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Thermal hydraulic modeling and analysis of ITER tungsten divertor monoblock

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In previous work [1 & 2], the author developed a computer code to simulate the cooling processes of a flat tile divertor in both normal and off-normal operation. In the present work, the previous model is modified and updated to deal with the ITER tungsten divertor monoblock in order to simulate its performance under both steady and transient states. The model predicts the thermal response of the divertor structural materials and coolant tube. The divertor plate is divided into specified radial zones, and a two-dimensional heat conduction calculation is performed to predict the temperature distribution for both steady and transient states where the finite difference technique is adapted and 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. The model is then used to predict the steady-state thermal behaviour of the divertor under incident surface heat fluxes ranges from 2 to 20 MW/m2 for a bare cooling tube and cooling tube with swirl-tap insertion. The model predicts the maximum tube surface heat flux and the minimum critical heat flux ratio for all cases as well. The model is also used to simulate the divertor materials response subjected to high heat flux during a vertical displacement event (VDE) where 60 MJ/m2 plasma energy is deposited over 500 ms.

Methodology
• 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.
• 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.

Model verification
The previous model was validated, verified and benchmarked in the previous work [1 & 2] for flat tile dirvertor. However, the present version for tungsten divertor monoblock is verified by comparing its results for DEMO divertor against previous calculation of F. Crescenzi et al. 3 at incident surface heat flux of 10 MW/m2. Calculation is performed for the following divertor dimensions and operating conditions:
• The armor thickness from the surface to the interlayer: 5 mm,
• Tube inner diameter: 12 mm,
• Tube thickness: 1.5 mm,
• Interlayer thickness: 1 mm,
• Armor side thickness: 3 mm.
• Divertor height: 25 mm.
• Divertor width: 23 mm.
• Coolant temperature: 150C,
• Water pressure: 5 MPa,
• Water velocity: 16 m/s.
Figure 1 shows a good agreement where the maximum surface temperature predicted by the present model is 20C higher than the corresponding value predicted by F. Crescenzi et al. This could be attributed to the difference in the correlations used for heat transfer coefficient determination in both models, where the present model uses Dittus & Boelter correlation while Sieder & Tate correlation was used by F. Crescenzi et al.

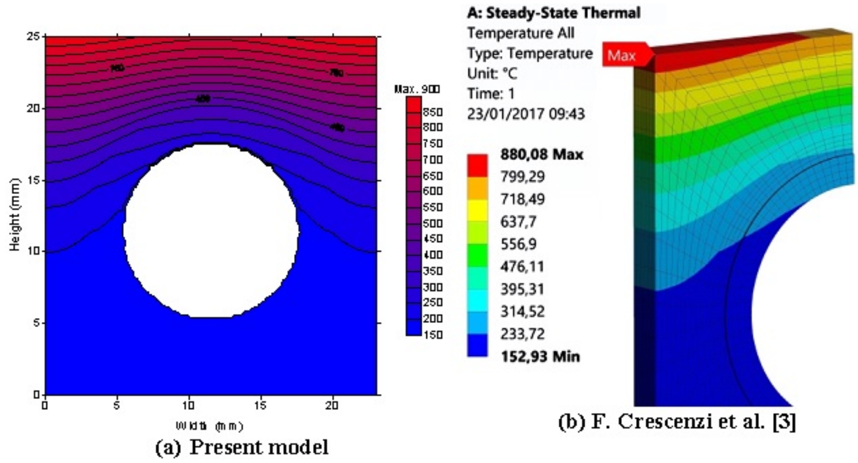


Fig. 1 Temperature distributions for DEMO divertor under an incident surface heat flux of 10 MW/m^2.

Figure 1: Temperature distributions for DEMO divertor under an incident surface heat flux of 10 MW/m2.

