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The Effects of Fuel Pellet Eccentricity on Fuel Rod Thermal Performance

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핵연료의 편심이 연료봉 열적 성능에 미치는 영향

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Abstract

This study investigates the effect of fuel pellet eccentricity on fuel rod thermal performance under the steady state condition. The governing equations in the fuel pellet and the cladding region are set up in 2-dimensional cylindrical coordinate (r, θ) and are solved by finite element method. The angular-dependent heat transfer coefficient in the gap region is used in order to account for the asymmetry of gap width. Material propeties are used as a function of temperature and volumetric heat generation as a function of radial position. The results show the increase of maximum local heat flux at the cladding outer surface and the decrease of maximum and average fuel temperatures due to eccentricity. The former is expected to affect the uncertainties in the minimum DNBR calculation. The latter two are expected to reduce the possibility of fuel melting and the fuel stored energy. Also, the fuel pellet eccentricity introduces asymmetry in fuel pellet temperature and movement of the location of maximum fuel pellet temperature.

요 약

핵연료소결체의 편심이 정상상태에서 핵연료봉 열적 성능에 미치는 영향을 조사하였다. 지배방정식은 핵연료소결체와 피복관영역에 대해 2차원 원통좌표계 (r, θ)로 각각 세우고 유한요소법으로 풀었다. 갭(gap)영역에서 방위각 의존적인 열전달계수를 사용하여 동심구조는 그대로 두는 반면 갭크기의 비대칭성을 고려하였다. 재료물성치는 온도의 함수로 사용되었으며 체적 열발생은 반경의 함수로 고려하였다. 핵연료 소결체의 편심으로 인해 피복관 외부 표면에서 최대국부열속은 증가하였고, 핵연료 소결체의 최대온도와 핵연료 평균온도는 감소하였다. 전자는 최소 DNBR계산시 불확실도에 영향을 미칠 것으로 생각되며, 후자의 두현상은 핵연료 소결체의 용융 가능성과 사고시 핵연료 잠재에너지를 줄어 들게 할 것으로 예상된다. 또한, 핵연료 소결체의 편심으로 인해 핵연료 소결체의 온도분포는 비대칭을 이루고 최대온도의 위치는 변동되었다.

I. Introduction

In a light water reactor fuel rod, a number of fuel pellets are piled vertically within the cladding. Heat produced in the fuel pellet is released into the coolant through the fuel pellet-to-cladding gap and the cladding under high temperature and pressure. It is, therefore, necessary to analyze the thermal and mechanical performance for the design of fuel rod. Most of commercial fuel rod performance codes[1),2)] assumes that the fuel pellets are located concentrically within the cladding. However, some fuel pellets are often located eccentrically in the cladding during the manufacturing process. If a fuel pellet is eccentircally placed, there will be azimuthal variation of temperature and heat flux during in-reactor power operation and it will in turn affect the fuel rod performance.

McNARY, et al.[3)] analytically investigated the effects of a non-axisymmetric gap conductance on the steady state temperature distribution in the fuel pellet, using the angular-dependent heat transfer coefficient in the gap region. And McNAIR, et al.[4)] tried to develope the improved finite difference method and a geometry-dependent conductivity in the gas gap to account for the eccentric geometry.

This study investigates the effects of fuel pellet eccentricity on the fuel rod thermal performance. The governing equations for a fuel rod are set up in the 2-dimensional cylindrical coordinate (r, θ) and are solved by finite element method. In order to account for the eccentric geometry, the angular-dependent heat transfer coefficient in the gap region is applied. The material properties are taken to be temperature-dependent. The volumetric heat generation rate in the fuel pellet region is considered as a function of radial position. Calculations were performed for a number of eccentricity ratios. The emphasis is placed on how temperature and heat flux in a fuel rod will be varied and in turn affect the fuel rod thermal performance.

