9.1 PRELIMINARY MULTI-PHYSICS DESIGN OF THE FIRST WALL AND BLANKET SYSTEM IN THE FUSION NUCLEAR SCIENCE FACILITY (FNSF) — Yue Huang, Nasr Ghoniem (UCLA), Jake Blanchard, Laila El-Guebaly (UW-Madison), Charles Kessel (Princeton Plasma Physics Laboratory), Siegfried Malang (Nuclear Technology Consulting), Mark Tillack (UCSD)

OBJECTIVE

The objective of this work is to optimize the design of the first wall and blanket system in FNSF so as to develop a reliable configuration that can achieve long lifetime, maintainability, and high reliability. The blanket structural design needs to meet strict temperature and stress design limits while maintaining credible configuration and maintenance characteristics.

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 Pb-Li breeding zone. 3D solid modeling was achieved with *SOLIDWORKS*, while 3D finite element multiphysics modeling of the DCLL first wall and blanket (mid-plane part of one sector) has been performed by *COMSOL 5.0* via coupling of the CFD, heat transfer in solids, and heat transfer in fluids modules. Design optimization is realized by seamless connection of two main software platforms with life-links. The results of velocity, pressure, and temperature distributions of helium flow, as well as the primary and secondary thermal stress of the structure were obtained. This is followed by determination of the factors of safety based on the ITER design rules of un-irradiated components. Future efforts will consider the effects of radiation on the lifetime and reliability of the design, improvements in the geometric layout of the FW/B structure, improvements in heat transfer and fluid flow models, and integration of multiscale models of plasticity and fracture.

PROGRESS AND STATUS

Introduction

The major design characteristics of the DCLL blanket include helium flow paths for cooling the first wall and blanket structures, and Pb-Li liquid metal paths for cooling all blanket regions[1]. A simplified diagram for the in-board configuration is shown in Figure 1.

The CAD model in Figure 2 for the In-board (IB) blanket represents one of a total of 16 blanket sectors at midplane, showing the breeding zones, tungsten armor, SiC inserts, stiffening and back plates with poloidal cooling channels and separation plates with toroidal cooling. There are 4 radial stiffening plates connecting the first wall and back wall to accommodate the bending stress due to the pressure of helium flow, which is taken to be 8 MPa. The separation wall divides the blanket into two sets of breeding zones. The cooling pathways for the separation wall will be modified from the current toroidal direction to a poloidal direction, similar to the cooling pattern of the back wall. Each breeding cell is 25 cm in the radial direction. The first wall is 3.8 cm thick with a 3 cm cooling channel. The FW structure is curved with a radius of 4.8 m. The first and the back walls are connected by the radial stiffening plates so as to accommodate bending stresses in these walls caused by: (a) the PbLi pressure during normal operation, and (b) the He-pressure during an internal Loss of Coolant Accident (LOCA). There is a 2 mm tungsten (W) armor layer attached to the first wall, designed for (a) accommodating the peak surface heat flux caused by high-temperature plasma transients, and (b) reduce FW surface erosion caused by sputtering.

