Preliminary Results of Linear Source Approximation for Three-dimensional Neutron Transport Calculation in STREAM

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1. Introduction

This paper presents preliminary results of STREAM (Steady-state and Transient REactor Analysis code with Method of Characteristics) adopting linear source approximation in 3D/2D Method of Characteristics (MOC) / Diamond Differencing (DD). STREAM, a neutron transport analysis code, has developed to perform a whole LWR core simulation in UNIST CORE: group constants generation as a lattice code, and direct three-dimensional whole-core calculation. There have been suggested various methodologies regarding deterministic neutron transport analysis for three-dimensional core simulations.

A 2D/1D method solves 3D problems as a coupled system of radial transport and axial transport or diffusion. The 2D/1D methods are considered the best option in LWR 3D neutron transport analysis in accuracy and computation efficiency; thus, DeCART, nTRACER, and MPACT select this method [1-3]. However, the 2D/1D method has some weaknesses; unstable convergence behavior for a problem with high leakages, and integration over a square pin region for an axial neutron leakage. [4]

A direct 3D MOC approach has been presented to eliminate approximations in the 2D/1D method [5]. OpenMOC with 3D MOC, which is developed in MIT, successfully has resolved the memory burden issue in the direct 3D MOC transport calculation. However, the long run time remains an issue in the 3D MOC.

Recently, UNIST CORE proposed a new 3D neutron transport method to resolve the 2D/1D method's issues and the direct 3D MOC method. The proposed method, which is named the 3D method of characteristics/diamond-difference (MOC/DD), is implemented in the STREAM. This method constructs 3D flux and source as a combination of the 2D radial and the 1D axial components. It does not use the axial solver and not homogenizes the axial source into a pin-wise square cell. The 3D MOC/DD method is a 2D/3D method and a compromise between the 2D/1D and direct 3D methods [4].

In the 2D/3D MOC/DD method, the axial neutron source occupies a part of the source in the MOC solver. The axial source is a function of the source region and the neutron streaming angle, which depends on the flat source region in a radial direction. The STREAM3D shows good agreement for calculation results when using a flat source with source regions of properly small meshes. The memory usage and calculation time raise as increasing the number of source regions.

In order to reduce memory usage and calculation time, the linear source (LS) approximation applies to the 2D/3D MOC/DD method. R.M. Ferrer proposed the LS approximation to improve accuracy while reducing the number of source regions by applying a linear source approximation to the 2D MOC in the CASMO code [6]. A.P. Fitzgerald introduced the linear source approximation used in 2D CASMO to MPACT using the 2D/1D MOC method, resulting in the accuracy improvement [3]. In this study, the method is extended to be applicable to not only fission scattering sources but also surface sources.

The paper introduces the 2D/3D MOC/DD method with the LS approximation briefly and presents preliminary results in simple pin-cell models.

2. Methods

2.1 2D/3D MOC/DD Method with LS Approximation

The 2D/3D MOC/DD method with the flat source approximation is well presented in Choi's paper [4]. In the 2D/3D MOC/DD method, the 3D flux and source are constructed as a combination of the 2D radial and the 1D axial components using a union radial (or x-y) mesh for all axial planes. The 3D angular flux, scalar flux and source are expressed as follows:

$$\begin{cases} \psi^{g,\pm}_{i,j,k}(s) = \psi^{g}_{i,j,k}(s)b(z^{\pm}) \\ \bar{\phi}^{g,\pm}_{m} = \bar{\phi}^{g}_{m}b(z^{\pm}) \\ \bar{Q}^{g,\pm}_{i,j,m} = \bar{Q}^{g}_{i,j,m}b(z^{\pm}) \end{cases} ,\Delta z = z^{+} - z^{-}, (\bar{\theta}_j > 0) \quad (1)$$

where m is a source region, z is a coordinate in the axial direction, Δz is the axial mesh size, z^{-} and z^{+} are a lower and a upper limits of axial domain, respectively, k is a track in MOC ray segment belongs to the source region, m $(k \in m)$. i is an azimuthal direction, and j is a polar direction. $\psi^{g}_{i,j,k}$ is angular flux along the track distance, s, $\bar{\phi}^{g}_{m}$ is region averaged scalar flux, $\bar{Q}^{g}_{i,j,m}$ is track averaged fission and scattering source.