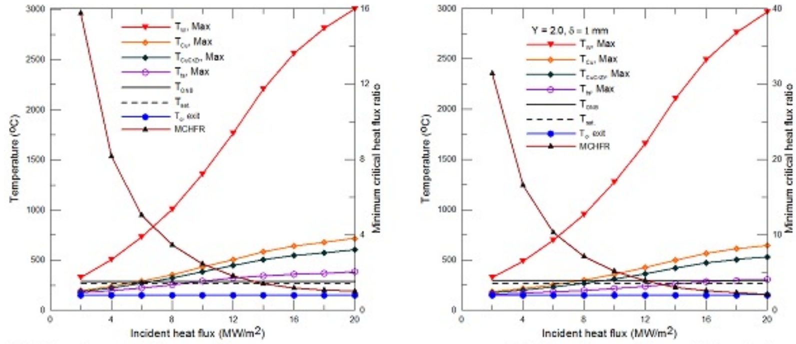
Results

The mathematical model is applied on ITER tungsten divertor monoblock for the following dimensions and operating conditions 4:

- Tube inner diameter: 12 mm
- Tube thickness: 1.5 mm
- Interlayer thickness: 1 mm
- Armor side thickness: 8 mm
- Divertor length: 12 mm
- Divertor height: 28 mm
- Divertor width: 28 mm
- Coolant temperature: 150⊠C,
- Water pressure: 5 MPa,
- Water velocity: 16 m/s.

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/m2. Fig. 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/m2, while for swirl-tape tube divertor, the MCHFR > 2.14.



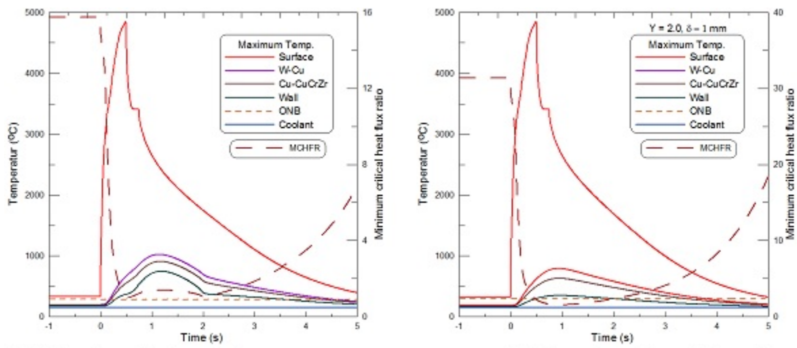
(a) Divertor with bare tube (b) Divertor with swirl tap tube

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

Figure 2: Predicted maximum temperatures and minimum critical heat flux ratio.

Transient results

Fig. 3 shows a simulation of VDE of 60 MJ/m2 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. 3 Predicted divertor temperatures and MCHFR under 60 MJ/m^2 VDE in 0.5 s.

Figure 3: Predicted divertor temperatures and MCHFR under 60 MJ/m2 VDE in 0.5 s

Fig. 4 shows both the melted and evaporated layer thickness due to plasma energy deposition. The tungsten upper layer starts to melt at τ =0.144 s and the melted layer thickness reaches 1480 μm at τ =0.515 s, then resolidification starts till τ = 075 s. The evaporation thickness reaches 44 μm at τ =0.6 s.

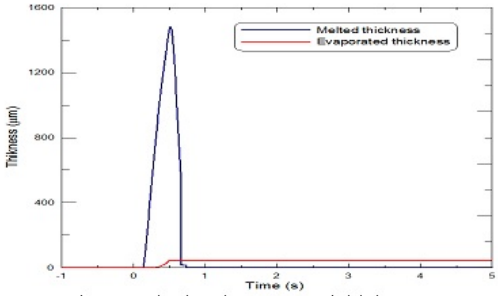


Fig. 4 Melted and evaporated thickness.

Figure 4: Melted and evaporated thickness.

Conclusions
• 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/m2 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/m2 deposited in 500 ms leads 1480 μm of the tungsten upper layer to melt and 44 μm to evaporate.

References
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