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Development of discrete ordinates code supporting unstructured tetrahedral mesh and applied in neutronics analysis for the Korea Helium Cooled Ceramic Reflector Test Blanket Module

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HIGHLIGHTS

- We developed discrete ordinates transport solver which uses discontinuous finite element method (DFEM) as a spatial discretization to deal with an unstructured tetrahedral mesh.
- For pre- and post-processing, Gmsh is used to generate unstructured tetrahedral mesh by importing CAD file (*.step) and visualize the calculation results.
- We applied this code to a TBM neutronics analysis, the neutron flux distribution in the Korea HCCR TBM is compared with that of MCNPX, and visualized in a three-dimensional system domain.
- Calculated total flux averaged over multilayer zone shows good agreement with that of MCNPX.

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ABSTRACT

The discrete ordinates code under development by KAERI uses an unstructured tetrahedral mesh, and thus it can be applied to solve the radiation transport in a complicated geometry. In addition, the geometry modeling process has become much easier because computational tetrahedral meshes are generated based on the CAD file by Gmsh.

As our first phase of applying the code to a TBM neutronics analysis, the neutron flux distribution in the Korea HCCR TBM is compared with that of MCNPX, and visualized in a three-dimensional system domain. Visualization of the fluxes and associated reaction rates in the whole system with a single run is one of the merits of a deterministic method and is very useful for checking hot spots.

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1. Introduction

Korea has been developing a solid-type Test Blanket Module (TBM) called a Korea Helium Cooled Ceramic Reflector (HCCR) TBM to be adopted in International Thermonuclear Experimental Reactor (ITER). For neutronics analyses, the MCNP(X) code has been used.

MCNP(X) is a well-known Monte Carlo code and has been widely used in ITER for neutronics analyses since it uses continuous cross sections and can handle a complex geometry without any assumptions or simplifications. However, the fluxes and responses are calculated at pre-selected locations (tallies) and to know the flux where particles are hardly reached, we need to increase particle number or use other variance reduction techniques.

Compared with the Monte Carlo method, the discrete ordinates method, referred to as the S_N method, has difficulties in modeling a complex three-dimensional geometry. A number of computer codes that use the S_N method require a regular mesh (rectangular, cylindrical, or spherical) to model the geometry. Using such a specific regular mesh leads to the simplest difference equations but may require an excessive number of mesh points to adequately model complicated geometries.

However, the code under development by KAERI uses an unstructured tetrahedral mesh, and can thus be applied to solve the radiation transport in a complicated geometry. In addition, the geometry modeling process has become much easier because Gmsh [1] generates an unstructured tetrahedral mesh by importing a CAD file.

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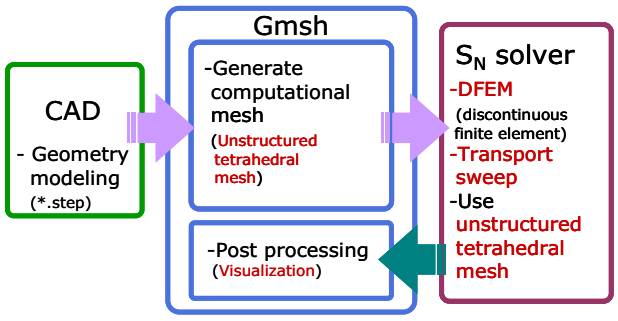

Fig. 1. Schematic diagram of our code system.

In this paper, we briefly introduce the discrete ordinates code under development by KAERI and applied in neutronics analysis for the Korea HCCR TBM. The neutron flux distribution is compared with that of MCNPX, and visualized in a three-dimensional system domain.

2. Brief introduction of the theory and method

Having a transport solver that uses a CAD tool for preparing the geometry input is one of our motivations for this work.

Every deterministic code needs a spatial discretization to solve the Boltzmann transport equation. An unstructured tetrahedral mesh has been used for the structural mechanics, fluid dynamics, and so on. However, it has not been widely used for radiation transport calculations such as a nuclear reactor design or radiation shielding problems.

To deal with an unstructured tetrahedral mesh in the discrete ordinates transport code, Wareing T.A. et al., proposed the discontinuous finite element method (DFEM) [2] in 2001 and developed the Attila code [3].

We also developed a discrete ordinates transport solver with DFEM [4] and have been enhancing its performance and adding functions. For pre- and post-processing, Gmsh is used to generate an unstructured tetrahedral mesh by importing a CAD file (*.step). The schematic diagram of our code system is shown in Fig. 1.

We divide problem domain into unstructured tetrahedral elements. Angular fluxes on each element k are shown in Fig. 2. Face index ℓ is assigned to the same number of opposite vertex index p.

