Thermal Stress Assessment of Graphite Fuel Blocks in a Very High Temperature Reactor Core

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1. Introduction

A prismatic block type VHTR(Very High Temperature Reactor) uses hexagonal graphite blocks which contains fuel compacts inside as reactor fuels. The main objectives of graphite blocks are to contain fuel compacts, to provide coolant flow channels, and to maintain structural integrity under very high temperature. The highest and the lowest temperatures in stacked graphite blocks are estimated to about 1200°C and 490°C which might cause severe thermal stress in a mechanical point of view. Thus, a precise thermal stress assessment is required to guarantee structural integrity of core graphite structures.

2. Method of Thermal Stress Analysis

Precise thermal stress analyses were performed in conjunction with a preceding CFD analysis of stacked fuel graphite blocks [1]. CFX 11 was used for the CFD analysis and whole temperature field of 1/12 symmetric model of 10 graphite fuel blocks and 2 graphite reflector blocks was calculated. A commercial finite element code, Abaqus v6.9, was chosen as a thermal stress analysis tool. A conversion program was written using Python programming language, and the program effectively converted CFX mesh and temperature data to Abaqus input data.

The thermal stress analysis is divided into two steps. First, Abaqus read converted CFX mesh and temperature field and performed a linear perturbation analysis which cannot consider temperature dependent material properties and nonlinear deformation such as contact between a graphite block and fuel compacts. The main purpose of performing the linear perturbation analysis is to get a first insight of the behavior of whole stacked blocks and to generate temperature output in Abaqus output database format which can be used as a temperature field input of the second step.

In the second step, sub-model analyses of stacked blocks were performed by forming new mesh input data of each block one-by-one. The sub-modeling of whole stacked graphite blocks makes full nonlinear thermal stress analysis possible because of reduced number of degrees of freedom. The nonlinear thermal analysis provides contact calculation between graphite blocks and fuel compacts and the use of temperature dependent material properties.

3. Material Properties

Applying material properties exactly as much as possible is very essential for the analysis. In addition, because the temperature values are in a very wide range from 490°C to around 1200°C, all the material properties are required to be temperature dependent values. Thus, the temperature dependent material properties were surveyed for graphite blocks and fuel compacts. The graphite material was chosen to IG-110 which is adopted in Japan. From the fact that a fuel compact is a compound of several material and there were a number of different composition and base materials, it was difficult to retrieve one naive set of material properties. None of the data set for fuel compacts was complete for the required material properties and any one of them is not temperature dependent either; however, the most recent data were available from HTTR in Japan. The collection of material properties of IG-110 graphite and fuel compacts is shown in Table 1.

4. Thermal Stress Analysis Results

As mentioned in section 2, the thermal stress analysis was divided into two steps. From the first step of analysis which performed a linear perturbation analysis, two major results were acquired; temperature field output database for an input of the next step and overall deformed shapes and stress level of stacked fuel blocks and fuel compacts. As a linear perturbation analysis does not allow temperature dependent material properties and contact calculation, the deformed shapes and stress level were not expected to be accurate enough. Fig. 1 shows the deformed shapes with stress contours of the stacked graphite blocks and the fuel compacts. Because one-body mesh for all stacked blocks was used, all stacked blocks behaved like one long slender column as shown in the figure, which is not expected to occur in a real structure. Also the similar behaviors were observed in the stacked columns of fuel compacts and even implausible penetration of fuel compacts into the graphite blocks occurred due to severe bending of one-body meshes for fuel compacts.

In the second step of analysis, for sub-model analyses of stacked blocks, the temperature field output database from the first step and local separate meshes of all fuel blocks were used as inputs for a Abaqus nonlinear thermal stress analysis. By performing sub-model analyses of stacked blocks, contact behaviors between a graphite block and fuel compacts, and detailed local thermal stress distribution can be observed for each block. The highest thermal stress level was found on the first fuel block from the base, on which maximum temperature also appeared. Fig. 2 shows the deformed shape of the block with stress contours and cross-section where the maximum stress was developed. The location of the maximum von-Mises stress was ~3 cm below from the top surface of the block and it is also exactly the end of one of the fuel plugs. Fig. 3 shows the deformed shape of the corresponding fuel plug. In the figure, it shows that the thermal expansion of fuel compacts below the fuel plug pulled the fuel plug outward and the maximum stress level was developed from the shear deformation of the fuel plug circumference. The stress level was 48.8 MPa which exceeds graphite tensile strength, 25.3 MPa; however, a failure is not expected because there is a small space between the plug and the fuel compact in a real design (which is not modeled in this study) to compensate the thermal expansion of the fuel compact.

