THERMAL ANALYSIS OF A SOLID BREEDER TBM UNDER ITER OPERATIONAL CONDITIONS

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The Quarter Port Submodule (QPS) was proposed as a Solid Breeder (SB) Test Blanket Module under the US program of the SB blankets. The QPS features layer configuration, in its left half, where the SB pebble beds are parallel to the first wall and edge-on configuration, in its right half, where the SB pebble beds are perpendicular to the first wall. The objective of this study is to investigate: (i) the QPS thermal profile under steady state conditions and ITER transient loads, and (ii) the impact of the interface conductance h on the QPS thermal profile. In addition the effect of lack of contact, at the SB pebbles/structure interface, on the QPS thermal profile is presented. The results of the steady state cases showed that h has a significant impact on the QPS thermal profile. The QPS transient analysis provided results on: (i) QPS thermal profile under a pulse length of 400s, (ii) burning time required for reaching the equilibrium temperatures, and (iii) time needed to cool the QPS. In the cases of lack of contact, the maximum temperature of the SB pebble beds exceeded the SB temperature limit, which may cause sintering of the pebbles and consequently inhibit the tritium release.

I. INTRODUCTION

The International Thermonuclear Experimental Reactor (ITER) will be the first machine available to test the burning of fusion plasma and blanket technology. ITER will provide three equatorial ports where the Test Blanket Modules (TBMs) will be inserted to test their design concepts and technology. The SB blanket features the following materials: lithium ceramic as a tritium breeder, helium for cooling, beryllium (Be) as a neutron multiplier and the Reduced Activation Ferritic Martensitic steel (e.g. Eurofer) for structure. Lithium metatitanate and lithium orthosilicate are the main candidates to serve as tritium breeder for the SB blankets. The SB and Be, in form of pebble beds, are contained and cooled by cooling plates. Under the US TBM program, two blanket concepts: (i) helium cooled SB blanket and (ii) dual coolant lithium-lead blanket were selected. Two designs of the SB TBMs were proposed: (i) Quarter Port Submodule (QPS), and (ii) unit cells. Figure 1 shows the QPS which was selected to investigate its thermal performance in this study. The left half of the QPS is based on layer configuration where the SB and Be pebble beds are arranged parallel to the First Wall (FW) which faces the plasma. Edge-on configuration was utilized for the right half of the submodule, where the SB and Be pebble beds are placed perpendicular to the FW. Figure 2 shows the dimensions (given in millimeters) and configurations of the QPS. The QPS has a length of 730mm in the toroidal direction and a width of 600mm in the radial direction. Finite Element software (ANSYS) was utilized to perform the thermal analyses of the QPS to (i) study the temperature profile of the QPS under steady state conditions, (ii) study the thermal performance of the QPS under ITER transient loads, and (iii) model the interface thermal conductance inside the QPS and show its impact on the thermal profile.

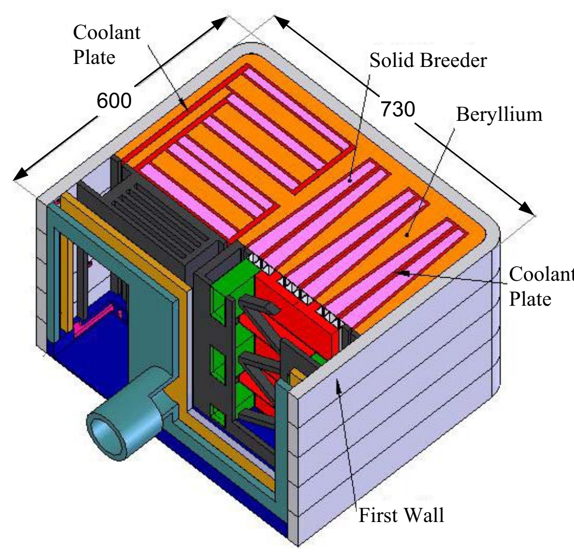

Fig. 1. Isometric view of the Quarter Port Submodule[1].

