Effect of Space Dependent Self-Shielding on Doppler Reactivity Calculation for Thermal Reactore Cells

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ABSTRACT

The Doppler reactivity worth for thermal reactor cells has been evaluated taking into account the space dependence of self-shielding effect and the temperature distribution within a fuel rod. The self-shielding and temperature effects on effective cross sections are taken into account using the multiband method.

Two conditions of steady state and transient state are considered to evaluate the space dependence of the Doppler broadening effect. The calculated results are compared with those estimated by using the commonly used method with the constant self-shielding and temperature averaged over a fuel rod, and with the reference Monte-Carlo calculations. It is found that the commonly used method overestimates the Doppler reactivity worth by about 10 % for the steady state, but well predicts the Doppler reactivity worth for the transient state.

1. INTRODUCTION

The Doppler reactivity worth is usually calculated using self-shielded cross sections averaged

over a fuel rod. This approximation of constant cross sections is satisfactory for fast reactor cells. However, for thermal reactor fuel cells, the self-shielding effect has space dependence within a fuel rod. The space-dependence of the ^{238}U capture cross section may have an effect on the capture rate, and so on the difference between capture rates of different temperatures, which is the main contribution to the Doppler reactivity worth.

In the steady state, the temperature distribution is parabolic, and the Doppler broadening becomes space-dependent. The space dependence of the self-shielding and the Doppler broadening is investigated based on the multiband method[1-2].

In the transient state such as nuclear excursion and loss of flow accidents, the temperature distribution is rather uniform. In order to evaluate the time-dependent temperature distribution, we use the improved quasi-static approximation based on the transport theory. The neutron flux is expressed by the product of the amplitude function and the shape function. The shape function is formulated based on the collision probability method with a source term. In this collision probability the space-dependent effective cross sections which contain the space-dependent self-shielding and Doppler broadening effect are utilized.

The purpose of this study is to investigate the effect of space-dependent self-shielding on the Doppler reactivity worth in the steady and transient cases.

Chapter 2 describes the calculational methods and the calculational models for the steady and the transient cases. The calculated results are shown in Chapter 3. Chapter 4 shows the conclusion.

2. CALCULATIONAL METHOD AND MODELS

The calculational model of the Doppler reactivity worth are the 3.4 % ^{235}U enriched UO_2 fueled cell and the mixed oxide (MOX) cell with Pu enrichment of 6.0 % shown in Fig.1. The cylindrical cell approximation is used at the cell boundary. The fuel radius and the equivalent cell radius were set to 0.52 cm and 1.08 cm, and the void fraction of the moderator was set to 40%. To treat the space dependence of the self-shielding and the temperature distribution the fuel rod was divided into 10 equivolume regions. The cell calculations were performed in 107 energy groups using the JENDEL3.2[3] library. The effective cross sections were obtained based on the multiband method (3band).

For the steady state, the 107 group cell calculations were performed based on the collision probability method using the RESPLA[4] code. The linear heat-generation rates were assumed to be 150 and 190 W/cm and the k_∞ difference for the two conditions was taken as the Doppler reactivity worth. In this study, the following two methods were used.

The method 1 is a conventional one: The average self-shielded neutron cross sections are calculated over the fuel rod based on the multiband method. The flux and power are assumed to be constant over the fuel rod.

The method 2 is a present method: The space-dependent neutron cross sections are calculated for the 10 regions based on the multiband method taking into account the temperature distribution. The power distribution is calculated by the neutron cross sections. So it is necessary to iterate the temperature calculation and the cross sections calculation.

As a reference we used the continuous energy Monte-Carlo code MVP[5] version 2.0 which can use region-wise temperatures.

