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Plus7 Fuel Rod Heat Transfer Analysis

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1. Introduction

The objectives of fuel system safety are to provide assurance that the fuel system is not damaged as a results of normal operation(NOP) and anticipated operational occurrences(AOO), fuel system damage is never so severe as to prevent control rod insertion when it is required, the number of fuel rod failure is not underestimated for postulated accidents, and cool-ability is always maintained.

According to requirement above, heat transfer in nuclear system has to be done properly to make core cooled. It is very important to predict the temperature distribution of fuel rod. Heat removal from nuclear reactors involves the removal of heat from the cylindrical fuel elements, this occurs in the radial direction, through the principles of heat resistances by conduction and radiation. The heat generated by nuclear fission is conducted through the fuel rod and convected by the surrounding coolant. Fuel temperature distribution in a pellet due to internal heat generation at 100% power condition is analyzed in this study using ANSYS workbench. The analysis results are compared with value of APR1400 SSAR. The temperature of 2D and 3D analysis results is plotted against radial distance 3D analysis is carried out for reference purposes.

The results show that the temperature of fuel centerline is almost same between the value of APR1400 SSAR and 2D and 3D model results but the temperature difference of cladding between the value of APR1400 SSAR and 2D and 3D is up to 11%. This is because Zircaloy-4 was used for cladding material instead of Zirlo. Another reason is that average film coefficient is applied to this analysis. More detailed analysis need to be done to get more correct analysis results.

2. Methods and Results

2.1 Modeling

The fuel rod consists of fuel pellets(Uranium dioxide), fill gas(Helium gas) and cladding(Zirlo) presented in Fig. 1.

Parameters from APR1400 SSAR are tabulated in Table 1 and it is used for fuel dimensions. Material properties from Table 2 to Table 4 were used for fuel modelling. Zircaloy-4 is used for cladding model instead of Zirlo for analysis convenience. Two and three dimensional model presented in Fig. 1 were generated. Each model has been created as half and quarter fuel model for analysis convenience.

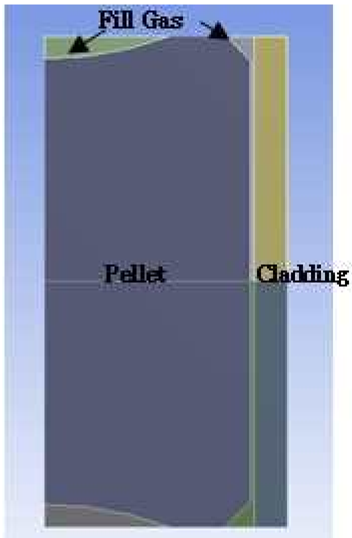

Fig. 1 Two-Dimensional Fuel Model

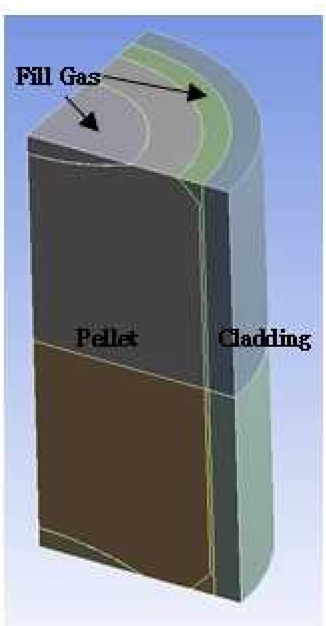

Fig. 2 Three-Dimensional Fuel Model

Table 1 APR1400 Design Parameters[3]

Nuclear Design Data	
Total Core Heat Output(W)	3.983×10^9
System Pressure(MPa)	15.51
Average Film Coefficient(W/mm^2K)	0.03577
Clad Surface Temperature at Nominal Pressure, (℃)	347
Fuel Centerline Temperature at Nominal Pressure, (℃)	1,712
Fuel Rod Data	
Number of fuel assembly(EA)	241
Number of fuel rod location(EA)	56,876
Pellet diameter(m)	0.00826
Pellet length(m)	0.00991
Clad Inner diameter(m)	0.00843
Clad outer diameter(m)	0.00970
Clad thickness(m)	0.000635

Table 2 Material Property of Helium[4]

Temperature(℃)	25	100	200	300	400
Conductivity (W/mK)	0.15	0.174	0.205	0.237	0.270

Table 3 Material Property of Uranium Dioxide[4]

Temperature(℃)	27	127	227	327
Conductivity (W/mK)	8.1	7.1	6.15	5.33
Temperature(℃)	427	527	627	727
Conductivity (W/mK)	4.7	4.27	3.88	3.61

Table 4 Material Property of Zircaloy-4[4]

Temperature(℃)	100	200	300	400
Conductivity (W/mK)	13.6	14.3	15.2	16.4
Temperature(℃)	500	600	700	800
Conductivity (W/mK)	18.0	20.1	22.5	25.2

2.2 Assumption

Heat transfer is perfectly insulated along the fuel rod axial direction. Convection due to a gas flow through the pellet cracks is neglected. Strain effects on the temperature field of the fuel is not considered. The gap for heat transfer coefficient, which depends on the gap width, the temperature at the fuel outer surface and the cladding inner surface, the inner gas pressure, and the mean temperature, is modeled by a given function of time. The latter can also include effects arising from radiation. The heat transfer coefficient in the film between cladding and coolant is also approximated by a given function of time.

