Thermal and Hydraulic Analysis of the ITER Upper Vertical Stabilization Coil

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Abstract The ITER upper vertical stabilization (VS) coil is a part of the ITER in-vessel coil (IVC) system, which has the abilities of restraining edge localized modes (ELMs) and maintaining plasma vertical stability. Preliminary structural analysis of the coil has revealed serious thermal stress problems. Due to the very restricted geometry space, it is necessary to perform detailed analysis on thermal and hydraulic characteristics to help optimal design of the coil. It will focus on the temperature distribution and energy balance, as well as some key factors, such as the coolant flow state and surface emissivity, which have influences on the coil performance. The APDL code and some hand calculations are employed in the analysis. The results show that the coolant convection can effectively take away the heat deposited in the coil. But improving the coolant flow state can hardly mitigate the peak temperature occurring at the edges of coil attachments, which are located far away from the coolant. Thermal radiation was expected to be a good method of cooling down these parts. But the reality is not so optimistic since it usually contributes little in the whole energy balance. However, the effect of thermal radiation will become remarkable when bad scenarios or accidents take place. Poor radiation performance of the coil will result in a potential safety hazard.

Keywords: VS coil, thermal, hydraulic

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(Some figures may appear in colour only in the online journal)

1 Introduction

The ITER in-vessel coil (IVC) system consists of 27 edge localized mode (ELM) coils and 2 vertical stabilization (VS) coils. The ELM coils are designed to provide magnetic perturbations resonant to minimize potentially high power deposition onto plasma facing components by ELMs, while the VS coils are designed to provide fast vertical stabilization control of the plasma. All the coils are located behind the blanket shield modules and are mounted to the vacuum vessel inner wall. One of the VS coils is located in the upper half of the machine just above the upper ports and the other is located in the lower half of the machine just above the triangular support. The saddle connection of upper and lower VS coils tends to stabilize the plasma vertical position by induction, and the connection of power supply in the VS coil circuits allows for generation of current flow which can stabilize the plasma vertical position in a feedback loop [1−3].

The ITER upper VS coil is designed with four turns of conductor and other attachments including spine, clamp and rail support. The “Stainless Steel Jacketed Mineral Insulated Conductor (SSMIC)” is the key feature of the design. The C10200 copper is used to deliver currents, magnesium oxide is used as insulation, and AISI 316LN is used in the jacket and other attachments in the structures of the coil [1]. The coil is very axisymmetric and in a circular structure with no bends until the 120 degree joints, break-outs and leads are encountered (Fig. 1) [4,5]. Therefore, a typical sector of the coil can be chosen as the analysis model and the results will reasonably represent the performance of the whole upper VS coil. The material properties used in the analysis are referred to the values under 100°C from ITER material properties handbook (MPH), as shown in Table 1.

![Fig.1 ITER upper VS coil global and sectional views](image-url)
2 Load description

Because of the special location of the ITER IVC system, the VS coils can control the plasma vertical position more sensitively and faster than other coils. But they have to endure very severe thermal loads and work in a bad environment. During tokamak operation, a large amount of heat coming from deuterium-tritium reaction will deposit in surrounding components in the form of neutron irradiation [1,2]. For the upper VS coil, the nuclear heat is remarkable with the peak value of about 0.7 MW/m³ and decay distance of 0.17 m [6-7]. To realize the VS feedback control, the upper VS coil is designed to carry a periodic transient current with the waveform of 240 kAt peak value and 36 kAt effective value [3]. The current will be divided equally onto each undamaged conductor and keep the total value constant when the coil is working. It means the peak value of 60 kA per turn in normal mode and 80 kA per turn in the mode “one turn out”, and so on [8]. As another kind of heat generation loads, Ohmic heat will be generated in the copper conductor. The values can be calculated as follows based on the coil operation modes.

\[
g = \frac{I^2R}{V} = \frac{I^2 \cdot \rho}{AM} = \frac{I^2 \rho}{(na)^2} = \frac{36.687}{n^2} \text{ MW/m}^3
\]

\[
= \begin{cases} 
2.29 \text{ MW/m}^3 & n = 4, \text{ normal case,} \\
4.08 \text{ MW/m}^3 & n = 3, \text{ one turn out,} \\
9.17 \text{ MW/m}^3 & n = 2, \text{ two turns out,} \\
36.7 \text{ MW/m}^3 & n = 1, \text{ three turns out,}
\end{cases}
\]

where \( I, \rho, l, A, a, n \) are the effective value of total current (36 kAt), copper resistivity (2.21e-8 \( \Omega \cdot \text{m} \)), conductor length, cross-section area of all turns, cross-section area per turn (8.84e-4 \( \text{m}^2 \)) and the number of remaining turns, respectively.

