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Inter-Assembly Thermal Flux Gradient Correction of Homogenization Parameters Based on One-Dimensional Heterogeneous Interface Model

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Abstract

To remedy the deficiency of single assembly homogenization with zero current boundary condition, proposed is a new approach solving a simple few-region one-dimensional one-group model consisting of pin columns of two adjacent assemblies. The cross-sections representing each pin column come from the single assembly homogenization. After solving analytically for the thermal flux across each interface of materials by the integral transport method, equivalence theory parameters or form factors are corrected during the nodal diffusion calculation to take into account the effect of the thermal flux gradient.

The accuracy and the applicability of the proposed method were tested against a small benchmark problem consisting of MOX fuel and bare water reflector. The result shows that the method solving the one-dimensional model consisting of only six regions per interface can reduce significantly the errors in reconstructed pin powers near strong material interfaces.

I. Introduction

The reactor core analysis system based on the two-level calculations of the lattice physics transport calculation and the nodal diffusion calculation is widely adopted to predict the neutron behavior in the commercial light water power reactors. The key idea employing the two level calculations is to avoid the limitations in calculational resources involved in the detailed pin-wise transport calculation in the complicated spectral and geometric structure of a real rector core. The lattice physics calculation in this system plays a role in providing the homogenized equivalence theory parameters for the nodal diffusion calculation and the flux form factors for the detailed pin-wise flux reconstruction. This calculation is usually done in a somewhat complicated energy-group structure but in a small geometry consisting of an assembly or a few assemblies with imposing zero-current boundary conditions on the outer boundary of the geometry. On the other hand, the nodal diffusion calculation takes part in calculating the smoothly varying flux distribution over the whole core by taking the homogenized parameters resulting from the lattice physics calculation as input. This calculation is done in a large geometry e.g., the whole core geometry but in a simple energy group structure consisting usually of two energy groups. The main output of this system is the detailed pin-wise flux distribution that is a simple superposition of the smoothly varying flux shape resulted from the nodal diffusion calculation and the pin-wisely bumpy flux form factors from the lattice physics transport calculation.

This procedure works relatively well in the interior core region where no significant fuel material discontinuities across assembly interfaces are involved. However, it shows poor performance in predicting the detailed pin-wise fluxes near the fuel/reflector interface or the mixed oxide (MOX)/uranium oxide (UO_2) fuel interface, where step change in material occurs. Figure 1 is an example of errors in the pin-wise powers reconstructed by a typical two-level analysis procedure with single assembly homogenization. Large errors are clearly shown in this figure near regions with strong material discontinuity. It is well understood that this is caused by the fact that the equivalent theory parameters homogenized by the single assembly transport calculation with zero neutron current boundary condition cannot reflect the actual flux gradient across an assembly interface. Errors caused by the homogenization imperfection are unavoidable even though a very accurate lattice physics transport calculation and an error free nodal diffusion calculation are combined in a system.

To remedy this shortcoming of the single assembly homogenization with zero current boundary condition, the multi-assembly (or color-set) homogenization may be utilized so that the flux gradient across an assembly interface is taken into account in the equivalence theory

parameters. Even though this can reduce significantly the large errors in the reconstructed pin-wise powers near the interface, tremendous calculations are required during the homogenization stage in sweeping a large number of multi-assembly geometries, each of which represents a combination of assemblies in a various state of burnup that may appear in a part of the reactor core through reload cycles. Another approach to capture the effects of the flux gradient on the equivalence theory parameters is to redo the single assembly homogenization calculation with the current boundary conditions updated after the nodal diffusion calculations. The boundary perturbation theory may help reducing the calculational effort involved in the second homogenization for a same type of assemblies with different current boundary conditions.

As shown in figure 1, the fuel pins with large errors in the reconstructed powers are usually concentrated in the very narrow range near the material interface mostly in the first row of fuel pins facing the interface directly. A distinct systematic pattern in the sign and magnitude of errors can also be observed in these pins. As the more accurate homogenization and nodal diffusion calculations are combined in the system based on the single assembly homogenization, such a trend in errors gets more dominant due to cancellation of error sources except homogenization imperfection. If the fast and thermal fluxes are separately examined, errors by any causes in modeling the fast flux that shows a relatively smooth distribution appear in a somewhat wide range due to its long diffusion length. Therefore, it can be concluded with confidence that the errors concentrated on a narrow range near the material discontinuity are caused by the fact that the single assembly homogenization with zero current boundary condition cannot handle the steep thermal flux gradient across the interface.

