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Thermal-Hydraulic Modeling and Analysis of ITER Tungsten Divertor Monoblock

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ABSTRACT

In this work a mathematical model has been developed/updated to investigate the steady-state and transient thermal-hydraulic performance of ITER tungsten divertor monoblock. A two-dimensional numerical finite difference technique is adapted in Cartesian coordinate system where the implicit scheme is used for transient calculation. The model accounts for the melting, vaporization, and solidification of the upper layer of the divertor. The model is used to predict the steady-state thermal behaviour of the divertor under incident surface heat fluxes ranges from 2 to 20 MW/m^2 for a bare cooling tube and cooling tube with swirl-tap insertion. The model is also used to simulate the thermal response of the divertor structure materials subjected to high heat flux during a vertical displacement event (VDE) where 60 MJ/m^2 plasma energy is deposited over 500 ms.

INTRODUCTION

The divertor target plates are the most thermally loaded in-vessel components in a fusion reactor where high heat fluxes are produced on the Plasma Facing Components (PFCs) by intense plasma bombardment, radiation and nuclear heating by neutron irradiation. PFCs are designed to withstand the highest surface heat fluxes, i.e. 10 MW/m^2 during steady state operation and 20 MW/m^2 during slow transients. In order to meet these requirements, the PFCs employ a monoblock technology, made of pure tungsten armor joined to the copper alloy pipe via a pure copper interlayer. In a previous work, the author developed a computer code entitled ITERTHA to simulate the cooling processes of a flat tile divertor. The objective of the present work is to modify and update the previous model to deal with the ITER tungsten divertor monoblock to simulate its performance under both normal and off-normal operation.

METHODOLOGY

The present design for the water-cooled divertor consists of tungsten monoblocks crossed by a CuCrZr pipe where the coolant circulates while pure copper is used as interlayer as shown in Fig. 1.

Coolant temperature

The coolant is treated as one lumped node, thus it is assumed that the coolant is well stirred and has a uniform temperature. The coolant tube is divided into a given number of elements in the axial z-direction where the general energy balance equation is applied to each element.

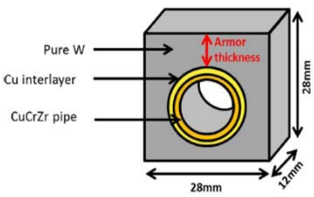


Fig.1 ITER tungsten divertor monoblock.

Divertor temperature

A two-dimensional numerical finite difference technique is adapted for the heat conduction through the divertor where the implicit scheme is used for transient calculation. The model also accounts for the melting, vaporization, and solidification of the upper layer of the divertor facing plasma.

Coefficient of heat transfer

The flow regime is defined at each axial node and then the heat transfer coefficient is determined. The selected heat transfer correlations cover all possible operating conditions of ITER under both normal and off-normal situations.

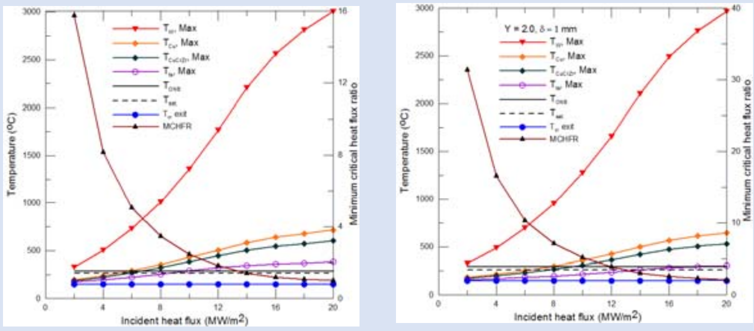
Swirl-tap insertion

Swirl-tap insertion in the coolant tube significantly increases the heat transfer coefficient in forced convection regime, while its influence on the fully developed nucleate boiling regime is negligible; however, it considerably increases the critical heat flux. When the tube features a swirl-tape insert, swirl-tape factors are applied.

