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Thermal radiation analysis to calculate the temperature and heat load of Wendelstein 7-X Inertially Cooled Test Divertor Unit Scraper Element

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***Abstract*— The W7-X divertor was designed to have a maximal allowable heat flux of 5MW/m^2. However, in certain magnetic configurations, high flux footprints due to the evolution of bootstrap currents results in high heat loads to the divertor units. Previous study shows the heat load can be >10MW/m^2, which significantly exceeds the allowable. Thus the scraper element was designed to protect the sensitive areas of the divertor and at the same time, not to affect normal configurations.**

A one dimensional radiation analysis was used to evaluate transient heating and cooling processes of the scraper element. A three dimensional radiation simulation, with views of cooler regions of the vessel interior, demonstrates better heat removal from the components behind the plasma facing tile surface. A three dimensional ANSYS model has been built that includes the scraper, its backing and neighboring vessel internals. The Test Divertor Units (TDU), and wall panels act as thermal shields to protect the vacuum vessel. View factors are calculated using ANSYS /AUX12. The advantage of using aux12 is that the view factor matrix may be calculated once, after that, changing the thermal load just requires another run. There is no need to calculate the view factors again. Simulation shows that with 8MW/m^2 peak to 0.05m wide area of scraper, 20 minutes for cooling, the scraper temperature thermal ratcheting is within the 1740K tile limit and the wall panel temperature within 355K. Heat flux plots have been provided for other analysis. Temperature results have been transferred to a structural run. Temperature results for the scraper and other areas behind the test divertor units are provided.

Keywords—W7x, Scraper Element.

I. INTRODUCTION

WENDELSTEIN 7-X (W7-X), the world's largest fusion device of the stellarator type, is currently under construction at the Greifswald branch of the Max-Planck-Institut für Plasmaphysik (IPP). W7-X uses superconducting magnet system and will allow steady state operation, with a pulse length of up to 30 min [1]. Due to the technique challenges, for the first three years it will operate at short pulse lengths, aiming at optimization of operating scenarios to realize steady-state operation of high density (n ~10^{20} m^{-3}), high temperature (multi-keV), high-beta (~5%), stellarator plasmas [2]. During this time, the inertially cooled divertor, which is called the test divertor units (TDU), will first be installed and later be replacement with the water cooled high heat flux (HHF) divertor for steady state operation. TDU was designed to have a maximal allowable heat flux of 5MW/m^2 [3]. However, in certain magnetic configurations, high flux footprints due to the evolution of bootstrap currents results in high heat loads to the divertor units. Previous study shows the heat load can be >10MW/m^2 [4], which significantly exceeds the allowable. Thus the scraper element was designed to protect the sensitive areas of the divertor and at the same time, not to affect normal configurations. The intrinsic challenges are the high heat load, the complicated three-dimensional geometry and the limited available space within the vacuum vessel.

A one dimensional radiation analysis was used to evaluate transient heating and cooling processes of the scraper element [5]. In this paper, a three dimensional radiation simulation, with views of cooler regions of the vessel interior, demonstrates better heat removal from the components behind the plasma facing tile surface.

II. MODELING AND RESULTS

A. Thermal analysis of the scraper and wall panel

A three dimensional ANSYS model (fig. 1) has been built that includes the scraper, its backing and neighboring vessel internals. The Test Divertor Units (TDU), and wall panels act as thermal shields to protect the vacuum vessel. The heat load was initially set to 8MW, rectangular in cross section, over 0.1m wide strips, 6s, totally 3.26MJ, and 20 minutes for cooling. Later, it was modified to 8MW peak, triangular cross section, over 0.05m wide stripe, 6s, totally 0.82MJ. View factors are calculated using ANSYS /AUX12. For large 3D models, calculation of view factors will take a lot of time. The advantage of using aux12 is that the view factor matrix may be calculated once, after that, changing the thermal load just requires another run. There is no need to calculate the view factors again. Wall panel has conduction links to simulate the bolts connection of assembly. Emissivity was set to be 0.4~0.8 to represent the uncertain emissivity range due to physical nature of the surface such as roughness, texture and oxidation. Vacuum vessel temperature maintains at room temperature, 293K and environment temperature is 343K (70 ºC). Ref. [5]

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compares different tile materials' properties and finally Rinsdorf R6510 was chosen as tile material which has better thermal shock resistance and has been tested in the high heat flux facility in Greifswald, GLADIS.