Fortunately, this thermal gradient ends within the depth of a few pins from the interface. The effect of such a gradient on the homogenized equivalence theory parameters can easily be captured during the homogenization stage with the inclusion of a few rows of edge pins of adjacent fuel assemblies in a certain fuel assembly to be homogenized, although it requires to sweep the same number of combinations of assemblies as those required in the multi-assembly homogenization. Instead of this approach, a powerful but simple approach is proposed in this study that is still based on single assembly homogenization. The basic idea of this approach is that the flux gradient near material discontinuity can be modeled well by a multi-region one-dimensional transport model consisting of pin columns of two adjacent assemblies sharing the interface, each region of which represents the pin column in a same distance from the interface. This model is solved by one of analytic methods to solve the one-dimensional transport equation for each interface of materials. It can be solved either during the nodal diffusion calculation to improve the homogenized equivalence parameters or just after the nodal diffusion calculation to improve the flux form factors used in the pin-wise power reconstruction. The

additional effort required in the single assembly homogenization stage is minor to edit a few sets of the cross-sections for edge pin rows.

A streak of luck makes the one-dimensional model simulating the flux gradient across the material discontinuity very simple. Even the nodal method that uses the lower order polynomials for representing the fast group flux and uses the equivalence theory parameters obtained by the single assembly homogenization can accurately handle the fast flux gradient across the interface. Therefore, the one-group model to be solved for only the thermal flux is possible with the fast flux assumed known from the nodal calculation. The further simplification of the one-dimensional model comes from the fact that the assembly interface is usually quite long compared to the diffusion length of thermal neutron. This enables the thermal neutron moving across the interface to be modeled in the infinite slab geometry with no transverse leakage. In addition, it is sufficient to include only a few rows of edge pins of two assemblies sharing the interface into the one-dimensional model, because the thermal gradient ends in a very short distance from the interface and easily reaches its asymptotic value corresponding to the fast flux distribution. The conventional fuel assembly design that usually contains relatively uniform fuel pins in the most and the second most edge rows may also allows retaining the one-dimension model.

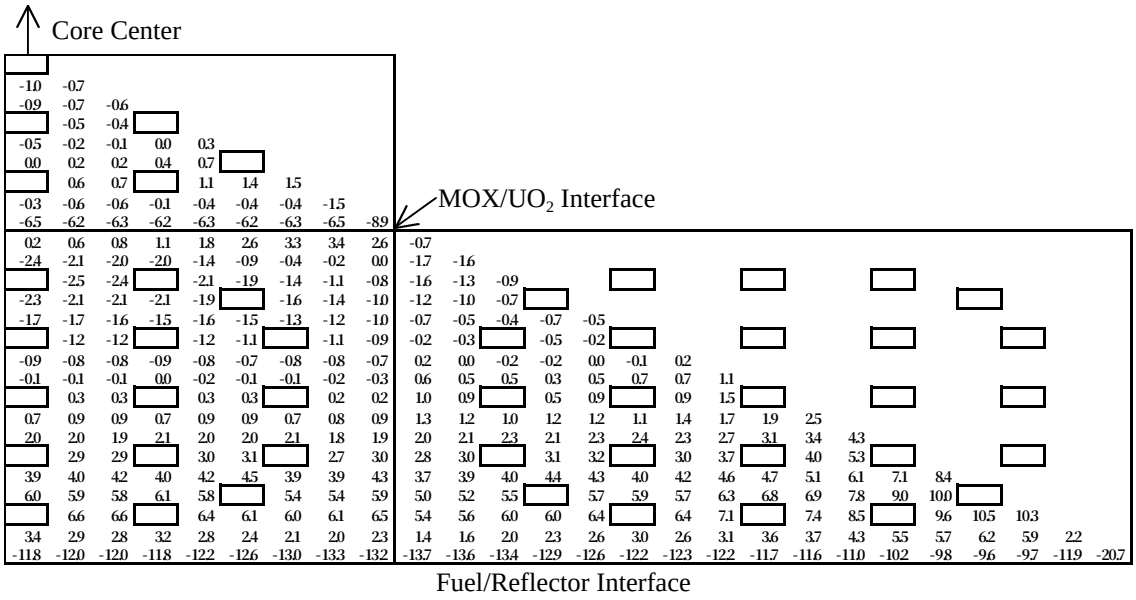

Figure 1. An Example of Pin Power Errors (%) Calculated by Single Assembly Homogenization Parameters

II. One-Dimensional Multi-Region One-Group Model

Figure 2 shows the one-dimensional model constructed near an interface of two adjacent fuel assemblies. Analogous one-dimensional models may be constructed on all interfaces of materials including the fuel/reflector interfaces. Each region in the model e.g., region i in figure 2 is the projected image of a column of pins in the same distance from the interface into the one-dimensional model, which is represented by the cross-sections edited from the single assembly homogenization. The outmost region at each end of the model is made to complement an assembly with the columns of pins that are not treated explicitly.