The MOC equation is derived on the x-y plane in the middle of the axial mesh in the source region, as depicted in Fig. 1. A track-based simplified transport equation integrated over an axial domain dividing it by the axial height is given by

$$\cos\theta_j \frac{\partial \psi^{g}_{i,j,k}(s)}{\partial s} + \frac{2\sin\theta_j}{\Delta z}\psi^{g,0}_{i,j,k}(s) + \Sigma^{g}_{tr,m}\psi^{g,0}_{i,j,k}(s) = \bar{Q}^{g,0}_{i,j,k}(s) + \frac{2\sin\theta_j}{\Delta z}\psi^{g,-}_{i,j,k}(s) \qquad (2)$$

The term of $\frac{2\sin\theta_j}{\Delta z}\psi^{g,-}_{i,j,k}(s)$ on the right-hand side of Eq.(2) plays role of a surface source from the bottom plane. The flat source approximation is used for this surface source to simplify the equation so that the surface source can be merged with the fission and scattering source [4].

$$\frac{2\sin\theta_j}{\Delta z}\psi^{g,-}_{i,j,k}(s) \approx \frac{2\sin\theta_j}{\Delta z}\bar{\bar{\psi}}^{g,-}_{i,j,m} \qquad (3)$$

where $\bar{\bar{\psi}}^{g,\mp}_{i,j,m}$ is the x-y plane region-averaged angular flux.

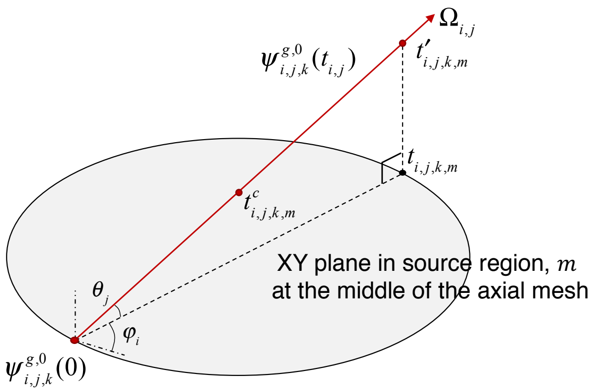

Fig. 1. Diagram of the track length, $t'_{i,j,k} = t_{i,j,k}/\cos\theta_j$, on x-y plane in source region, m, in the middle of the axial mesh.

The LS approximation considers both fission and scattering source and surface source to change as track position in x-y source region. The LS for fission and scattering, $\bar{Q}^{g,0}_{i,j,k}$, and the surface LS, $\bar{Z}^{g,0}_{i,j,k}$ ($= \frac{2sin\theta_j}{\Delta z}\bar{\bar{\psi}}^{g,\mp}_{i,j,m}$), along the track length, $t'_{i,j,k}$ are assumed to have the following forms:

$$\bar{Q}^{g,0}_{i,j,k}(s) = \bar{q}^{g,0}_{i,k,m} + \hat{q}^{g,0}_{i,j,m}\left(s - t^{c}_{i,j,k,m}\right) \qquad (4)$$

$$\bar{Z}^{g}_{i,j,k}(s) = \bar{\zeta}^{g}_{i,j,k} + \hat{\zeta}^{g}_{i,j,m}\left(s - t^{c}_{i,j,k,m}\right) \qquad (5)$$

where $0 \le s \le t_{i,j,k}$, $\bar{q}^{g,0}_{i,k,m}$ and $\hat{q}^{g,0}_{i,j,m}$ are expansion coefficients for the LS of fission and scattering, $\bar{\zeta}^{g}_{i,j,k}$ and $\hat{\zeta}^{g}_{i,j,m}$ are expansion coefficients for the surface LS.