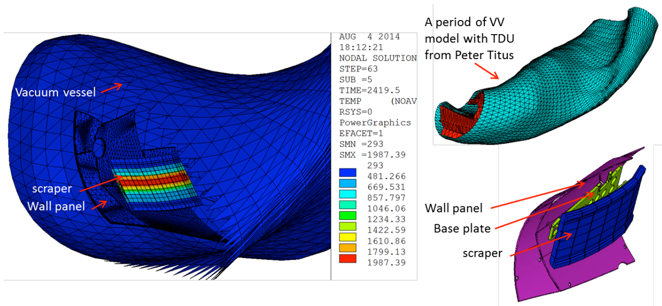

Fig. 1. A 3D ansys model to simulate radiation in the vessel.

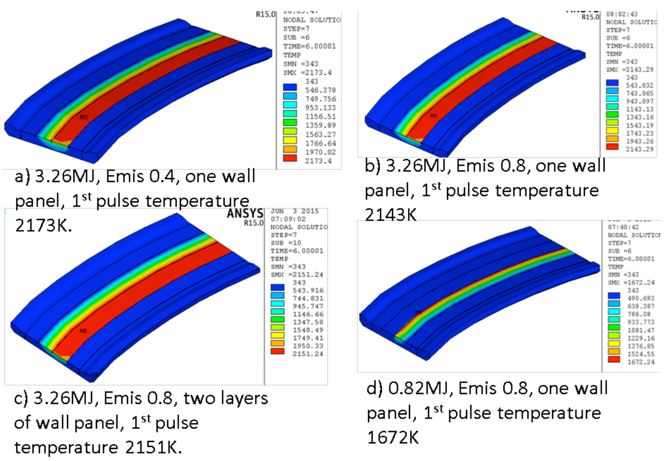

Fig. 2. Comparison of scraper temperature.

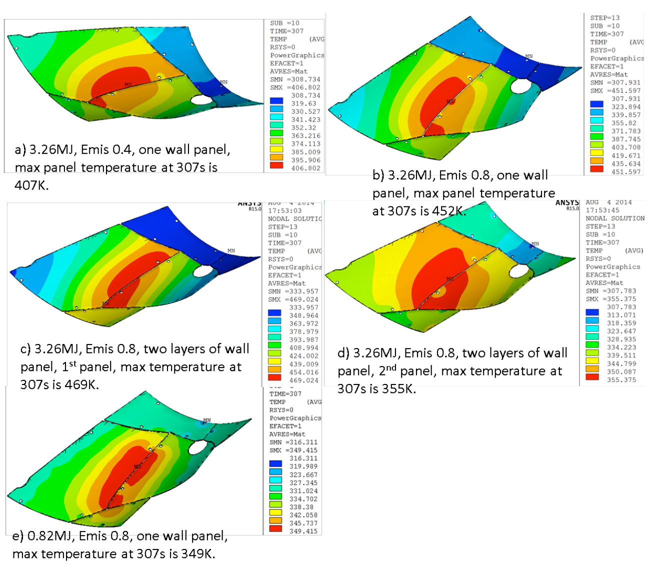

Fig. 3. Comparison of wall panel temperature at 307s.

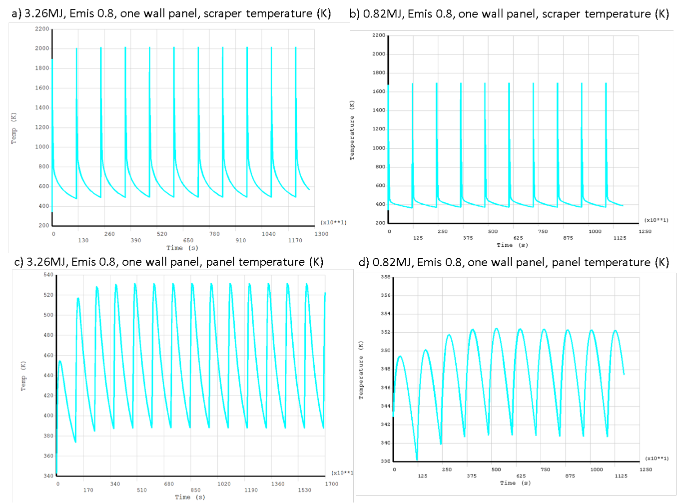

Fig. 4. Thermal ratcheting of scraper and panel temperatures.

For 3-D radiation analysis, Ansys has a limit that total node number of radiating surfaces should be less than 20000. With a large model including many components, the mesh density has to be carefully controlled so that the details of the component interested could be addressed while the remaining areas also have adequate mesh to contribute to the radiation computation. The surface mesh of the scraper in this model is 0.033 m. Thus the 8MW/m^2 peak over 0.05m wide stripe was averaged to a 0.033m wide stripe, which becomes 6.015MW/m^2, and with same total heat 0.82MJ.