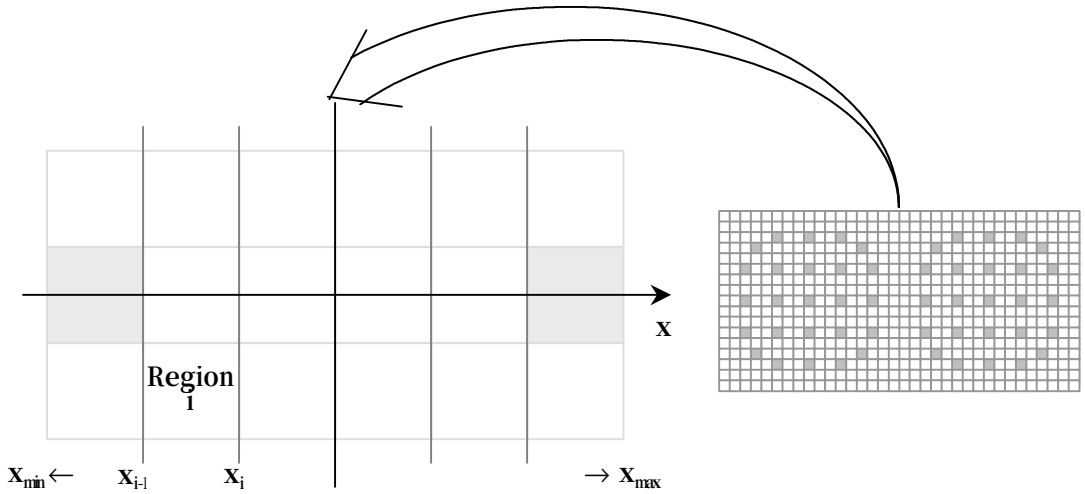

Figure 2. One-Dimensional Multi-Region Interface Model

Only the thermal flux gradient is solved across the interface in the model, assuming that the fast flux of each region is given by the conventional reconstruction i.e., the simple superposition of the homogeneous region flux from the nodal calculation and the region flux form factor from the homogenization calculation. This conventionally reconstructed fast flux shows good agreement with that of the reference fine mesh transport calculation in most cases.

For isotropic fission and scattering, the one-dimensional thermal neutron transport equation without external source is given for region i in figure 2 by

$$m\frac{dj_{2i}(x,m)}{dx}+s_{2i}j_{2i}(x,m)=\sum_{g'=1,2}s_{p2g'i}f_{g'i}(x) \qquad (1)$$

where the scalar flux ϕ is expressed into the angular flux φ as follows,

$$f_{gi}(x) = \frac{1}{2}\int_{-1}^{1} j_{gi}(x,m)dm \tag{2}$$

Each term in Eq. (1) reflects a component contributing to the thermal neutron balance in μ at x in region i. For example, $\sigma_{pgg'i}$ is the production cross-section due to fission and scattering that can be broken down into

$$s_{pgg'i} = s_{sgg'i} + \frac{1}{k_{eff}} c_g n s_{fg'i} \tag{3}$$

Any methods may be used in solving this one-dimensional transport equation. One of the most likely candidates is the analytic S_N method that has no spatial discretization error.(Ref.1) This method discretizes the thermal angular flux into angles and substitutes the thermal scalar flux with the weighted sum of the discretized angular fluxes. Then, it solves analytically the resulting ordinary differential equations in x for all the discretized angular fluxes. The only approximation used in this method is the angular discretization of the angular flux. The total number of unknowns to be solved for in this method is the product of the number of spatial regions and the number of angles discretized in S_N.

Another candidate that will be described here in detail is the integral transport method. Setting x_{min} and x_{max} in figure 2 to -∞ and ∞, respectively, so that the boundary conditions may be neglected, the solution of Eq. (1) at x in region i becomes

$$f_{2i}(x) = \frac{1}{2}\sum_j \int_{x_{j-1}}^{x_j} \sum_{g'=1,2} s_{p2g'j} f_{g'j}(x') \int_1^{\infty} \frac{d}{dg} e^{-gt(x,x')} dg\, dx' \tag{4}$$

where τ(x,x') is the optical path defined as the sum of products of the total cross-section and the path length over all regions between x in region i and x' in region j. Only the unknowns as many as spatial regions are involved in this method. In spite of small number of unknowns, this equation has a crux of containing the thermal scalar flux to be solved for in the right-hand-side. This requires assumption on the shape of the thermal scalar flux even before it is solved, although it is not a necessarily absolute known function. Reminiscent of the diffusion solution, it can be approximated as a combination of region-wise exponential function part that attenuates spatially and the asymptotic part that varies proportionally to the fast flux.

$$f_{2i}(x) = a_i e^{-k_i\left(x - x_i + \frac{\Delta_i}{2}\right)} + b_i e^{k_i\left(x - x_i + \frac{\Delta_i}{2}\right)} + \frac{s_{m21i}}{s_{2i}} f_{1i}(x) \tag{5}$$

where

$$\Delta_i = x_i - x_{i-1} \tag{6}$$

$$k_i = \sqrt{\frac{s_{2i} - s_{p22i}}{D_{2i}}} \tag{7}$$

$$s_{m1i} = \frac{s_{2i} s_{p21i}}{s_{2i} - s_{p22i}} \tag{8}$$

The smooth varying fast flux in this equation is approximated as a region-wise linear function whose coefficients are assumed known from the conventional reconstruction calculation.