Putting Eqs.(3)-(5) into Eq.(2), then the track based transport equation with the linear source is described as

$$\cos\theta_j \frac{d\psi^{g,0}_{i,j,k}(s)}{ds} + \tilde{\Sigma}^{g}_{tr,m}\psi^{g,0}_{i,j,k}(s) = \left(\bar{q}^{g,0}_{i,k,m} + \bar{\zeta}^{g}_{i,j,k}\right) + \left(\hat{q}^{g,0}_{i,j,m} + \hat{\zeta}^{g}_{i,j,m}\right)\left(s - t^{c}_{i,j,k,m}\right) \qquad (6)$$

Integrating of Eq.(6) along the projected track length in the source region, m yields the characteristics equation, then outgoing angular flux is derived as

$$\psi^{g,0}_{out,i,j,k} = \psi^{g,0}_{in,i,j,k} + \left(\frac{\bar{q}^{g,0}_{i,k,m} + \bar{\zeta}^{g}_{i,j,k}}{\tilde{\Sigma}^{g}_{tr,m}} - \psi^{g,0}_{in,i,j,k}\right)F_3(\tilde{\tau}'^{g}_{i,j,k}) + \frac{\hat{q}^{g,0}_{i,j,m} + \hat{\zeta}^{g}_{i,j,m}}{2\left(\tilde{\Sigma}^{g}_{tr,m}\right)^2}F_4(\tilde{\tau}'^{g}_{i,j,k}) \qquad (7)$$

where

$$\tilde{\tau}'^{g}_{i,j} = \tilde{\Sigma}^{g}_{tr,m}t'_{i,j,k}\,, \qquad (8)$$

$$F_3(\tilde{\tau}'^{g}_{i,j,k}) = 1 - \exp(-\tilde{\tau}'^{g}_{i,j,k})\,, \qquad (9)$$

$$F_4(\tilde{\tau}'^{g}_{i,j,k}) = 2(\tilde{\tau}'^{g}_{i,j,k} - F_3(\tilde{\tau}'^{g}_{i,j,k})) - \tilde{\tau}'^{g}_{i,j,k}F_3(\tilde{\tau}'^{g}_{i,j,k})\,, \qquad (10)$$

$\psi^{g,0}_{out,i,j,k}$ and $\psi^{g,0}_{in,i,j,k}$ are outgoing and incoming angular fluxes to the ray segment, $\Delta'^{g}_{i,j,k}\left(= \psi^{g,0}_{out,i,j,k} - \psi^{g,0}_{in,i,j,k}\right)$ is the change in angular flux. The coefficients, F_3 and F_4 are pre-computed and saved as hash-table.

2.2 Linear Source in Local Coordinate Systems

The source is given differently depending on track locations in the source region; thus, it is necessary to define a local coordinate system in each source region. Before defining track location in the local coordinate, the centroid in the global coordinate is pre-calculated with the numerical method. The centroids (X^c_m, Y^c_m) are defined as follows [6]:

$$\left(X^c_m, Y^c_m\right) = \left(\left\langle 1, \frac{1}{4\pi}X\right\rangle_m, \left\langle 1, \frac{1}{4\pi}Y\right\rangle_m\right) \qquad (11)$$

where d_i is an azimuthal angle dependent ray spacing, ω_i and ω_j are weights for the azimuthal and polar angles, respectively.

