Thermo-mechanical Analysis of ITER Test Unit Cell under Pulse Operation

Zhiyong An, Alice Y. Ying, and Mohamed Abdou
43-133 Engr. IV Building, University of California, Los Angeles, 90095-1597

Abstract—In this paper, a 3-D finite element model has been built to do thermo-mechanical analysis about an ITER test unit cell with edge-on configuration under pulse operation. In previous works, the constitutive equations of effective material properties, which are dependent on local temperature and stress, have been empirically derived. In our program, these material properties of ceramic pebble beds (lithium breeders & beryllium neutron multipliers) are implemented the model. Based on current simulation results, it can provide the stress and temperature magnitude and distribution inside the blanket structure when it is under pulse radiation heating. These structural responses due to deformation of particulate materials and material thermal creep are important for assessment of thermo-mechanical behaviors and characterization of tritium release.

Keywords-ITER-TBM; thermo-mechanical analysis; pebble bed.

I. INTRODUCTION

The US has selected the helium-cooled solid breeder concept with ferritic steel structure and beryllium neutron multiplier as one of the candidate breeder blankets for ITER TBM testing. [1] The concept is based on the use of lithium-ceramic pebbles as breeder material. Rather than testing a fully independent TBM, the US testing approach is to design unit cell/submodule test articles. At present, there are two reference configurations for designing the ITER test unit cell/submodules: 1) a layered configuration where the solid breeder and beryllium pebbles are placed parallel to the first wall (FW), and 2) an edge-on configuration where both beryllium and breeder beds are placed perpendicular to the FW facing the plasma region. The preliminary results show that temperature and stress distribution are different in these two designs. Considered the movability of a pebble bed, the edge-on design shows better stress reduction. [2] However, the exact description of thermo-mechanical behaviors is still limited in the previous simulations.

One important limitation is caused by the nonlinear material properties of pebble beds. The phenomena involved in ceramic breeder pebble beds are complex and include many parameters. Based on previous experimental results, the elastic modulus and plastic deformation of a packed pebble beds are functions of stress, temperature and material properties. At the current stage of research, effective constitutive equations derived experimentally are implied to describe the elastic and plastic deformation. Thereafter, these equations are incorporated into the finite element model. The previous results demonstrated that finite element analysis is effective in studying macroscopic stress and deformation during ITER operation. [2] However, it should be noted that the accuracy of the numerical results strongly depends upon the constitutive equations and the quality of the material parameters. A recent paper has shown that those constitutive equations of pebble beds can be much different when the geometry and loadings of pebble bed systems are different. [3]

In this paper, a 3-D thermo-mechanical finite element model will be used to analyze an ITER test unit cell with edge-on configuration. In the model, revised effective material properties, derived from experimental works, will be utilized to simulate the beryllium and breeder pebble beds. Our study will focus on the effects of pulse nuclear heating operation condition and effective constitutive equations. Numerical simulation results will show that, under pulse radiation heating, the time-dependent stress and temperature distribution are much different from the static case.

II. NUMERICAL MODEL

With the aim of evaluating blanket thermo-mechanical performance, our numerical model is based on a proposed ITER test blanket submodule, which is to be inserted into the EU HCPB structural box and to be subjected to an ITER 400s burn cycle. Following the design, the ceramic breeder (Li$_4$SiO$_4$, 75% Li-6) and beryllium pebbles can be packed into the layered and the edge-on configurations. The different configurations will affect the thermo-mechanical performance of the test blanket. However, in this paper, the calculation is performed on an edge-on configuration, as shown in Fig. 1. [4] One basic assumption of our finite element model is that the vertical movement of the structures can be neglected compared to the movement in the spanwise direction and the movement along the radial direction (along the pebble bed). Based on this assumption, boundary conditions close to ITER test conditions have been applied in our model.