$$f_{1i}(x) = a_i (x - x_i + \frac{\Delta_i}{2}) + b_i \tag{9}$$

The coefficients a_i and b_i in the thermal scalar flux of Eq. (5) that will be used in evaluation of the right-hand-side of Eq. (4) are expressed into the interface thermal scalar fluxes.

$$a_i = \frac{1}{e^{\frac{1}{2}k_i\Delta_i} + e^{-\frac{1}{2}k_i\Delta_i}} (\frac{f_{2i} + f_{2i-1}}{2} - \frac{s_{m1i}}{s_{2i}} b_i) - \frac{1}{e^{\frac{1}{2}k_i\Delta_i} - e^{-\frac{1}{2}k_i\Delta_i}} (\frac{f_{2i} - f_{2i-1}}{2} - \frac{\Delta_i}{2}\frac{s_{m1i}}{s_{2i}} a_i) \tag{10}$$

$$b_i = \frac{1}{e^{\frac{1}{2}k_i\Delta_i} + e^{-\frac{1}{2}k_i\Delta_i}} (\frac{f_{2i} + f_{2i-1}}{2} - \frac{s_{m1i}}{s_{2i}} b_i) + \frac{1}{e^{\frac{1}{2}k_i\Delta_i} - e^{-\frac{1}{2}k_i\Delta_i}} (\frac{f_{2i} - f_{2i-1}}{2} - \frac{\Delta_i}{2}\frac{s_{m1i}}{s_{2i}} a_i) \tag{11}$$

where

$$f_{2i} = f_{2i}(x_i) \tag{12}$$

Analytical integration of Eq. (4) with substituting Eq. (5) and Eq. (9) into the right-hand-side results in

$$\begin{aligned} f_{2i}(x) = \frac{1}{2} \sum_{j=\min}^{i-1} {}_{+1} \Bigg(& \frac{1}{2} (W[t_{j,i-1} + c_i(x)] - W[t_{j+1,i-1} + c_i(x)]) \frac{s_{m2j}}{s_{2j}} \frac{a_j}{s_{2j}} \\ & - (F[0, t_{j,i-1} + c_i(x)] - F[0, t_{j+1,i-1} + c_i(x)]) \frac{s_{m2j}}{s_{2j}} b_j \\ & + (F[0, t_{j,i-1} + c_i(x)] + F[0, t_{j+1,i-1} + c_i(x)]) \frac{\Delta_j}{2} \frac{s_{m2j}}{s_{2j}} a_j \\ & - (e^{\frac{1}{2}k_j\Delta_j} F[-\frac{k_j}{s_{2j}}, t_{j,i-1} + c_i(x)] - e^{-\frac{1}{2}k_j\Delta_j} F[-\frac{k_j}{s_{2j}}, t_{j+1,i-1} + c_i(x)]) \frac{s_{p2j}}{s_{2j}} a_j \\ & + (-e^{-\frac{1}{2}k_j\Delta_j} F[\frac{k_j}{s_{2j}}, t_{j,i-1} + c_i(x)] + e^{\frac{1}{2}k_j\Delta_j} F[\frac{k_j}{s_{2j}}, t_{j+1,i-1} + c_i(x)]) \frac{s_{p2j}}{s_{2j}} b_j \Bigg) \end{aligned}$$

$$
\begin{aligned}
&+\frac{1}{2}\sum_{j=i+1}^{\max}\Bigg(\frac{1}{2}(-W[t_{i+1,j}+m_i(x)]+W[t_{i+1,j-1}+m_i(x)])\,\frac{s_{m2j}}{s_{2j}}\frac{a_j}{s_{2j}}\\
&-(F[0,t_{i+1,j}+m_i(x)]-F[0,t_{i+1,j-1}+m_i(x)])\,\frac{s_{m2j}}{s_{2j}}b_j\\
&-(F[0,t_{i+1,j}+m_i(x)]+F[0,t_{i+1,j-1}+m_i(x)])\,\frac{\Delta_j}{2}\frac{s_{m2j}}{s_{2j}}a_j\\
&-(e^{\frac{1}{2}k_j\Delta_j}F[-\frac{k_j}{s_{2j}},t_{i+1,j}+m_i(x)]-e^{-\frac{1}{2}k_j\Delta_j}F[-\frac{k_j}{s_{2j}},t_{i+1,j-1}+m_i(x)])\,\frac{s_{p2j}}{s_{2j}}a_j\\
&+(-e^{-\frac{1}{2}k_j\Delta_j}F[\frac{k_j}{s_{2j}},t_{i+1,j}+m_i(x)]+e^{\frac{1}{2}k_j\Delta_j}F[\frac{k_j}{s_{2j}},t_{i+1,j-1}+m_i(x)])\,\frac{s_{p2j}}{s_{2j}}b_j\Bigg)
\end{aligned}
\qquad (13)
$$

