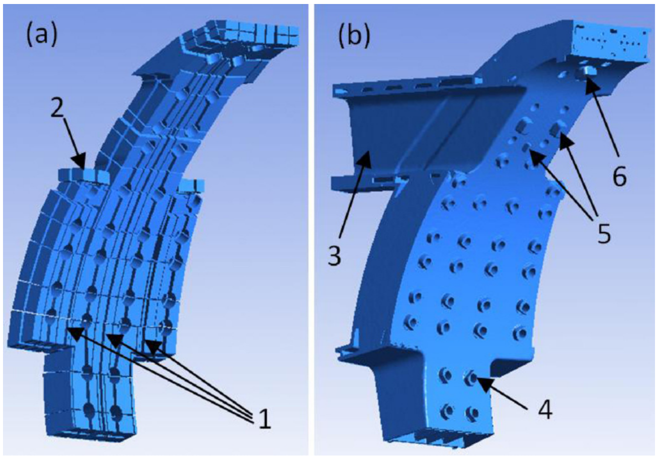

Fig. 3. OT solid domain: (a) IWS, with empty space left by the poloidal ribs (marked with 1), including horizontal tiles below the upper port (marked with "2″). (b) Skeleton with upper port (marked with 3), blanket support housings (marked with 4), centering keys (marked with 5) and the IMK #9 (marked with 6).

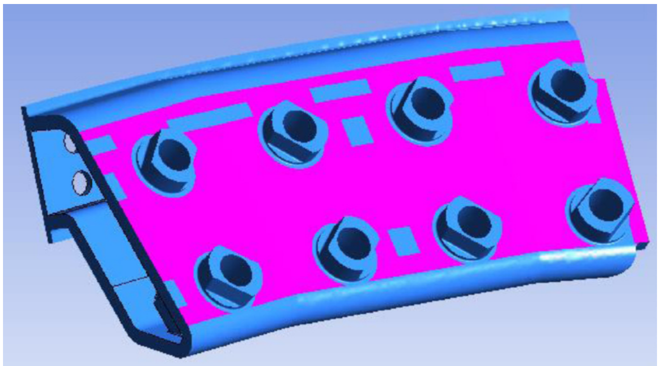

Fig. 4. TrS solid domain (stainless steel in blue, copper plates in pink). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)