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Thermal Stress Mitigation in the Fuel Elements of the Very High Temperature Reactor

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1. Introduction

NHDD(Nuclear Hydrogen Development and Demonstration) project consider the prismatic block type VHTR(Very High Temperature Reactor) which uses hexagonal graphite fuel elements containing fuel compacts inside [1]. A previous study [2] was carried out to evaluate detailed thermo-fluidal characteristics of the fuel elements in normal operation condition. A structural integrity assessment under the operating temperature was followed by Kang et al [3]. In the structural integrity assessment, fuel element showed relatively high stress level due to large thermal expansion of the fuel compacts. In this study, small gaps between fuel compacts and graphite plugs was modeled and the stress mitigation by the gaps was investigated.

2. Gap Modeling

The previous study by Kang et al [4] showed that the larger thermal expansion of the fuel compacts made the graphite plugs under high stress level. Fig. 1 showed the peak maximum principal stress of one of the fuel elements which experienced the largest thermal stress in the previous study. The fuel compacts is contacted with the graphite plugs at the initial state and the expanded fuel compacts pushes up the graphite plugs upward. Those upward motion on the graphite plugs makes relatively large tensile stress along the circumferences on the bottom surfaces of the graphite plugs. To release this undesirable stress, small gaps are included between the fuel compacts and the graphite plugs. A proper size of gap can compensate the difference of the thermal expansions of the fuel compacts and the graphite block. The size of the gap is determined by the following equation.

$$L_{gap} = \alpha_{FC}\left(T_{FC,max} - 20℃\right) - \alpha_{BL}\left(T_{BL,min} - 20℃\right) \quad (1)$$

where, L_{gap} is the size of the gap and α is the mean coefficient of thermal expansion and T is the temperature. The subscript, FC means fuel compacts and BL means graphite block. The Eqn. (1) calculates the maximum thermal expansion of the fuel compacts compensated by the thermal expansion of the graphite block. From the temperature data and the men coefficients of thermal expansion of the fuel elements in the previous study [3], the minimum size of the gap was calculated to be 1.50 mm.

In the previous study [4], the fuel compacts were modeled to contact with the graphite block at the initial state as shown in the Fig. 2 (a). Because the average temperature fuel compacts is always higher than that of graphite block, the fuel compacts is always in contact with the graphite plugs with positive contact pressure and the convergence of FEM analysis is well guaranteed. By including the gap which is empty space between the fuel compacts and the graphite plug, the fuel compacts are not fully constrained and the fuel compacts will behave like rigid bodies resulting in divergence of the FEM solution. Fig. 2 (b) shows the gap and the unconstrained fuel compacts. To avoid the divergence of the problem, a fictitious buffer material fills up the empty space between the fuel compacts and the graphite block. The fictitious buffer acts like a very soft spring to constrain the fuel compacts. The buffer should be soft enough not to change the original problem much. To determine the material properties of the buffer, a parametric study was performed by decreasing the density, the thermal expansion, and the elastic modulus.

3. Results

Table 1 shows the material properties of the buffer and the peak Mises stresses in the specific parts of the fuel element. In the case 1, the same material properties of the graphite block at room temperature. For the subsequent cases, each material property was divided by 10 to soften the material. In the Fig. 3, it shows that the buffer material is soft enough not to change physical behavior of the fuel elements in the case 7.

Using the material properties of the buffer determined from the parametric study, the thermal stress analysis was carried out with the model including the gaps. The temperature profile was selected for the Block 10 in the previous study [4] which had the largest peak stress among all the fuel elements. Fig. 4 shows the stresses in the specific parts of the fuel element without and with the gaps. In the figure, the largest peak stress in the graphite plug was 8.13 MPa without the gaps; however, it was reduced to be 1.59 MPa when the gaps were included. The peak stresses in the fuel compacts also reduced much due to the gaps. The peak stresses in the graphite block remained almost same regardless of existence of the gaps. From the stress mitigation due to the gaps, the inclusion of the gaps is indispensable in the fuel element design of the VHTR.

6. Summary

Stress mitigation in the fuel elements of the VHTR by the inclusion of the gaps between the graphite plugs and the fuel compacts was investigated in this study. Due to the space in the gaps, the fuel compacts showed rigid body motions and the FEM analysis failed to be converged. To avoid the rigid body motions, fictitious materials were inserted as buffer between the walls of the holes in the graphite block and the fuel compacts. A parametric study was carried out to minimize the influence of the buffer to the FEM model and obtain a converged solution. The thermal stresses of the fuel element which showed the maximum thermal stress in the previous study[4] were compared with the thermal stress when the fuel element included the gaps. The result showed that the inclusion of the gaps reduced the maximum thermal stress from 8.13 MPa to 1.59 MPa and it substantiated that the gaps are indispensible in the fuel elements of the VHTR.