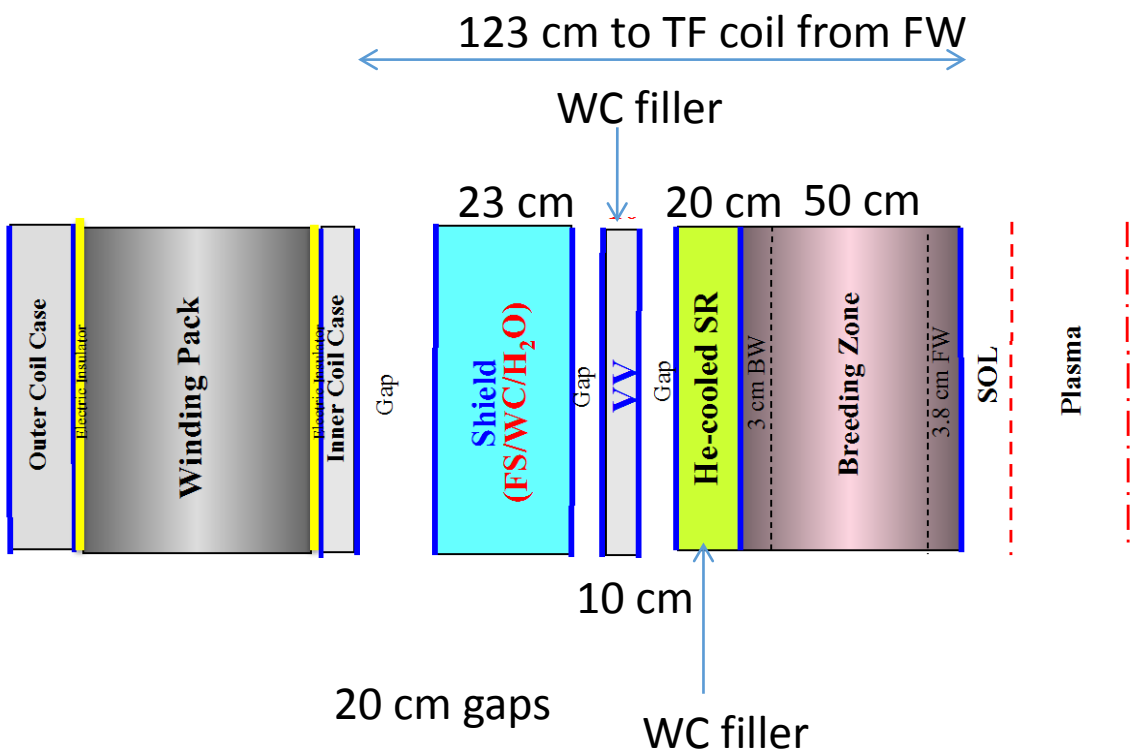


Figure 1. Inboard configuration of FNSF power system.

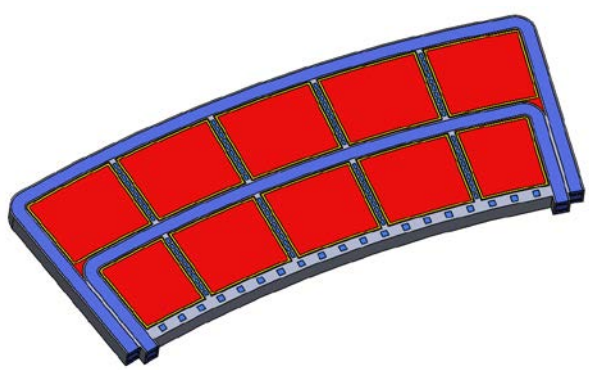


Figure 2: CAD model of Inboard Blanket at midplane

Computer Simulations

Three major multi-physics modules have been coupled in the current design. These are: Non-isothermal Fluid Flow, Heat Transfer in Solids, and Solid Mechanics. They are coupled in the Conjugate Heat Transfer module. Non-isothermal Fluid was used to simulate the helium flow inside the channels. The helium flow was considered as laminar due to the limit of current computation capabilities. Turbulent flow simulations are expected to result in higher heat transfer coefficients, thus reducing the structure temperatures. Turbulent flow will be considered in the future. The temperature and pressure distributions of helium flow can be obtained in this module. Heat Transfer in the Solid was used to compute the temperature distribution of the blanket RAFS structure. Both surface heat flux on the first wall and volumetric heating were considered. The Solid Mechanics module was used to compute the stress

distribution in the structure. The primary stress is due to the helium pressure against the channel wall. To calculate secondary (thermal) stress, the Heat Transfer in Solids and Solid Mechanics were coupled in Multiphysics simulations. Couplings between physics modules are shown schematically in Figure 3.

