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Proposal of Two-Material Coexisting Ring Model to Improve the Conventional Fast Reactor Analysis Method for Group Condensation

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1. Introduction

In fast reactor cross-section generation, simplified R-Z geometry is analyzed to condense fine-group constants as shown in Fig.1. Because of the long mean-free path of the fast neutron, an accurate model for simplified fast reactor is required rather than lattice calculation, which is generally used for thermal reactor system.

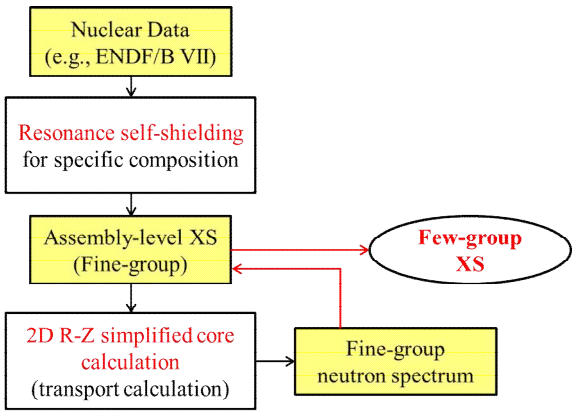
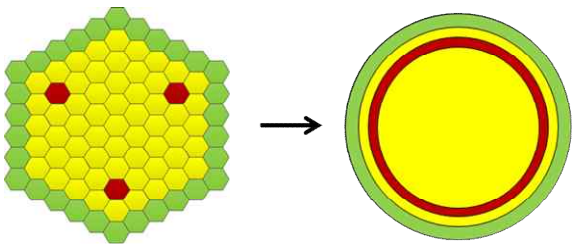


Fig.1: Flow chart of fast reactor XS generation [1]

Conventionally, simplified fast reactor model is R-Z geometry with volume conservation for each region. An example of hexagonal-Z configuration and its simplified R-Z model is shown in Fig.2.



(a) (b)

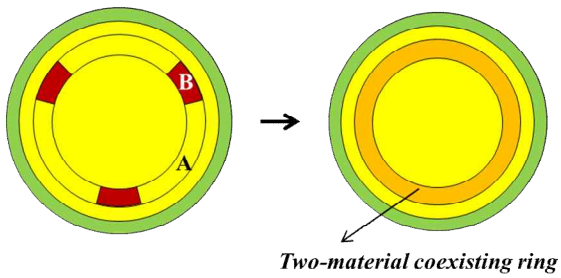
Fig.2: Radial view of (a) Hex-Z fast reactor core, and (b) Simplified R-Z model

In real hexagonal-Z configuration, control assembly position (red in Fig.2) is isolated. However, this control assembly position is converted to a single cylindrical ring in simplified R-Z geometry as shown in Fig.2-(b), which is far from original configuration. In Ref [2], the "RRZ" simplified model is proposed and analyzed by Monte Carlo simulation to deal with this problem. The control assembly is converted to isolated cylinder in "RRZ" simplified model. It shows good performance with use of discontinuity factors. But, "RRZ" simplified model is developed for Monte Carlo method, not for deterministic method. The other option would be R-θ-Z simplified geometry, but calculation burden for simplified core analysis will be dramatically increased in this approach.

In this paper, a two-material coexisting ring model is proposed to improve simplified fast reactor geometry. In this newly proposed model, θ-direction homogenized model from R-θ-Z geometry will be solved, but neutron flux for each material in homogenized region will be obtained separately. This can be achieved by decoupling the balance equation and by introducing a proper streaming model between two materials at homogenized region, similarly to the "two-temperature homogenized model" [3]. The detail description and numerical results are followed.

2. Methodology

The two-material coexisting ring model solves θ-direction homogenized model from R-θ-Z geometry as described in Fig.3. Technically, the newly proposed model deals with R-Z simplified geometry, but neutron flux for each region is obtained separately at the two-material coexisting ring domain.



(a) (b)

Fig.3: Radial view of (a) R-θ-Z geometry, and (b) two-material coexisting ring model

In this paper, 2-D hexagonal fast reactor geometry is considered as a reference configuration for sake of simplicity. In this case, infinite cylindrical geometry is a conventional simplified fast reactor configuration. The extension of the two-material coexisting ring model to the 3-D hexagonal-Z fast reactor geometry will be straightforward.

