Thermal stress analysis of the annular fuel

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1. Introduction

Lately several studies have been carried out to develop advanced fuels and, as an example, a nuclear fuel with dual side cooling was proposed by MIT in NERI project. Later it turns out that the advanced annular fuel can successfully achieve the power up-rating but the structure of the fuel was not compatible to existing PWR reactors [1]. Recently, KAERI proposed 12×12 annular fuel assembly for 16×16 solid structure, which can be applicable to existing PWR reactors [2]. 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 [3].

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,

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

2.2 Thermal stress-strain in the annular fuel

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

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

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:

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

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

$$\varepsilon_r = \frac{\alpha q'''(1+\nu)}{16k(1-\nu)}\left[(1-4\nu)r^2 - \frac{a^2b^2}{r^2}\right] + \frac{\alpha q'''(1+\nu)}{16k(1-\nu)}\left(b^2 - a^2\right)\left\{(1-2\nu) - \frac{2(1-2\nu)\ln(r/a) + 2\nu}{\ln(b/a)}\right\}$$
$$+ \frac{\alpha(T_b - T_a)(1+\nu)}{2(1-\nu)}\left[\frac{(2\nu-1)\ln(r/a) + \nu}{\ln(b/a)} - \frac{b^2}{b^2 - a^2}\left\{\frac{a^2}{r^2} + (2\nu - 1)\right\}\right] + \alpha(1+\nu)\left\{T(r) - T_0\right\} - \nu\varepsilon_0$$

The ε_o can be obtained on the basis of the assumption which is based on the fact that the axial displacement is proportional to radial displacement, and total axial force is zero, that is,

$$\varepsilon_o = \frac{\alpha q'''}{8k}\left[\left(b^2 + a^2\right) - \frac{\left(b^2 - a^2\right)}{\ln b - \ln a}\right] + \alpha\left[\left\{\frac{b^2T_b - a^2T_a}{\left(b^2 - a^2\right)} - T_O\right\} - \frac{(T_b - T_a)}{2(\ln b - \ln a)}\right]$$

Fig. 1 and Fig. 2 are the calculation results of radial stress and strain of the annular pellet using the proposed value [2]. Lines (a) in Fig.1 and Fig.2 are respectively radial stress and strain of annular pellet when heat generation rate is 387.25 kw/cm^3 and gap is filled with He**,** lines (b) are respectively radial stress and strain of annular pellet when heat generation rate is 387.25 kw/cm^{3}and gap is filled with 50 %He+ 50%Kr gas, lines (c) are respectively radial stress and strain of

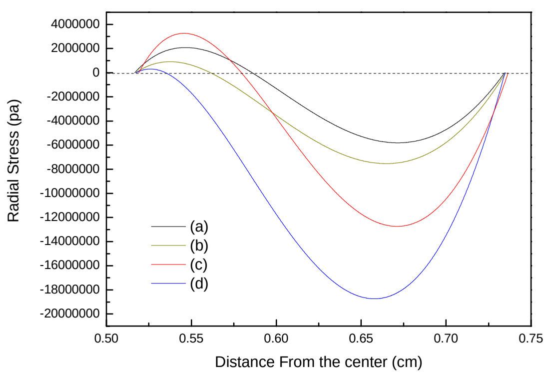

Fig. 1. Radial stress of annular pellet

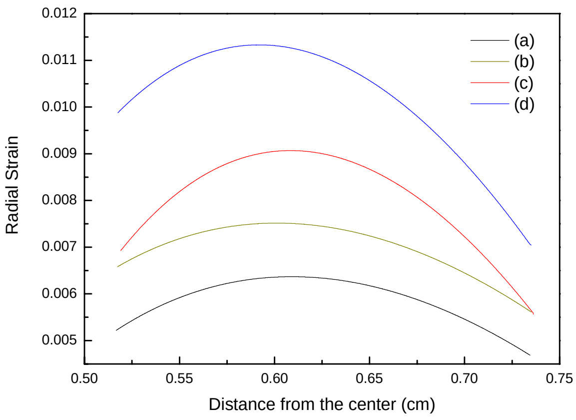

Fig.2 . Radial strain of the annular pellet

Annular pellet when heat generation rate is 774.5 kw/cm^3 and gap is filled with He, and lines (d) are respectively radial stress and strain of annular pellet when heat generation rate is 774.5 kw/cm^3 and gap is filled with 50 %He+ 50%Kr. The material properties and dimensions are list as followings [4]:

Table I: Material properties and dimensions of Annular fuel

Material properties and dimensions	UO_2
Thermal conductivity [w./cm ℃]	0.037
Thermal expansion coefficient [1/℃]	0.000012
Poisson's ratio	0.316
Young's modulus[n/m^2]	1.6×10^{11}
inner /outer radius [mm]	10.28/14.62

2.3 Measurement of the thermal expansion

The thermal expansion of an annular specimen is measured by a laser ccd camera (model: LS-7070m, Keyence Corp., Japan) whose resolution is 3 micro meter. In the high temperature Ar environment, The specimen is heated up to 800℃ and cooled down to the ambient temperature. The property and experimental results are shown in Table II , Fig.3, and Fig.4.

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. Degradation of fuel thermal conductivity keep the pellet temperature low and unless heat flux ratio, q''_{outer}/q''_{inner} , is less than unity, thermal expansion of pellet takes place outward. 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.

Table II: Material property of specimens

Material	SUS304	Alumina 95% density
Dimensions[mm] (inner/outer/height)	9.58/14.41/25	9.99 /14.96/ 10
Thermal expansion coefficient [1/℃]	0.000017	0.0000081

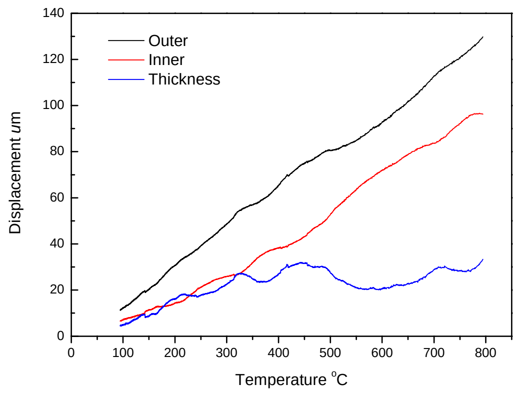

Fig.3. Displacement of annular SUS304

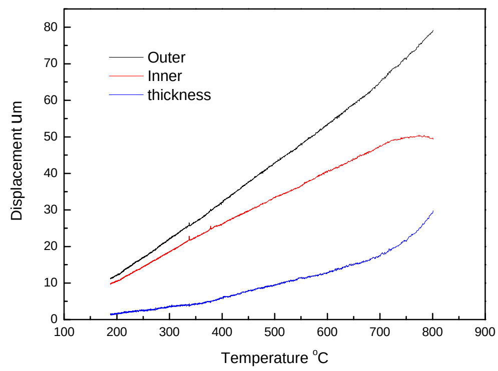

Fig.4. Displacement of annular Alumina

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