High heat flux thermal–hydraulic analysis of ITER divertor and blanket systems

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Abstract

Three separate cooling systems are used for the divertor and blanket components, based mainly on flow routing access and on grouping together components with the highest heat load levels and uncertainties: divertor, limiter/outboard baffle, and primary first wall/inboard baffle. The coolant parameters for these systems are set to accommodate peak heat load conditions with a reasonable critical heat flux (CHF) margin. Material temperature constraints and heat transport system space and cost requirements are also taken into consideration. This paper summarises the three cooling system designs and highlights the high heat flux thermal–hydraulic analysis carried out in converging on the design values for the coolant operating parameters. Application of results from on-going high heat flux R&D and a brief description of future R&D effort to address remaining issues are also included. © 1998 Elsevier Science S.A. All rights reserved.

1. Divertor and blanket systems

Fig. 1 shows a poloidal cross-section of the ITER device. The blanket/first wall (FW) system consists of a number of modules mechanically attached to a back plate [1]. The size of the modules is limited by the capacity of fabrication equipment and the weight which can be handled by the remote handling equipment (~ 4.3 tons). Three types of shielding modules, determined by the requirements of their first wall, can be identified. The majority of the modules, known as primary first wall (PFW) modules, have a first wall designed to dissipate a maximum steady-state heat flux of 0.5 MW m⁻². The two toroidal belts of modules located opposite the X-point on the inboard and outboard are referred to as baffle modules and are designed to accommodate steady-state heat loads up to 3 MW m⁻². The limiter modules form four toroidal belts located beneath the outboard ports covering an area of ~ 210 m². They are in contact with the plasma during start-up and shutdown and are designed to accommodate a steady-state heat flux of up to 5 MW m². Alternatively, it is being considered to use only two limiter modules at the equatorial ports of total area ~ 10 m². These modules would be subjected to higher heat loads during start-up and shutdown (~ 10–15 MW m⁻²) and would have to be designed accordingly, however it would be easier to replace them.
The divertor, using a single null poloidal geometry with active pumping located at the bottom of the device, will provide for power and particle exhaust [2]. It consists of 60 cassettes onto which are mounted high heat flux components (HH-FC’s) which can be installed and removed outside the vessel (in a hot cell).

The plasma facing component (PFC) configuration of the PFW, limiter and baffle, and divertor consist typically of a coolant tube inside a heat sink on top of which is attached the armour. Presently, Be is used as armour for the PFW. It is also a candidate for the limiter and baffle and has been considered for some regions of the divertor. Tungsten and carbon-fibrecomposites (CFC) are considered for the lower baffle area and limiter respectively, and are also prime candidates for the scrape-off layer (SOL) strike zone of the vertical

Fig. 1. Cross section of the ITER device showing the blanket and divertor systems.
### Table 1
Cooling system design parameters

<table>
<thead>
<tr>
<th>Cooling system</th>
<th>PFW/IB</th>
<th>Limiter/OB</th>
<th>Divertor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal power (MW)</td>
<td>1500</td>
<td>580</td>
<td>400</td>
</tr>
<tr>
<td>Coolant conditions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inlet temperature (°C)</td>
<td>140</td>
<td>140</td>
<td>140</td>
</tr>
<tr>
<td>Inlet pressure (MPa)</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Mass flow rate (kg s(^{-1}))</td>
<td>6500</td>
<td>4500(^{a})</td>
<td>∼3700</td>
</tr>
<tr>
<td>Nominal temperature rise (°C)</td>
<td>52</td>
<td>∼30(^{a})</td>
<td>∼25</td>
</tr>
<tr>
<td>Pressure drop (MPa)</td>
<td>∼0.7</td>
<td>∼1.0(^{a})</td>
<td>∼1.5</td>
</tr>
<tr>
<td>Number of loops</td>
<td>10</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Average heat flux (MW m(^{-2}))</td>
<td>0.25 for PFW 2.4 for limiter</td>
<td>5 for VT(^{b})</td>
<td></td>
</tr>
<tr>
<td>Peak heat flux (MW m(^{-2}))</td>
<td>0.5 for PFW 5 for limiter</td>
<td>20 for VT</td>
<td></td>
</tr>
<tr>
<td>PFC coolant velocity (m s(^{-1}))</td>
<td>∼3–5 for PFW 8.5(^{a}) for limiter</td>
<td>∼12–15 for VT</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.5 for baffle</td>
<td>3.5 for baffle</td>
<td>3.5 for baffle</td>
</tr>
</tbody>
</table>

