Transactions of the Korean Nuclear Society Autumn Meeting
PyeongChang, Korea, October 25-26, 2007

Thermal Behaviors of Annular Fuel Pellet under Generalized Plane Strain Condition

Yong Sik Yang, Dae Ho Kim, Sun Ki Kim, Je Geon Bang, Gun Woo Song
P. O Box 150, Yuseong, Daejeon, Korea, 305-600
Korea Atomic Energy Research Institute
yys@kaeri.re.kr

1. Introduction

The concept of an internally and externally cooled annular fuel employs an internal cooling channel with its own cladding so that the fuel can be cooled from both sides.(Fig. 1)

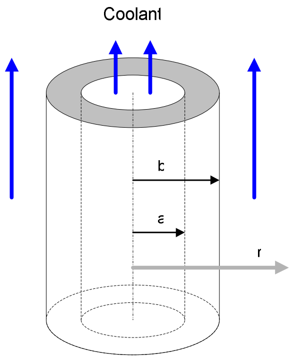

Figure 1. Concept of annular fuel (ignore clad)

For a fuel performance point of view, thermal deformation and stresses which are caused by a radial temperature distribution are very important factors. Because a fuel pellet thermal expansion coefficient is larger than cladding, thermal expansion displacement of a pellet outer surface can reduce outer gap thickness but inner gap thickness will be enlarged. The difference of both sides gap thickness may cause gap conductance discrepancy and asymmetrical heat split problems.

A radial relocation which is caused by thermal stress is one of the important factors affecting gap thickness variation. So, a thermal stress distribution in a fuel pellet must be evaluated from a thermal performance aspect.

2. Model of annular pellet thermal behaviors

For the calculation of annular pellet thermal behaviors, a hollow circular cylinder shape thermal deformation and stress estimation method was reviewed and its detailed models and derivation procedure are presented in Ref [1]. So, in this paper, only the conclusion and its explanation are summarized briefly. All thermal deformations and stresses of a discussed below are derived under the assumptions that generalized plane strain condition.

From the one-dimensional equilibrium equation in the radial direction of a thick hollow cylindrical body and generalized Hook's law by using traction free surface boundary conditions at r=a(inner radius) and r=b(outer radius), the radial and hoop thermal deformations and stresses can be written as,

$$u = \frac{1+\nu}{1-\nu}\alpha\left\{\frac{1}{r}\int_a^r \tau r dr + \left(\frac{1-3\nu}{1+\nu}r + \frac{a^2}{r}\right)\frac{1}{b^2-a^2}\int_a^b \tau r dr\right\} \quad (1)$$

$$\sigma_{rr} = \frac{\alpha E}{1-\nu}\left[-\frac{1}{r^2}\int_a^r \tau r dr + \frac{r^2-a^2}{r^2(b^2-a^2)}\int_a^b \tau r dr\right] \quad (2)$$

$$\sigma_{\theta\theta} = \frac{\alpha E}{1-\nu}\left[\frac{1}{r^2}\int_a^r \tau r dr + \frac{r^2+a^2}{r^2(b^2-a^2)}\int_a^b \tau r dr - \tau\right] \quad (3)$$

where,

u = radial thermal displacement at position r [m]
σ = thermal stress at position r (radial/hoop) [Pa]
τ = temperature change from the room temperature [K]
α= liner thermal expansion coefficient [/K]
E = Young's modulus [Pa]
r = radial distance [m]
ν = Poisson's ratio

3. Annular pellet modeling

For the annular pellet thermal behavior calculation, all the models are programmed by FORTRAN (named Annul_th_perform module). In this module, for the consideration of a pellet radial temperature profile, the annular pellet is divided into equal width radial node and the maximum node number is 500. The node 1 is located in inner surface and the maximum node is equal to the outer surface. The radial temperature distribution was described by the τ(r) function. In the steady state condition, τ(r) can be expressed by a 2nd order polynomial form.

The material properties which are used in these calculation are E, α and ν. The ν can be varied with a temperature change but its difference is very small, so typical value of 0.316 is adopted as a Poisson's ratio. The UO_2 Young's modulus and linear thermal expansion coefficient as a function of the temperature by the MATPRO[2] model were inserted into the Annul_th_perform module.