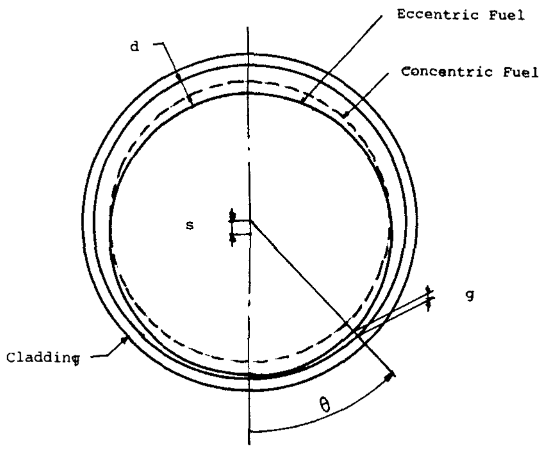

Fig. 1. Cross Section of a Fuel Rod

II. Numerical Analysis

1. Governing Equations and Boundary Conditions

It is assumed that a fuel rod, whose cross section at a axial position is shown in Figure 1, lies in an infinite flow field. The main assumptions are as follows: (1) axial heat transfer is negligible, (2) temperature and heat transfer conefficient in coolant region is uniform with respect to azimuthal angle, (3) the neutron flux distribution in the fuel pellet region is a function of radial position, and (4) the heat generation in the cladding region is negligible.

The governing equation and boundary conditions for fuel pellet region are

$$\frac{1}{r}\frac{\partial}{\partial r}\left(K^P(T)\, r\frac{\partial T}{\partial r}\right)+\frac{1}{r}\frac{\partial}{\partial \theta}\left(\frac{K^P(T)}{r}\frac{\partial T}{\partial \theta}\right)+q'''(r)=0$$

$$T(r, \theta)<\infty \qquad \text{at } r<R_{ps}$$

$$-K^P(T)\frac{\partial T}{\partial r}=h_g(\theta)(T_{ps}-T_{ci}) \qquad \text{at } r=R_{ps}$$

Where K^P (T): temperature-dependent thermal conductivity of the fuel pellet

q''' (r): volumetric heat generation rate

Rps: fuel pellet radius

h_g (θ): angular-dependent heat transfer coefficient

Tps: fuel pellet surface temperature

Tci: cladding inner surface temperature

Meanwhile, governing equation and boundary conditions for cladding region are

$$\frac{1}{r}\frac{\partial}{\partial r}(K^c(T)\, r\frac{\partial T}{\partial r})+\frac{1}{r}\frac{\partial}{\partial \theta}(K^c(T)\frac{\partial T}{r\partial \theta})=0$$

$$-K^c(T)\frac{\partial T}{\partial r}=h_g(\theta)(T_{ps}-T_{ci}) \text{ at } r=R_{ci}$$

$$-K^c(T)\frac{\partial T}{\partial r}=h_c(T_{co}-T_{oo}) \text{ at } r=R_{co}$$

where $K^c(T)$: temperature-dependent thermal conductivity of the cladding

h_c: coolant heat transfer coefficient

T_{co}: cladding outer surface temperature

T_{oo}: coolant temperature

R_{ci}: cladding inner surface radius

R_{co}: cladding outer surface radius

An expression for angular-dependent heat transfer coefficient in gap region can be derived from the geometry as schematically illustrated in Figure 1. If the fuel pellet eccentricity with the cladding exists, the gap width between the fuel pellet and cladding varies around the circumference. When the fuel pellet is eccentrically placed with distance s, the local gap width g is approximated by

$$g=d-s\cos\theta$$

The local gap conductance h_g (s, θ) can be written as

$$h_g(s, \theta)=h_n/(1-(s/d)\cos\theta)$$

where h_n: nominal gap heat transfer coefficient

Also, the azimuthally averaged heat transfer coefficient in the gap region can be written as

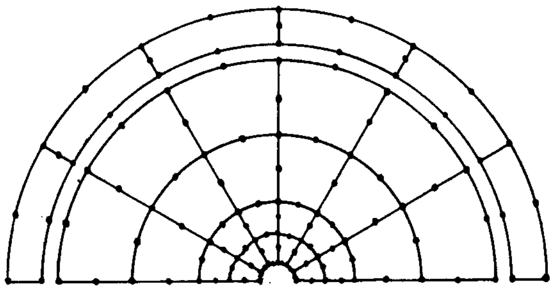

Fig. 2. Finite Element Discretization

$$h_g(S)=\frac{1}{2\pi}\int_0^{2\pi} h_g(s, \theta)\, d\theta=h_n/\sqrt{1-(s/d)^2}$$

In the above equation, one can see that the azimuthally averaged gap heat transfer coefficient is minimum when the fuel pellet is concentrically located. The nominal heat transfer coefficient in gap region is taken from Beyer, *et al.*[1]