2.1. Governing equation for two-material coexisting ring

To obtain neutron flux for each region separately in the two-material coexisting ring, the balance equation for coexisting ring domain should be derived first. Eq.(1) shows the integrated balance equation at *i*-th fine mesh cell in S_N formulation in infinite cylindrical geometry:

$$\begin{aligned}&\mu_n[L_{i+1/2}\bar{\psi}_{n,i+1/2}-L_{i-1/2}\bar{\psi}_{n,i-1/2}]\\&+\frac{\alpha_{n+1/2}\bar{\psi}_{n+1/2,i}-\alpha_{n-1/2}\bar{\psi}_{n-1/2,i}}{w_n}(L_{i+1/2}-L_{i-1/2})\\&+\bar{\sigma}_i\bar{\psi}_{n,i}A_i=\bar{q}_{n,i}A_i.\end{aligned}\tag{1}$$

The "bar" represents the homogenized parameters and the others follow the standard notation.

In Eq.(1), homogenized parameters are unknown. Eq.(2) shows the definition of the homogenized parameters in Eq.(1):

$$\bar{\psi}_{n,i\pm1/2}=\frac{f_A L_{i\pm1/2}\psi^A_{n,i\pm1/2}+f_B L_{i\pm1/2}\psi^B_{n,i\pm1/2}}{L_{i\pm1/2}},\tag{2a}$$

$$\bar{\psi}_{n,i}=\frac{f_A A_i\psi^A_{n,i}+f_B A_i\psi^B_{n,i}}{A_i},\tag{2b}$$

$$\bar{\sigma}_i=\frac{\sigma^A_i\psi^A_{n,i}A_i f_A+\sigma^B_i\psi^B_{n,i}A_i f_B}{\bar{\psi}_{n,i}A_i},\tag{2c}$$

$$\bar{q}_{n,i}=\frac{q^A_{n,i}A_i f_A+q^B_{n,i}A_i f_B}{A_i},\tag{2d}$$

where f_A is the fraction of material A occupied in coexisting ring, and f_B is the fraction of material B occupied in coexisting ring.

After inserting Eq.(2) into Eq.(1), then Eq.(1) is decomposed into two equations after some algebra. One is the balance equation for material A, and the other is for material B. Eqs.(3a) and (3b) show the two-decomposed balance equations:

$$\begin{aligned}&\mu_n[f_A L_{i+1/2}\psi^A_{n,i+1/2}-f_A L_{i-1/2}\psi^A_{n,i-1/2}]\\&+\frac{\alpha_{n+1/2}\psi^A_{n+1/2,i}-\alpha_{n-1/2}\psi^A_{n-1/2,i}}{w_n}(L_{i+1/2}-L_{i-1/2})f_A+\sigma^A_i\psi^A_{n,i}f_A A_i\\&+[\text{Streaming between Material A and B}]=q^A_{n,i}f_A A_i,\end{aligned}\tag{3a}$$

$$\begin{aligned}&\mu_n[f_B L_{i+1/2}\psi^B_{n,i+1/2}-f_B L_{i-1/2}\psi^B_{n,i-1/2}]\\&+\frac{\alpha_{n+1/2}\psi^B_{n+1/2,i}-\alpha_{n-1/2}\psi^B_{n-1/2,i}}{w_n}(L_{i+1/2}-L_{i-1/2})f_B+\sigma^B_i\psi^B_{n,i}f_B A_i\\&-[\text{Streaming between Material A and B}]=q^B_{n,i}f_B A_i.\end{aligned}\tag{3b}$$

In the decomposition procedure, it is noted that there is a cancelled term in Eq.(1). Physically, that is the neutron streaming between two materials. Therefore, in decomposed balance equation, this neutron streaming between two materials should be added as described in Eq.(3).

Up to now, there is no approximation. If we sum up Eqs.(3a) and (3b), and use relationship of the homogenized parameters (Eq.(2)), Eq.(1) can be simply re-obtained. If the streaming term between two materials is specified properly, it is expected that the neutron flux solution for material A and B can be obtained accurately.

