9.1 MULTI-PHYSICS DESIGN OF THE FIRST WALL AND BLANKET SYSTEM IN THE FUSION NUCLEAR SCIENCE FACILITY (FNSF)—Yue Huang, Nasr Ghoniem, Mark Tillack, Jake Blanchard, Laila El-Guebaly, Chuck Kessel

SUMMARY

The dual coolant lead-lithium (DCLL) blanket concept is based on a helium-cooled first wall and blanket structure with RAFS (Reduced Activation Ferritic Steel) and a self-cooled LiPb breeding zone. 3D finite element multiphysics modeling of the DCLL first wall and blanket has been performed using *COMSOL 5.0.* The multiphysics aspect of the design is demonstrated via coupling of fluid dynamics, conjugate heat transfer and solid mechanics modules within the COMSOL. The results of primary and thermal stress of the structure were obtained. This was followed by determination of the factors of safety along three critical paths based on the ITER Structural Design Criteria for In-vessel Components (ISDC-IC). We show that the structural design meets the design rules under both normal and off-normal operating conditions, though the safety factors under off-normal condition are marginal. Thus simple design optimization was conducted based on a parametric study on first wall dimensions to improve the design.

PROGRESS AND STATUS

Approach

Three major multiphysics modules have been coupled in the current design. These are: Non-isothermal Fluid Flow, Conjugate Heat Transfer, and Solid Mechanics. The Non-isothermal Fluid module was used to simulate helium flow inside cooling channels. CFD simulations were based on k-epsilon turbulent flow model. The temperature and pressure distributions of the helium coolant can be obtained in this module. The “Conjugate Heat Transfer” module was used to compute the temperature distributions of the blanket RAFS structure. Both the surface heat flux on the FW and volumetric heating rates were considered. The “Solid Mechanics” module was used to compute the stress distributions in the structure. The primary stress is due to the pressurization of fluid flow (helium in FW, BW and stiffening plates, and PbLi in the FCI channels). Thus the pressure distribution results from CFD simulation were used as boundary condition for stress analysis. To calculate secondary (thermal) stress, it is necessary to couple heat transfer, CFD and stress analyses. The basic simulation process is shown in Fig. 1.

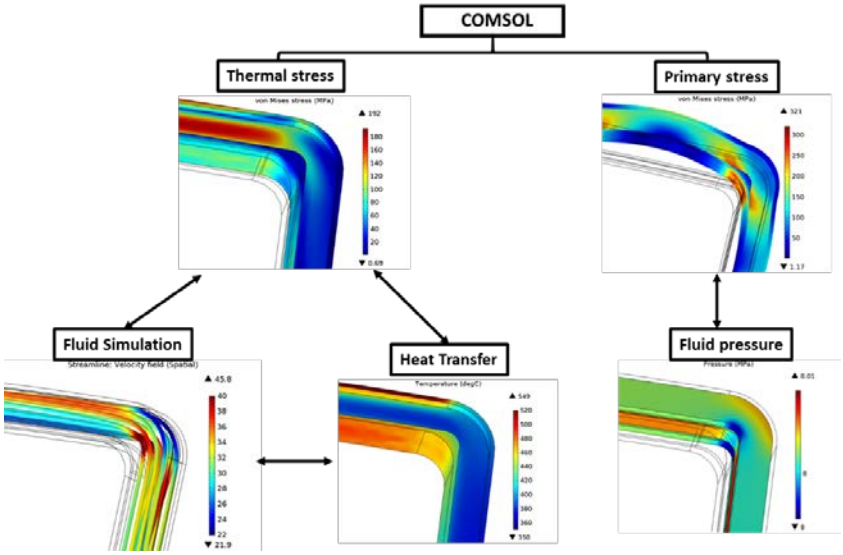


Figure 1. Summary of the multiphysics simulation process sequence.