The thermal conductivity of UO_2, Zircaloy and helium gas is considered as temperature-dependent and taken from MATPRO.[5] The volumetric heat generation in the fuel pellet is derived from a heat balance equation in unit-length of fuel considering the neutron flux depression effect in the fuel

$$q'''(r)=\frac{k}{2\pi R_{ps}}\cdot\frac{I_0(kr)}{I_1(k R_{ps})}\cdot q'$$

where q': linear heat generation rate

k: inverse diffusion length

I_0, I_1: modified Bessel function of the first kind

2. Finite Element Analysis

The fuel pellet and the cladding regions are divided into many 8-node isoparametric elements as shown in Figure 2. For each element, the temperature is approximated as the following form,

$$T(r, \theta)=\mp(r, \theta)=\sum_{j=1}^{n} N_j(r, \theta)T_j$$

where N_j (r, θ): interpolation function

T_j: temperature at node j
n: node number of an element

This approximate temperature (T) is substituted into the governing equation for an element. After multiplying the interpolation function (Ni) and integrating over the element domain, we obtain

$$\iint N_i\left(r^2K^p\frac{\partial^2 T}{\partial r^2}+r\cdot K^p\frac{\partial T}{\partial r}+K^p\frac{\partial^2 T}{\partial \theta^2}+r^2q'''\right) drd\theta = 0$$

By Green's theorem, the first and third terms of LHS in the above equation can be written as

$$1\text{st term}=\iint N_i r^2K^p\frac{\partial^2 T}{\partial r^2}drd\theta$$
$$=\int N_i r^2K^p\frac{\partial^2 T}{\partial r^2}d\theta-\iint\frac{\partial}{\partial r}(N_i r^2)K^p\frac{\partial T}{\partial r}drd\theta$$

$$3\text{rd term}=\iint N_iK^p\frac{\partial^2 T}{\partial \theta^2}drd\theta$$
$$=\int N_iK^p\frac{\partial T}{\partial \theta}dr-\iint\frac{\partial N_i}{\partial \theta}K^p\frac{\partial T}{\partial r}drd\theta$$

After substituting the two terms into the governing equation for the element and applying the convection boundary condition at the fuel pellet surface, we can write the finite element equatjion for the fuel pellet as

$$[K_{ij}]^p\cdot\{T_j\}^p-[L_{ij}]^c\{T_j\}^p=\{F_i\}^p$$

$$\text{where } [K_{ij}]^p=\iint\left(K^pr^2\frac{\partial N_i}{\partial r}\cdot\frac{\partial N_j}{\partial r}+K^prN_i\frac{\partial N^j}{\partial r}+K^p\frac{\partial N_i}{\partial \theta}\cdot\frac{\partial N_j}{\partial \theta}\right)drd\theta+\int N_irh_gN_jd\theta$$

$$[L_{ij}]^c=\int N_irh_gN_jd\theta$$
$$\{F_i\}^p=\iint N_ir^2q'''drd\theta$$

Following similar procedure, one can obtain the finite element equation for the cladding. The convection boundary condition is applied to the cladding inner and outer surface, but the specified heat flux boundary condition to the axi-symmetric surface. The finite element equation for the cladding is written as

$$[K_{ij}]^c\cdot\{T_j\}^c+[L_{ij}]^p\{T_j\}^c=\{F_i\}^c$$

$$\text{where } [K_{ij}]^c=\iint\left(K^cr^2\frac{\partial N_i}{\partial r}\cdot\frac{\partial N_j}{\partial r}+K^crN_i\frac{\partial N^j}{\partial r}+K^c\frac{\partial N_i}{\partial \theta}\cdot\frac{\partial N_j}{\partial \theta}\right)drd\theta-\int N_irh_gN_jd\theta$$

$$[L_{ij}]^p=\int N_irh_gN_jd\theta$$
$$\{F_i\}^c=\int N_irh_cT_{oo}d\theta$$

It has been already mentioned in section II.1 that the finite element equations for fuel pellet and cladding were coupled by the boundary conditions. Therefore, the solution is calculated after the elements in fuel pellet and cladding are assembled together. In addition, since the governig equations are nonlinear, the solution is obtained through the direct iteration method. The error bound is taken as 10^{-2}(°K).