2.2. Streaming model between two materials in coexisting ring

In the two-temperature homogenized model [3], heat exchange between fuel kernel and graphite matrix is expressed as $(\textit{Couping coeff.})\times(T_f-T_m)$. Because the heat conduction equation is similar to the neutron diffusion equation, this diffusion-like heat exchange model (driving force is a difference of temperatures) is a useful point of reference. However, in the two-material coexisting ring model, we are dealing with neutron transport equation. Therefore, in two-material coexisting ring model, streaming model between two materials is provided by using angle-dependent CMR (Coarse Mesh Rebalancing)-like concept.

In this steaming model, two coupling coefficients are introduced. One is for neutron streaming from material A to B, $C_{A\to B}$, and the number of neutrons passing from material A to B is expressed as $C_{A\to B}\psi^A\Delta r$. The other one is for streaming from material B to A, $C_{B\to A}$, and the number of neutrons passing from material B to A is expressed as $C_{B\to A}\psi^B\Delta r$.

Putting these streaming models into Eq.(3), we obtain the final form of governing equations in the coexisting ring region :

$$\begin{aligned}&\mu_n[f_A L_{i+1/2}\psi^A_{n,i+1/2}-f_A L_{i-1/2}\psi^A_{n,i-1/2}]\\&+\frac{\alpha_{n+1/2}\psi^A_{n+1/2,i}-\alpha_{n-1/2}\psi^A_{n-1/2,i}}{w_n}(L_{i+1/2}-L_{i-1/2})f_A+\sigma^A_i\psi^A_{n,i}f_A A_i\\&-C_{A\to B,n}\psi^A_{n,i}\Delta r_i+C_{B\to A,n}\psi^B_{n,i}\Delta r_i=q^A_{n,i}f_A A_i,\end{aligned}\tag{4a}$$

$$\begin{aligned}&\mu_n[f_B L_{i+1/2}\psi^B_{n,i+1/2}-f_B L_{i-1/2}\psi^B_{n,i-1/2}]\\&+\frac{\alpha_{n+1/2}\psi^B_{n+1/2,i}-\alpha_{n-1/2}\psi^B_{n-1/2,i}}{w_n}(L_{i+1/2}-L_{i-1/2})f_B+\sigma^B_i\psi^B_{n,i}f_B A_i\\&+C_{A\to B,n}\psi^A_{n,i}\Delta r_i-C_{B\to A,n}\psi^B_{n,i}\Delta r_i=q^B_{n,i}f_B A_i.\end{aligned}\tag{4b}$$

If we use auxiliary equation such as DD (Diamond Difference) scheme on angular and spatial differencing, Eq.(4) can be solved.

2.3. Determination of coupling coefficients

The coupling coefficients are determined by solving a 1-D stretched geometry problem as shown in Fig.4. This 1-D stretched geometry problem is built by selecting a unit segment of the coexisting ring region with reflective boundary condition, and converting this into simple 1-D slab geometry with volume conservation. Conversion of a curvilinear geometry to the slab geometry can reduce the calculation burden significantly.

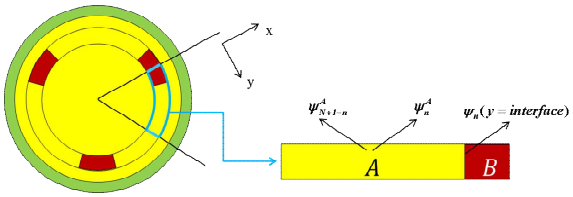


Fig.4: 1-D stretched slab geometry to determine coupling coefficients

After solving 1-D stretched slab geometry problem, coupling coefficient $C_{A\to B}$ is calculated as:

$$C_{A\to B,n}=\frac{\eta_n\times\psi_n(y=interface)}{[\psi_n^A(averaged)+\psi_{N+1-n}^A(averaged)]/2} \quad (5)$$

The coupling coefficient $C_{B\to A}$ can be calculated in a similar way.

The two-material coexisting ring model for simplified fast reactor geometry requires additional calculation in determining the coupling coefficients. However, if level-symmetry quadrature is used, quadrature angles for 1-D stretched slab geometry can be collapsed. In level-symmetry quadrature, there are angles which have the same η values, and these angles can be collapsed into one angle. Hence, the calculational burden to solve 1-D stretched slab geometry problem is not heavy.

3. Numerical Results

In this paper, a simple 2-D hexagonal fast reactor test problem is considered. The core configuration is shown in Fig.5.