2.3 Mesh

Sufficient numbers of nodes and elements were generated both two-dimensional and three-dimensional model and is expected to get reliable analysis results. Mapped mesh presented in Fig. 3 is applied in two-dimensional model and hex dominant method presented in Fig. 4 applied in three-dimensional model, respectively. The total number of generated nodes and elements are summarized in Table 5.

Table 5 Number of Element and Node

Item	2D	3D
Node	15,145	225,991
Element	4,753	904,649

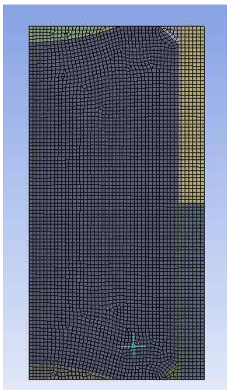

Fig. 3 Two-Dimensional Fuel Model Mesh

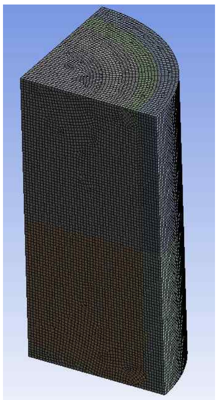

Fig. 4 Three-Dimensional Fuel Model Mesh

2.4 Boundary Condition and load application

Axisymmetric condition is applied to fuel rod axial direction in order to convert cylindrical shape to 2D plane. Internal heat generation calculated above is applied to fuel pellet. Top and bottom of pellet is perfectly insulated and the convection is applied to the surface of the cladding. Also, a value of 0.85[3] is used for the emissivity of fuel pellet over the temperature range of 800 to 2,600K.

2.5 Internal Heat Generation

The internal heat generation(Q) is calculated by dividing total core heat output into total pellet volume. Total core heat output is represented in Table 1. Total pellet volume is calculated by multiplying the side area of pellet by number of fuel pellets. The calculated value are as follow.

$$Q = \frac{W}{V} = \frac{3.983 \times 10^{9}}{1.12 \times 10} = 3.55\times10^{8}(W/m^{3})$$

Q : Pellet internal heat generation(W/m^3)
W : Total core heat output(W)
V : Total pellet volume(m^3)

3. Conclusions

The results from two & three dimensional analysis are compared with APR1400 SSAR value and presented in Table 6. Each analysis results are plotted in Fig. 7. The graph shows that two & three dimensional analysis results have similar temperature distribution against fuel radius.

In Table 6, temperature of pellet centerline have similar value. But, temperature of clad have difference up to 11 %. This difference is estimated applying Zircaloy-4 instead of Zirlo. And average film coefficient were applied in this analysis. Both high temperatures and the steep temperature gradients are important for predicting fuel element performance. The temperature gradients in the fuel cause pore migration and formation of the central void, cause thermal stresses or fuel cracking, and pellet cladding interaction.

For the more accurate analysis, detailed material property of Zirlo and detailed film coefficient are needed to perform.

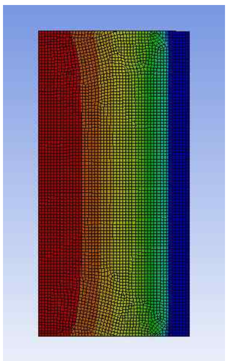

Fig. 5 Two-Dimensional Analysis Results

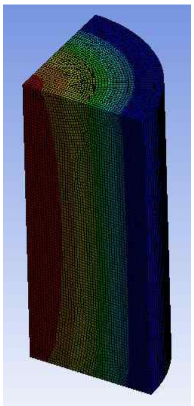

Fig. 6 Three-Dimensional Analysis Results

Table 6 Analysis Results

Item	APR1400 SSAR	ANSYS		Diff.(%)	
		2D	3D	2D	3D
Clad temperature	347	386	384	-11	-10
Pellet centerline temperature	1,712	1,753	1,737	-2.4	-1.4

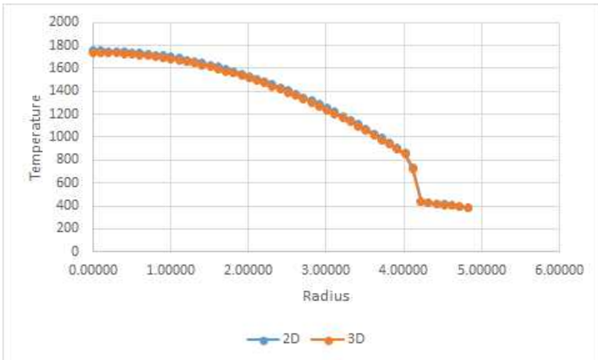

Fig. 7 Two & Three Dimensional Results Comparison

REFERENCES

[1] 10 CFR Part 50 Appendix A, General Design Criteria for Nuclear Power Plant.

[2] 10 CFR 50.46, Acceptance Criteria for Emergency Core Cooling Systems for Light Water Nuclear Power Reactor

[3] APR1400 SSAR, Advanced Power Reactor 1400MWe for Standard Safety Analysis Report.

[4] Sung-Hwan Chung, Kyoung-Myung Chae, Byung-il Choi and Heung-Young Lee, Calculation of the Effective Thermal Conductivity for PWR Spent Fuiel Assembly, May, 2003.