Table 1. Input Data

Input Parameter		Input Value
Linear Heat Generation Rate	(Kw/m)	0.05052
Coolant Temperature	(°K)	594.0
Coolant Heat Transfer Coeff.	(W/m^2 °K)	3.5×10^{-4}
Fuel Pellet Density	(g/cm^3)	10.96
Fuel Pellet Diameter	(mm)	9.2936
Cladding Density	(g/cm^3)	6.54
Cladding Outer Diameter	(mm)	10.7188
Cladding Thickness	(mm)	0.6172

III. Results and Discussion

Temperature and heat flux distribution in fuel pellet and cladding regions are calculated by the program developed in this study. The input data are shown in Table 1. The eccentricity ratio is

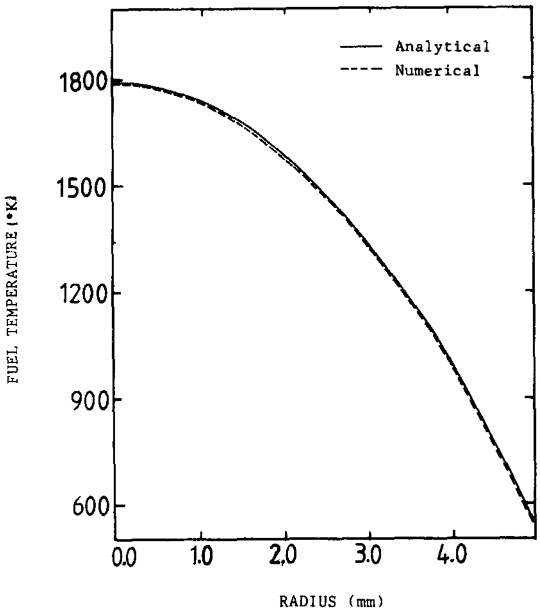

Fig. 3. Comparison of the Analytical Solution and the Numerical Solution.

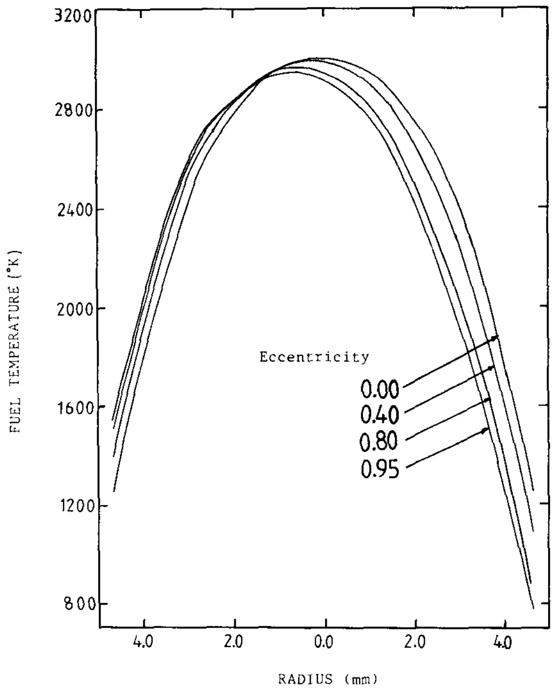

Fig. 4. The Variation of Temperature Distribution in the Fuel.

defined as the ratio of eccentric displacement to nominal gap size (s/d). The azimuthal angle is indicated in Figure 1. The focus of this study is placed on the fuel rod thermal performance parameters such as temperature and heat flux in fuel and cladding. Before the effects of fuel eccentricity are investigated, the verification of the program has been carried out.

1. The verification of the program

The verification of the program is performed by comparing the code calculation results with analytically calculated results for simple concentric fuel case. The conditions for simple calculation are as follows: (1) volumetric heat generation rate is 500 W/cm^3, (2) thermal conductivity of fuel pellet is 2.5 W/m °K, (3) fuel pellet radius is 5.0 mm, (4) heat transfer coefficient is 3.0×10^4 W/m^2 °K and (5) cladding inner surface temperature is 500 °K. The results are compared with the analytical solution derived by McNARY, *et al.*[3] The comparison shows a maximum difference of only 1.1 % (4.0 °K) as shown in Figure 3.

2. Effects of eccentricity on temperature

Temperature in fuel and cladding region is an important parameter for evaluating fuel rod thermal performance. Maximum temperature of fuel pellet is not allowed to exceed the melting point because the melting of fuel could deteriorate fuel rod integrity. The average temperature of fuel before the onset of an accident is an important performance parameter because it decides the stored energy in fuel and the fuel behavior during the accident. If cladding surface temperature is too high, it could cause departure from nucleate boiling (DNB) or accelerate the cladding local corrosion.

