Development of Preliminary Performance Analysis Model Concepts for Annular Metal Fuel

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1. Introduction

An annular metal fuel concept is being developed for the higher burnup and safety [1]. In order to carry out the performance evaluation, it is necessary to develop a performance analysis model of the annular metal fuel. In this paper, the preliminary model concepts for the temperature analysis and the swelling evaluation were developed. The radial temperature distribution of the annular fuel slug according to the inner radius was calculated. The swelling of the annular fuel according to the hydrostatic stress was also evaluated.

2. Methods and Results

In this section, some of the preliminary performance analysis model concepts for annular metal fuel are described including the preliminary evaluation results. The preliminary model concepts include the preliminary annular metal fuel temperature analysis model, and the preliminary swelling analysis model.

2.1 Preliminary Annular Metal Fuel Temperature Analysis Model

The annular metallic fuel design with a lower smeared density has been considered to accommodate the fuel-cladding mechanical interaction (FCMI) at high burnup. It is also possible for the annular fuel to eliminate the use of liquid sodium as bonding material.

It is necessary to develop the temperature analysis model for the performance evaluation. The temperature distribution model of an annular metal fuel was developed and inserted into the MACSIS code [2].

Fig.1 shows the fuel and cladding geometry for the annular fuel. For the derivation of the annular metal fuel temperature, following symbols are defined: P_p = plenum pressure, P_c = external cladding pressure, P_{fc} = interface pressure, r_{fc} = fuel-cladding interface radius, r_i = fuel inner radius, and r_c = cladding outer radius.

In cylindrical coordinates for axial symmetry and long cylinders (no axial heat transfer), the steady state heat conduction equation [3] becomes

$$\left[\frac{1}{r}\frac{\partial}{\partial r}(rk\frac{\partial T}{\partial r})\right] = -q(r) \qquad (1)$$

where, k = conductivity (temperature dependent), q = the volumetric heat generation rate.

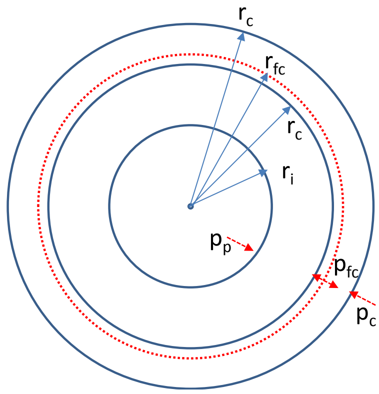

Fig. 1. Fuel and cladding geometry & elastic fuel-cladding mechanical interaction schematic

Let r_0 and r_i be defined as in Fig. 1, and let the boundary condition be $T = T_i$ at $r = r_i$, and $T = T_o$ at $r = r_o$, then it is possible to obtain the following:

$$\int_{T}^{T_o} kdt = -\frac{q}{2}\left\{\frac{r_o^2 - r^2}{2} - r_i^2 \ln\left(\frac{r_o}{r}\right)\right\} \qquad (2)$$

If the fuel is a solid type instead of an annular type, r_i becomes 0 in Equation (2), and it is possible to use the equation (2) for the prediction of the temperature distribution of the solid metal fuel.

Fig. 2 shows the annular fuel slug radial temperature distribution according to inner radius at 1.3 at.% burnup by using the material properties for SFR metal fuel [3] and the ATR irradiation history [4].

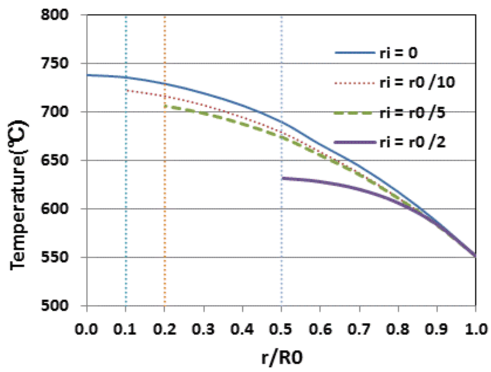

Fig.2. Annular fuel slug radial temperature distribution according to inner radius (helium gap, burnup : 1.3 at.%)

In the case of 550℃ of fuel surface temperature, it was calculated that the centerline temperature of the fuel were about 632℃ for $r_i = r_o/2$, 706℃ for $r_i = r_o/5$, 722℃ for $r_i = r_o/10$, and 735℃ for $r_i = 0$.