\(^{a}\) Assuming 2-pass poloidal flow in the first wall. For 3-pass FW poloidal flow, the mass flow rate, pressure drop, temperature rise and FW velocity are 3600 kg s\(^{-1}\), ∼1.2 MPa, 37°C, and 11.6 m s\(^{-1}\), respectively.

\(^{b}\) VT, vertical target.

The PFW and limiter use tubes of stainless-steel, while the baffle and divertor use Cu alloy tubes due to the higher heat flux requirements, and have a thin SS insert (0.1–0.2 mm) or Ni−Cr plating inside the coolant tube to avoid Cu contact with water. This avoids the uncertainty associated with Cu/H\(_2\)O corrosion and erosion which could lead to high levels of activated products in the coolant.

Three separate cooling systems are used, based mainly on flow routing access and on grouping together components with the highest heat load levels and uncertainties: divertor, limiter/outboard baffle (L/OB), and PFW/inboard baffle (PFW/IB). For all three systems, the inlet pressure and temperature are set at 4 MPa and 140°C, respectively based on maintaining reasonable critical heat flux (CHF) and saturation margin while maintaining the Cu above ∼140–150°C to limit the irradiation embrittlement. A 140°C inlet temperature also results in good heat transfer in the heat exchanger which helps maintain its size and cost to a reasonable level. Typical design parameters and operating conditions for the PFW, limiter, baffle and divertor are summarised in Table 1, including the flow rates whose bases are discussed in the following sections.

### 2. Divertor cooling system

Fig. 2 shows a cross-section of a divertor cassette illustrating the location of the different components. Fifteen such cassettes are fed in parallel by each of the four cooling loops along radial straight feed and return lines. Three cassettes are fed through each port, 6 pipes per port (3 feed and 3 return). On entering the cassette, the coolant is split in two, half to feed each toroidal half of the cassette. The currently preferred coolant circuit through each half cassette is illustrated in Fig. 3, including flow distribution for an upper bound total divertor flow rate of 3700 kg s\(^{-1}\). The coolant is routed through the cassette body to cool, in parallel, the inner and outer vertical target assemblies, which are the highest loaded components. The vertical targets are fed in series with the dump target which also receives...
high flux ($\sim 20 \text{ MW m}^{-2}$) during transient excursions when the SOL is swept rapidly across its surface. However, the thermal load is absorbed inertially by the CFC and Cu, mitigating the thermal–hydraulic requirements of the short dump. Depending on this mitigating effect, it could be possible to reduce the flow through the dump by cooling it in parallel with the wing and liner, and, thus, lower the overall pressure drop. This alternative is being studied.

The coolant is subsequently fed in the parallel and series configuration shown in Fig. 3 to cool several sub-circuits in parallel, namely the cassette body, the wing and liner assemblies of the inner and outer channels, and the dome assembly. For the wing, the coolant first enters the wing foot (incident flux $3 \text{ MW m}^{-2}$) and then passes along the length of the wing through a series of $\sim 6 \text{ mm}$ channels to the upper foot before returning via the gas box liner to the lower foot and then to the cassette body. For the wing nose, a separate annular flow is under consideration as an alternative. Coolant to the dome is used to cool the dome block which, due to the high neutron heating in this region, has closely packed coolant channels, and to cool the dome PFC, a hypervapotron structure. The coolant is then recombined in the cassette body before leaving the vessel.