To cool down the conductors and attachments, the hollow copper pipe is designed to force the water flow with velocity of 3 m/s and inlet temperature of 100 °C [1]. The film coefficient of convection relating to the water properties, flow rate and the hydraulic diameter of the pipe can be calculated as follows.

\[
N_U = 0.023Re_1^{0.5}Pr_1^{0.4} (n = 0.4)
\]

\[
= 0.023 \left( \frac{VD}{\nu} \right)^{0.8} \left( \frac{\mu\nuC_p}{k} \right)^{0.4}.
\]

\[
= -\frac{hD}{k}.
\]

\[
h = 6726.2V^{0.8}
\]

where \( V, D, \nu, \rho, C_p, k \) are flow rate, hydraulic diameter (0.03 m), kinematic viscosity (2.94e-7 \( \text{m}^2/\text{s} \)), density (1000 kg/m³), specific heat at constant pressure (4200 J/kg · °C) and thermal conductivity (0.68 W/m · °C) of water in the state of 1.82 MPa and 100°C, respectively.

In addition, cooling shared by the vacuum vessel plays another role of taking away heat in the upper VS coil. The vacuum vessel is cooled and maintained at about 110°C in the normal operation of the tokamak. This provides thermal boundary conditions for the coil: temperature constraints at the interface between vacuum vessel and rail support, and thermal radiation from the coil surfaces to the vacuum vessel inner wall.

Due to the difficulties of remote maintenance, the ITER upper VS coil is designed to work in normal and degraded mode “one turn out”, in which the faulty conductor doesn’t deliver source current or water coolant [7,8]. Worse cases with more faulted turns may happen as accidents. To check the coil thermal-hydraulic performance in detail, the normal and all the faulted cases are taken into account in the following analysis.

3 Thermal performance and energy balance

In normal operation, the ITER upper VS coil is delivering the designed current which can generate Ohmic heat in copper, while enduring nuclear heat everywhere, and is cooled by water in the hollow conductors with a flow rate of 3 m/s. The interface between rail support and vacuum vessel is constrained at the temperature of 110°C, and the surfaces of the coil which are facing the surrounding components are set with emissivity of 0.3 and exposure to ambient temperature of 110°C. The finite element model is built in ANSYS with a 40 degree sector of the upper VS coil based on its cyclic symmetry characteristic. Temperature and thermal gradient distributions are extracted from the results and shown in Fig. 2.

The IVCs shall have a design temperature of 250°C [1]. The peak temperature of the upper VS coil is 198°C in the normal case, which can meet the design requirements. From the view of thermal gradient vector on the coil cross-section, the values are much higher at the locations between spine and rail support than anywhere else. It will result in high thermal stress nearby, especially at the right angles of spine notches. This has

<table>
<thead>
<tr>
<th>Material properties at 100 °C from ITER MRI</th>
<th>Copper</th>
<th>MgO</th>
<th>316LN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>DENS</td>
<td>8903</td>
<td>2200</td>
</tr>
<tr>
<td>Thermal conductivity (W/m-K)</td>
<td>KXX</td>
<td>395</td>
<td>2.36</td>
</tr>
<tr>
<td>Specific heat (J/kg-K)</td>
<td>C</td>
<td>394</td>
<td>940</td>
</tr>
<tr>
<td>Electrical resistivity (Ω-m)</td>
<td>RSVX</td>
<td>2.21e-8</td>
<td></td>
</tr>
</tbody>
</table>


been proved by other structural analyses. Obviously, the area which has higher thermal gradient needs more cooling to take away more heat. So the cooling pipes which are marked “2” and “3” are more important than “1” and “4”. Besides, the rails on the outside of the circular coil have more volume than the inside, and so the outside rails deposit more nuclear heat and need more cooling than the inside. Therefore, cooling pipes close to the outside rails, marked “3” and “4”, are more important than the pipes marked “2” and “1”, respectively. Accordingly, the importance of the four cooling conductors has the sequence of “3, 2, 4, 1”. To perform the analysis conservatively, a specific faulted situation will be assumed in which turns in the coil break down one by one with the above sequence. The temperature distributions of these faulted cases exhibit very different behavior, as shown in Fig. 3.