The spatial coordinates (X, Y) in the global system are related to track length as follows:

$$X(t_{i,j}) = \cos\theta_j\cos\varphi_i t_{i,j}/\xi_{i,m} + X^{in}_{i,k,m}\,, \qquad (12)$$

$$Y(t_{i,j}) = \cos\theta_j\sin\varphi_i t_{i,j}/\xi_{i,m} + Y^{in}_{i,k,m}\,, \qquad (13)$$

where $\xi_{i,m}$ is an angle dependent adjusting factor to conserve volume. The local coordinate (x, y) is defined as $(X - X^c_m, Y - Y^c_m)$, and $\left(x^c_{i,k,m},\ y^c_{i,k,m}\right)$ is the track midpoint coordinates in the local system.

2.3 Region-averaged Angular Flux Moments

The isotropic fission and scattering LS on x-y plane is considered as:

$$q^g_m(x, y) = \frac{1}{4\pi}\left(\bar{q}^g_m + q^g_{m,x}x + q^g_{m,y}y\right) \qquad (14)$$

The coefficients for the source along a track in Eq.(4) are determined by

$$\bar{q}^{g,0}_{i,k,m} = \left(\bar{q}^{g,0}_m + q^g_{m,x}x^c_{i,k,m} + q^g_{m,y}y^c_{i,k,m}\right)/4\pi\,, \qquad (15)$$

$$\hat{q}^{g,0}_{i,j,m} = \cos\theta_j\left(\cos\varphi_i q^g_{m,x} + \sin\varphi_i q^g_{m,y}\right)/4\pi\xi_{i,m}\,. \qquad (16)$$

In the same way of the fission and scattering source, the surface LS on x-y plane is considered as:

$$\bar{\zeta}^{g}_{i,j,m}(x, y) = \left(\bar{\zeta}^{g}_{i,j,m} + \zeta^{g,x}_{i,j,m}x + \zeta^{g,y}_{i,j,m}y\right) \qquad (17)$$

The coefficients for the source along a track in Eq.(5) are determined by

$$\bar{\zeta}^g_{i,j,k} = \left(\zeta^g_{i,j,m} + \zeta^{g,x}_{i,j,m} x^c_{i,k,m} + \zeta^{g,y}_{i,j,m} y^c_{i,k,m}\right), \quad (18)$$

$$\hat{\zeta}^g_{i,j,m} = \cos\theta_j \left(\cos\varphi_i \zeta^{g,x}_{i,j,m} + \sin\varphi_i \zeta^{g,y}_{i,j,m}\right) / \xi_m . \quad (19)$$

The track-averaged angular flux and the first-order spatial moment of the angular flux along each track are defined as:

$$\bar{\psi}^{g,0}_{i,j,k} = \frac{\int_0^{t'_{i,j,k}} \psi^{g,0}_{i,j,k,m}(s)\,ds}{\int_0^{t'_{i,j,k}} ds} = \frac{\bar{q}^{g,0}_{i,k,m} + \bar{\zeta}^g_{i,j,k}}{\tilde{\Sigma}^g_{tr,m}} - \frac{\Delta'^g_{i,j,k}}{\tilde{\Sigma}^g_{tr,m} t'_{i,j,k}} \quad (20)$$

$$\begin{aligned}\hat{\psi}^g_{i,j,k,m} &= \frac{\int_0^{t'_{i,j,k}} s\psi^{g,0}_{i,j,k,m}(s)\,ds}{\int_0^{t'_{i,j,k}} ds} = \frac{\left(\bar{\psi}^{g,0}_{i,j,k} - \psi^g_{out,i,j,k}\right)}{\tilde{\Sigma}^g_{tr,m}} \\ &+ \frac{t'_{i,j,k}}{2}\left(\frac{\left(\bar{q}^{g,0}_{i,k,m} + \bar{\zeta}^g_{i,j,k}\right)}{\tilde{\Sigma}^g_{tr,m}} + \frac{\left(\hat{q}^{g,0}_{i,j,m} + \hat{\zeta}^g_{i,j,m}\right)}{\tilde{\Sigma}^g_{tr,m}} \frac{t'_{i,j,k}}{6}\right)\end{aligned} \quad (21)$$