$$
\begin{aligned}
&+\frac{1}{2}\Bigg((W[c_i(x)]-W[m_i(x)])\,\frac{s_{m2i}}{s_{2i}}\frac{a_i}{s_{2i}}-(F[0,c_i(x)]+F[0,m_i(x)]-2)\,\frac{s_{m2i}}{s_{2i}}b_i\\
&+\frac{1}{2}\big[(F[0,c_i(x)]-F[0,m_i(x)])\Delta_i s_{2i}+2(c_i(x)-m_i(x))\big]\frac{s_{m2i}}{s_{2i}}a_i\\
&-(e^{-\frac{1}{2}\frac{k_i}{s_{2i}}(c_i(x)-m_i(x))}a_i+e^{\frac{1}{2}\frac{k_i}{s_{2i}}(c_i(x)-m_i(x))}b_i)\,\frac{s_{p2i}}{s_{2i}}F[-\frac{k_i}{s_{2i}},0]\\
&+e^{\frac{1}{2}k_i\Delta_i}(F[-\frac{k_i}{s_{2i}},c_i(x)]a_i+F[-\frac{k_i}{s_{2i}},m_i(x)]b_i)\,\frac{s_{p2i}}{s_{2i}}\\
&+(e^{-\frac{1}{2}\frac{k_i}{s_{2i}}(c_i(x)-m_i(x))}a_i+e^{\frac{1}{2}\frac{k_i}{s_{2i}}(c_i(x)-m_i(x))}b_i)\,\frac{s_{p2i}}{s_{2i}}F[\frac{k_i}{s_{2i}},0]\\
&-e^{-\frac{1}{2}k_i\Delta_i}(F[\frac{k_i}{s_{2i}},c_i(x)]b_i+F[\frac{k_i}{s_{2i}},m_i(x)]a_i)\,\frac{s_{p2i}}{s_{2i}}
\end{aligned}
$$

where

$$c_i(x)=(x-x_{i-1})s_{2i} \qquad (14)$$

$$m_i(x)=(x_i-x)s_{2i} \qquad (15)$$

$$t_{i,j}=\sum_{k=i}^{J}\Delta_k s_{2k} \qquad (16)$$

$$F[a,t]=\int_1^{\infty}\frac{e^{-lt}}{l(l+a)}dl \qquad (17)$$

$$W[t]=2\int_1^{\infty}\frac{e^{-lt}}{l^3}dl \qquad (18)$$

Functions $F[a,t]$ and $W[t]$ here can be explicitly expressed into gamma and logarithmic functions.

The interface fluxes contained in a_i and b_i in this equation will be determined by forcing them to be equal to their left-hand-side partners at interfaces. Assuming that the thermal flux

reaches to its asymptotic value at one end of the one-dimensional model, this requires the direct inversion of a full square matrix with the rank of the number of interfaces. The accuracy of the resulting thermal flux depends on the number of regions.

The region average flux can be obtained by integrating Eq. (13) analytically after defining the following integrals for convenience:

$$G[a,t,h] = \frac{1}{h}\int_0^h F[a, x+t]dx \tag{19}$$

$$U[t,h] = \frac{1}{h}\int_0^h W[x+t]dx \tag{20}$$

Assuming the uniform fast flux, the thermal flux solved by a one-dimensional model is compared with the reference flux in Figure 3. This model represents the MOX/UO_2 fuel assembly interface and consists of three material regions for each fuel assembly. The reference flux is obtained by the S_N transport calculation with the mesh interval of 0.063cm and the angular quadrature set of S_{16}. Even the flux of the model treating only three calculational regions for each assembly shows a pretty good agreement with the reference flux.

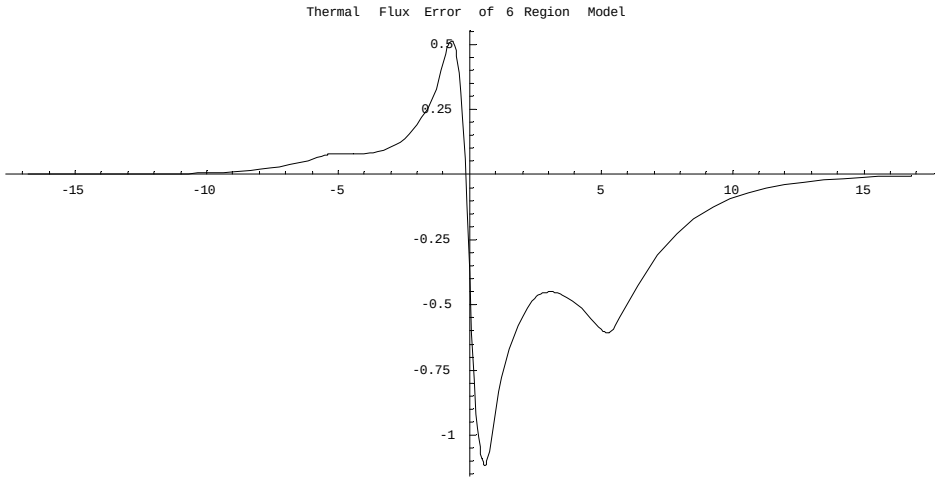

Figure 3. Thermal Flux Error (%) of One-Dimensional Interface Model

In solving the integral transport equation (4), matching the right-hand-side thermal currents to the left-hand-side ones at interfaces may give better results than matching fluxes. This expectation comes from the equivalence theory observation that the region-wise neutron balance using the assumed flux (5) becomes equivalent to that of the solved flux (13) when their interface currents match. The study to solve Eq. (4) by the interface current matching is in progress. The assumed flux (5) may be discontinuous across interfaces in this study.