The peak temperature of the faulted case “one turn out” is less than the design temperature 250°C, but those of other faulted cases are not [2]. According to the temperature requirements, the upper VS coil is one-sidedly proved to be able to work in the degraded mode “one turn out”. But the anticipated design of the coil with this mode also needs other verifications such as detailed structural analysis.

Nuclear heat and Ohmic heat are two main heat sources of the coil. The heat is taken away mainly by water convection, supplemented by conduction and radiation, to cool the coil down and keep it in energy balance. Heat flow contribution of each load can be calculated based on the results of the steady thermal analysis of the coil (Table 2). The positive values represent energy input into the coil, while the negative values represent energy output. As we can see, Ohmic heat increases with occurrence of more faulted turns, except for the case “all turns out”. The same phenomenon occurs for the heat taken away by water convection. Conduction through the rail support and thermal radiation to the vacuum vessel have relatively little contribution to the coil cooling, especially in the former four cases. So they can be ignored to some extent to get more conservative results, with less amount of calculation.
Table 2. Heat flow contributions in normal and faulted cases (for the whole upper VS coil, 360 degrees)

<table>
<thead>
<tr>
<th></th>
<th>Normal</th>
<th>1 turn out</th>
<th>2 turns out</th>
<th>3 turns out</th>
<th>All turns out</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ohmic heat (kW)</td>
<td>295</td>
<td>393</td>
<td>589</td>
<td>1171</td>
<td>0</td>
</tr>
<tr>
<td>Nuclear heat (kW)</td>
<td>328</td>
<td>328</td>
<td>328</td>
<td>328</td>
<td>328</td>
</tr>
<tr>
<td>Water convection (kW)</td>
<td>–585</td>
<td>–675</td>
<td>–857</td>
<td>–1395</td>
<td>0</td>
</tr>
<tr>
<td>Support conduction (kW)</td>
<td>–34</td>
<td>–39</td>
<td>–47</td>
<td>–65</td>
<td>–113</td>
</tr>
</tbody>
</table>

4 Water flow influence and hydraulic performance

According to the energy balance analysis, water flow plays the most important role in cooling down the coil. To research in depth its influence on the coil’s thermal and hydraulic performance, scenarios with flow rate from 1 m/s to 10 m/s are analyzed. The tendencies of two important parameters, “coil peak temperature” and “temperature rise of water”, are depicted with curves in Figs. 4 and 5, respectively. The case of “all turns out” is not considered since there is no water flowing in the conductors based on the mode hypothesis.

For the normal case and the cases with some faulted turns, low-speed water flow has not so obvious impact on the peak temperature of the coil, and even exhibits less influence in the high-speed flow phase. It seems contrary to our expectation, but it can be explained as follows. Since the peak temperature appears at the edges of coil attachments (as shown in Fig. 2 and Fig. 3), these locations are so far away from the coolant that the water convection can help little for cooling down. Shared cooling by the vacuum vessel in the forms of conduction through rail support and thermal radiation between surfaces is expected to help solve this issue, especially the latter, which can be controlled conveniently by changing emissivity and will be studied in depth in the next section. As a conclusion and corollary, the peak temperature of the coil can’t be mitigated by improving coolant flow state like increasing velocity or changing direction. However, the temperature rise of water coolant can be affected more significantly, especially in the faulted cases (Fig. 5). When the flow rate is set above 4 m/s or even higher, the curves of temperature rise tend to be gentle. So increasing water velocity in the high-speed phase has little effect on the decrease of temperature rise of coolant. The ITER upper VS coil is designed with inlet temperature of 100°C and outlet temperature of 125°C and should have water temperature rise less than 25°C [2]. To meet this requirement and make allowance for the possibility of operating in the degraded mode “one turn out”, the flow rate of 3-5 m/s is recommended.