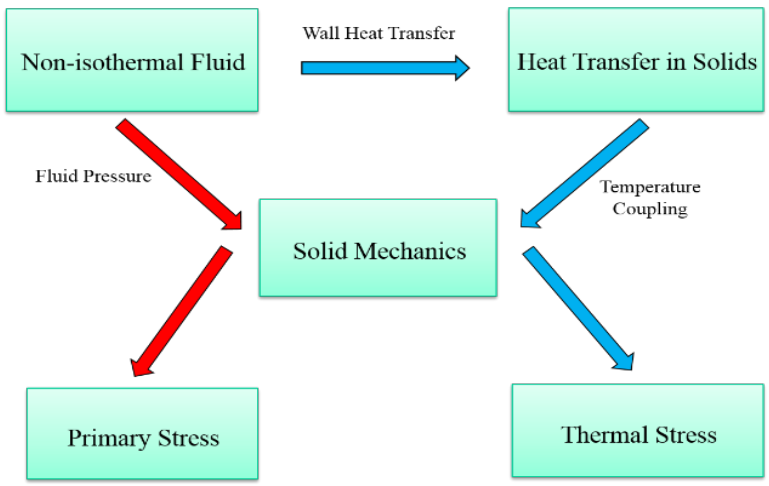


Figure 3. Summary of Models

Results

Helium Flow

The inlet helium operating pressure is assumed to be 8 MPa [1]. As Figure 4 shows, the pressure drops all the way through the helium flow channel. With the laminar flow assumption, the average velocity was set to be over 100 m/s to reach the required heat transfer coefficient.

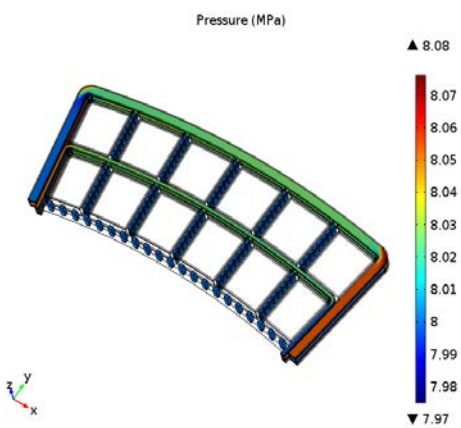


Figure 4. Pressure distribution of helium flow

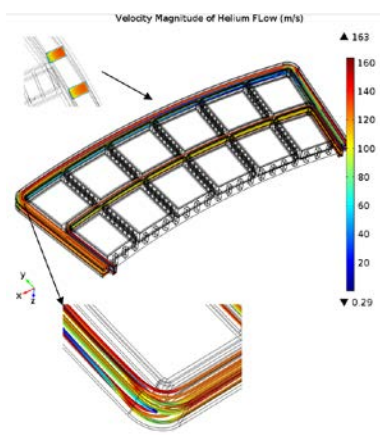


Figure 5. Streamlines of helium flow

The streamlines of helium flow with velocity information are shown in Figure 5. The entire helium flow stream with an inlet temperature of 400 ℃ (Figure 6) enters the blanket sector. So far, only one channel layer at midplane was studied for the present preliminary design. For the entire FW/B design, there are stacks of helium flow channels in the poloidal direction, and an alternating flow configuration will be applied to create a more uniform temperature thus reducing thermal stresses.