3. Vertical target CHF analysis

The overall flow rate requirement of the divertor system is derived mainly from accommodation of the high quasi-steady state heat flux at the vertical target with an acceptable CHF margin. The vertical target must accommodate a steady state peak heat flux of $5 \text{ MW m}^{-2}$ and a transient peak heat flux of $20 \text{ MW m}^{-2}$ over 10 s. For such a high heat flux, a CFC monoblock (or as an alternative saddle block) with a swirl tape insert is the preferred configuration. Its geometry provides good accommodation of pressure and thermal stress and the resulting CHF values are superior or roughly comparable to other CHF enhancement techniques tested at ITER divertor coolant conditions [3]. The configuration considered for the analysis and shown as part of Fig. 4 consists of a CFC monoblock with a $10 \text{ mm}$ Cu tube and a swirl tape of thickness $2 \text{ mm}$ and of twist ratio $2$. The monoblock pitch and diameter, and, for transient cases, the armour thickness, $\Delta X$, are important factors influencing the heat flux peaking factor (the ratio of peak coolant heat flux at the top of the tube to incident heat flux), $f_p$, and CHF margin. For a tube diameter of $10 \text{ mm}$ under steady state conditions, $f_p$ increases from $\sim 1.46$ for a pitch of $19 \text{ mm}$ to $\sim 1.6$ for a pitch of $24 \text{ mm}$ [4]. For a tube diameter of $10 \text{ mm}$, the pitch should not be less than $\sim 20 \text{ mm}$ based on
the structural integrity of the minimum section on each side of the tube. Currently, minimum pitches of 20.4 and 20.8 mm are considered for the inner and outer target, respectively. These correspond to 14 and 20 monoblock assemblies per half cassette respectively.

The incident heat flux at which CHF is reached (ICHF) in the coolant tube was calculated locally along the vertical target as a function of the local coolant conditions (velocity, temperature and pressure) based on the CEA-corrected TONG-75 correlation [5,6]. The temperature was adjusted along the vertical target coolant tubes based on the heat flux profile and the coolant mass velocity and specific heat. The pressure was estimated based on the CEA correlation for swirl tape tube made of bored copper of roughness, 6 μm [7]. The coolant temperature and pressure at the inlet to the vertical target were assumed to be 140°C and 3.9 MPa, respectively. The results are summarised in Fig. 4 for the inner vertical target of a sample case with a coolant velocity of 15 m s⁻¹. The left axis of the figure shows the heat flux profile during the 10 s transient along the vertical target [8] and the ICHF calculated from the local coolant conditions. The right axis shows the coolant temperature along the vertical target, calculated incrementally from the local heat flux, and
the saturation temperature corresponding to the local pressure. The local pressure is shown on the upper scale corresponding to the distance along the vertical target.

From the figure, the local coolant temperature can be seen to rise rapidly at the region of peak IHF, while the local coolant saturation temperature falls gradually with decreasing coolant pressure. The corresponding ICHF in this case is \( \sim 40\% \) higher than the peak IHF and much higher at other locations. It is hoped that this CHF margin could be extended due to the effect of the highly peaked incident heat flux profile, which is being addressed by the ongoing R&D. A coolant velocity of \( \sim 15 \text{ m s}^{-1} \) in the vertical target would result in a total divertor coolant flow rate of \( \sim 3300 \text{ kg s}^{-1} \).

With such velocity the pressure drop is a concern and the length of the swirl tape portion of the vertical target should be minimised. An important parameter is the channel roughness which can substantially affect the pressure drop and whose end-of-life value is difficult to estimate as it depends on the coolant chemistry control and operation in the unique fusion environment. An R&D effort is underway to address this issue. The divertor vertical target configuration and thermal hydraulic design parameters will be finalised in light of the information to be obtained from the on-going R&D on those key issues affecting the CHF and pressure drop, and on other issues such as fabrication and thermomechanics performance of the PFC configuration.

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**Fig. 4.** Incident heat flux and CHF, and coolant temperature and pressure along inner vertical target of divertor (coolant velocity = 15 m s\(^{-1}\); pitch = 20.4 mm).
4. Blanket cooling systems

The PFW/IB cooling system comprises 10 loops each feeding two sectors (i.e. 49 modules and the horizontal port shield plugs). The coolant is fed through the top port and routed through the double-walled back plate which acts as a manifold feeding the different modules in parallel and then routing the water exiting the modules to the bottom of the back plate. The return leg of the coolant utilises the maximum back plate flow area to maximise the coolant residence time before leaving the in-vessel region in order to mitigate the coil gamma-heating and neutron-activation problems associated with the short half-life $^{16}$N (7.1 s) and $^{17}$N (4.1 s), respectively.