The final form of DFEM can be written as

$$\left[\sum_{\ell=1}^{N_{faces}}\int_{\delta v_{k,\ell}}\left(\vec{\Omega}_m\cdot\vec{n}_\ell\right)\vec{\Theta}(\vec{r})\vec{\Theta}^T(\vec{r})d\delta v_{k,\ell}\right]\vec{\psi}^s_{k,m} + \left[-\vec{\Omega}_m\cdot\int_{v_k}\left(\nabla\vec{\Theta}(\vec{r})\right)\vec{\Theta}^T(\vec{r})\;dv_k+\sigma_{t,k}\int_{v_k}\vec{\Theta}(\vec{r})\vec{\Theta}^T(\vec{r})dv_k\right]\vec{\psi}_{k,m} = \left[\sigma_{s,k}\int_{v_k}\vec{\Theta}(\vec{r})\vec{\Theta}^T(\vec{r})dv_k\right]\vec{\phi}_k+\left[\int_{v_k}\vec{\Theta}(\vec{r})Q(\vec{r})\;dv_k\right], \quad (1)$$

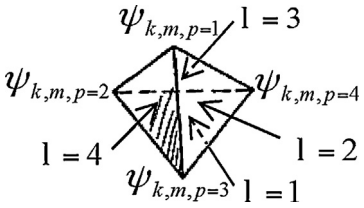

Fig. 2. Angular fluxes on each vertex p, ordinate m, and element k.

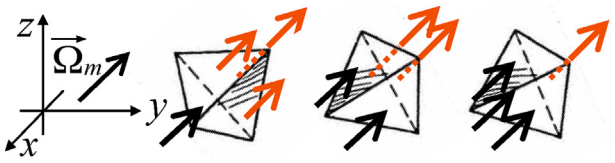

Fig. 3. Three orientations of tetrahedral element for a given ordinate direction $\vec{\Omega}_m$ (from left to right: one incoming/three outgoing, two incoming/two outgoing, and three incoming/one outgoing).

where

$$\vec{\psi}^s_{k,m}=\begin{cases}\vec{\psi}_{k,m} & \vec{\Omega}_m\cdot\vec{n}_\ell>0,\\ \vec{\psi}^{Inc}_{k,m} & \vec{\Omega}_m\cdot\vec{n}_\ell<0,\end{cases} \quad (2)$$

$$\vec{\psi}_{k,m}=\left[\psi_{k,m,p=1},\psi_{k,m,p=2},\psi_{k,m,p=3},\psi_{k,m,p=4}\right]^T, \quad (3)$$

$$\underline{\Theta}=[\gamma_{p=1}(\underline{r}),\gamma_{p=2}(\underline{r}),\gamma_{p=3}(\underline{r}),\gamma_{p=4}(\underline{r})]^T. \quad (4)$$

$\underline{\Theta}$ is a linearly independent set of basis functions $[\gamma_p(\underline{r}),\,1\le p\le 4]$, indices of element volume v_k, surface of ℓth face $\delta v_{k,\ell}$, and outward normal vector of ℓth face $\vec{n}_\ell$.

In the first term of LHS of Eq. (1), $\vec{\psi}^s_{k,m}$ is given respect to the $\vec{\Omega}_m\cdot\vec{n}_\ell$. If it is positive for given face ℓ, $\vec{\psi}^s_{k,m}$ is replace by $\vec{\psi}_{k,m}$ which is angular flux of element k to be calculated. However, if it is negative, $\vec{\psi}^s_{k,m}$ is replace by $\vec{\psi}^{Inc}_{k,m}$ which is incoming angular flux from neighbor element on ordinate m. We solve Eq. (1) element by element with a transport sweep.

For a given ordinate direction $\vec{\Omega}_m$, tetrahedral elements are placed in one of three orientations in view of incoming/outgoing fluxes, as shown in Fig. 3.

With the known incoming fluxes from the neighbor element $\vec{\psi}^{Inc}_{k,m}$, four new vertex fluxes of the present tetrahedral element $\vec{\psi}_{k,m}$ are calculated using Eq. (1). Then, some of these newly calculated vertex fluxes are used as incoming fluxes to the next neighboring downstream element based on the transport sweep order. These chains of the tetrahedral elements along each ordinate direction make it possible to perform the successive transport calculation.

For easy understanding, let us consider a transport sweep in a two-dimensional problem and vacuum boundary condition. As shown in Fig. 4, we can consider two orientations which unstructured triangle can be placed respect to the ordinate direction $\vec{\Omega}_m$.

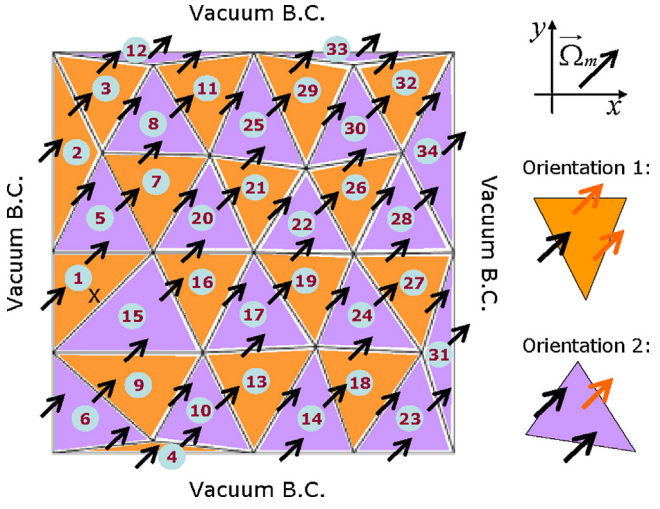

Fig. 4. Illustration of transport sweep in a two-dimensional problem (Orientation 1: one incoming/two outgoing, Orientation 2: two incoming/one outgoing).

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