In the following, we show the calculational model and method for the transient case. As a transient a start-up accident was considered. The linear heat-generation rate was 190×10^{-5} W/cm before the reactivity insertion, and the ramp reactivity of 30 \$/sec was added during the time interval of 0.05 sec. The calculational method is based on the improved quasi-static approximation[6]. The flux is expressed by

$$\Phi\left(\vec{r},\vec{\Omega},E,t\right)=\phi(t)\psi\left(\vec{r},\vec{\Omega},E,t\right) \tag{1}$$

The amplitude function $\phi(t)$ is calculated by the conventional equation.

$$\frac{d\phi(t)}{dt}=\frac{\rho(t)-\beta(t)}{\Lambda(t)}\phi(t)+\sum_m \lambda_m C_m(t) \tag{2}$$

The notations in Eq.(2) are the commonly used ones, and the precursor densities $C_m(t)$ are calculated in 6-groups. The shape function is calculated using the integral transport theory. The g-group shape function in region i at time step t_k, ψ^g_{i,t_k}, satisfies the equation

$$\Sigma^g_{i,t_k}\psi^g_{i,t_k}V_i=\sum_j\sum_{g'}P^g_{ji,t_k}\left\{\Sigma^{g'\to g}_{s,j,t_k}\psi^{g'}_{j,t_k}+S^{g,g'}_{j,t_k}\right\}V_j \tag{3}$$

The source term $S^{g,g'}_{j,t_k}$ is given by

$$S_{j,t_k}^{g,g'} = -\frac{1}{\nu^{g'}}\left\{\frac{\psi_{j,t_k}^{g'}}{\phi_{t_k}}\frac{\phi_{t_k}-\phi_{t_{k-1}}}{\Delta t_{k,k-1}}+\frac{\psi_{j,t_k}^{g'}-\psi_{j,t_{k-1}}^{g'}}{\Delta t_{k,k-1}}\right\}$$
$$+(1-\beta)\chi_p^g \nu \Sigma_{f,j.t_k}^{g'}\psi_{j,t_k}^{g'} \qquad (4)$$
$$+\sum_m \chi_m^g \lambda_m C_{m,j,t_k}/\phi_{t_k}$$

By solving Eqs.(2) and (3), the flux is obtained. From the flux, the power distribution $Q(\vec{r},t)$ is calculated, and the temperature distribution is calculated by the following heat transfer equation

$$C_f\rho_f(T)\frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left\{k_f(r)r\frac{\partial T}{\partial t}\right\}+Q(\vec{r},t) \qquad (5)$$

where T : fuel temperature
C_f : fuel heat capacity
ρ_f : fuel density

The calculated temperature is used to calculate the Doppler broadening in individual regions, which is necessary to calculate the cross sections in Eq.(3). So the iterations are necessary to solve Eq.(3) and (5). Equation (3) was solved in 107 groups similar to the steady state, the self-shielded neutron cross sections in fuel rod were calculated based on the multiband method. The following calculations were performed.

The method 1 is the conventional one: The average self-shielded neutron cross sections, the average temperature, flux and power are used.

The method 2 is the present method: The space-dependent neutron cross sections are calculated by dividing the fuel rod into the equivolume 10 regions and the space dependent power distribution is used.

3. RESULTS AND DISCUSIONS

3.1 STEADY STATE

Let us first compare the ^{238}U capture cross section which largely contributes to the Doppler reactivity worth. The ^{238}U capture cross sections are shown in Fig.2 for the methods 1 and 2 as a function of distance from the fuel center. The space-dependent self-shielded cross section of the method 2 is large near the fuel edge because the self-shielding effect becomes small. The difference between the ^{238}U capture cross sections for the liner heat-generation rates of 150 and 190 W/cm is shown in Fig.3. The fuel-averaged temperature increases from about 809 K to 886

K. However, considering the space-dependent temperature distribution, the increase of the temperature at the edge of fuel pellet is smaller than the average temperature increase as shown in Fig.4. Therefore, the contribution of the fuel peripheral region to the cross section difference is small except the rod edge. At the rod edge the difference is almost the same between methods 1 and 2. This is because the ^{238}U capture cross section is large as shown in Fig.2.

The Doppler reactivity worths calculated by the methods 1, 2, and the reference Monte-Carlo method are shown in Table 1. The present method (method 2) decreases the Doppler reactivity worth by 20 % compared to the method 1[7]. However, in the reference calculation, this decrease is 8 %. This is due to the use of only 3 band in the multiband method, and it will be necessary to increase the band number.

