Minimum Required Spring Force and In-grid Spring Analysis of Spacer Grids for Dual-Cooled Fuels

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1. Introduction

In the dual-cooled annular fuel rod, an inner flow passage as well as an outer one is used not only to enhance the fuel safety but to achieve a power uprating through the decreasing fuel center temperature and increasing the heat transfer area between fuel and coolant. As a result, the diameter of a dual-cooled fuel becomes 1.6 times bigger than a conventional solid fuel and the gap between an annular fuel and spacer grid's straps is narrowed. To accommodate the narrowed gap, spacer grids, such as the cantilever type, hemi-sphere type [1], circular insertion type [2], etc., were suggested.

In this paper, the minimum spring force to prevent a dual-cooled fuel from dropping during normal reactor operation is calculated. The spring characteristics of a cantilever type and a hemi-sphere type are predicted. The finite analysis is carried out by using a commercial code, ABAQUS. The analysis results are verified by experiments. Finally, whether the property of the suggested springs is satisfied the minimum required spring force is checked.

2. Minimum spring force

The mass of an annular fuel rod is calculated conservatively at about 4.899 Kg. If n spacer grids are used in a fuel assembly, the force to hold a fuel rod per unit cell will be obtained by using Eq. (1) [3].

$$F \geq \frac{4.899}{\mu n}[Kg] = \frac{16.33}{n}[Kg] = \frac{160.034}{n}[N] \qquad (1)$$

Here, each parameter is below;

where n : the number of spacer grids, μ : the friction coefficient between supports and fuel rods(0.3 is used here).

The number of spacer grids is designed as 9~11, then the holding force of the unit cell is about 14.55~17.78 N. If there are 4 supports in a unit cell, the minimum force for one support is 3.64~4.45 N. And then, the relaxation ratio of elastic modulus at the operating temperature, 320℃, is 70% of that at the normal temperature. Finally, the required spring force about a support has to be larger than 5.2~6.36 N.

3. Spring characteristic analysis in grid condition

To obtain the spring characteristics in grid condition, a 4x4 model was used. Elastic-plastic analysis was performed. Analysis was composed of two steps: shrink fit and loading process [4]. During shrink fit, the circular analytical rigid elements simulated as fuel rods pushed back a grid spring by an initial interference between a fuel rod and a grid spring. This interference is one of the parameters to decide spring stiffness. During this process, the curved rigid element, simulated as a loading bar, was made as a partial model and apart from a grid spring to prevent contact with other supports. Reference nodes were assigned to rigid elements to control them. Especially, the reference node assigned to the curved rigid element was used to apply specified deformation, 0.7 mm downward and obtain the reaction force. There was a rigid plate to provide the boundary condition. This plate was tied with the lowest plate of a 4x4 grid model. 6 degree of freedom such as 3 transitions and 3 rotations of its reference node were constrained to prevent rigid body motion. Reaction force and displacement was obtained. Two kinds of strap material, the SS-304 and the Zry-4, were considered in the analysis.

3. Comparison with the results of spring characteristic test and analysis

Table 1 shows the results of the spring characteristic test conducted with the cantilever and hemi-sphere type supports. The test specimen was a 4x4 partial model and made of SS-304. The tests were performed until the maximum load was reached to 30 N and repeated five times [5].

Table 2 summarizes the analytic results of the two types of spring for dual-cooled fuel. In the case of the cantilever type, the ratio of analysis to experimental results is about 0.69. It is 0.73 in the case of the hemi-sphere type. In the results, it should be noted that the loading force is the same as the initial spring force.

Table 1 Experimental spring stiffness [N/mm]

Model	Cantilever	Hemi-sphere
1st	68.6	1039.5
2nd	66.7	1437.6
3rd	70.7	-
4th	69.7	-
5th	-	1504.1
mean	68.9	1327.1

Table 2 Numerical results

Model	Cantilever	Hemi-sphere

Material	SS-304	Zry-4	SS-304	Zry-4
Interference [mm]	0.32	0.32	0.2	0.2
Loading force [N]	16.8	8.9	101.6	83.0
Stiffness [N/mm]	47.8	30.3	973.8	599.2

The characteristic curves of spring obtained from the experiment and analysis are shown as Fig. 1. Both results coincide well until the deformation reaches 0.15 mm. Discrepancy appears beyond 0.15 mm. The sharply increasing region is attributed to the contact of the loading bar and base plate of supports. If the contact occurs, the loading bar pushes the fuel rod (or circular rigid element) of the adjacent cell. Finally the stiffness difference between the analysis and experiment was around 30%. It is attributed to the plastic property of SS-304, non-uniform welding bead, manufacturing errors and test errors.

These results are for SS-304 spacer grids. However, the Zry-4 is usually used for material of spacer grids. So the characteristics of the spring made of Zry-4 have to be obtained. The calculation results and added in Table 2. Although the relationship between the test and analysis may include nonlinearity, we could predict at least the trend of the Zry-4 spring. The analytic results obtained from the pre-established in-grid spring analysis model were smaller than the experimental results by about 30%. So the suggested spacer grids for dual-cooled fuels could satisfy the minimum required spring force.

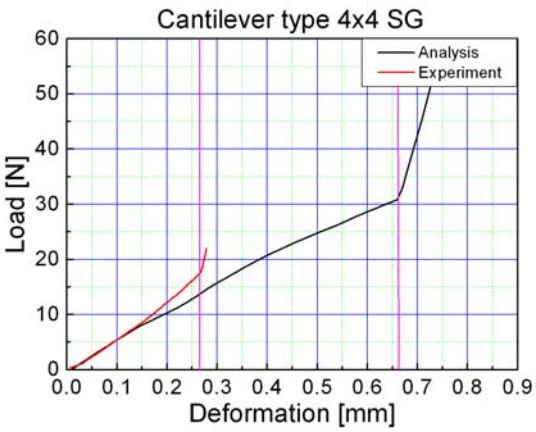

Fig. 1 Characteristic curves of the cantilever spring.

4. Conclusion

A minimum spring force to prevent the dual-cooled fuel rod from dropping is evaluated. With considering relaxation ratio of elastic modulus at the operating temperature, 320℃, the minimum required spring force is about 5.2~6.36 N. The spring stiffness predicted by the finite element analysis was lower than the experimental results by around 30%, but the trend of each parameter's variation was acceptable. Finally, it is verified that the suggested two spacer grids made of the Zry-4 will satisfy the required spring force.

ACKNOWLEDGEMENTS

This project has been carried out under the nuclear R&D program by Ministry of Education, Science and Technology of Korea.

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