In Figure 4, the temperature distribution in the fuel region is shown. The maximum temperature slightly decreases as the eccentricity ratio increases. The location of maximum temperature moves due to eccentricity. When the eccentricity ratio is 0.95, the decrease of maximum temperature is 1.9 % (57 °K) and the location of maximum fuel pellet temperature moves 15.6 % of fuel pellet radius. The decrease of maximum

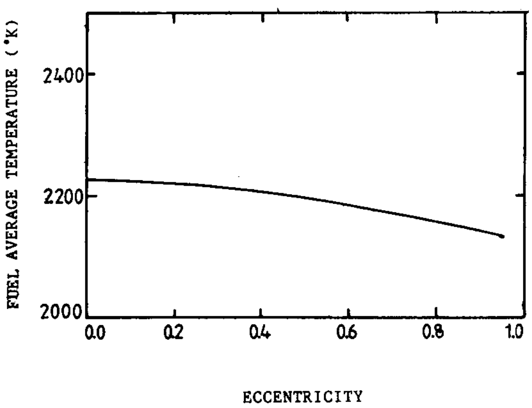

Fig. 5. The Variation of Average Temperature in the Fuel.

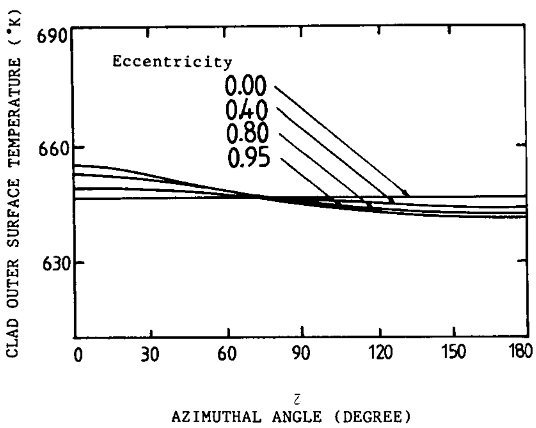

Fig. 7. The Azimuthal Variation of Cladding Outer Surface Temperature.

temperature will reduce the possibility of fuel melting.

Figure 5 shows the change of volumetric average temperature. The average temperature of fuel decreases slightly as the eccentricity increases. When eccentricity is 0.95, the decrease of average temperature is 4.3 % (95 °K) of the average temperature in concentric fuel. The reason is that the heat transfer coefficient in the gap region increases due to eccentricity as mentioned before. In other words, the eccentricity enhances the heat transfer from fuel to cladding and coolant region. The decrease of fuel average temperature is ex-

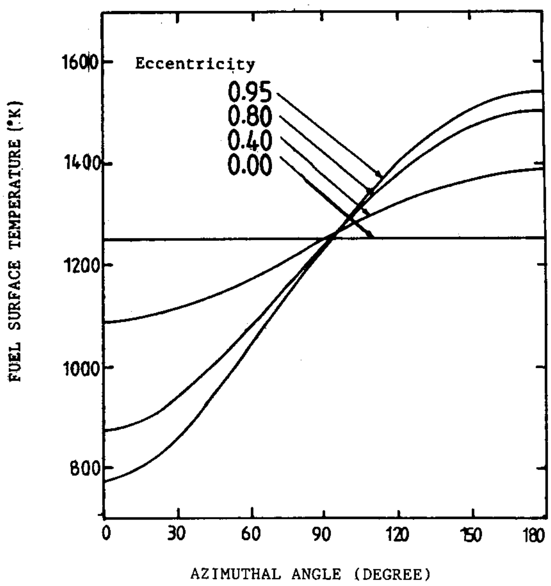

Fig. 6. The Azimuthal Variation of Fuel Surface Temperature.

pected to reduce the stored energy in fuel and thus to enhance the fuel performance during a postulated accident.

In Figure 6, the azimuthal variation of fuel pellet surface temperature is shown. The maximum temperature occurs at an angle of 180° where the heat transfer coefficient is at its maximum while the minimum temperature at an angle of 0°. When the eccentricity is 0.95, the maximum increase of local surface temperature is 23.1 % (289.0 °K) and the maximum decrease of the temperature is 38.2 % (478.4 °K) of average fuel pellet surface temperature. From this result, one can also see that the eccentricity introduces asymmetry in the fuel temperature distribution.