3.2 TRANSIENT STATE

The Doppler reactivity worth calculated by the present method (method 2) is shown in Fig.5 as a function of time as well as the difference between the Doppler reactivity worth for the method 1 and 2. The difference between the methods is small. This is because, upon inserting reactivity in cold stand-by, the fuel temperature increases under an adiabatic process until about 1 sec after the reactivity insertion. So the temperature distribution in the fuel pellet at the time (<1.0 sec) was nearly flat as shown in Fig.6. Fig.7 shows that the difference between the space-dependent ^{238}U capture cross sections at the time 0.5 sec and 1.0 sec. The difference at the edge of fuel pellet becomes larger for the method 2 than that for the method 1. Therefore, the Doppler reactivity worth evaluated by the method 2 becomes almost the same as that by the method 1[8].

4. CONCLUSIONS

In the steady state case a significant difference was seen for the Doppler reactivity worths calculated by the conventional method and the present method. The present method which treats the space dependence of the self-shielding and the temperature distribution within a fuel rod decreased the Doppler reactivity worth by about 10 % compared to the conventional method.

However for the transient case, the difference was small. This is due to the rather flat temperature distribution during the transient.

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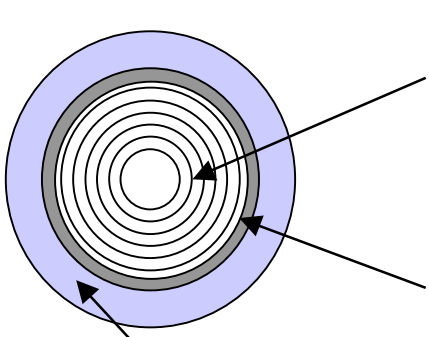
Table 1. Doppler reactivity worth calculated by different methods

Cell	Multiband Method		Monte-Carlo	
	Conventional (Method1)	Present (Method2)	Constant temperature	Temperature distribution
UO_2	-2.7042*	-2.2957	-1.9643	-1.8167
MOX	-3.1387	-2.7302	-----	-----

*unit:$\times 10^{-5}\,\Delta$ k/k/K



Fuel
UO_2 pellet (MOX pellet)
theoretical density : 97%
enrichment : 3.4 wt% (6.0% Pu)
radius : 0.52 cm