The region-averaged angular flux is defined as:

$$\begin{aligned}\bar{\bar{\psi}}^{g,0}_{i,j,k} &= \frac{\sum_{k\in m} \bar{\psi}^{g,0}_{i,j,k} t'_{i,j,k} d_i}{\sum_{k\in m} t'_{i,j,k} d_i} \\ &= \frac{1}{\tilde{\Sigma}^g_{tr,m}}\left(\frac{\bar{q}^{g,0}_m}{4\pi} + \bar{\zeta}^g_{i,j,m}\right) + \frac{d_i \cos\theta_j}{A_m \tilde{\Sigma}^g_{tr,m}} \bar{\Delta}'^g_{i,j,m} \\ &+ \frac{d_i}{4\pi A_m \tilde{\Sigma}^g_{tr,m}}\left(q^g_{m,x} \sum_{k\in m} x^c_{i,k,m} t_{i,j,k} + q^g_{m,y} \sum_{k\in m} y^c_{i,k,m} t_{i,j,k}\right) \\ &+ \frac{d_i}{A_m \tilde{\Sigma}^g_{tr,m}}\left(\zeta^{g,x}_{i,j,m} \sum_{k\in m} x^c_{i,k,m} t_{i,j,k} + \zeta^{g,y}_{i,j,m} \sum_{k\in m} y^c_{i,k,m} t_{i,j,k}\right)\end{aligned} \quad (22)$$

where $\bar{\Delta}'^g_{i,j,m} = -\sum_{k\in m} \Delta'^g_{i,j,k}$.

The region-wise angular flux moments are obtained by the discrete-to-moments operators,

$$\left\langle \bar{\bar{\psi}}^{g,0}_{i,j,m} \right\rangle_x = \frac{\sum_{k\in m} \left(a^x_{i,j} \hat{\psi}^{g,0}_{i,j,k,m} / \xi_m + x^{in}_{i,k,m} \bar{\psi}^{g,0}_{i,j,k}\right) t'_{i,j,k} d_i}{\sum_{k\in m} t'_{i,j,k} d_i} \quad (23)$$

$$\left\langle \bar{\bar{\psi}}^{g,0}_{i,j,m} \right\rangle_y = \frac{\sum_{k\in m} \left(a^y_{i,j} \hat{\psi}^{g,0}_{i,j,k,m} / \xi_m + y^{in}_{i,k,m} \bar{\psi}^{g,0}_{i,j,k}\right) t'_{i,j,k} d_i}{\sum_{k\in m} t'_{i,j,k} d_i} \quad (24)$$

2.4 Cell-averaged Scalar Flux and Source

The scalar flux moments, $\vec{\phi}^g_m = \left[\phi^{g,0}_m, \Phi^g_{m,x}, \Phi^g_{m,y}\right]^T$ are calculated as,

$$\phi^{g,0}_m = 4\pi \sum_j \sum_i \bar{\bar{\psi}}^{g,0}_{i,j,m} \omega_i \omega_j \quad (25)$$

$$\begin{aligned}\Phi^g_{m,x} &= 4\pi \sum_j \sum_i \frac{d_i \left(a^x_{i,j} \hat{\Psi}^{g,0}_{i,j,k,m} / \xi_m + \bar{\Psi}^{g,0,x}_{i,j,k}\right)}{\sum_{k\in m} t'_{i,j,k} d_i} \omega_i \omega_j \\ &= 4\pi \sum_j \sum_i \left\langle \bar{\bar{\psi}}^{g,0}_{i,j,m} \right\rangle_x \omega_i \omega_j\end{aligned} \quad (26)$$

$$\begin{aligned}\Phi^g_{m,y} &= 4\pi \sum_j \sum_i \frac{d_i \left(a^y_{i,j} \hat{\Psi}^{g,0}_{i,j,k,m} / \xi_m + \bar{\Psi}^{g,0,y}_{i,j,k}\right)}{\sum_{k\in m} t'_{i,j,k} d_i} \omega_i \omega_j \\ &= 4\pi \sum_j \sum_i \left\langle \bar{\bar{\psi}}^{g,0}_{i,j,m} \right\rangle_y \omega_i \omega_j\end{aligned} \quad (27)$$