III. Discontinuity Factor and Form Factor Update

The results of the one-dimensional model may be used either to update the thermal group discontinuity factor at the interface during the nodal calculation or to update the form factors of edge-pins during the flux reconstruction calculation. A similar procedure to that of the multi-assembly homogenization is followed to update the discontinuity factor. It starts from solving the homogeneous single assembly model that is modeled one-dimensionally with cross-sections weighted-averaged by the thermal flux (13). Imposing the current boundary condition on the interface-side of the assembly, this model is solved by the nodal method that will use the resultant discontinuity factor. The discontinuity factor defined as the ratio of the interface heterogeneous thermal flux calculated by Eq. (13) to the homogeneous flux solved here can replace the thermal group discontinuity factor obtained from the single assembly homogenization.

The thermal group form factors of edge pins are updated so that the flux reconstruction for the edge fuel pins reproduces the average of the thermal flux (13) over a region in the one-dimensional model representing a row of edge pins. For this purpose, the conventional flux reconstruction using the form factors of single assembly homogenization is simulated one-dimensionally. The diffusion equation to solve for the homogeneous flux used in this flux reconstruction is given by

$$-D\frac{d^2}{dx^2}\hat{f}_2(x)+s_{2}\hat{f}_2(x)=s_{p21}\hat{f}_1(x)+s_{p22}\hat{f}_2(x) \tag{21}$$

The cross-sections in this equation come from the single assembly homogenization. The fast group flux is again approximated as a known linear function. Solving this equation for the homogeneous thermal flux $f_2(x)$ with the flux boundary condition at the interface to be concerned, the homogeneous flux averaged over the outmost edge pins is expressed in the following form:

$$\hat{f}_{p2}=\frac{(e^{-kh}-1)(e^{kh}-e^{kH})}{(e^{kH}-1)kh}(\hat{f}_{20}-\frac{s_{m21}}{s_{2}}\hat{f}_{10})+\frac{s_{m21}}{s_{2}}\hat{f}_{p1} \tag{22}$$

where ^ on the flux means the homogeneous flux. f_{10} and f_{20} are the interface fast and thermal fluxes from the nodal calculation and f_{p1} is the pin average fast flux. Note that the boundary condition used in solving the homogeneous flux depends on the reconstruction method being used. Some methods may use the interface current as the boundary condition instead of the interface flux.

The reconstructed flux simulated one-dimensionally with the form factors of the single assembly homogenization becomes

$$f_{p2} = f_p \hat{f}_{p2} \tag{23}$$

where f_p is the form factor averaged over edge fuel pins. Of course, this reconstruct flux does not sufficiently take into account the effect of the thermal flux gradient across the interface, because it is calculated by cross-sections and form factors from the single assembly homogenization. Therefore, the edge-pin form factor correction factor is defined as the ratio of this reconstructed flux to the edge-pin average flux calculated from the heterogeneous one-dimensional flux of Eq. (13), so that the reconstructed flux with the corrected form factor can reproduce at least the heterogeneous one-dimensional flux. The form factors for all the pins in the edge row are multiplied by this correction factor and renormalized with their remainders. This correction may also be done analogously for the second outmost fuel pins although it is not necessary for most cases.

IV. Numerical Test Results and Discussion

To test the accuracy and the applicability of the presented model to overcome the limitations of the single assembly homogenization, a benchmark problem designated as “the Benchmark Calculations of Power Distribution within Fuel Assemblies (PDWA)”(Ref. 2) is explored. In order to compare different techniques for pin flux prediction in systems partially loaded with MOX fuel assemblies, this benchmark problem was launched in 1996 by the Nuclear Energy Agency (NEA) Nuclear Science Committee (NSC) of the Organization for Economic Cooperation and Development (OECD). The core configuration shown in Figure 4 was constructed based on the VENUS-2 MOX core measurement data. This core consists of a central MOX assembly, eight surrounding UO_2 fuel assemblies, and peripheral water reflector regions. The steel shroud baffle is not modeled explicitly in the outer region of the core. Therefore, there occurs a strong thermal flux gradient especially near the fuel/reflector interface, which defies an easy analysis based on the conventional single assembly homogenization.

