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Calculations of the IAEA-CRP-6 Benchmark Cases by Using the ABAQUS FE Model for a Comparison with the COPA Results

Moon-Sung Cho, Y. M. Kim, Y. W. Lee, K. C. Jeong, Y. K. Kim, S. C. Oh
Korea Atomic Energy Research Institute, 150 Dukjin, Yuseong, Daejeon, Korea, mscho1@kaeri.re.kr

1. Introduction

The fundamental design for a gas-cooled reactor relies on an understanding of the behavior of a coated particle fuel. KAERI, which has been carrying out the Korean VHTR (Very High Temperature modular gas cooled Reactor) Project since 2004, is developing a fuel performance analysis code for a VHTR named COPA (COated Particle fuel Analysis). COPA predicts temperatures, stresses, a fission gas release and failure probabilities of a coated particle fuel in normal operating conditions. Validation of COPA in the process of its development is realized partly by participating in the benchmark section of the international CRP-6 program led by IAEA which provides comprehensive benchmark problems and analysis results obtained from the CRP-6 member countries[1]. Apart from the validation effort through the CRP-6, a validation of COPA was attempted by comparing its benchmark results with the visco-elastic solutions obtained from the ABAQUS code calculations [2] for the same CRP-6 TRISO coated particle benchmark problems involving creep, swelling, and pressure. The study shows the calculation results of the IAEA-CRP-6 benchmark cases 5 through 7 by using the ABAQUS FE model for a comparison with the COPA results.

2. Methods and Results

2.1 ABAQUS Finite Element Model

The finite element(FE) model deals with the stresses in three load-bearing layers of the TRISO coated particle: the inner pyrocarbon (IPyC) layer, the SiC barrier layer, and the outer pyrocarbon (OPyC) layer. The two- dimensional finite element model is shown in Figure 1 by representing a quarter of a sphere. The elements are four-noded axisymmetric quadrilaterals (CAX4 in ABAQUS). The nodes along the bottom surface extend along the equator of the sphere. To enforce a spherical symmetry of the model, the nodes along the horizontal and the vertical surface of the model are constrained to move only in the radial direction. Elements are grouped together in logical sets to allow for a specification of the material properties for the PyC and the SiC. Because of the anisotropic nature of the PyC irradiation induced dimensional changes, the material properties are evaluated at the integration points in a spherical coordinate system: The first component direction is aligned along the radial direction, and the second and the third are aligned in the hoop direction. The stresses reported below are taken from this intrinsic spherical coordinate system. Fission gas pressure is applied to the inner surface of the IPyC layer and the external ambient pressure is applied to the outer surface of the OPyC layer.

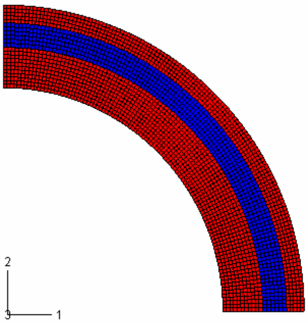

Figure 1. ABAQUS 2-D Finite Element Model for TRISO Coated Particle Fuel

The problem selected for a verification is adopted from Miller's publication[3] which provides the dimensions, applied pressures, an irradiation temperature, creep coefficients, and swelling rates of a nominal target particle.

The particle is irradiated to a fluence (E>0.18 MeV) level of 1.5×10^{25} n/m^2 in the problem. Comparison of the ABAQUS results with Miller's analytical solution is presented in table 1, where the values calculated for four stress components at the end of an irradiation are listed. The stress σ_T is the tangential stress at the inner surface of the SiC layer. This value is crucial because it determines the failure of a particle. Subscripts r and t represent the radial and the tangential directions and subscripts I and O represent the interfaces between the IPYC and the SiC layers and the OPYC and the SiC layers, respectively. In the first case considered in table 1, no internal or external pressures are applied. In the second case of table 1, an internal gas pressure and an external ambient pressure are applied. In both cases, ABAQUS shows a quite good agreement in results with Miller's solutions.

Table 1. ABAQUS results vs. Millers's derivation

Stress Components	**ABAQUS Results (MPa)**	**Miller's Derivation (MPa)**
Without pressures applied		
σ_{rI}	20.77	21.36
σ_{rO}	-7.13	-7.59
σ_{tO}	55.8	56.68
σ_T	-163.0	-165.3
With pressures applied		
σ_{rI}	-8.22	-7.94
σ_{rO}	-13.99	-14.11
σ_{tO}	50.44	51.34
σ_T	-45.39	-47.69

2.2 ABAQUS Calculations of IAEA-CRP-6 benchmark Cases 5 through 7 in Comparison with COPA

Calculations of the IAEA-CRP-6 benchmark cases 5, 6 and 7 for the TRISO coated single particle problems were carried out by using the ABAQUS FE model and the results were compared to the COPA calculation for the same cases[1]. Input parameters for the three benchmark cases are summarized in table 2.