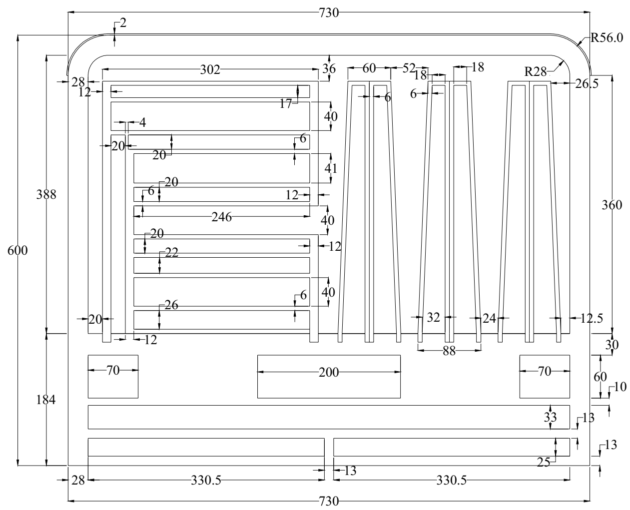

Fig. 2. Dimensions and geometry of the QPS.

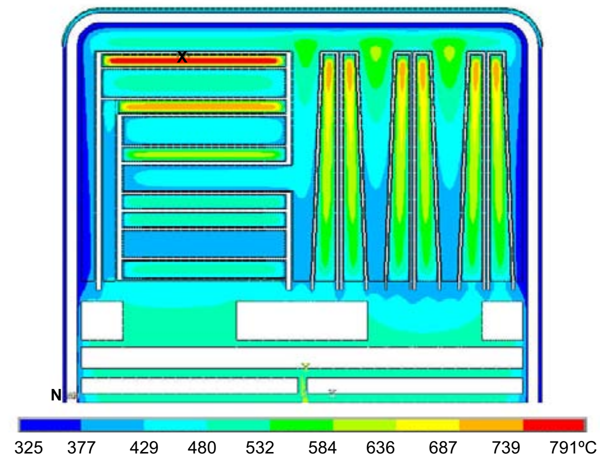

Fig. 3. QPS Thermal profile under steady state conditions.

II. STEADY STATE ANALYSIS

The thermal loads, applied to the QPS model, are based on ITER conditions, such as: surface heat flux of $0.3MW/m^2$ and neutron wall load of $0.78MW/m^2$. Heat generation was applied all over the model to simulate the nuclear heating values[2] and a heat flux of $0.3MW/m^2$ was applied at the FW. Convection (heat transfer coefficient, HTC = $6000W/m^2.K$ and bulk temperature = 325°C) was applied at the FW internal walls. Convection (HTC = $1000W/m^2.K$ and bulk temperature = 400°C) was used with all cooling plates in the layer and edge-on configurations while convection (HTC = $2000W/m^2.K$ and bulk temperature = 500°C) was applied in the back cooling plates. Different values of HTC are used to keep each material within its allowable temperature window. Figure 3 shows the QPS thermal profile where the maximum temperature (791°C) occurs at the first SB pebble bed within the layer-configuration while the minimum temperature (325°C) locates mostly at structure of the side FW. In all figures, the maximum temperature is marked with X and the minimum temperature is marked with N. The maximum temperature in the SB pebble beds is below their typical temperature limit (900°C). The temperatures of the SB pebble beds in the first two layers, closer to the FW, are higher than those of the SB pebble beds in the edge-on configuration at the same radial distance. This means that the heat extraction in the edge-on configuration is more efficient than that of the layer configuration near the FW. The structure temperatures range from 325 to 502°C and the maximum temperature (502°C) appears near the back cooling plates while the minimum temperature (325°C) locates at the entrance of the left-side FW, therefore the structure temperatures are below the design maximum temperature (550°C).