We consider in the present design three possible scenarios; two of them are operational, and one is unlikely and requires plant interruption. These design basis scenarios are summarized in Table 1 [1]. One of the critical regions would be any breeder cell that is over-pressurized beyond the normal design basis. In the SDC-IC level A (normal operations), breeding cells would experience 1.6 MPa LiPb pressure, while an internal LOCA will lead to the off-normal condition with a pressure of helium pressure [2]. We will consider both "normal' and "upset" design conditions here.

Table 1. SDC-IC criteria levels vs. loading categories

Loading Category	Category Conditions (Damage limits)	SDC-IC Criteria Level	Incidents
I Operational Loading	Normal	A	Normal Condition: P_{LiPb}=1.6MPa
II Likely Loading	Upset	A	Off-normal Condition: (1) LOCA, P_{LiPb}= P_{He} (2) Minor plasma disruptions
III Unlikely Loading	Emergency	C	Major plasma destruction (Inspection and repair is required)

Results

Helium Flow

As Figure 2 shows, helium flow velocity should be at least 30 m/s under 8 MPa operating pressure and 48 m/s under 5 MPa to maintain the steel structure temperature below the limit. It is clear that we need to pay for higher pumping power to reduce the operating pressure. The streamlines of helium flow with velocity magnitude are shown in Figure 3 (with pressure of 8 MPa and inlet velocity of 30 m/s).

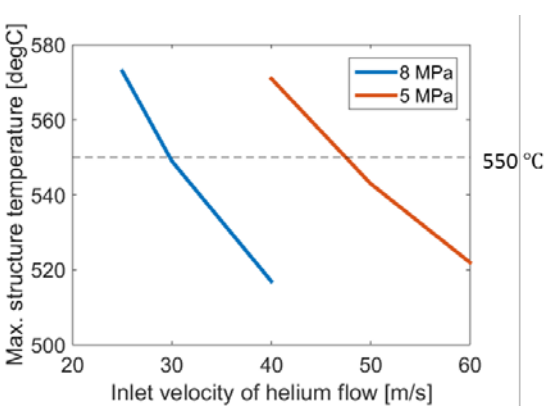


Figure 2. Max. structure temperature v.s. inlet velocity.

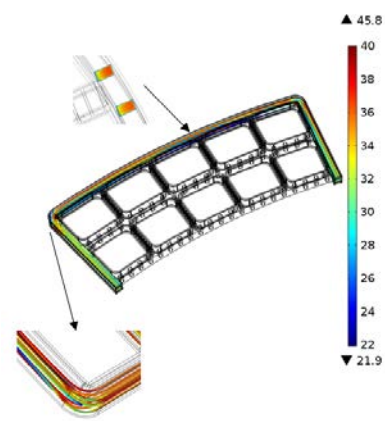
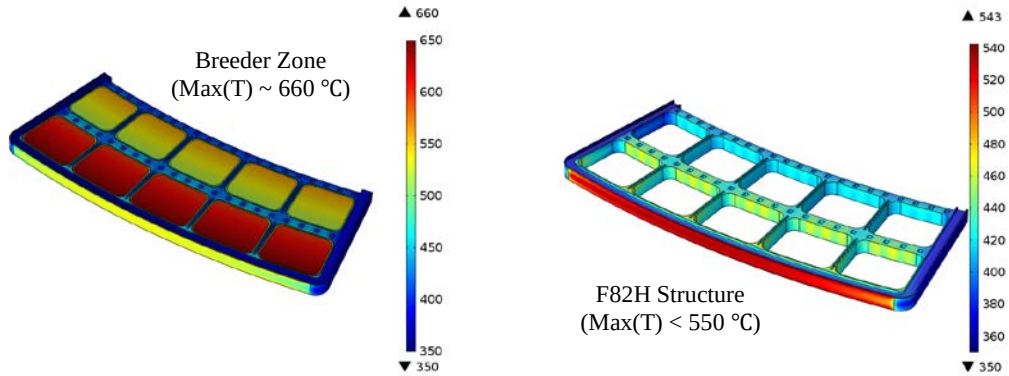


Figure 3. Streamlines of helium flow.