6. Summary

Thermal stress on the stacked fuel blocks which consists of a VHTR reactor core structure was investigated. A commercial FEM code was used to perform thermals stress analysis and CFD temperature results were used as input from a preceding study.

Thermal stress analysis was performed in two steps. In the first step, a linear perturbation analysis was performed to generate the temperature field output database for an input of the next step. The analysis result showed the necessity of nonlinear contact analysis.

In the second step, a nonlinear contact analysis was performed on each block to obtain the detailed block-by-block thermal stress distribution. Thermal stress of all 10 blocks were investigated and the maximum von-Mises stress was found on one of the fuel plugs of the first fuel block from the base. The predicted maximum stress level was 48.8 MPa which exceeds graphite tensile strength. Therefore, a small space between the plug and the fuel compact is required to avoid such a high stress.

REFERENCES

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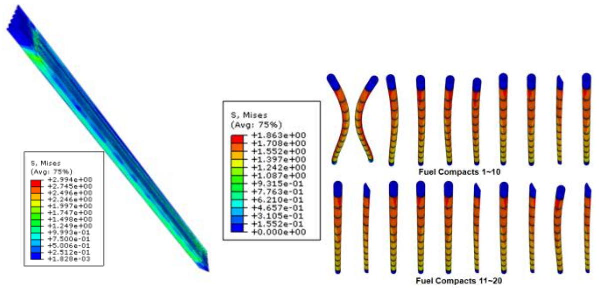
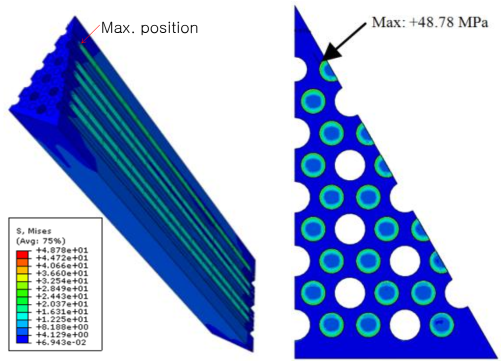
Table 1 Material properties of IG-110 and fuel compacts

Properties	Symbols	Units	IG-110 (Ref. [2])		Fuel compacts
Density	ρ	g/cm^3	1.78 (at 300K)		1.74 (Ref. [3])
Young's modulus	E	GPa	E=E20*∑Ci*T^i 20≤T(℃)≤1700		6.89 (Ref. [4])
			E20	7.9	
			C0	1.0	
			C1	1.3328E-05	
			C2	-1.5281E-07	
			C3	4.4335E-10	
			C4	-2.5016E-13	
			C5	4.8723E-17	
Poisson's ratio	ν		0.14		0.19 (Ref. [5])
Compressive strength	σ_c	MPa	76.9 (at 300K)		25.7 (Ref[. 4])
Tensile strength	σ_t	MPa	25.3 (at 300K)		5.94 (Ref. [4])
Mean coefficient of thermal expansion	α	1/K	α=α400*(Ci*T^i) 100≤T(℃)≤1500		4.86E-06 (Ref. [6]) (within the range of room temperature to 800℃)
			Ref temp.	20	
			α400	4.06E-06	
			C0	0.853157	
			C1	4.26564E-04	
			C2	-1.42849E-07	



(a) Graphite blocks (b) Fuel compacts

Fig.1 Deformed shapes with stress contours of graphite block and fuel compacts



(a) Fuel block (b) Cross-section of max. stress

Fig. 2 Stress contours on the 1st fuel block and cross-section of maximum stress

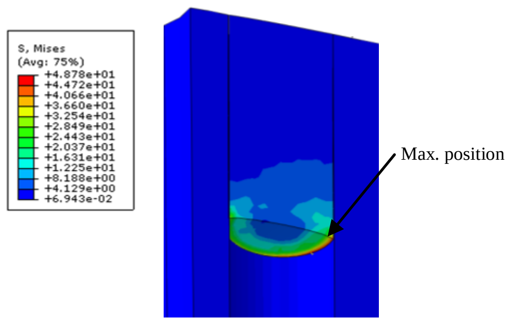


Fig. 3 Deformed shape and stress contour of the fuel plug on which maximum stress was developed