The source moments, $\vec{Q}^g_m = \left[\bar{q}^{g,0}_m, Q^g_{m,x}, Q^g_{m,y}\right]^T$ are obtained by applying

$$\vec{Q}^g_m = \frac{1}{4\pi}\left(\frac{\chi^g_m}{k_{eff}} \sum_{g'} \nu\Sigma^{g'}_{f,m} \vec{\phi}^{g'}_m + \sum_{g'} \Sigma^{g'\to g}_{s,m} \vec{\phi}^{g'}_m\right) \quad (28)$$

where $\Sigma^{g'\to g}_{s,m}$ is scattering cross section matrix, $\upsilon\Sigma^g_{f,m}$ is nu-fission cross section matrix, χ^g_m is fission spectrum, k_{eff} is eigenvalue. According to numerical integration of Eq.(14) over a source region [6], the correlation between source coefficients and source moments is

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & M_{m,xx} & M_{m,xy} \\ 0 & M_{m,xy} & M_{m,yy} \end{bmatrix} \begin{bmatrix} \bar{q}^{g,0}_m \\ q^g_{m,x} \\ q^g_{m,y} \end{bmatrix} = \begin{bmatrix} \bar{q}^{g,0}_m \\ Q^g_{m,x} \\ Q^g_{m,x} \end{bmatrix} \quad (29)$$

where $M_{m,xx} = \langle x, x\rangle / 4\pi$, $M_{m,yy} = \langle y, y\rangle / 4\pi$, $M_{m,xy} = \langle x, y\rangle / 4\pi$.

2.5 Region-averaged Surface Source Moments

The region-wise angular flux plane interface at z+ is defined as below, and it is used as the surface source at the bottom position of the upper plane.

$$\bar{\bar{\psi}}^{g,+}_{i,j,m} = 2\bar{\bar{\psi}}^{g,0}_{i,j,m} - \bar{\bar{\psi}}^{g,-}_{i,j,m} = 2\bar{\bar{\psi}}^{g,0}_{i,j,m} - \frac{\Delta z}{2\sin\bar{\theta}_j}\left(\bar{S}^g_{i,j,m} - \bar{Q}^{g,0}_{i,j,m}\right) \quad (30)$$

where $\bar{S}^{g,0}_{i,j,m} = \bar{q}^{g,0}_m + \bar{Z}_{i,j,m} = \bar{Q}^{g,0}_{i,j,m} + \left(2\sin\bar{\theta}_j / \Delta z\right) \bar{\bar{\psi}}^{g,-}_{i,j,m}$.

According to numerical integration of Eq.(17) over a plane, surface source moments can be updated in the same way as Eq.(30). Then, surface source coefficients can be updated from the bottom plane as below:

$$\begin{bmatrix} 1 & 0 & 0 \\ \bar{T}^{xc}_{i,m} & \bar{T}^{xx}_{i,m} & \bar{T}^{xy}_{i,m} \\ \bar{T}^{yc}_{i,m} & \bar{T}^{xy}_{i,m} & \bar{T}^{yy}_{i,m} \end{bmatrix} \begin{bmatrix} \bar{\zeta}^g_{i,j,m} \\ \zeta^{g,x}_{i,j,m} \\ \zeta^{g,y}_{i,j,m} \end{bmatrix} = \frac{2\sin\theta_j}{\Delta z} \begin{bmatrix} \bar{\bar{\psi}}^{g,-}_{i,j,m} \\ \left\langle \bar{\bar{\psi}}^{g,-}_{i,j,m} \right\rangle_x \\ \left\langle \bar{\bar{\psi}}^{g,-}_{i,j,m} \right\rangle_y \end{bmatrix} \quad (31)$$