Figure 4 shows the temperature profile of the Be pebble beds where the temperature ranges from 333 to 594°C, therefore their maximum temperature is below the design limit (650°C). The hottest spots of the Be pebble beds are near the front FW in the edge-on configuration where the temperature difference is 240°C over a thickness of ~30mm. Figure 5 shows the temperature profile of the SB pebble beds where their temperatures are within the design window (400 - 900°C). The maximum temperature (791°C) locates within the front pebble bed while the minimum temperature (404°C) occurs around the back pebble bed. One can see that the hottest regions in all SB pebble beds locate within the front-most pebble bed in the layer configuration where the radial temperature gradient is 346°C over a thickness of ~9mm. The location of the hottest temperatures depends on some factors such as: nuclear heating value, effective thermal conductivity of the pebble bed, geometry and arrangement of the pebble beds and cooling plates, and the interface thermal conductance between the pebbles and structure.

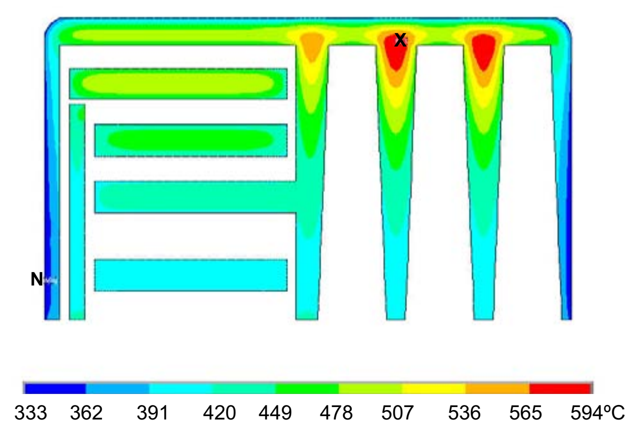

Fig. 4. Thermal profile of the Be pebble beds.

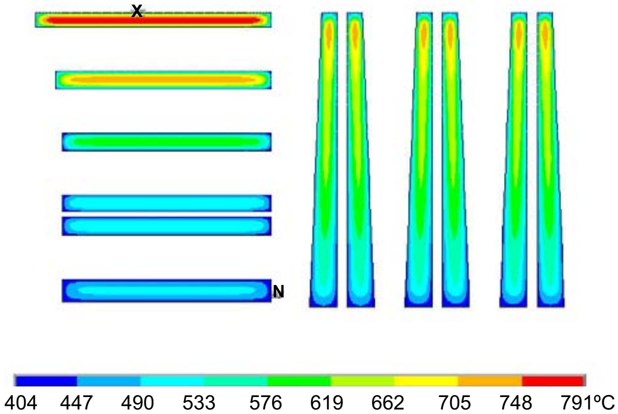

Fig. 5. Thermal profile of the SB pebble beds.

III. TRANSIENT ANALYSIS

Transient thermal analyses of the QPS were performed, using ITER-relevant transient pulse load, to study (i) the QPS temperature profile under a pulse of 400s, (ii) the burning time required to reach the equilibrium temperatures, and (iii) the time required for the QPS to cool down. The ITER burn cycle, which was used in the transient analyses, has four phases: (i) heating up for 50s, (ii) steady burning from time = 50 to 450s, (iii) termination of burning from time = 450 to 500s, and (iv) cooling phase that starts at time = 500s and ends at different times. The thermal profile of the QPS for the heating phase, where the nuclear heating increases from zero to its full value in 50s, has a maximum temperature of 551ºC and it occurs within the Be pebble bed in the edge-on half. This maximum temperature is about 70% of the maximum temperature of the steady state case.

Figure 6 shows the QPS thermal profile at the end of 450s that includes 50s of heating and 400s of steady burning. In this case the maximum temperature is 789ºC which is about 99.7% of the maximum temperature of the steady state case. This means 400s of burning is nearly enough to reach the maximum temperature of the steady state case. The maximum temperature is located within the first SB pebble bed in the layer-configuration half while the minimum temperature (325ºC) occurs at the entrance of the side first wall. Another case with longer burning phase (550s) was performed and the thermal profile and maximum temperature obtained were similar to those of the steady state case. For the phase of burn termination, Figure 7 shows the QPS thermal profile at the end of 500s where the burn termination occurs during the last 50s. In this case the maximum temperature dropped to 605ºC and took place in the first SB bed while the minimum temperature is 325ºC and located at the entrance of the side FW.