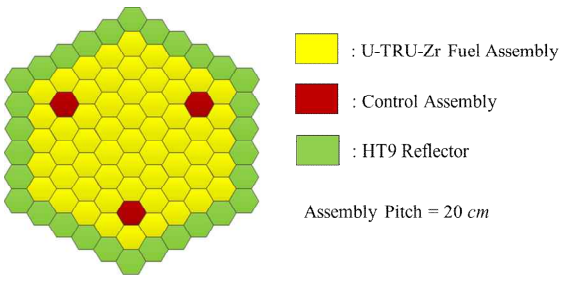


Fig.5: 2-D hexagonal fast reactor test problem configuration

The conventional simplified fast reactor geometry (infinite cylinder in this case) and newly proposed two-material coexisting ring model will be solved, and the results of the average neutron spectrum for each region are compared with 2-D hexagonal and R-θ geometry solutions.

All calculations are done under S_8 discrete ordinates method. Cross-section set is generated in 150-group structure with isotropic scattering by the TRANSX code [4].

Fig.6 shows the average neutron flux of 2-D hexagonal reference configuration. This calculation is done by the TWODANT code [5].

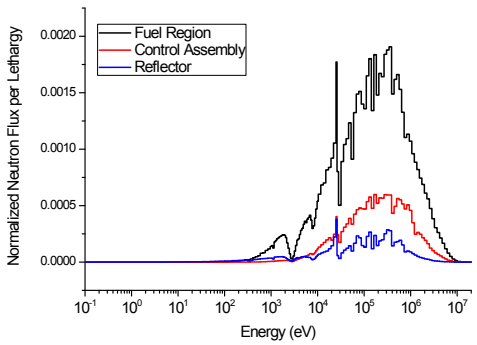


Fig.6: Average neutron flux of 2-D hexagonal configuration for each region.

In neutron spectrum comparison, average neutron spectrum at each region is normalized to have the same integrated value over the whole energy range.

When 2-D hexagonal configuration is considered as a reference, Figs.7 and 8 show the relative error of the average neutron spectrum for conventional simplified model and two-material coexisting ring model, respectively. Below 10,000 eV, the neutron flux level is very low compared to higher energy region. Hence, Figs.7 and 8 focus on the energy region above 10,000 eV.

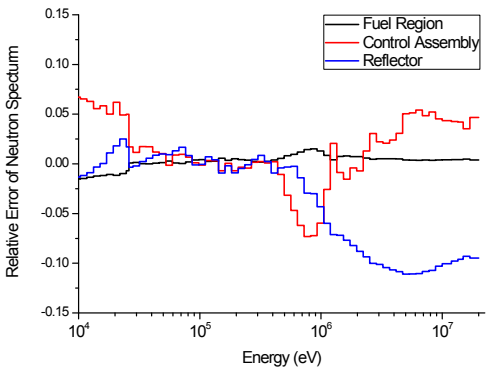


Fig.7: Relative error of the average neutron spectrum between conventional simplified model and 2-D hexagonal geometry

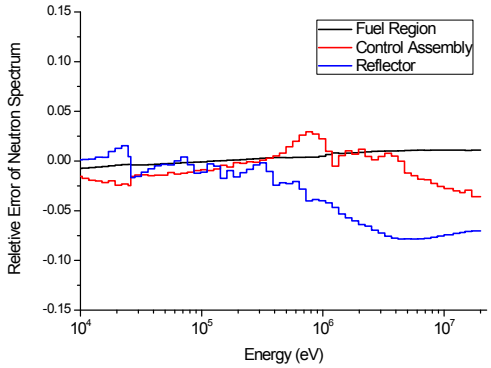


Fig.8: Relative error of the average neutron spectrum between two-material coexisting ring model and 2-D hexagonal geometry

As shown in Figs.7 and 8, newly proposed model shows better neutron spectrum results compared with conventional simplified model. Especially in control assembly, relative error in the spectrum is much flattened. The reason of this is that the effect of distinct locations of control and fuel materials is considered in two-material coexisting ring model unlike in the conventional model.

However, in Fig.7, significant discrepancy in neutron spectrum still exists in the reflector region. This discrepancy comes from the difference between 2-D hexagonal and R-θ geometries.

When R-θ configuration is considered as a reference, Figs.9 and 10 show the relative error of the average neutron spectrum for conventional simplified model and two-material coexisting ring model, respectively.