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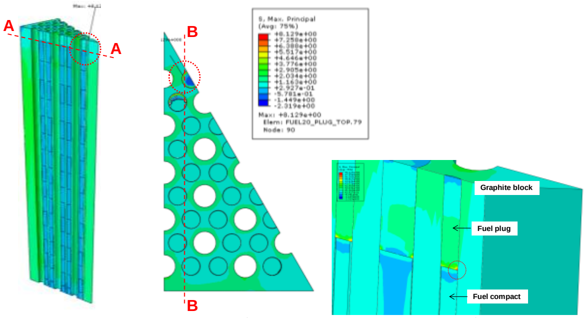
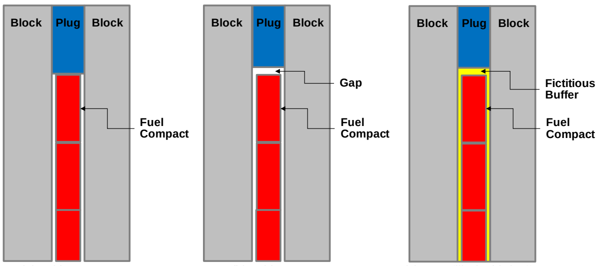


Cross-Section A-A   Cross-Section B-B

Fig.1 Maximum thermal stress location in the fuel element



(a) Without gap   (b) With gap   (c) Gap filled with buffer

Fig.2 Method of gap modeling

Table 1 Material properties and peak stress for parametric study

Case	Density (g/cm^3)	Elastic modulus (MPa)	Mean coefficient of thermal expansion (10^{-6}/K)	Peak Mises stress (MPa)		
				Graphite block	Graphite plugs	Fuel compacts
1	1.78	7900	3.63	3.907	10.2	17.87
2	1.78E-1	790	3.63E-1	3.879	9.544	15.21
3	1.78E-2	79	3.63E-2	3.685	7.617	5.498
4	1.78E-3	7.9	3.63E-3	3.327	3.519	2.492
5	1.78E-4	0.79	3.63E-4	3.261	3.669	0.9793
6	1.78E-5	0.079	3.63E-5	3.250	3.762	1.023
7	1.78E-6	0.0079	3.63E-6	3.249	3.776	1.016

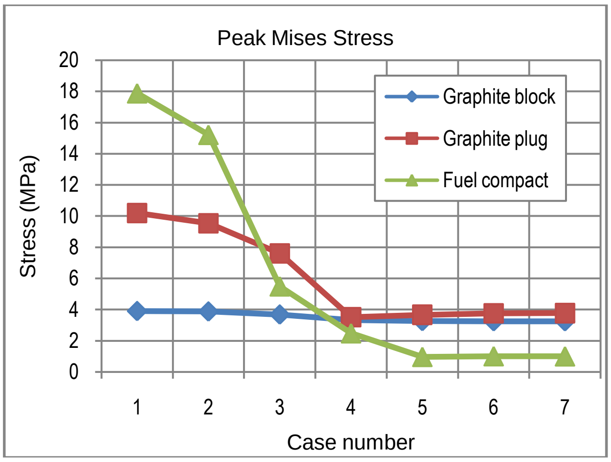


Fig. 3 Change of peak Mises stress in the fuel element as buffer material softened

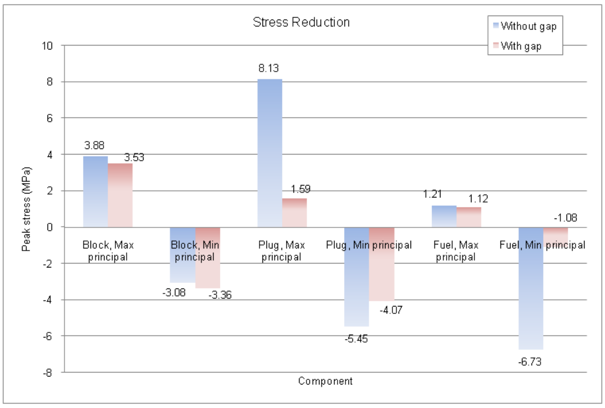


Fig. 4 Stress reduction due to the gap in the fuel element