An Improved Monte Carlo Method Applied to Heat Conduction Problem of a Fuel Pebble

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1. Introduction

There are many deterministic techniques to solve heat transfer problems. However, they are difficult to deal with problems having complex geometry. Because Monte Carlo method deals well with complicated geometries, it could be used to deal with such heat transfer problems.

Heat conduction is a diffusion process that is analogous to the neutron diffusion equation under no absorption, no fission and one speed condition [1, 2]. That is, the steady state differential equation of heat conduction for a stationary, isotropic solid is given by [1]

$$\nabla \cdot K(\vec{r})\nabla T(\vec{r}) + q'''(\vec{r}) = 0, \qquad (1)$$

where $K(\vec{r})$ =thermal conductivity, $q'''(\vec{r})$ =internal heat source. On the other hand, the steady state, one-speed neutron diffusion equation under isotropic scattering, no absorption, and no fission condition is given by [2]

$$\nabla \cdot \frac{1}{3\Sigma_s}\nabla\phi(\vec{r}) + S(\vec{r}) = 0, \qquad (2)$$

where ϕ =neutron flux, Σ_s =scattering cross section, S=internal neutron source.

While neutron diffusion is an approximation of neutron transport phenomena, inversely it is applicable to solve diffusion problems by a transport method with

$$\Sigma_s = \frac{1}{3K(\vec{r})} \text{ and } S = q''' . \qquad (3)$$

Based on this idea, a Monte Carlo method of solving heat conduction problems was applied to the pebble problem. Sensitivity studies were performed on how to choose scaling factor, β . The temperature profiles obtained by the Monte Carlo method are compared to those of the usual method based on homogenized models.

2. Problem Description

In this paper, FLS (Fine Lattice Stochastic) model [3] for random distribution of fuel particles in a pebble is used. More detail information is described in Table 1 and Fig. 1. A Monte Carlo program HEATON was written to solve heat conduction problems using the MCNP5 code as the major computational engine.

Table 1 : Problem description

	Thermal conductivity	Radius (cm)		Thermal conductivity	Radius (cm)
Kernel	0.0346	0.0251	Outer Pyc	0.04	0.04576
Buffer	0.01	0.03425	Graphite matrix	0.25	2.5
Inner Pyc	0.04	0.03824	Graphite shell	0.25	3.0
Sic	0.183	0.04177	Helium layer	0.0097	3.1

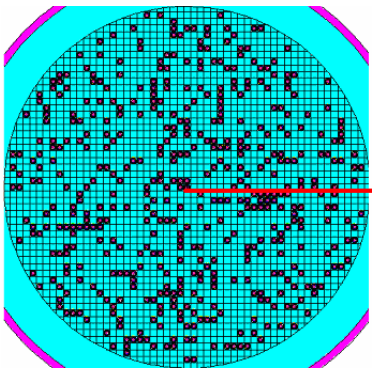

Fig. 1. Geometry for pebble problem

3. Solutions of Pebble Problem vs Scaling Factor

The thermal conduction solutions for the pebble problem using the Monte Carlo method are shown in Fig. 2. In this problem, the number of particles used is 10^8, parallel computation with 60 CPUs (3.2GHz) was used, and boundary temperature is 0(°K). When scaling factor becomes larger, the solution of the pebble problem converges. However, the computational time increases rapidly with increasing scaling factor.

In Fig. 2, it is confirmed that the scaling factor of 10 is not sufficient. Therefore, it is tested to find reasonable scaling factor in solving the pebble problem.

Table 2: Results of Fig. 1 Problem

Scaling factor	Maximum temp.(°K)	Computational time (sec)	Standard deviation(°K)	
			Min.	Max.
1	501.21	534	0.0081	8.3998
10	383.96	6,692	0.0008	4.4081
20	385.54	20,297	0.0004	4.3333
50	380.22	99,454	0.0001	4.2646

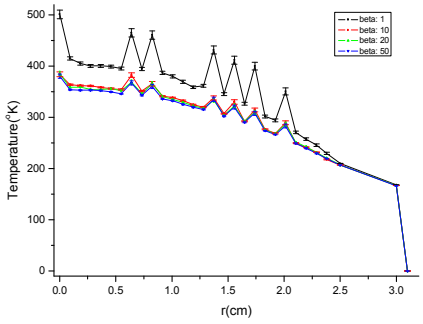

Fig. 2. Results along red line of Fig. 1 vs beta

4. Scaling Factor in Heterogeneous Problems

In a previous paper [4], α =10 was sufficient for simple problems. However, it is inadequate in more

heterogeneous problems such as a pebble. Therefore, it is necessary to choose appropriate scaling factor in realistic pebble problems.