It is observed that two-material coexisting ring model is relatively in good agreement with R-θ geometry reference in spectrum comparison.

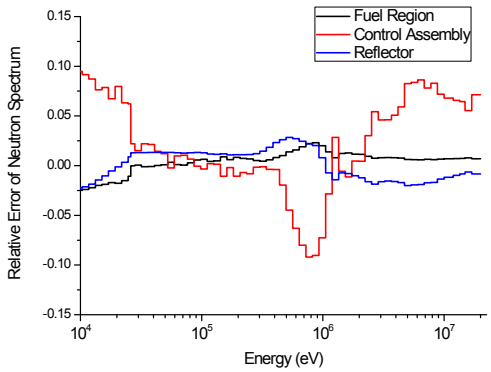


Fig.9: Relative error of the average neutron spectrum between conventional simplified model and R-θ geometry

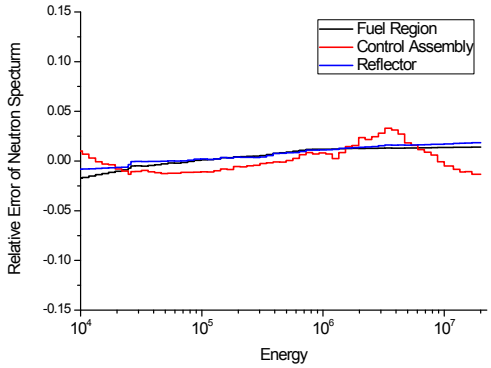


Fig.10: Relative error of the average neutron spectrum between two-material coexisting ring model and R-θ geometry

Although neutron spectrum results are improved when two-material coexisting ring model is adopted, there is a problem to be solved on the effect of incoming angular flux splitting. Figure 11 shows the relative difference of the average neutron "flux level" between two-material coexisting ring model and R-θ geometry reference.

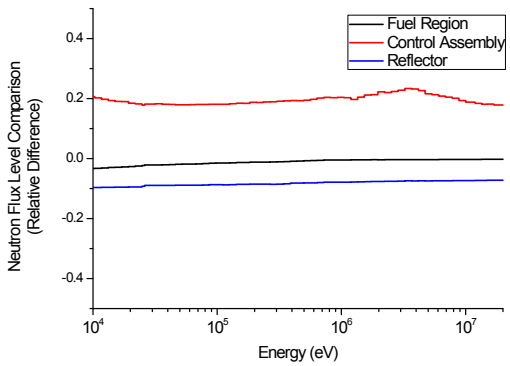


Fig.11: Comparison of average neutron flux levels between two-material coexisting ring model and R-θ geometry

As shown in Fig.11, two-material coexisting ring model over-estimates neutron flux in control assembly region. However, the relative differences are rather flat, so that good agreement on neutron spectrum is obtained as shown in Fig.10.

In the present two-material coexisting ring model, incoming angular flux from non-coexisting ring region to coexisting ring region is split based on fraction occupied in coexisting ring. However, physically, neutron flux near the control assembly is lower than other regions, so fewer neutrons should go into control assembly in the coexisting ring region than the present treatment used in the two-material coexisting ring model. Therefore, a more appropriate incoming angular flux splitting model should be investigated for coexisting ring region.

4. Conclusions and Future Work

To improve current simplified fast reactor analysis for group condensation in fast reactor analysis, two-material coexisting ring model is proposed in this study. In the two-material coexisting ring model, θ-direction homogenized model from R-θ-Z geometry is solved, but neutron flux for each material in homogenized region is obtained separately.

To describe neutron streaming between two materials in the coexisting ring, two coupling coefficients are introduced, and these are determined by solving a simple 1-D stretched slab geometry problem.

In the numerical results on simple 2-D fast reactor test problem, newly proposed two-material coexisting ring model shows better neutron spectrum estimation compared with conventional simplified model. From these results, it is expected that accurate group condensation procedure can be achieved. In addition, a coarser few-group structure may be possible to analyze fast reactor systems.

However, it is also shown that there is an issue of incoming angular flux splitting in coexisting ring region. In the present two-material coexisting ring model, neutron flux in control assembly region is over-estimated.

As a further study, a more appropriate incoming angular flux splitting model will be investigated. After that, few-group fast reactor analysis by using the two-material coexisting ring model for condensation is also planned.

Acknowledgement

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