Six runs were performed to study the QPS thermal profile with different cooling times (i.e. after 600, 800, 1000, 1200, 1400, and 1600s). Within the first 400s (time = 600 to 1000s) of the cooling phase, the maximum temperature decreased by ~100ºC. However during the following 400s (time = 1200 to 1600s) the maximum temperature dropped by ~7ºC. Table I shows the maximum temperature for these six cases as well as the 450s-burn phase and 500s-burn phase. The maximum temperature decreases with time and approaches the coolant's temperature (325ºC); for example after 1600s the maximum and minimum temperature are 327ºC and 325ºC respectively.

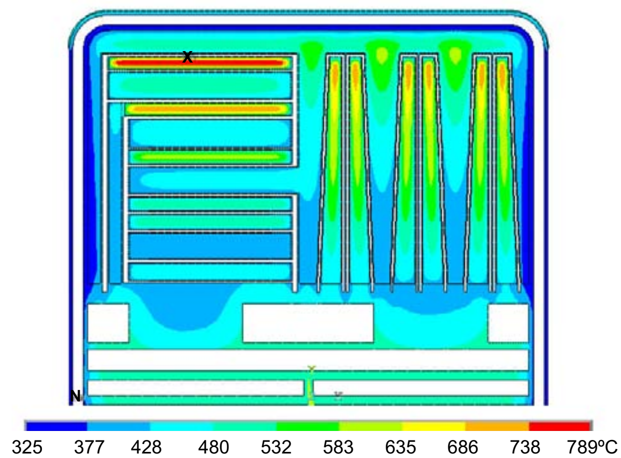

Fig. 6. Thermal profile of the QPS after 450s.

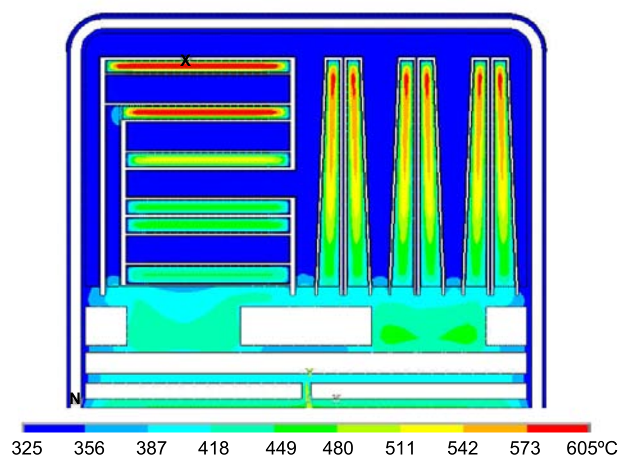

Fig. 7. Thermal profile of the QPS after 500s.

TABLE I. Maximum temperature in the transient cases.

Time, s	450	500	600	800	1000	1200	1400	1600
T_{max},ºC	789	605	445	369	344	334	329	327

IV. INTERFACE CONDUCTANCE

In this section the impact of applying different values of the interface conductance on the QPS thermal profile is presented. The objective is to check the sensitivity of the QPS thermal profile to any change in the interface conductance value. As shown in Table II the value of the interface conductance varies from "0.1*h*" to "2*h*", where *h* is the original value of interface conductance[3] (given in Table III). Table II shows the maximum temperature obtained in each case and it is noted that the maximum temperature is inversely proportional to the interface conductance value because the high interface conductance allows more heat to transfer from the pebble beds to the structure of the cooling channels leading to a drop in the maximum temperature of the pebble beds. Also a special case was performed where the ANSYS default setting (perfect interface conductance is applied at all interfaces) was used. In such case (Q-10) the maximum temperature has the lowest value among all cases. Figure 8 shows the thermal profile of case Q-5 where the original values of *h* were used.