The limiter/OB cooling system comprises four loops each feeding five sectors (60 modules) and is fed through the horizontal port and routed through the double-walled back plate in a similar fashion. For both systems, it is desirable to subdivide the loop into several independent subcircuits within the back plate to facilitate the draining/drying and leak testing procedures.

5. Blanket module flow routing and flow parameters

The blanket module configuration is longer toroidally ($\sim 2$ m) than it is poloidally ($\sim 1$ m) and in that sense, it is more amenable for a toroidal flow layout based on geometry. However, high off-normal plasma energy deposition occurring, for example as a result of a plasma vertical displacement event (VDE), is predicted to have a poloidal profile but to be toroidally uniform. Thus, although the maximum heat flux on a first wall tube will be about the same for both toroidal and poloidal arrangements, the integrated heat flux on a first wall tube will be higher for a toroidal flow arrangement than for a poloidal flow arrangement. Results of initial analysis indicate that, in relative terms, in order to prevent the coolant from reaching CHF-like conditions following a VDE (60 MJ m$^{-2}$ energy deposition over 0.3 s), an extra Be armour thickness of $\sim 1$–$2$ mm would be required in the case of toroidal cooling as opposed to the case of poloidal cooling. This extra armour thickness provides longer lifetime for an already tight armour thickness design window [9]. Poloidal cooling is then preferred for the first wall on this basis while toroidal cooling is used in the shield part of the module.

This choice is even clearer for the limiter where the maximum design heat flux during start-up/shutdown of 5 MW m$^{-2}$ is toroidally continuous, however, the average poloidal heat flux is only $\sim 2.4$ MW m$^{-2}$ over 1 m. Similarly, for the baffle, the maximum design heat flux of 3 MW m$^{-2}$ is toroidally continuous, however, the average poloidal heat flux is 1 MW m$^{-2}$. For example, to achieve a desirable CHF margin of $\sim 2$ based on the CEA-corrected TONG-75 correlation [5,6], a velocity of 8.5 m s$^{-1}$ is required for 2-pass poloidal flow through the limiter first wall. Single pass toroidal flow would require a velocity of 11.6 m s$^{-1}$ resulting in a 36% increase in cooling system flow requirements and a $\sim 0.4$ MPa increase in pressure drop.

Fig. 5 shows a cross section of a blanket module. The flow enters and exits the module through branch pipe connections to the back plate. The coolant is routed through the module by a combination of series flow to effectively cool the first wall (2-pass poloidal flow), the shield (2-pass toroidal flow through each coolant channel layer) and the four protruding structures housing the mechanical attachment (1-pass radial flow through each structure). Parallel coolant connections at the back are planned for cooling the flexibles and bolt structure and the module shear keys.

The coolant temperature rise through the modules is maintained at $\sim 50^\circ$C based on thermal stress considerations. This also provide a good saturation margin, even during a power excursion. For the limiter and baffle, as described previously, the higher heat loads require faster flow to maintain a reasonable CHF margin, resulting in a lower coolant temperature rise, as summarised in Table 1.
The potential for instability exists for the flow through all of the parallel channels in the first wall of the modules. A detailed analysis of static and dynamic instability was performed for the limiter, baffle and PFW modules to ascertain the flow parameters required to avoid instability. It was found that the selected combination of velocity, pressure and temperature fall safely outside the instability parameter range \[10\]. Note that for the divertor case, the velocity and pressure drop are much higher and the flow is inherently more stable, however, calculations are planned to confirm this.

6. Conclusions

Three separate cooling systems are used for the divertor and blanket components. The coolant parameters for these systems are set to accommodate peak heat load conditions with a CHF margin. Material temperature constraints, heat transport system space and cost requirements are also taken into consideration. Current flow parameters and their bases have been presented. In the future, in light of ongoing R&D results, the PFC geometry and coolant parameters could be adjusted to maintain reasonable margins.

Acknowledgements

This report is an account of work undertaken within the framework of the ITER EDA Agreement. The views and opinions expressed herein do not necessarily reflect those of the Parties to the ITER Agreement, the IAEA or any agency thereof. Dissemination of the information in this paper is governed by the applicable terms of the ITER EDA Agreement.

References