As the inner radius of the annular metal fuel increases, it was calculated that the centerline temperature of the fuel decreases. The fuel temperature distribution will be calculated in consideration of the burnup and the inner radius change due to fuel swelling. In addition, it is necessary to continuously review the model sensitivity with the specification, and the gap model etc.

AFC-4C ATR irradiation test is under progress including the annular metal fuel. Joint evaluation of fuel temperature will also be carried out with the irradiation data from INL [4].

2.2 Preliminary Swelling Analysis Model

In the annular fuel, fuel slugs are contacted with the cladding in BOL (Beginning Of Life), so the fission gas induced swelling may be affected by the hydrostatic stress due to constraints from the cladding.

In order to assess the swelling of the annular fuel in BOL, the interface pressure due to the contacting between fuel slug and cladding is considered for the hydrostatic stress.

The interface pressure calculation is computed by considering only elastic deformation in BOL. As shown in Fig. 1, the fuel outer radius exceeds the cladding inner radius by Δr, it is assumed that the cladding and fuel deform elastically by this amount. For the derivation of the interface pressure the following symbols are defined: σ^c_r, σ^c_θ = cladding radial and hoop stresses, σ^f_r, σ^f_θ = fuel radial and hoop stresses, ε^c_r, ε^c_θ = cladding radial and hoop strains, ε^{cf}, ε^f_θ = fuel radial and hoop strains, E_f, E_c = fuel and cladding Young's Moduli, ν_f, ν_c = fuel and cladding Poisson's ratios, and Δr = fuel-cladding interference.

The radial & the hoop stress relationships at the interface, r_{fc}, are as followings;

$$\sigma^f_r = -P_{fc} \qquad (3)$$

$$\sigma^f_\theta = \frac{P_{fc}(r_{fc}^2 + r_i^2)}{(r_{fc}^2 - r_i^2)} + \frac{2P_c r_i^2}{(r_{fc}^2 - r_i^2)} \qquad (4)$$

If we solve the Δr, the radial and the hoop strains based on the Lame's equation, the following expression is obtained for P_{fc}.

$$P_{fc} = \left\{ \frac{\Delta r}{r} E^c + 2\left[\frac{P_c r_c^2}{(r_c^2 - r_{fc}^2)} + \frac{P_p r_i^2}{(r_{fc}^2 - r_i^2)} E^c/E^f \right] \right\} \times \left\{ \nu^c + \frac{(r_c^2 + r_{fc}^2)}{(r_c^2 - r_{fc}^2)} + \left[\frac{(r_{fc}^2 + r_i^2)}{(r_{fc}^2 - r_i^2)} - \nu^f \right] (E^c/E^f) \right\}^{-1} \qquad (5)$$

GRSIS [5] is adopted for evaluating the swelling rate with considering Equation (5). GRSIS was simulated and validated for the solid metal fuel by considering the burnup and the key parameters.

In this paper, the swelling of the annular fuel was evaluated by assuming the swelling of the solid fuel matched with the general behavior of a solid metal fuel.

Comparison of the swelling of the annular fuel according to the hydrostatic stress as well as the swelling of the solid fuel is shown in Fig. 3.

It was calculated that the swelling rate of annular fuel was lower than that of solid fuel due to the compressive hydrostatic stress in BOL. It was also calculated that the swelling rate of annular fuel was affected by the hydrostatic stress. The post irradiation examination results of AFC irradiation test [4] will be used to benchmark this calculation.

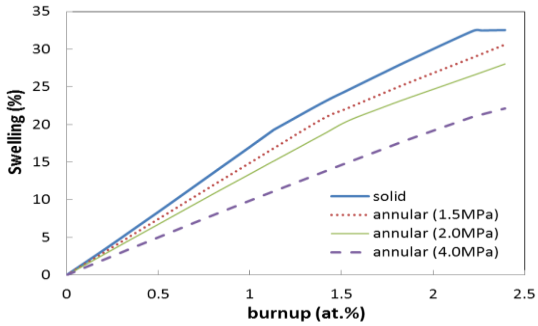

Fig.3. Comparison of the swelling of the annular fuel according to the hydrostatic stress.

3. Conclusions

The preliminary model concepts for the temperature analysis and the swelling evaluation were developed for the annular metal fuel. It was calculated that the temperature distribution of the annular fuel was affected by the size of inner radius. It was also expected that the swelling rate of the annular fuel was affected by the interface pressure between the fuel slug and the cladding. In the future, the swelling model in GRSIS will be inserted into MACSIS, and the temperature distribution considering the inner radius change will be evaluated according to the burnup. The results of this study will be utilized to establish the performance analysis codes and to evaluate the fuel performance.

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