![Figure 1. The submodule of ITER test blanket](image)

(a) The unit cell of ITER-TBM
(b) Box cell
A. Thermal loads and boundary conditions

After the model was built and meshed, the appropriate thermal and mechanical loadings were applied to the model. For the fusion nuclear reactor, the profiles of the tritium production rates in the radial direction are essential and can be achieved based on different blanket configuration. The heating generation rates obtained from the neutronics inside the submodule have been obtained by Youssef, et al. [5]. Fig. 2 shows the heating rate profiles of different material structures in our simulation. Typically, in the edge-on configuration, the heating rate presents a large steep gradient near the FW.

![Radial profile of nuclear heating rates of different materials inside edge-on submodule](image)

The thermal loading and boundary conditions applied to the model are relevant to ITER operational conditions and can be summarized as follows:

- Heat generation was applied in the structures to simulate nuclear heating. The nuclear heating values are shown in Fig. 2. These calculations are one-dimensional (radial direction) and are based on ITER operational conditions (neutron wall load of 0.78 MW/m²).
- Heat convection \((h = 1000 \text{ W/m}^2\cdot\text{K})\) and bulk temperature \(= 350^\circ\text{C}\) was applied in all helium coolant channels.

Fig. 3 shows the 3-D meshed finite element model and the thermal loads and boundary conditions.

![Thermal loads and boundary conditions applied to the FEA model](image)

B. Effective Material Properties

In the edge-on configuration, the solid breeder and beryllium pebble beds are arranged perpendicular to the front first wall and separated by cooling channels. To analyze the structures, the pebble beds have to be treated as continuous materials. Similar to Fokkens [6], the effective thermal conductivity of the lithium orthosilicate material is treated as temperature dependent, with a typical value of 1 W/m·K at 400–500°C. The effective thermal conductivity of beryllium pebble beds depends on the temperature and the stress/strain, and has a typical value of 3–4 W/m·K in the same temperature range at a stress value of 0.5 MPa.

The elastic modulus and creep compaction \((E_c \text{ and } \varepsilon_c)\) of solid breeder and beryllium pebble beds are related to stress and temperature levels by the expression. Based on previous research [3], our revised effective constitutive equations are:

\[
E_c = E_0 \cdot (1 + A_i \cdot T^4) \cdot (1 + A_j \cdot \sigma^4)
\]

where

- \(E_c\): Effective Young’s modulus of pebble beds [MPa]
- \(T\): Temperature [°C]
- \(E_0\): Young’s modulus after initial packing [MPa]
- \(\sigma\): Von Mises stress [MPa]
- \(A_i\): experimentally derived constants.

and

\[
\varepsilon_c = B_i \cdot \sigma^B \cdot \exp(B_2 / T) \cdot t^B
\]

where

- \(\varepsilon_c\): Effective creep strain of pebble beds
- \(\sigma\): Von Mises Stress [MPa]
- \(T\): Temperature [°C]
- \(t\): Time [s]
- \(B_i\): experimentally derived constants.

Using the above equations, the exact equivalent result is totally dependent on the experimentally derived constants. Currently, those constants are based on the research done by Reimann et al. [6-8]. Their experiments have provided fundamental and far-sighted data to study the behaviors of blanket structures. However, the macroscopic properties of pebble beds are complex and the effects of boundary conditions and microscopic properties of pebble beds, such as friction and local plastic contact deformation, still need to be examined. In order to achieve accurate results, simulations based on discrete element method are being conducted.

III. RESULTS WITH PULSE HEATING

In this section, the results of dynamic state thermomechanical analysis of the edge-on submodule are presented. This analysis was conducted in the finite element program...
Using a coupled thermo-mechanical model, which can simultaneously calculate temperature and stress, the thermo-mechanical behaviors of the edge-on submodule under pulse heating can be simulated. The effective thermo-physical constitutive equations (Equations (1) and (2)) are defined in user subroutines (HOOKLW and CRPLAW). Our goal is to study the impact of the applied constitutive equations.

A. Thermal profile

To simulate pulse operation, there are 5 cycles in our simulation. The total time of one cycle is 1000s, the burn time is about 400s, the transient time is 100s, including 40s to start burning and 60s to stop burning, and the interval time between two pulses is 500s. The sketch map of the pulse cycles is shown in Fig. 4. The results in Fig. 4 show the change of maximal temperature inside different pebble beds under pulse operation. The solid and dot lines respectively represent the change of maximal temperature inside the solid breeder and beryllium pebble beds and both curves behave like repeat waves. The maximal temperature in the solid breeder is about 760°C, and 620°C in the beryllium pebble bed. This shows that effective thermal conductivity will determine the temperature profile inside the structures. Higher effective thermal conductivity will reduce the maximal temperature of the pebble bed.