where

$$\bar{T}^{xc}_{i,m} = \tfrac{d_i}{A_m} \sum_{k\in m} x^c_{i,k,m} t_{i,j,k} \quad (32)$$

$$\bar{T}^{yc}_{i,m} = \tfrac{d_i}{A_m} \sum_{k\in m} y^c_{i,k,m} t_{i,j,k} \quad (33)$$

$$\bar{T}^{xx}_{i,m} = \tfrac{d_i}{A_m}\left(\sum_{k\in m} (x^c_{i,k,m})^2 t_{i,j,k} + \cos^2\varphi_i \sum_{k\in m} t_{i,j,k} s^2_{i,j,k} / 12\right) \quad (34)$$

$$\bar{T}^{yy}_{i,m} = \tfrac{d_i}{A_m}\left(\sum_{k\in m} (y^c_{i,k,m})^2 t_{i,j,k} + \sin^2\varphi_i \sum_{k\in m} t_{i,j,k} s^2_{i,j,k} / 12\right) \quad (35)$$

$$\bar{T}^{xy}_{i,m} = \tfrac{d_i}{A_m}\left(\sum_{k\in m} x^c_{i,k,m} y^c_{i,k,m} t_{i,j,k} + \cos\varphi_i \sin\varphi_i \sum_{k\in m} t_{i,j,k} s^2_{i,j,k} / 12\right) \quad (36)$$

An assembly shares the same source region radially even in a different axial configuration since the characteristics of MOD/DD methods; therefore, Eqs.(32) -(36) are pre-computed during centroids calculation and stored as coefficients.

The computation algorithm of 2D/3D MOC/DD with LS approximation is summarized in Fig. 1.

```
                 do Outer iterations
                  CMFD acceleration
                  Update fission source
                  do Inner iterations
                   Collect Boundary Angular Flux
MPI               do Assemblies
                    Update scattering source moments
                    do Azimuthal angles
                     do Upward & downward
OPENMP                do Planes
                       Get axial source &
                       surface source coefficients
                       do Parallel rays (Forward & Backward)
                        do Segments(Tracks)
                         Get source expansion coefficient
                         do Energy groups
                          do Polar angles
                           Compute and collect angular flux change
                           Update segment outgoing flux
                          end do
                         end do
                        end do
                       end do
                       Update region avg angular flux &
                       axial surface source
                      end do
                     end do
                    end do
                    Calculate scalar flux moments
                   end do
                  end do
                  Check convergence
                  Feedback calculation
                 end do
```

Fig. 1. Algorithm of 3D neutron transport calculation with LS approximation in STREAM.

3. Preliminary Results

This paper shows results of a simple model as a starting step. The benchmark (Fig. 2) consists of two assemblies of 4 cells with one group UO_2 cross-section to demonstrate the impact of the LS approximation clearly. The right side is given as void boundary condition only, the boundary condition for the remaining five sides is reflective. The pin pitch is 1.26 cm, and it is divided into a square mesh. The total axial height is 20 cm, and the mesh size is 1 cm.

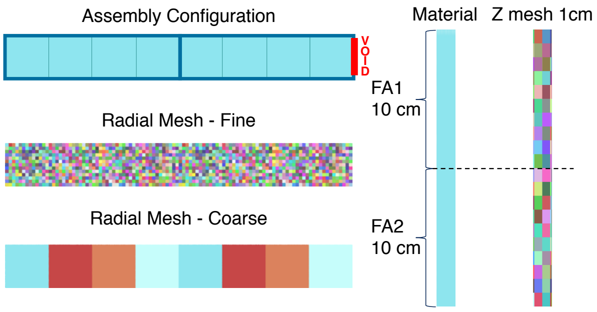

Fig. 2. Simple model of UO_2 square cells.