RESULTS

Steady-state results

Calculations are performed for Incident Surface Heat Flux (ISHF) values of 2, 4, 6, 8, 10, 12, 14, 16, 18 and 20 MW/m^2 under coolant inlet temperature of 150°C, pressure of 5 MPa and velocity of 16 m/s. Figure 2 shows the variation of the predicted maximum temperature values as well as the minimum critical heat flux ratio (MCHFR) versus ISHF. It is found that, for bare tube divertor, the MCHFR < 1.4 for ISHF > 14 MW/m^2, while for swirl-tape tube divertor, the MCHFR > 2.14.

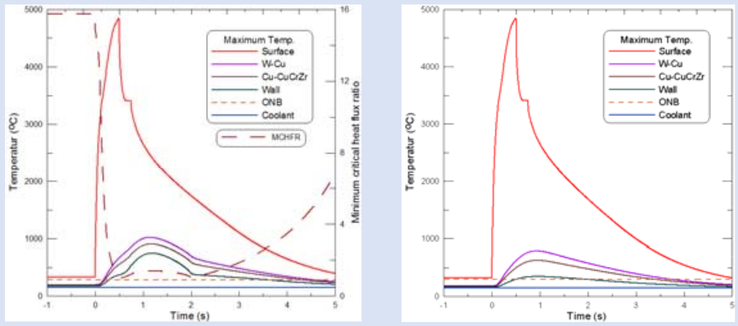


(a) Divertor with bare tube (b) Divertor with swirl tap tube

Fig. 2 Predicted maximum temperatures and minimum critical heat flux ratio.

Transient results

Figure 3 shows a simulation of VDE of 60 MJ/m^2 during 0.5 s. It is noticed that, in case of bare tube divertor, the MCHFR is < 1.4 for a period of 2.123 s, while the predicted MCHFR is 1.548 for swirl-tape tube divertor.



(a) Divertor with bare tube (b) Divertor with swirl tap tube

Fig. 2 Predicted divertor temperatures and MCHFR under 60 MJ/m^2 VDE in 0.5 s.

Figure 3 shows both the melted and evaporated layer thickness due to plasma energy deposition. Figure 4 shows a contour plot of the temperature distribution through the divertor at (a) time = 0.5 s (at the end of the VDE and (b) time = 5.0 s (end of calculation time).

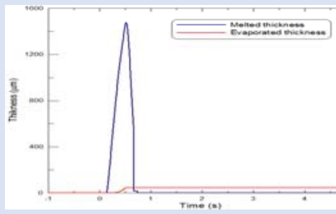
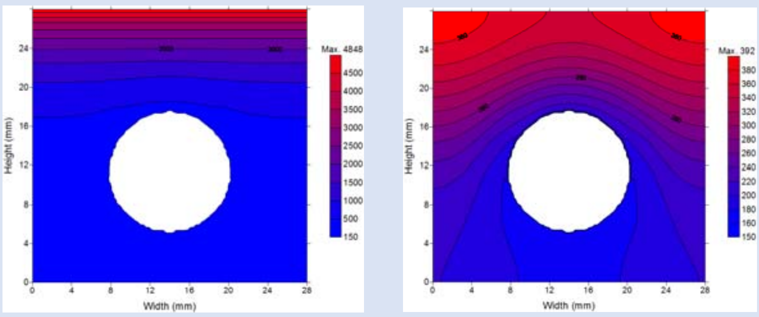


Fig. 3 Melted and evaporated thicknessVDE.



(a) Time = 0.5 s (b) Time = 5.0 s

Fig. 4 Predicted divertor temperature distribution under 60 MJ/m^2 VDE in 0.5 s.

CONCLUSION

- A mathematical model has been developed/updated to simulate the thermal-hydraulic behaviour of ITER tungsten divertor monoblock under both steady and transient states.
- The model is used to predict the temperature distribution through the divertor structure materials as well as the minimum critical heat flux ratio for incident surface heat flux values of 2, 4, 6, 8, 10, 12, 14, 16, 18 and 20 MW/m^2 for both bare and swirl-tap cooling tube.
- The model is also used to simulate the thermal response of ITER divertor under intense transient energy deposition of vertical displacement events. This VDE of 60 MJ/m^2 deposited in 500 ms leads 1480 μm of the tungsten upper layer to melt and 44 μm to evaporate.