Cladding
outer radius : 0.615cm

Moderator (coolant)
H_2O
equivalent outer radius : 1.08 cm

Fig.1 Calculational geometry

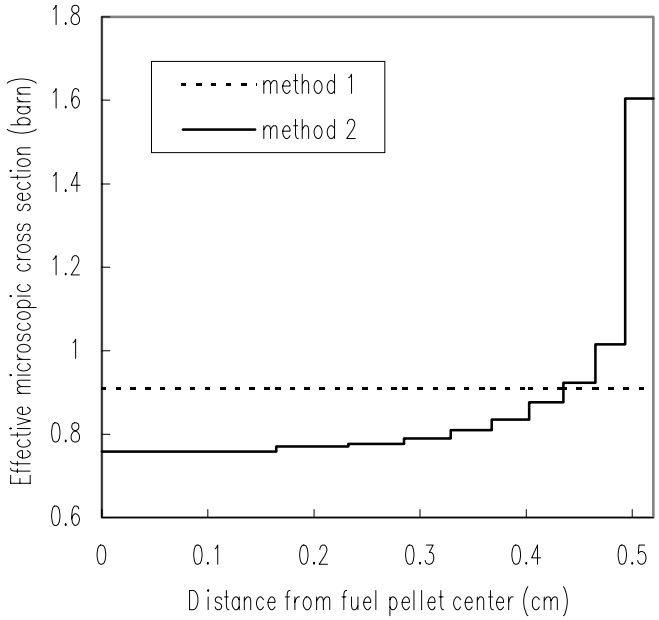


Fig.2 Space dependent 238U capture cross sections in fuel pellet

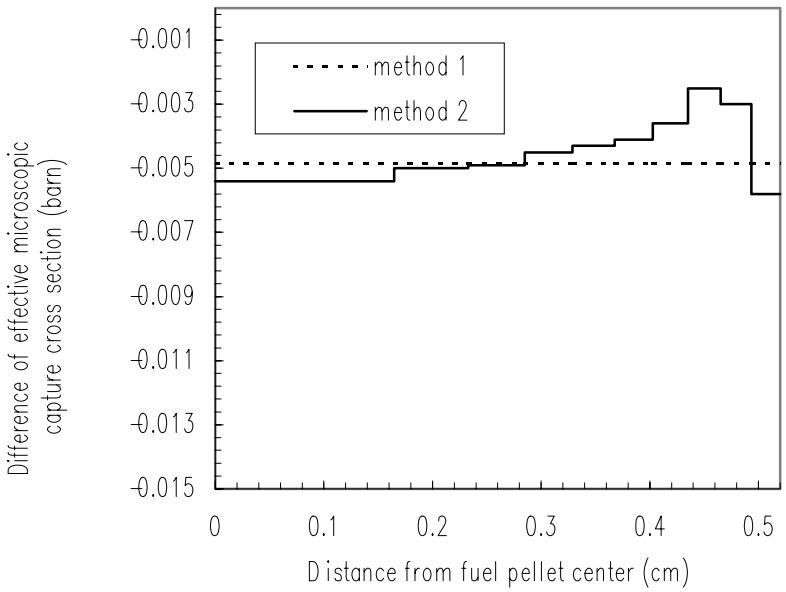


Fig.3 Difference between 238U capture cross sections for linear heat-generation rates for 150 and 190 W /cm