Fig.2 and 3 compare the system temperature with different emissivity and backing structures. With higher emissivity, the scraper temperature will be lower but not very much, while the wall panel temperature has relatively bigger difference. Simulation shows that with 8MW/m^2 to 0.1m wide area of scraper, 20 mins for cooling, the scraper temperature thermal ratcheting is 2198K (fig. 4a), which exceed the allowable of 1800 ^{o}C or 2073K. And the wall panel temperature reaches 535K (fig. 4c), which is above the requirement of 200 ^{o}C or 473K. If adding one more wall panel, the second layer panel temperature can be reduced 403K or 130 ^{o}C. Although this configuration is recommended, due to the limited space in the vessel, the second layer wall panel is hard to be installed. When the design basis heat load reduced to 0.82MJ, scraper temperature is reduced to 1740K (fig. 4b), within the allowed 2073K (1800^{o}C). The wall panel temperature is 352.4K, within the allowable of 473K (200^{o}C) (fig. 4d). Considering the heat flux in this model is averaged to rectangular cross section, with triangular shape heat flux distribution, the peak temperature of the scraper should be a little higher than simulation result, while should be much less than the 3.26MJ heat load temperature. The wall panel temperature should not be influenced much by this averaging.

B. Thermal structural analysis of the back plate

The scraper tiles were first designed to be assembled together by six individual support plates and many "V" clips and "L" springs (fig. 5). To simplify the assembly, a continuous back plate was proposed by G.D. Loesser, which will reduce the total number of components and simplify the assembly procedure. A parametric model of a continuous back plate was added to the thermal model to calculate back plate temperature (fig. 6 and 7). Then the temperature was mapped to the structural model to compute stress and determine the adequate supporting structure to allow thermal expansion of the back plate (fig. 8).

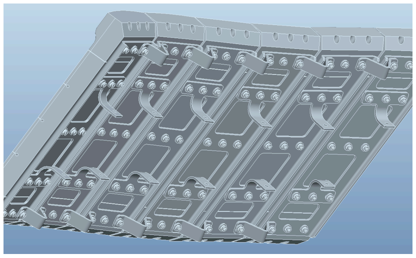

Fig. 5. Six individual plates with “V” clips an “L” springs to fix tiles.

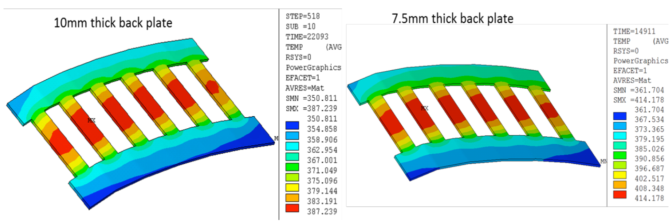

Fig. 6. Parametric model for the thermal analysis of continuous back plate.

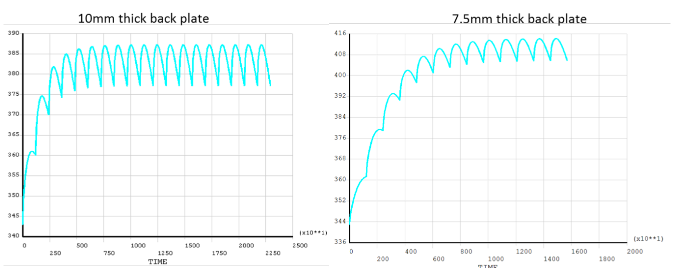

Fig. 7. Thermal ratcheting of the back plate temperature.

With the same basic back plate design, two different supporting mechanisms were analyzed:

1) The back plate is supported by three spots (fig. 8b): one is fixed and the other two are springs to provide flexible supports to allow thermal expansion of the back plate.

2) The back plate has slits which gives the plate more compliance to tolerate thermal expansion without induce high stress (fig. 10). And the supports become quite simple, just fix supports on three spots, and save space. However, the manufacturing of the plate will cost more.

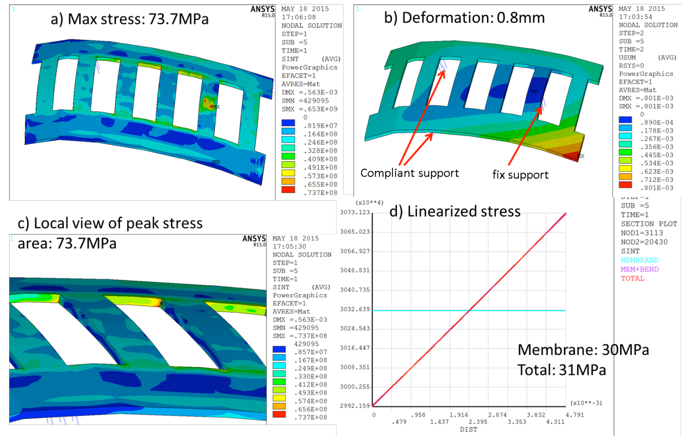

Fig. 8. Method 1: 7.5mm thick plate with two springs and one fix support, thermal and gravity (118KG) load applied.