However, the extended boundary was not used in the problem because the improved method [5] is effective in a large size problem in terms of mean free path.

By adjoint calculation, whether the thermal conduction solution converges or not was tested with increasing scaling factor. The computation was done in parallel with 60 CPUs (3.2GHz) and the number of particles used is 10^6.

We can confirm that the temperature of center point for pebble converges when the scaling factor becomes large. Therefore, it is judged that the scaling factor of 50 is sufficient in very heterogeneous problems.

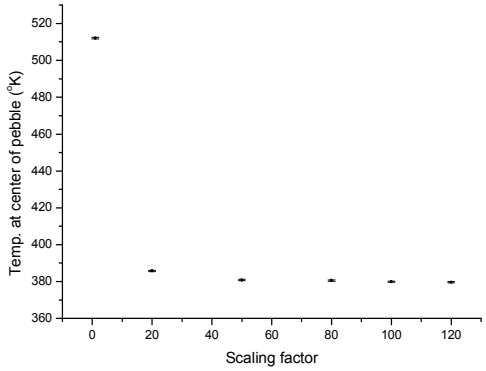

Fig. 3. Center temperature by adjoint calculation

Table 3: Maximum temp. and computational time for Fig. 3.

Scaling factor	Max. Temp.(°K)	Standard deviation (°K)	Computational time (sec)
1	512.131	0.409	47
20	385.817	0.308	1,427
50	380.931	0.304	7,298
80	380.586	0.304	17,976
100	379.995	0.303	27,240
120	379.713	0.303	39,435

5. Diffusion (Conduction) Solutions for the Pebble Problem

In this problem, the data such as geometry information and thermal conductivity are the same with those in Table 1. Based on the results in Section 4, we calculated temperature distributions using scaling factor of 50. We considered three triso particle configurations obtained by random sampling (using the FLS model in Ref. 3). In contrast to the runs in Ref. 4, we chose tally regions as in Fig. 4.

If a (fine) lattice has heat source, the tally is done over the kernel volume. If the lattice consists of only graphite, tally is done over the lattice volume.

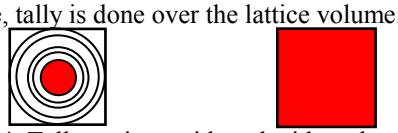

Fig. 4. Tally regions with and without heat source

Fig. 5 shows the temperature distributions obtained from the Monte Carlo method, compared to the two analytic solutions based on commonly quoted homogenized models. Note that the volumetric analytic solution usually presented in the literature underestimates the Monte Carlo results.

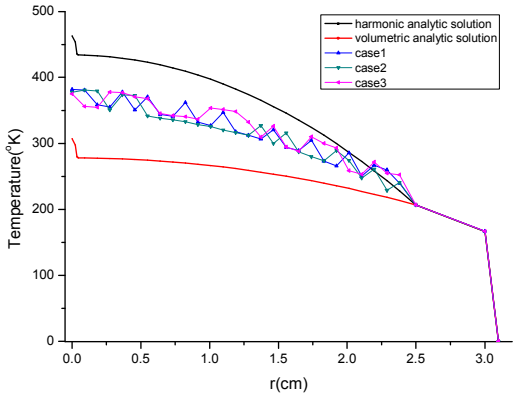

Fig. 5. Temperature profiles depending on triso particle distribution configuration compared to two homogenized models

Table 4: Max., average kernel temp. and graphite temp. from Fig. 5.

	Max. temp.(°K)	Averaged Kernel temp.(°K)	Averaged graphite temp.(°K)
Case1	382.067	324.838	315.244
Case2	380.768	327.177	307.643
Case3	374.988	322.506	316.924
Average	379.273	324.840	313.270

6. Conclusions

The Monte Carlo method for solving heat conduction problems (with complicated geometry due to heterogeneity) was further refined. The value of around 50 for scaling factor is adequate for the fuel pebble in VHTRs. The Monte Carlo results for randomly sampled configurations were presented (showing fuel kernel temperatures and graphite matrix temperatures distinctly). The volumetric analytic solution commonly used in the literature underestimates the Monte Carlo results in this paper.

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