In a real fuel rod condition, a radial temperature gradient causes a different axial expansion along the radial direction. But, in this module, an axial thermal expansion is always constant along the r direction due to the generalized plane strain assumption.

The calculation results such as radial & axial thermal deformations and thermal stresses were compared with the analytical results which were calculated by Mathmatica[3] for a model verification.

4. Results and discussion

For the calculation, current annular fuel pellet inner/outer radius were considered as 5.135mm and 7.315 mm respectively. Radial temperature profile in the annular pellet was obtained from released data and converted by a polynomial fitting[4]. Fig. 2 shows a used radial temperature profile for the calculation.

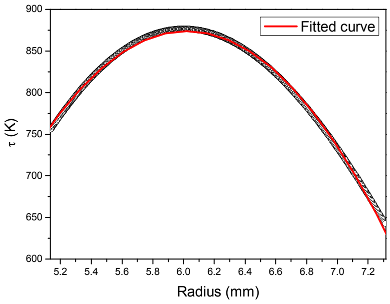

Figure 2. Radial temperature profile

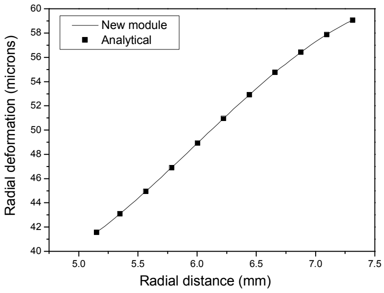

Figure 3. Radial thermal deformation of annular pellet

Fig. 3 shows the result of radial thermal displacement of the annular fuel pellet. In this result, the inner and outer thermal deformations were estimated as 39 and 59 microns respectively.

The radial and hoop stress distribution calculation results are presented in Fig. 4 & 5 and show a good agreement with the analytical values. In both sides of the cold region, in Fig. 4, a high tensile stress is applied which can exceed UO_2 fracture stress(~100MPa). Therefore, it can be concluded that radial relocation can occur at both sides of the annular pellet.

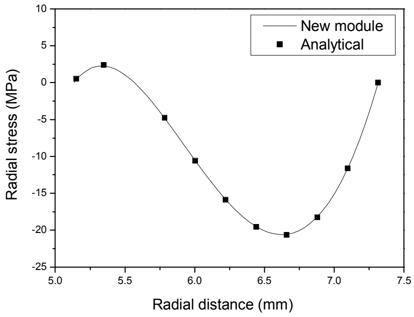

Figure 4. Radial thermal stress distribution

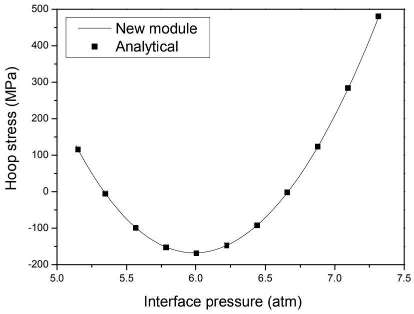

Figure 5. Hoop thermal stress distribution

Conclusion

Hollow circular cylinder structure thermal deformation and stress analysis models were presented by many researchers. But these models can not be applied to nuclear fuel pellet directly because the local material properties and temperature change very rapid.

So, a new module which can consider local characteristics changes by a small ring division technique was developed and all the calculation results were compared to the analytical solutions and showed a good agreement. The calculation results show that an outer surface thermal expansion will be larger than inner surface one and both sides hoop stresses could exceed the UO_2 fracture stress limit.

Reference

[1] Naotake Node et al., "Thermal Stresses", 2nd edition, Taylor & Francis

[2] SCDAP/RELAP5/MOD 3.3 code manual, NUREG/CR-6514, Vol 4, Rev 2.

[3] Wolfman Mathmatica 6, WolfmanResearch.

[4] K. H. Chun et al., "Assessment of Gap Conductance Impact on Heat Split in Duel Cooled Annluar Fuel", KAERI/TR-3430/2007