The calculation results are summarized in Table I and Figs. 3-6. The reference solution is STREAM result with fine-mesh with denser ray-spacing condition. Figs. 3-4 shows source distributions, which, consists of fission and scattering source and surface source, along the tracks. Figs. 5-6 show the scalar flux distribution along the track. LS approximation well estimates real solution in this extremely coarse mesh problem.

Table I: k_{eff} results

Source	Radial Mesh	MOC ray Δcm/#azi/#pol	k_{eff}	Δk_{eff} [pcm]	Time [sec]
Flat	126x126	0.005/128/6	1.32151	-	41.0
Flat	1x1	0.01 / 48 / 6	1.29883	-2268	5.49
Linear			1.32157	6	11.4

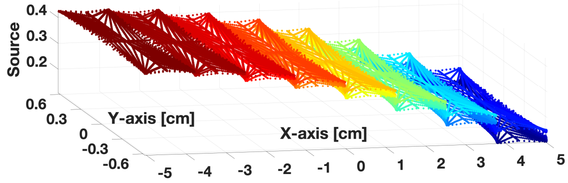

Fig. 3. Angle dependent flat source distribution.

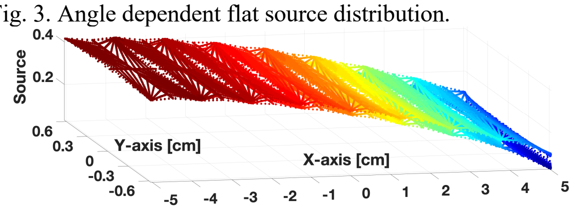

Fig. 4. Angle dependent linear source distribution.

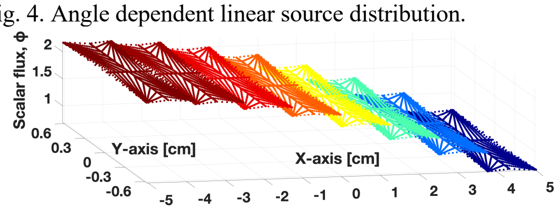

Fig. 5. Scalar flux distribution by flat source approximation.

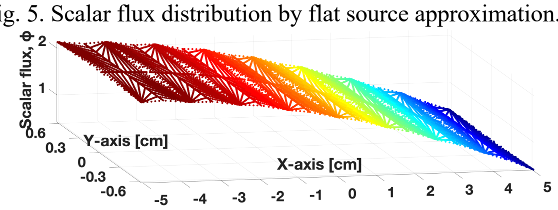

Fig. 6. Scalar flux distribution by linear source approximation.

4. Conclusions

This paper presents LS approximation in 2D/3D MOC/DD methods and shows the impact in the simple problem. When the angle-dependent axial source adopts LS approximation, the solution is well estimated. In future work, the optimization of LS approximation for reducing calculation time and detailed performance will be analyzed in large-scale problems.

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REFERENCES

[1] Joo, H. G., et al. (2004). Methods and Performance of a Three-Dimensional Whole-Core Transport Code DeCART. In PHYSOR 2004. La Grange Park, IL: ANS.

[2] Jung, Y. S., et al. (2013). Practical numerical reactor employing direct whole core neutron transport and subchannel thermal/hydraulic solvers. ANE, 62, 357–374.

[3] Fitzgerald, A. P., et al (2019). Improved formulation of the method of characteristics with linear source for 2D/1D and multiphysics calculations. M&C 2019. Portland, OR.

[4] Choi, S., et al. (2020). Three-dimensional method of characteristics/diamond-difference transport analysis method in STREAM for whole-core neutron transport calculation. Computer Physics Communications, 107332.

[5] Boyd, W., et al. (2014). The OpenMOC method of characteristics neutral particle transport code. ANE, 68, 43–52.

[6] Ferrer, R., et al. (2012). Linear source approximation in CASMO5. In International Conference on the Physics of Reactors 2012, PHYSOR 2012: Advances in Reactor Physics (Vol. 1, pp. 1–12). Cambridge, MA: ANS.