The pin-wise flux analysis based on the two-level calculations of the lattice physics transport calculation and the nodal diffusion calculation was carried out. Two-group cross-sections, discontinuity factors, and heterogeneous flux form factors were generated from HELLIOS(Ref.3) single assembly calculations. A few sets of cross-sections for edge pin rows required to build the one-dimensional model proposed in this study were obtained from these

homogenization calculations. The refined Analytic Function Expansion Nodal (AFEN) method(Ref.4) was applied for the homogeneous core flux distribution with one-node-per-assembly mesh grid. The intranodal homogeneous flux from the refined AFEN nodal calculation and the heterogeneous flux form factors from the HELLIOS homogenization calculations were modulated to estimate the pin-wise flux reconstruction. In the nodal calculation stage, any corrections of the thermal flux gradient effect on discontinuity factors were not applied. Then, only the outmost pin flux form factors of a fuel assembly were updated in the flux reconstruction stage according to the proposed procedure solving the one-dimensional material interface model. The one-dimensional model consists of only three regions per assembly, two of which represent explicitly the outmost and the second outmost pin rows of the assembly.

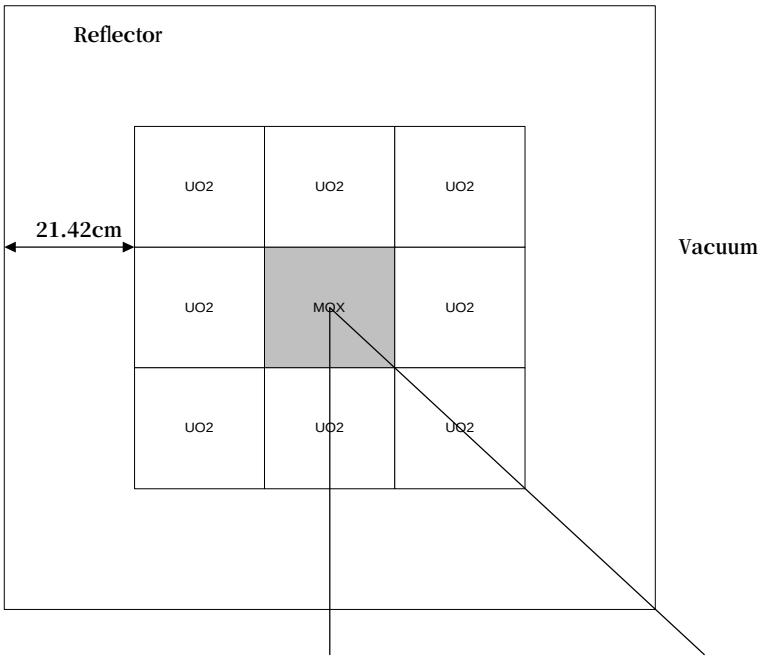

Figure 4. Core Configuration of OECD-NEA PDWA Benchmark Problem

Two pin power distributions reconstructed by the conventional procedure and by the new procedure were compared with the reference HELLIOS pin powers in Figure 5. This figure shows a distinct error pattern of the conventional method that underestimates systematically the powers in the edge pins facing the MOX/UO_2 interface and the fuel/reflect interface. This pattern owes to the fact that the form factors from the single assembly homogenization with zero current boundary condition cannot take into account the effect of the actual thermal flux gradient near the interfaces. The refined AFEN method that can calculate the homogeneous flux distribution accurately across

the interfaces also contributed to bringing the deficiency in form factors of single assembly homogenization into prominence. This figure also shows that the new method using form factors corrected by the thermal flux gradients across material interfaces can reduce significantly the errors in reconstructed pin powers near the interfaces. From these results, it is ascertained that the thermal flux gradient occurring in a very narrow range near a material interface can be accurately simulated by the one-dimensional model. This success of the simple one-dimensional model owes much to the short mean free path of thermal neutrons compared to assembly size. Note that the additional time needed in solving the one-dimensional models at interfaces is negligible compared to the total time needed in analyzing the detailed pin-wise powers in a reactor. Thus, the new model is practical to overcome the deficiency of single assembly homogenization.