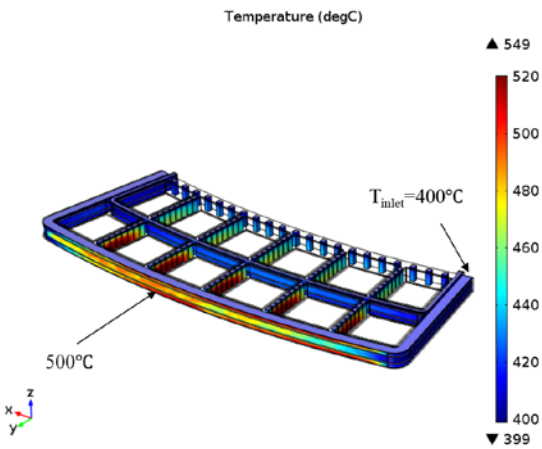


Figure 6. Temperature distribution of helium flow

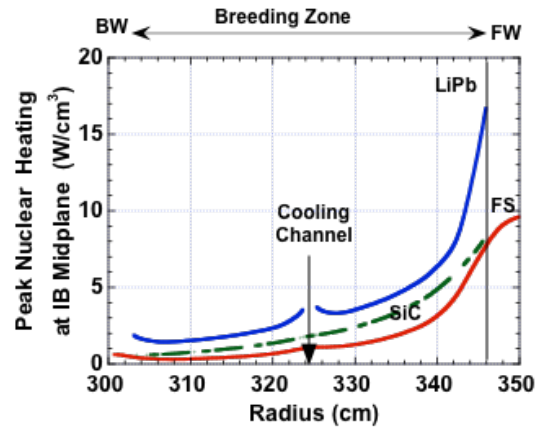


Figure 7. Radial Distribution of Nuclear Heating

Temperature distributions of the solid structure

The heat flux from the plasma results in temperature gradients inside the blanket structure, which cause secondary thermal stresses. The peak heat flux is taken as 1.4 MW/m^2 at the inboard blanket midplane. The dependence of peak volumetric heating on the radial distance at the midplane is shown in Figure 7. The 2 mm thick W armor, which is not shown in the plot, generates the highest heating, which is about 32 W/cm^3.

The surface heat flux and the volumetric heating rates were applied in the Heat Transfer in Solids module in COMSOL. The Pb-Li liquid metal's velocity will go down to 0.075 m/s in the considered temperature range[2,3]. So it is reasonable to consider the breeding zone as a solid, and perform heat transfer simulations in a Pb-Li solid material with appropriate heat flux boundary conditions. The result of the temperature distribution is shown in Figure 8. The maximum temperature of the Pb-Li is slightly above 750 ℃ in the interior parts of breeding cells. However, this is not a concern, since the outlet LiPb temperature is around 700 ℃, while the steel/LiPb interface temperature is kept at 500 ℃.This reveals that helium heat transfer coefficient is not sufficiently high, and this will be modified in the next design iteration. Typically, a heat transfer coefficient around 1000 W/m^2K[5] is assumed. 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 may 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.

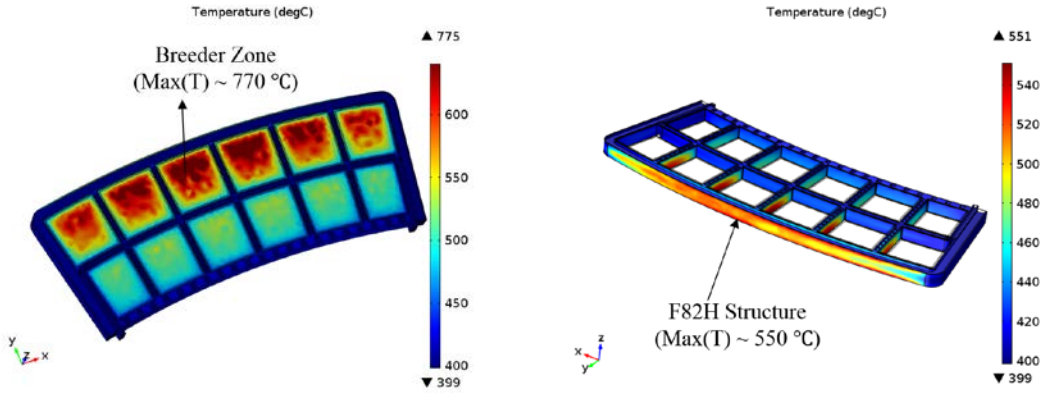
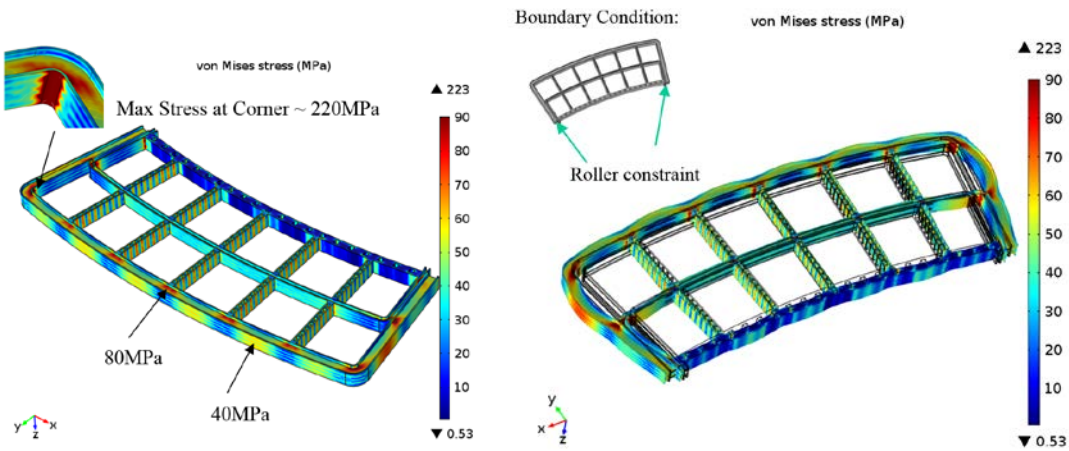