From the hydraulics viewpoint, coolant flowing faster will need more power and larger pressure drop. The hollow copper conductor is assumed to have roughness 1.5 μm on its inner surface. The total water pressure drop of the ITER upper VS coil can be calculated from the following formula:

\[ \Delta p = f \frac{\rho V^2}{2D} \cdot \Delta l, \]

where \( f \), \( \rho \), \( V \), \( D \), \( \Delta l \) are Moody friction factor, density (1000 kg/m³), flow rate, hydraulic diameter (0.03 m) and total conductor length per sub-circuit (56.3 m [1]), respectively. The Moody friction factor is a function of flow rate and influenced by surface roughness and can be acquired from the Moody diagram. The values of total water pressure drop are calculated for different flow rates, and shown with the black curve in Fig. 6.

Incidentally, the minimum power of the pump for each hollow conductor is estimated with the formula “\( P = (\Delta p) \cdot VA \)”, where \( V \) is the fluid flow rate, and \( A \)
is the area of fluid section per conductor. The results are shown with the blue curve in Fig. 6. Considering that faster turbulent flow will bring more severe corrosion, which will reduce the conductor lifetime, the final choice of water flow rate should be as low as possible among the values meeting the design requirements.

Fig. 6 The impacts of water flow rate on water pressure drop and pump power

5 Thermal radiation influence

Vacuum environment with relatively low temperature provides the ITER upper VS coil with thermal radiation to take away part of the heat during its operation. Even though thermal radiation has relatively low weight according to the energy balance results (Table 2), it may be important to cool down the edges of coil attachments where the peak temperature occurs. Therefore, the influence of radiation on the coil thermal performance is further studied with surface emissivity from 0 to 1.0 in exposure to ambient temperature of 110°C, which is the same as the bulk temperature of the vacuum vessel. The peak temperatures of the coil in normal and faulted cases are extracted from the results and shown with curves in Fig. 7.

As the figure depicts, the cooling effect of thermal radiation is relatively weak when the coil operation scenario is not so bad. But it performs remarkable under the worst case “all turns out”, in which thermal radiation will become an essential way of cooling down the coil. Consequently, ignoring thermal radiation in the analysis of the normal case and even “two turns out” is normally reasonable, but not for the worse cases “three turns out” and “all turns out”. If the common emissivity of 0.3 is used, the peak temperature of the coil will decrease by 100°C or so in the case of “three turns out”, as compared with the condition without radiation. Moreover, when all the conductors are faulted, the peak temperature will be above 3000°C, which is much higher than the melting point of 316LN (1375°C), if radiation is ignored. Another extreme and unlikely condition (not shown here) is when all of the turns are stopped cooling by water but the electricity is still alive, the peak temperature of the coil will be much higher than the values stated above because the continuous generation of Ohmic heat can’t be taken away. It possibly belongs to mal-operation but will dangerously cause some local areas to melt if the surface emissivity is too low. Exploration of thermal radiation influence offers a feasible optimization way to the coil design under faulty conditions.

Fig. 7 The impact of emissivity on the peak temperature of coil

6 Summary

Preliminary structural analysis has proved that thermal stress plays an important role in the ITER upper VS coil mechanical assessment. So it’s expected to be feasible to improve the coil design by enhancing its thermal performance. Thermal analysis of the coil shows detailed temperature and thermal gradient distributions, and heat flow contributions of each load in the normal and faulted cases. High thermal gradient in the regions between spine and rail support will result in large thermal stress concentration at the right angles of spine notches due to singularity effect. It may be mitigated by choosing a suitable fillet based on detailed structural analysis. Water convection is the most important way of cooling down the coil, but improving the coolant flow state can hardly mitigate the coil peak temperature. However, it can significantly decrease the temperature rise of water and influence the hydraulic performance of the hollow conductor. Considering the corrosion effect, the final choice of water flow rate should be as low as possible among the values meeting the design requirements. Thermal radiation was expected as a solution of cooling down the surfaces of coil and decreasing the peak temperature. But it’s proved too weak even under black body assumption when the working scenario is not so bad. The importance of thermal radiation will be remarkable in much worse cases such as “all turns out” and some unlikely accidents. It can prevent extremely high temperature and avoid thermal safety problems.
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