Thermal Deformation Analysis of the Annular Fuel

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1. Introduction

Recently Korea Atomic Energy Research Institute suggested 12 by 12 annular fuel assembly, claiming that this new design can be applied to PWR reactor of OPR-1000 that are using 16 by 16 assembly, Compared to current fuel system, heat transfer area is enlarged, and thus heat flux is diminished. This design demonstrates that CHF(critical heat flux) restricting the operation power condition. This advanced fuel is believed to many advantages such as lowered fuel temperature, reduced fission gas release, and so forth [1]. Nevertheless, annular geometry has some difficulties in predicting fuel performance behavior. This new design, heat transfer takes place in two directions through inner and outer gap. This heat split ultimately determines the inner and outer gap conductances that are key variables governing the fuel performance

2. Methods and Results

2.1 Temperature distribution in the annular fuel

We can solve the temperature distribution of annular geometry, Using the steady-state heat conduction equation with boundary conditions in the inner and outer surface of pellet, that is $T(r=a)=T_a$ and $T(r=b)=T_b$. Temperature profile of pellet T(r) is as follows,

$$T(r) = T_b + \frac{q'''}{4k}\left(b^2 - r^2\right) + \frac{\left(T_b - T_a\right) + \frac{q'''}{4k}\left(b^2 - a^2\right)}{\ln(b/a)}\ln(r/b) \qquad (1)$$

2.2 Thermal stress-strain in the annular fuel

Governing equation for the radial stress distribution in the cylindrical system is follow:

$$r\frac{d^2\sigma_r}{dr^2} + 3\frac{d\sigma_r}{dr} + \frac{E\alpha}{(1-v)}\frac{dT}{dr} = 0 \qquad (2)$$

the ordinary differential equation (2) can be solved for σ_r with the appropriate boundary conditions. Using the temperature distribution, we can finally solve equation with the boundary conditions that $\sigma_r(a)=0$ and $\sigma_r(b)=0$.
The solution is as follows:

$$\sigma_r = \frac{E\alpha q'''}{8(1-v)k}\left[\left(\frac{r^4 - a^2b^2}{2r^2}\right) + \left(b^2 - a^2\right)\left\{\frac{1}{2} - \frac{\ln(r/a)}{\ln(b/a)}\right\}\right] - \frac{E\alpha\left(T_b - T_a\right)}{2(1-v)}\left[\frac{\ln(r/a)}{\ln(b/a)} + \frac{b^2}{b^2 - a^2}\left(\frac{a^2}{r^2} - 1\right)\right] \qquad (3)$$

And we can find ε_r as a function of radius finally.

$$\varepsilon_r = \frac{\alpha q'''(1+v)}{16k(1-v)}[(1-4v)r^2 - \frac{a^2b^2}{r^2}] + \frac{\alpha q'''(1+v)}{16k(1-v)}\left(b^2 - a^2\right)\left\{(1-2v) - \frac{2(1-2v)\ln(r/a) + 2v)}{\ln(b/a)}\right\}$$

$$+ \frac{\alpha\left(T_b - T_a\right)(1+v)}{2(1-v)}\left[\frac{(2v-1)\ln(r/a) + v}{\ln(b/a)} - \frac{b^2}{b^2 - a^2}\left\{\frac{a^2}{r^2} + (2v-1)\right\}\right] + \alpha(1+v)\left\{T(r) - T_0\right\} - v\varepsilon_0 \qquad (4)$$

It is well-known that gap conductance, linear heat generation rate, and thermal conductivity are the most influential factors in the determination of the fuel temperature distribution. Here, in this study, temperature profiles inside the annular fuel rod are investigated by changing with material property and operational conditions.

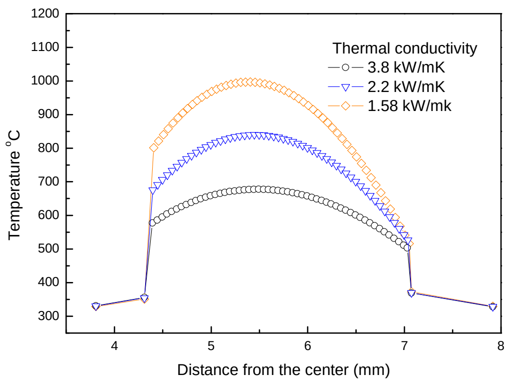

Fig.1. Temperature distribution of the annular fuel at the conditions that linear heat generate is 56kW/m

According to the steep temperature profile, compressive stresses are built up, as derived in Eq.(3), and accompanying strain develops. Eq.(4) expresses the thermal strain and it is plotted in Fig.2.and it's result is listed in table.1