Figure 8. Temperature distribution of global structure

The maximum temperature of the RAFM steel is also about to exceed the limit of 550 ℃. Since the velocity of helium flow is already pretty high, some other methods like roughening the channel wall or changing the structure configuration may need to be applied in future optimizations of the design, if turbulent flow does not result in enhancement of the wall heat transfer coefficient.

Primary stress of solid structure

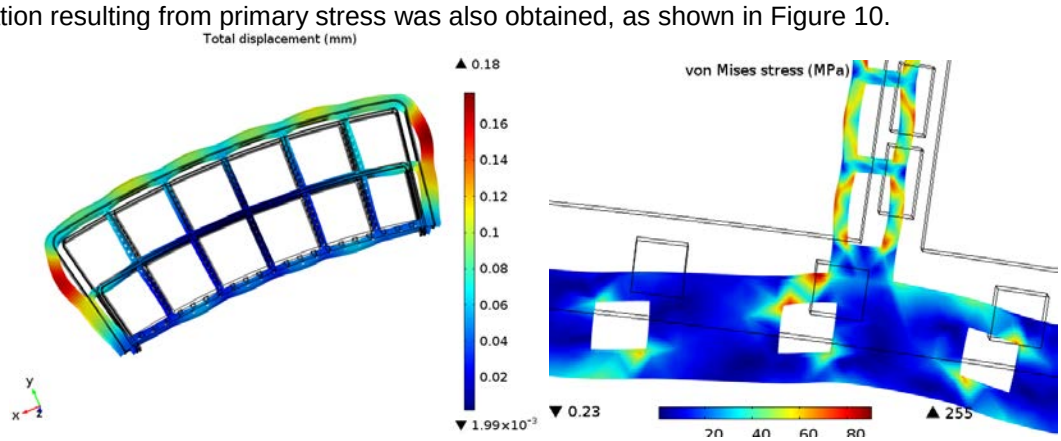
The helium and Pb-Li flow inside the channel generate the pressure against channel walls, which finally leads to the primary stress in the blanket structure. As discussed before, the pressure load in helium cooling channels and the Pb-Li breeding zone is set to be 8 MPa and 1.6 MPa, respectively. The current analysis of the primary stress is based on normal operating conditions, and future efforts will consider off-normal scenarios as well. Figure 9 shows the global primary stress distribution of the blanket structure. There are stress concentrations at the junctions and corners, which can reach more than 220 MPa. Rounding this junction area will help reduce the stress concentration.



(a) Undeformed configuration (b) Deformed configuration

Figure 9. Primary stress distribution

Deformation resulting from primary stress was also obtained, as shown in Figure 10.