Temperature distribution of the solid structure

The result of the temperature distribution is shown in Figure 4. The maximum temperature of the LiPb is around 660 ℃ at the mid-plane. In the present simulations, the heat transfer coefficient was not assumed, but rather calculated as a result of the fluid flow and heat transfer simulations. Ribs and grooves need to be manufactured inside the cooling channels to enhance wall heat transfer. The side effect is that a much

higher pressure drop in flow channels will occur. In the simulation, a correlation factor was introduced to account for the cooling enhancement due to the wall roughness.



(a) Breeding zone (b) Blanket structure

Figure 4. Temperature distributions of the global FW/B structure.

By controlling the inlet velocity of the helium, the maximum temperature of steel structure can be maintained below the limit. Even with the operating pressure of 5 MPa, only 50 m/s is required. The result reveals that tubulent flow together with roughing the channel wall can lead to effective cooling.

Primary stress

The following results shown in the figures below are based on normal operating conditions with helium pressure of 8 MPa. Results of other cases (like under off-normal conditions or with a pressure of 5 MPa) are listed in Table 2-5. Figure 5 shows the global primary stress distribution of the blanket structure. There are stress concentrations at the junctions and corners. After rounding and adding fillets to junction zones, the stress concentation was reduced to about 320 MPa. Deformation of the structure resulting from the primary stress was also obtained, as shown in Figure 6.

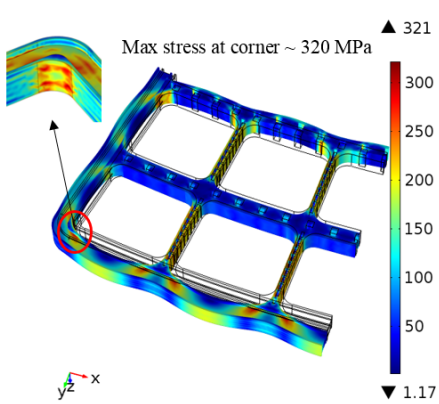


Figure 5. Primary stress distribution (Von-Mises stress).

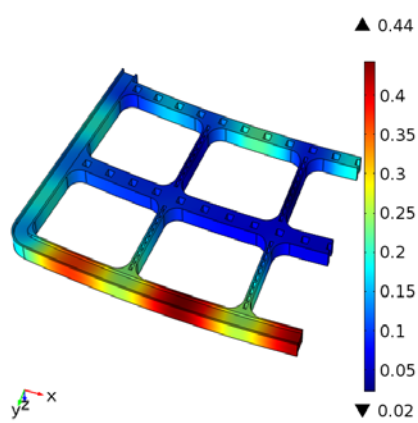


Figure 6. Displacement distribution due to the primary stress.

Thermal stress

Thermal stress was calculated based on the temperature obtained from coupled heat transfer and CFD analyses. As illustrated in Figure 7, the first wall has the largest thermal stress, although a directionally-alternating cooling channel layout has already reduced severe temperature gradients. Also, thermal

expansion is shown in Figure 8, illustrating the reason why we need to leave a gap of at least 2 cm between adjacent sectors during assembly to accommodate thermal expansion.

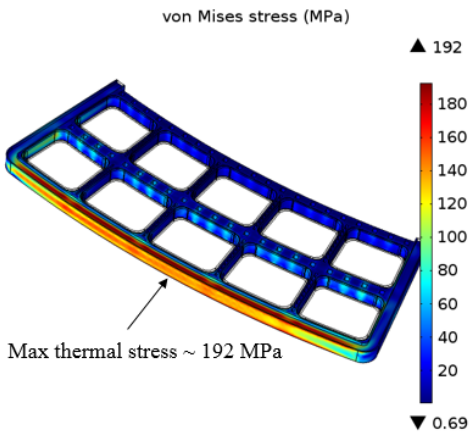


Figure 7. Thermal stress distribution.