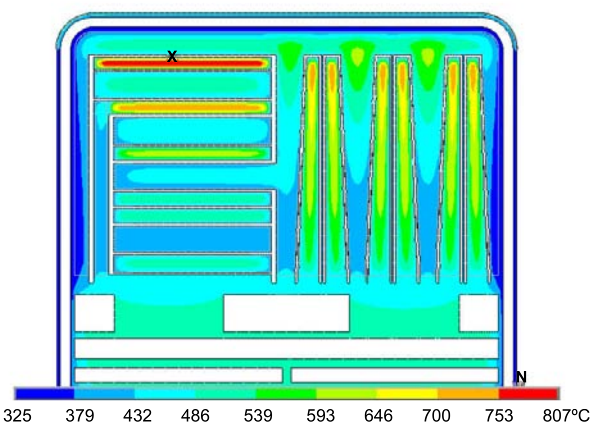

Fig. 8. Thermal profile of QPS in case Q-5.

The thermal profile of case Q-10 is similar to that of case Q-5, however, the difference in the maximum temperature of both cases is 39ºC. In cases Q-1, Q-2, Q-3, and Q-4 the value of interface conductance was assumed to be 0.1*h*, 0.25*h*, 0.5*h*, and 0.75*h* respectively, i.e. it was assumed to be fraction of its original value. The thermal profiles of these four cases are similar to the one of Figure 8. However, the maximum temperature decreases with increasing the value of interface conductance as shown in Table II. In case Q-1, the front SB pebble bed (in layer configuration half) has the maximum temperature of 929ºC and a large temperature gradient was seen in this SB pebble bed, especially in the radial direction. The results of case Q-1 shows the importance of having high values of the interface conductance between the pebbles and structure. The temperature profiles of the cases Q-6, Q-7, Q-8, and Q-9 where the value of interface thermal conductance is 1.25*h*, 1.5*h*, 1.75*h*, and 2*h* respectively were obtained. In these cases, the value of the interface conductance was assumed to be larger than its original value by a factor (1.25, 1.5, 1.75, and 2). The thermal profiles of these four cases are similar to the one of Figure 8 but the maximum temperatures are different as shown in Table II.

V. LACK OF CONTACT

Some pebbles/structure interfaces will possibly experience lack of contact during the blanket operation due to some factors such as differential thermal expansion, cyclic load, pebbles fracture, moving and relocation of pebbles, and poor packing. To study such lack of contact, three cases were performed where an artificial value of the interface conductance *h*, at the assumed location of the lack of contact, was applied. The gaps at the pebbles/structure interface are filled with helium, which serves as a purge gas. By simplifying the problem of heat transfer at these gaps, the artificial value of *h* was estimated to be 200W/m^2.K based on 1mm gap of helium with thermal conductivity of 0.2W/m.K. It was observed that, in most cases, the SB pebble bed at the front of the layer-configuration has the highest temperatures within the QPS; therefore it was selected to study the cases of lack of contact.

Figure 9 shows the thermal profile of case Q-11, where the lack of contact occurs at interface (1) and the maximum temperature is 807ºC. As shown the discontinuity of the temperature contours can be seen at the interface (1) due to the lack of contact. At the middle of this interface the SB pebbles' temperature (593-646ºC) is significantly larger than the structure's temperature (432-486ºC). Figure 10 shows the thermal profile obtained in case Q-12, where the lack of contact occurs at two interfaces (2) and (3) and the maximum temperature is 997ºC. It is noted that the maximum temperature's spot was shifted to a location between those two interfaces due to the lack of contact. A significant increase (190ºC) in the maximum temperature occurred in this case compared to the previous case. The discontinuity of the temperature contours is seen at the interfaces (2) and (3) and a temperature difference of ~300ºC can be observed within some spots of these interfaces. Figure 11 shows the thermal profile of case Q-13, where the lack of contact occurs at interface (4) and the maximum temperature is 961ºC. It is noted that the hottest spot (890-961ºC) occupies a bigger area of the SB pebble bed and the discontinuity of the temperature contours can be seen at the interface (4) where a temperature difference of

~350ºC is observed at this interface. In cases Q-12 and Q-13 the maximum temperature of the SB pebbles exceeds their upper temperature limit. This may cause sintering of the pebbles, which could inhibit the tritium release and transport inside the SB pebble bed.