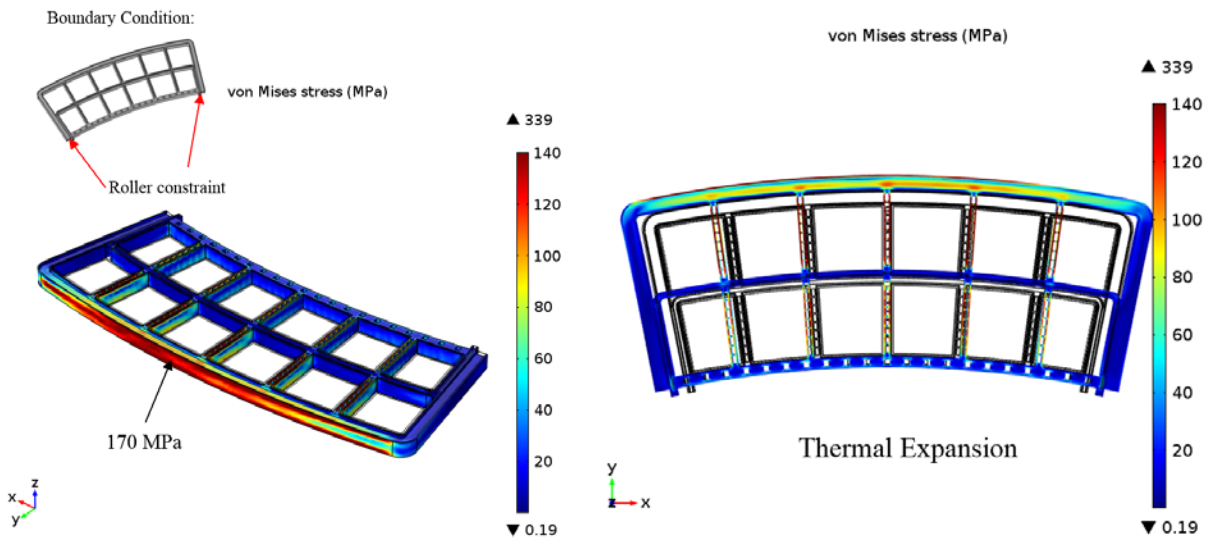


(a) Global deformation (b) Local deformation

Figure 10. Displacement distribution due to the primary stress

Thermal stress of the solid structure

Thermal stress was calculated based on the temperature distributions utilizing the Conjugate Heat Transfer module of COMSOL. As illustrated in Figure 11, the first wall has the largest thermal stress. Also, thermal expansion is shown in Fig 11 (b), illustrating the reason why we need to leave a gap between adjacent sectors during assembly.



(a) Undeformed configuration (b) Deformed configuration

Figure 11. Thermal stress distribution

Factors of Safety

With the results of the primary and thermal stresses, factors of safety were determined based on three different allowable values. These are: the allowable primary membrane stress intensity (S_m), the allowable total stress intensity (S_d), and the allowable primary plus secondary membrane stress intensity (S_e). The results are shown in the following tables. For reference on the mechanical design procedure, including path definitions and stress intensity parameters, please see reference [6].

Table 1. Factors of safety based on S_m

$\overline{P_m} \leq S_m(T_m, \varphi t_m)$			
Path	$\overline{P_m}[MPa]$	$S_m[MPa]$	Factor of Safety
1	23.6	144.8	6.1
2	32.1	150.1	4.7
3	48.3	154.3	3.2

Table 2. Factors of safety based on S_e

$\overline{P_L + Q_L} \leq S_e(T_m, \varphi t_m)$			
Path	$\overline{P_L + Q_L}[MPa]$	$S_e[MPa]$	Factor of Safety
1	18.4	204.3	11.1
2	65.4	211.8	3.2
3	66.9	217.7	3.3

Table 3. Factors of safety based on S_d

$\overline{P_L + P_B + Q} \leq S_d(T, \varphi t, r_3)$			
Path	$\overline{P_L + P_B + Q}[MPa]$	$S_d[MPa]$	Factor of Safety
1	50.9	408.5	8.0
2	85.1	423.5	5.0
3	57.3	435.5	7.6

Conclusions and Future Research:

We have demonstrated the feasibility of multiphysics design and optimization of the FW/B system, coupling fluid flow, heat transfer in fluids, heat transfer in solids, thermal stress, and mechanical stress simulations. The results are preliminary, as the design will continue to evolve this year. In particular, since the results of heat transfer and fluid flow are based on a laminar flow model for computational expediency, they are not realistic and will be replaced with a turbulent flow model. Future efforts will consider the following: (1) simulations of turbulent heat transfer for helium flow; (2) irradiation effects on material properties, (3) geometric optimization to reduce stress concentrations; (4) simulations of plasma transient effects; (5) multiscale modeling of smaller Representative Volume Elements (RVE) to include dislocation-based plasticity models; (6) Design and analysis of the FW/B system in accidental scenarios.

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