In Figure 7, the azimuthal variation of cladding outer surface temperature is shown. The maximum temperature of cladding outer surface occurs at an angle of 0° while the minimum temperature at an angle of 180°. When the eccentricity ratio is 0.95, the maximum surface temperature increase is 1.3 % (8.6 °K) of average cladding outer surface temperature. This result may have a minor effect on oxidation of cladding.

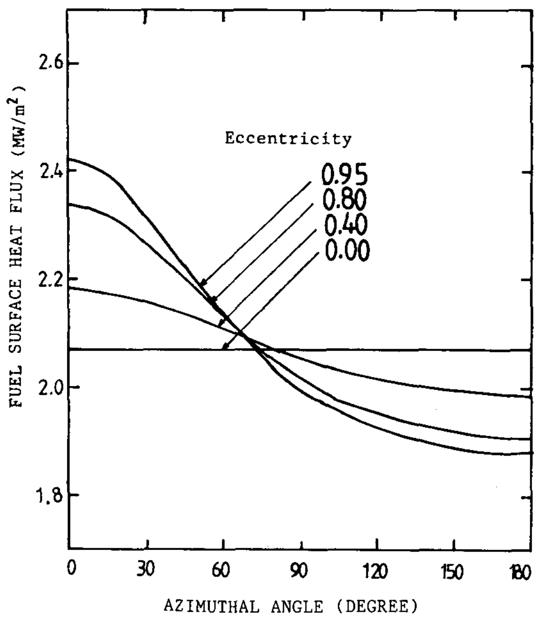

Fig. 8. The Azimuthal Variation of Fuel Surfce Heat Flux.

3. Effects of eccentricity on heat flux

The azimuthal variation of heat flux on fuel pellet surface is shown in Figure 8. The maximum heat flux occurs at an angle of 0° where the temperature is at its minimum. This result reveals that the eccentricity increases the maximum local heat flux. When eccentricity ratio is 0.95, the maximum local heat flux increases by 16.9 % of average heat flux, whereas minimum local heat flux decreases by 9.1 %.

Figure 9 shows the azimuthal variation of heat flux on the cladding outer surface. The maximum heat flux occurs at an angle of 0°, while the minimum heat flux at an angle of 180°. When eccentriciy ratio is 0.95, the maximum shows that the eccentricity can have a significant effect on local heat flux which is considered to be an important parameter for calculating the uncertainties in minimum DNBR evaluation.

IV. Conclusions

The effects of fuel pellet eccentricity has been

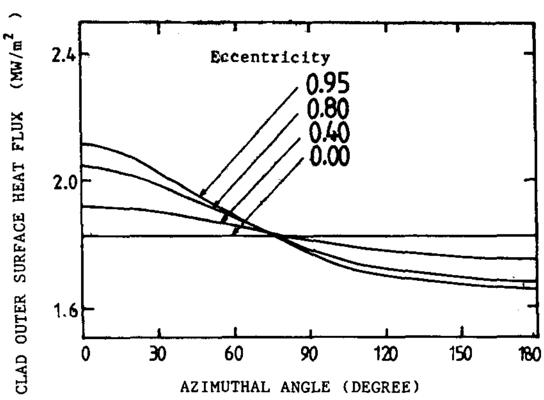

Fig. 9. The Azimuthal Variation of Cladding Outer Surface Heat Flux.

investigated using a program developed in this study. The following conclusions are drawn for a typical LWR fuel rod as shown in Table 1.

(1) The program developed in this study can be used as a supplementry code for calculating temperature and heat flux when the fuel pellet is located eccentrically within the cladding.

(2) The maximum temperature of fuel decreases 1.9 % while its location moves 15.6 % of fuel pellet radius at an eccentricity ratio of 0.95. The decrease of maximum fuel temperature will reduce the possibility of fuel melting.

(3) Average temperature of fuel decreases 4.3 % at an eccentricity of 0.95. This result reveals that eccentric fuel will reduce the stored energy of fuel and enhance the fuel performance during a postulated accident.

(4) The maximum local heat flux on the cladding outer surface increases by 15.7 % when eccentricity is 0.95. This result indicate that eccentric fuel could affect the uncertainties in DNBR calculation.

(5) The maximum local temperature of the cladding outer surface can increase only 1.3 % at an eccentricity of 0.95. This result indicates that eccentricity is expected to have minor effect on the oxidation of the cladding.

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