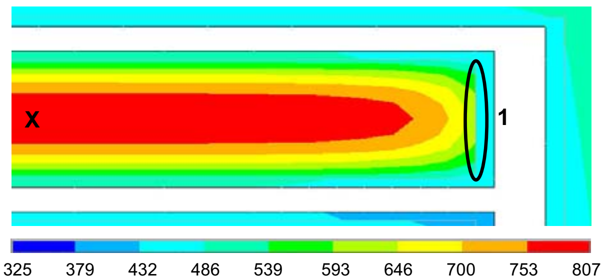

Fig. 9. Thermal profile of SB pebble bed in case Q-11.

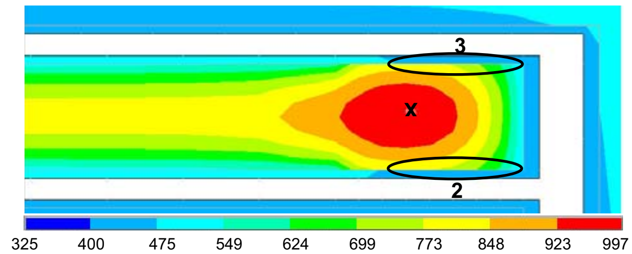

Fig. 10. Thermal profile of SB pebble bed in case Q-12.

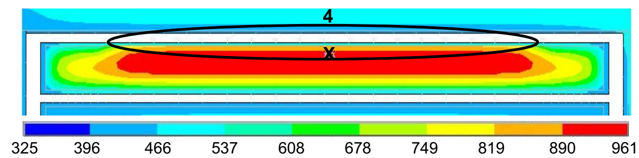

Fig. 11. Thermal profile of SB pebble bed in case Q-13.

TABLE II. The maximum temperature obtained in cases with different values of interface conductance.

Case	Q-1	Q-2	Q-3	Q-4	Q-5	Q-6	Q-7	Q-8	Q-9	Q-10
Interface Conductance	0.1 *h*	0.25 *h*	0.5 *h*	0.75 *h*	*h*	1.25 *h*	1.5 *h*	1.75 *h*	2 *h*	perfect
Max. Temperature, ºC	929	850	822	812	807	804	802	792	791	768

TABLE III. Original values of the interface thermal conductance (*h*)[3].

h, W/m^2.K	1800	2004	2207	2554	2859	3329	3567	3708	4098	4384	4867	5216	5300
Temperature, ºC	24	50	100	155	200	255	301	351	400	450	500	550	570

VI. CONCLUSIONS

Thermal analyses of the QPS were performed to investigate its thermal profile under steady state and transient conditions as well as different values of the interface thermal conductance *h*. The present results show that *h* has a significant impact on the QPS thermal profile, therefore, it is recommended to carefully include appropriate values of *h* in any thermal analysis of the TBMs. In case of lack of contact at the pebbles / structure interface, the maximum temperature of the SB pebble beds exceeded their temperature limit. This may cause sintering of the SB pebbles and consequently inhibit the tritium release.

REFERENCES

1. M. ABDOU, D. SZE, C. WONG, M. SAWAN, A. YING, N. MORLEY, S. MALANG, "U.S. Plans and Strategy for ITER Blanket Testing", *Fusion Science and Technology*, **47**, 475 (2005).
2. Personal communication with Dr. Mahmoud Youssef, youssef@fusion.ucla.edu.
3. A. ABOU-SENA, A. YING, M. ABDOU, "Experimental Measurements of the Interface Thermal Conductance of a Lithium Metatitanate Pebble Bed" presented in 18th TOFE 2008, in press of *Fusion Science and Technology*.