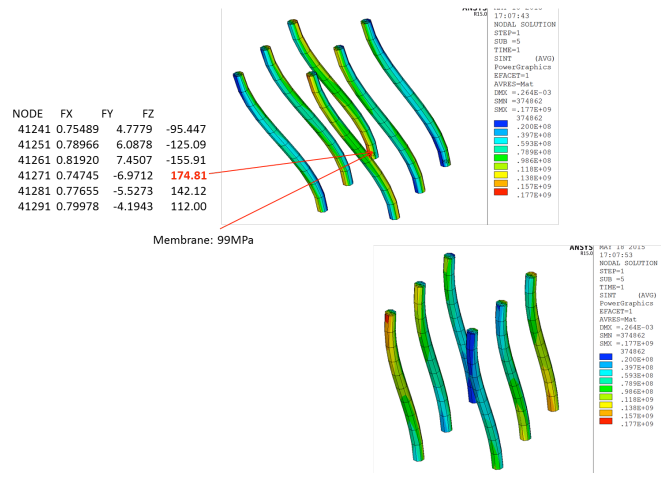

Fig. 9. Method 1, with six beams of 1.5mm DIA, 50mm long, beam stress upon thermal expansion of back plate.

Using method 1, peak stress in the back plate is 73.7MPa at the corner (fig. 8a and 8c). Before going to the detailed model with round corner and finer mesh, we use linearized stress to estimate the stress level. Membrane stress is 30MPa and total stress is 31MPa (fig. 8d), which is far below the allowable of stainless steel 316LN. Stress in the springs is 177MPa and membrane stress 99MPa (fig. 9). For the springs, Grade 660 steel or A286 super alloy, which has higher strength at higher temperature, can be used to give design more margin.

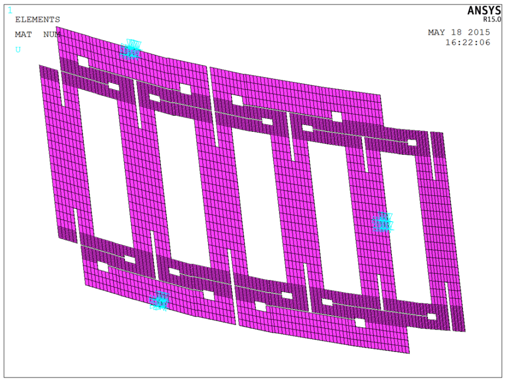

Fig. 10. Method 2: back plate with slits and three fix supports.

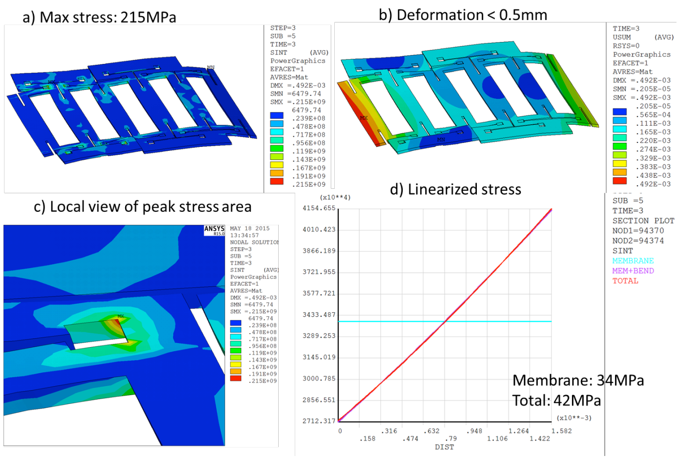

Fig. 11. 10mm thick back plate with slits, stress and deformation upon thermal expansion and gravity (118KG).

Using method 2, by cutting slits of 2mm and 5mm wide (fig. 10), even the three spots are fixed, the plate is compliant to tolerate thermal expansion without produce too much stress. Fig. 11a shows peak stress of 215MPa, which is a stress concentration at the corner. Linearized stress is 34MPa for membrane and 42MPa for total (fig. 11d). In this analysis, a sample slot cutting scheme is analyzed but the slot size and position hasn't been optimized. Using round corner and optimizing the slit size should be possible to reduce the max stress more. It saves the cost of additional support and save space. But the fabrication of back plate will be more complicated than before.

Both method can restrict the back plate deformation within 0.5mm and stress within allowable of stainless steel 316L. Both temperature range and vertical force applied to the structural model are higher than required, the results should be conservative enough. For easier manufacturing, method 1 selected.

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