Table 2. Input parameters for 3 benchmark cases

Parameters	Units	Case 1	Case 2	Case 3
Kernel Diameter	μm	350	500	500
Coat Layer Thickness	μm	215	215	215
PyC Swelling Strain Rate	$/10^{25}$ n/m^2	Correlation (a)	Correlation (a)	Correlation (b)
Others			same values	

Fuel particle in case 5 is a TRISO coated particle with a 350 μm diameter kernel under realistic service conditions. Fuel particle in case 6 has a 500 μm diameter kernel with all other parameters the same as in Case 5. Fuel particle in case 7 is the same as in Case 6 except that pyrocarbon BAF is increased to 1.06 and accordingly the PyC swelling strain rate is different from that of case 6.

Figures 2, 3 and 4 present the results of the IAEA-CRP-6 benchmark calculations of cases 5, 6 and 7, respectively. Hoop stresses at the interface surfaces between the SiC and the IPyC layers are plotted as a function of the fast neutron fluence of E>0.18 MeV.

In all three cases, results from the ABAQUS and COPA benchmark calculations are in good agreement in general. However, the ABAQUS model shows an under-prediction of the hoop stresses for the outer surface of the IPyC layer regardless of the cases. As for the hoop stresses of the SiC inner surface the ABAQUS model shows an under-prediction in magnitude for the fluence range of 0.5×10^{25} through 2.9×10^{25} n/m^2.

3. Conclusion

Calculations of IAEA-CRP-6 benchmark Cases 5 through 7 for a TRISO-coated fuel particle involving creep, swelling, and pressure were carried out by using the ABAQUS finite element model which was verified in a comparison with Miller's solution.

In all three cases, the calculation results from the ABAQUS FE model and COPA are found to be in good agreement in general. However, the ABAQUS model shows an under-prediction of the hoop stresses for the outer surface of the IPyC layer regardless of the cases. As for the hoop stresses of the SiC inner surface the ABAQUS model shows an under-prediction in magnitude for the fluence range of 0.5×10^{25} through 2.9×10^{25} n/m^2.

Acknowledgement

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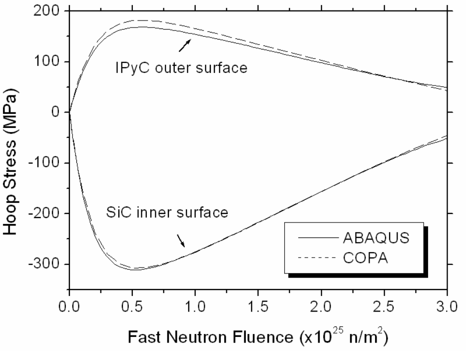

Figure 2. Case 5 Benchmark Calculations of ABAQUS and COPA for Hoop Stresses at SiC/IPyC Interface Surfaces

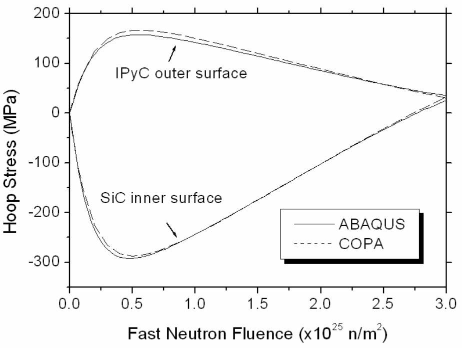

Figure 3. Case 6 Benchmark Calculations of ABAQUS and COPA for Hoop Stresses at SiC/IPyC Interface Surfaces

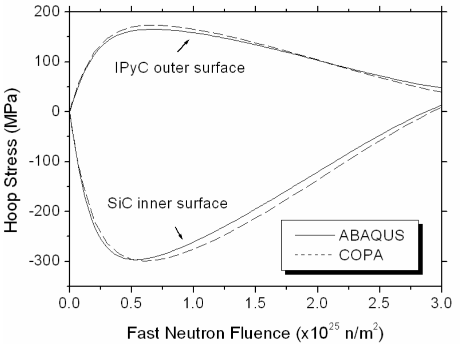

Figure 4. Case 7 Benchmark Calculations of ABAQUS and COPA for Hoop Stresses at SiC/IPyC Interface Surfaces

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