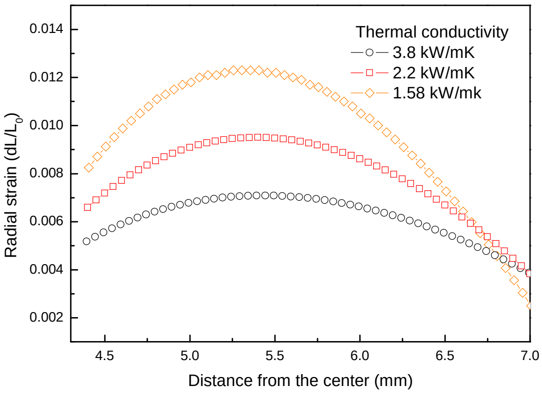

Fig.2. Temperature distribution and Thermal strain of the annular fuel at the conditions that linear heat generate is 56kW/m

As expected, the results show that the displacement of outer radius is larger than that of the inner radius, therefore, inner gap is enlarged and outer gap is reduced. Close examination of the results reveals that, without irradiation effects, most of dimensional change of the annular fuel pellet comes from the thermal expansion. However, the radial shrinkage due to Poisson's ratio must not be negligible in the precise determination of the gap thickness.

Table.I. Gap thickness of the analytical result

Thermal conductivity (kW/mK)	3.8	2.2	1.58
Heat split (Inner/Outer)	1.12	1.18	1.34
Inner gap thickness (㎛)	84	88	97
Outer gap thickness (㎛)	46	37	23

2.3 Finite Element Modeling

FE analysis was carried out by using ANSYS code with the temperature distribution derived in the previous analysis [2,3]. The VonMises' stresses of the annular pellet are shown in Fig.3. It can be seen that the stresses are higher at both the inner and outer surfaces and are relatively low in the interior. At the outer surfaces of the fuel, the stress exceeds the fracture stress of UO_2 (~100MPa) and fuel cracking is expected to occur. As burn-up increase, a lager stress are build up than BOL(Beginning of Life), As a result, the crack will be occur and propagate. and Therefore, it is concluded that fuel relocation will take place. At the point of radial value, inner and outer edges are in compression and middle section of the pellet is in tension. Fig.4 shows that pellet's outer edges are deformed more than its inner edges in the radial direction.

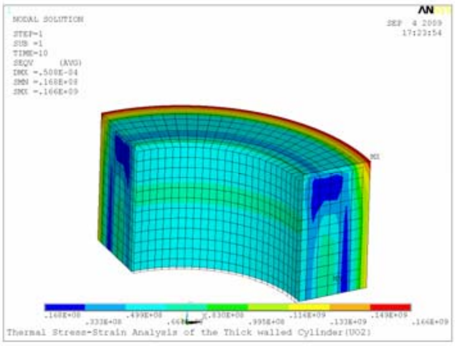

Fig.3. Von-Mises' stress of the annular pellet in the condition that linear heat generate is 56Kw/

On the other hand, inner edges are more deformed than outer edges in the axial direction. At half height of pellet, radial displacement inner and outer radius are 25 ㎛ and 40 ㎛ respectively.

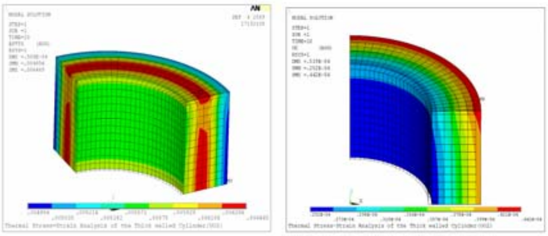

Fig.4. Radial strain and Displacement of the annular pellet in the condition that linear heat generate is 56kW/ m

3. Conclusions

In normal operation conditions, the maximum temperature of the annular pellet turns out to be below 700℃ and even in 200% power up-rated condition, the temperature remains below 950℃. Analysis shows that deformation due to thermal stress takes place outward, that is, inner gap increases and outer gap decreases. At the inner and outer surfaces of the fuel, the stress exceeds the fracture stress of UO_2 (~100MPa) and fuel cracking is expected to occur and cracks will develop and propagate. More accurate calculations will be need to reflect temperature dependent properties, and comprehensive performance of pellet, including cladding creep, fuel densification, swelling, and etc. will be carried out in the next step.

REFERENCES

[1] Y.S. Yang, K.M. Bae, C.H. Shin, T.H. Chun, J.G. Bang, K.W. Song, Proceedings of ICAPP 2007, paper 774

[2] ANSYS User's Manual, Version 10.0, Swanson Analysis Systems, Inc

[3] SCDAP/RELAP5/MOD3.1 Code Manual Volume IV:MATPRO