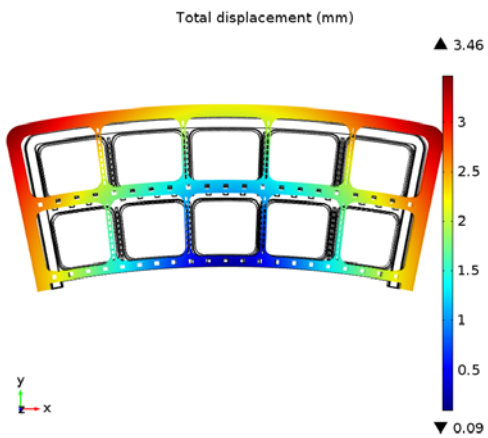


Figure 8. Thermal expansion.

Design Factors of Safety

Line integration through the thickness of the structure is used to resolve stresses into membrane, bending and non-linear components. The membrane stress tensor has components that are equal to the mean value of stresses through the thickness. The bending stress tensor has components that vary linearly through the thickness and which, when integrated through the thickness result in equilibrium with the section moment [3]. The line along which this integration is carried out is defined as "a supporting line segment." Three supporting line segments were selected as critical paths to determine the design safety factors, as shown in Figure 9 (the result in Figure 9 is under off-normal condition).

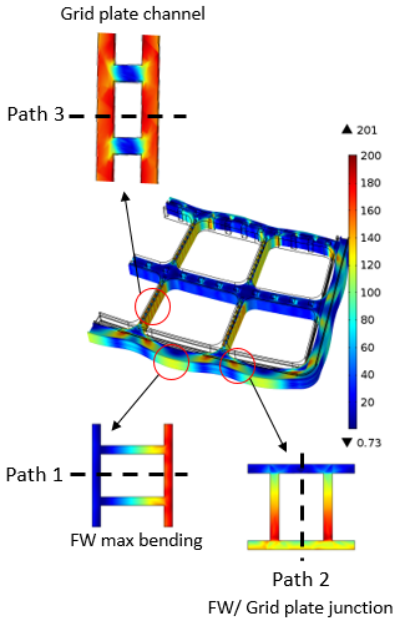


Figure 9. Critical supporting line segments.

With the results of the primary and thermal stresses, factors of safety were determined based on the three different allowable values and the low temperature design criteria. The results are shown in Table 2-5. For reference on the mechanical design procedure, including stress intensity parameters and design criteria, please see reference [4].

Table 2. Factors of safety based on necking and plastic instability limit

$\overline{P_m + P_b} \leq 1.5S_m$						
	5 MPa			8 MPa		
Path	$1.5S_m$[MPa]	Normal	Off-normal	$1.5S_m$[MPa]	Normal	Off-normal
1	205.1	4.6	1.7	203.1	4.0	**1.1**
2	206.0	4.3	1.7	204.2	3.7	**1.0**
3	228.5	5.8	2.0	228.5	5.4	**1.3**

Table 3. Factors of safety based on $3S_m$ criteria

$\overline{P + Q} \leq 3S_m$						
	5 MPa			8 MPa		
Path	$3S_m$[MPa]	Normal	Off-normal	$3S_m$[MPa]	Normal	Off-normal
1	410.1	3.4	4.7	406.2	3.8	3.1
2	411.9	2.6	2.3	408.3	2.4	2.0
3	456.9	9.2	2.6	456.9	8.3	1.6

Table 4. Factors of safety based on plastic flow localization limit

$\overline{P_m + Q} \leq S_e$						
	5 MPa			8 MPa		
Path	S_e[MPa]	Normal	Off-normal	S_e[MPa]	Normal	Off-normal
1	192.8	7.9	3.8	191.1	6.3	2.4
2	193.8	6.5	3.6	192.1	5.3	2.3
3	214.9	6.3	2.0	214.9	6.0	1.2

Table 5. Factors of safety based on ductility exhaustion limit

$\overline{P_m + P_B + Q} \leq S_d$						
	5 MPa			8 MPa		
Path	S_d[MPa]	Normal	Off-normal	S_m[MPa]	Normal	Off-normal
1	385.6	4.2	4.5	382.2	4.3	3.2
2	387.5	2.9	2.4	384.2	3.0	2.1
3	429.8	8.3	3.5	429.7	8.0	2.3

The current results indicate that structure, under normal operating conditions, meets all design criteria, while the safety factors under off-normal operating conditions are marginal. Therefore, it is recommended that further design optimization and parametric analyses be conducted.