Fig. 4 also shows that, after each cycle, the minimal temperature of each pebble bed is appreciably increased and the maximal temperature is unchanged. Based on the current numerical model, the pebble bed is assumed as a bulk material and this temperature increase is caused by structural gaps generated during the deformation cycle. However, in practice, the pebble beds will be more moveable, and the gaps between the pebble bed and the coolant structure could be filled by particles.

B. Stress distribution and magnitude

Stress distribution inside the structures (Fig. 5) shows that thermally induced stresses are unequally distributed in the pebble beds. The stresses inside the beryllium pebble beds are much higher than the stresses inside the solid breeder pebble beds. The highest stresses (about 20MPa) are concentrated near the front wall, especially around the corners of the coolant channel. The highest stresses inside the solid breeder are about 2.5MPa and are distributed in the front contact part of the coolant structures and the pebble beds.

Fig. 6 shows the curves of Von Mises stresses along the center line of solid breeder pebble bed when the bed temperature reaches maximum in different pulse cycles. The curves show that the stress distributed inside the bed can be divided into two parts: the ridge part and the plain part. The ridge part appears near the front wall and corresponds to the highest temperature region of the solid breeder pebble beds. The plain part covers nearly 3/4 of the pebble beds and the Von Mises stresses do not change much. The maximal stress in the ridge part increases with the cycles, whereas the stress in the plain part decreased with the cycles.

C. Young’s modulus inside solid breeder pebble beds

In our simulation, the constitutive equations are defined in Equations (1) and (2), which have included the impact of temperature and stress. Therefore, during pulsed operation, the stress-strain behaviors at the different locations, as shown in Figs. 7 and 8, exhibit significant difference. Figs. 7 and 8 are results of nodes in the ridge part and the plain part respectively.

Fig. 7 shows that the stiffness of the pebble bed corresponding to first loading and first unloading processes is significantly changed. After the first cycle, the stiffness of pebble bed does not change very much. However, in all cycles,
the stress-strain relations at the each end of unloading display unusual behavior, in which the stress increases as the strain decreases. Compared with the stress-strain curves shown in Fig. 8, the unusual behavior can be explained by movement inside the pebble bed. In our simulation, this movement characteristic of pebble bed is related to the stress-dependent Young’s modulus.

Fig. 8 shows the stress-strain behavior of the pebble bed in the plain part, where the stress lever is lower than the peak stress of the ridge part. The effective Young’s modulus of thermal loading and unloading is nearly the same in different cycles. At the same time, the maximal equivalent stress in each cycle decreases as cycle number increases.

![Figure 7. Stress-strain behavior of the node inside the ridge part of the solid breeder pebble bed.](image)

![Figure 8. Stress-strain behavior of the node inside the plain part of the solid breeder pebble bed.](image)

**IV. CONCLUSION**

3-D FEA simulations have provided important information about an ITER test unit cell with edge-on configuration under pulsed operation. First, numerical simulations show that in each cycle, the maximum temperature and stress in the breeder pebble bed are similar and the high temperature and stress are concentrated in the front part close to the First Wall panels. After each pulse cycle, the temperature inside the pebble bed appreciably increases. However, the stress at the front part of the pebble bed also increases. Second, simulation provides stress-strain behaviors with thermal creep deformation effects. Given the involved creep mechanism and moveable characteristics of the pebble bed, the results indicate that the stress-strain behavior is anisotropic and changed over time. Third and most important to our study, finite element analysis is effective in studying the macroscopic stress and deformation during operation; however, the accuracy of the results strongly depends upon the defined constitutive models used for the pebble beds and the quality of the material parameters. The effects of microscopic properties of particles, such as friction and local plastic contact deformation, on the bulk mechanical response still need to be examined in order to derive better constitutive models.

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