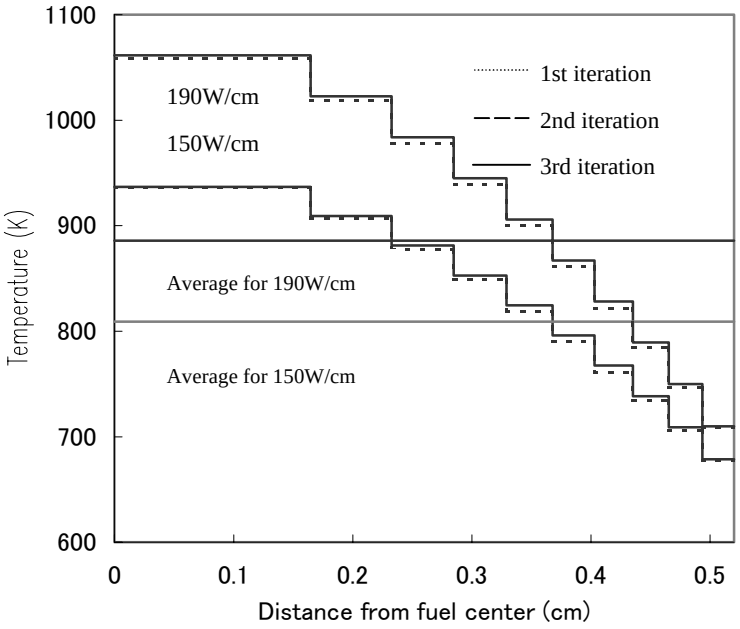


Fig.4 Temperature distribution within a UO2 fuel

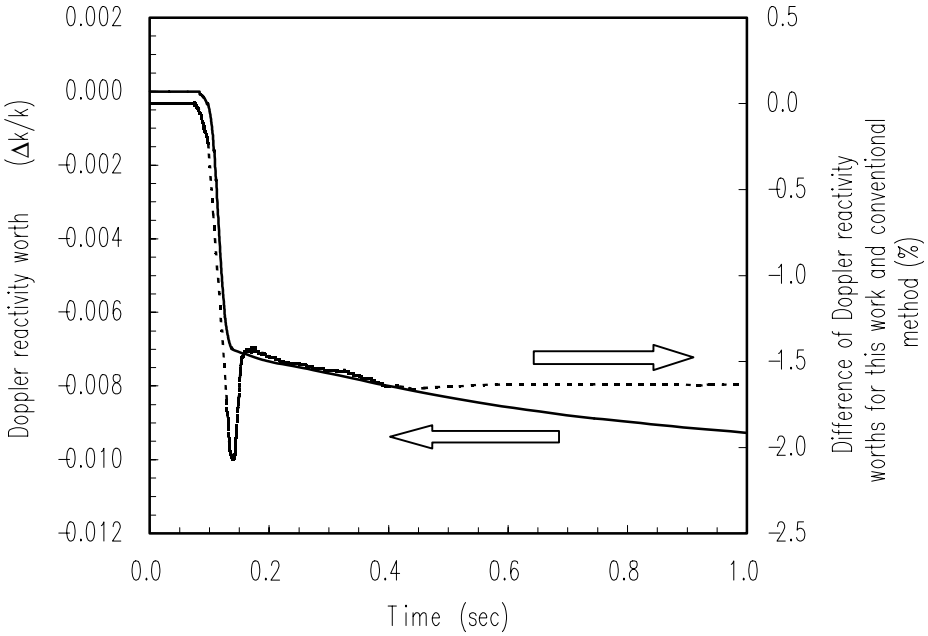


Fig.5. The time dependence of Doppler reactivity worth

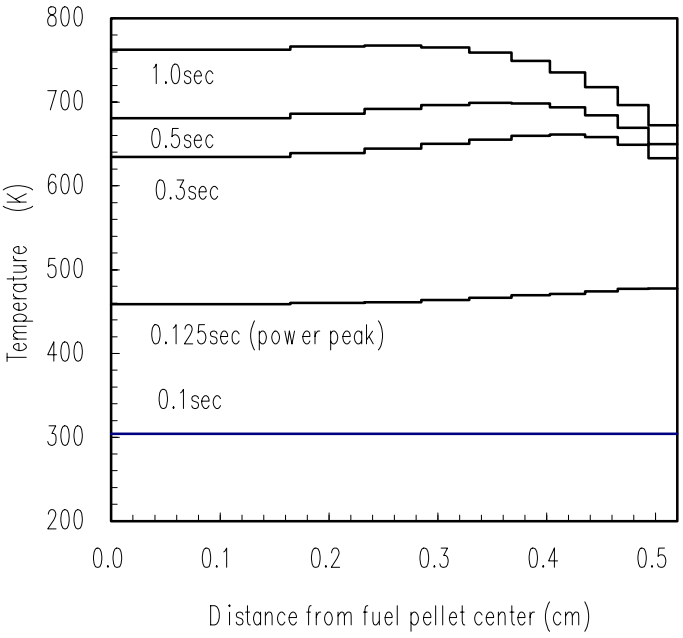


Fig.6 Temperature distribution in fuel pellet at each time step

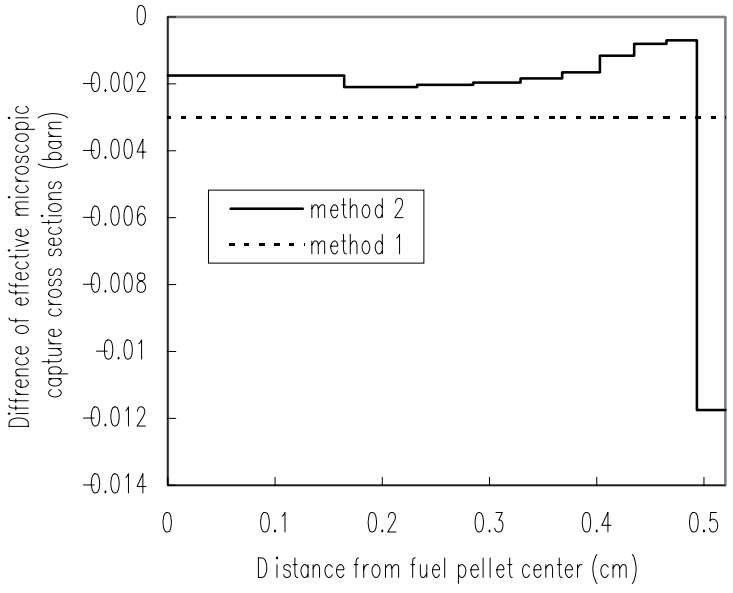


Fig.7 Difference of 238U capture cross sections between 0.5sec and 1.0sec