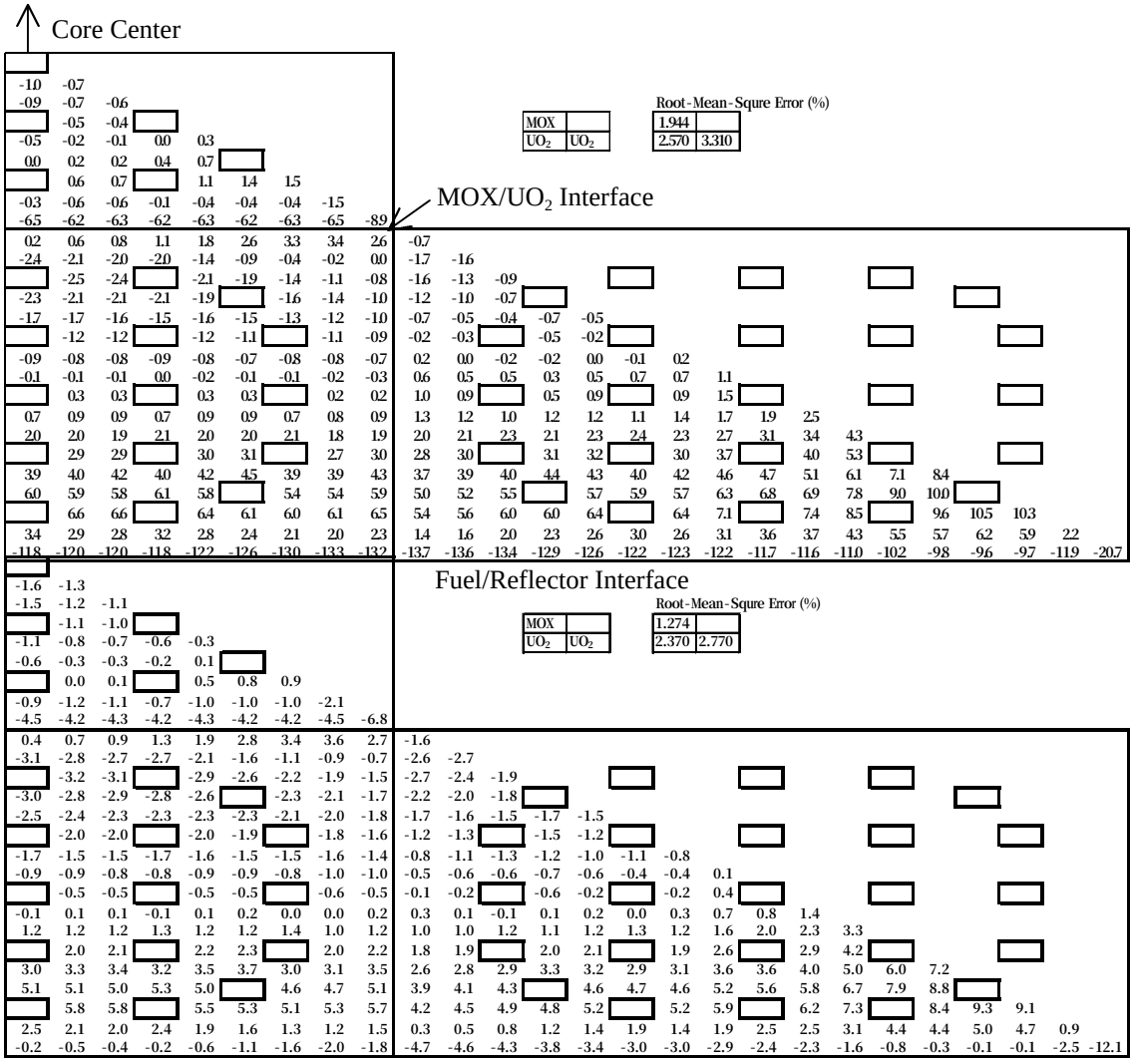

Figure 5. **Pin Power Errors (%) Calculated by Conventional Procedure (Upper) and New Procedure (Lower)**

V. Conclusions

The two-level reactor core analysis system consisting of the lattice physics homogenization calculation and the nodal diffusion calculation is usually based on single assembly homogenization calculations that impose zero-current boundary conditions. The system works relatively well in predicting the detailed pin-wise powers in the region where no significant material discontinuities are involved. However, it shows poor performance near material interfaces where the steep flux gradient occurs. It is commonly understood that large pin power errors concentrated in such a region are caused by the fact that the single assembly homogenization with zero neutron current boundary condition cannot handle the steep thermal flux change near the region having strong material discontinuity.

The multi-assembly homogenization or an approach using the boundary conditions updated from the nodal calculation may be utilized to remedy the limitations of the single assembly homogenization. Instead of such approaches requiring significant additional calculational efforts, a new approach solving a few-region one-dimensional one-group model consisting of some pin columns of two adjacent assemblies is proposed. This one-dimensional model owes to the short mean free path of thermal neutrons compared to the assembly size and relies still basically on the single assembly homogenization. The only additional effort required during the single assembly homogenization stage is to edit a few sets of the cross-sections for edge pin rows. This model for each interface of materials is solved analytically by the integral transport method to take into account the effect of the thermal flux gradient on equivalence theory parameters and form factors during or after the nodal diffusion calculation.

The accuracy and the applicability of the presented model were tested against a small benchmark problem consisting of MOX fuel and bare water reflector without baffle. After solving the one-dimensional model consisting of only six regions per interface, the outmost flux form factors of each assembly were corrected so that the effect of the thermal flux gradient across the interface is taken into account. The result shows that the new method based on this simple model can reduce significantly the errors in reconstructed pin powers near strong material interfaces. Therefore, it can be concluded that the thermal flux gradient near a material discontinuity can accurately modeled by the one-dimensional model. Noting that the additional time needed in solving the one-dimensional models at interfaces is negligible compared to the total time needed in analyzing the detailed pin-wise powers in a reactor, the new model can be used as a practical tool to overcome the deficiency of single assembly homogenization.

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