Design optimization

To reduce the stress at critical regions, one possible solution is to add more stiffening plates. However, the design with more stiffening plates has too much steel and results in tritium breeding concerns. Thus we focused on finding a solution by adjusting the dimension or configuration of the first wall channel

design. Additional to the original design, another two configurations, as Figure 10 shows, were investigated with detailed stress analyses. Configuration B retains the total thickness of the first wall panel (3.8 cm), but varies the thickness of the first wall. For configuration C, the wall thickness remains unchanged while varying the helium channel thickness.

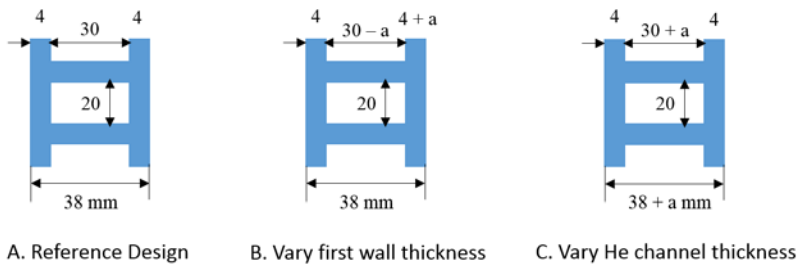
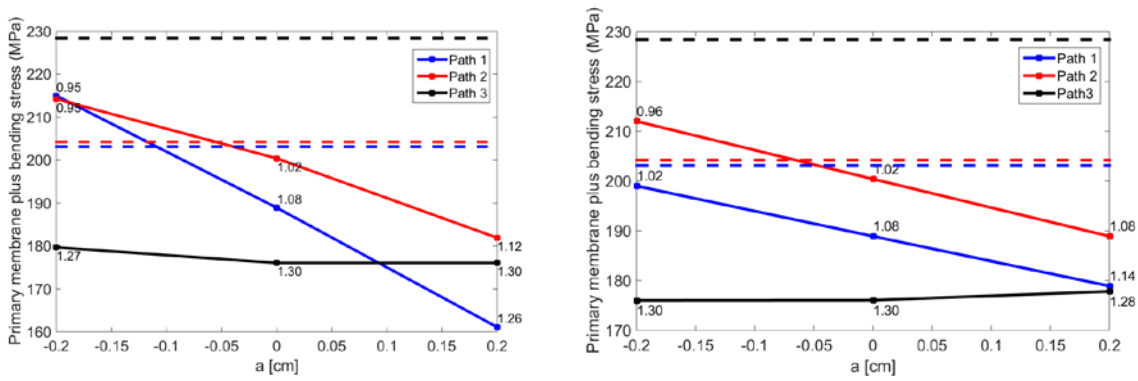


Figure 10. First wall configurations.

Parametric study on parameter a, which is the variation of the first wall thickness for configuration B or helium channel thickness for configuration C, was performed. The factors of safety results listed above show that the design criteria based on allowable primary membrane stress intensity S_m is the critical one. Thus only factors of safety based on the first design criteria were calculated for both configuration B and C with different values of parameter *a* to figure out the best solution. The results are shown in Figure 11. The dashed lines show the design limit. Increasing either the first wall thickness or helium channel thickness can help reduce the primary stress. It gives us the potential to optimize the first wall dimensions to accommodate more severe loading conditions.



(a) Configuration B (b) Confiruation C

Figure 11. Parametric study of first wall dimensions.

Acknowledgements

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[4] ITER Structural Design Criteria for In-vessel Components, ITER Doc. G 74 MA 8 01-05-28 W0.2, 1996