INTRODUCTION

Codes/Methods for transient calculation of nuclear reactor have been under development for many years, but their capability for solving full-scale space-time problems without diffusion approximation and spatial homogenization remains to be validated. For verifying those codes/methods, the C5G7-TD benchmark (Deterministic Time-Dependent Neutron Transport Benchmark without Spatial Homogenization) [1] was proposed by OECD/NEA.

RMC (Reactor Monte Carlo code) is a 3D neutron transport code developed by the REAL (Reactor Engineering Analysis Lab) group of Tsinghua University. The Monte Carlo improved quasi-static method(IQS) was adopted by RMC [2] previously for transient simulation capability. Afterwards, the Monte Carlo predictor-corrector quasi-static method(PCQS) was developed in order to decrease the time and memory cost. This method has already been demonstrated over several simplified benchmarks [3]. However, a common benchmark with detailed specifications is necessary for further validation and verification, and therefore RMC participates in the C5G7-TD benchmark work.

The PCQS method was further improved to increase the accuracy, and new features were added to the RMC code to satisfy the C5G7-TD specifications, such as the delayed neutron data input block, universal calculation-guiding script and data post-processing function. All the C5G7-TD benchmark Phase-I problems have been solved by RMC. In WPRS C5G7-TD-3 Workshop in March 2018, results generated by eight codes/methods were shown and compared, and RMC was the only code using the Monte Carlo method.

This paper presents all the C5G7-TD 2-D and 3-D results of RMC. The improvements of the PCQS method are discussed. The comparisons among results of RMC and others' shown in WPRS C5G7-TD-3 Workshop had a good agreement, and some of the comparisons are also presented in this paper.

THE PCQS METHOD

The aim of the nuclear reactor transient calculation is to solve the neutron time-space kinetic equation and to obtain the neutron flux $\phi$:

$$\frac{1}{v} \frac{\partial \phi}{\partial t} = L(t) \phi(t) + \frac{1}{4\pi} \sum_i x_i(E)\lambda_i C_i(r, t)$$

$$x_i(E) \frac{\partial C_i}{\partial t} = -\frac{x_i(E)}{4\pi} \lambda_i C_i(r, t) + F_i(t) \phi(t)$$

The neutron flux $\phi$ varies over angle, space, energy and time. We assume that the space shape of the neutron flux changes much slower against time compared to its amplitude, and therefore the quasi-static method is used:

$$\phi(r, E, \Omega, t) = T(t) \Psi(r, E, \Omega, t)$$

Where $T$ is the amplitude function, and $\Psi$ is the shape function. After this assumption, eq(1) will be:

$$L(t)\Psi(r, E, \Omega, t) + \frac{1}{4\pi} \sum_i \lambda_i x_i(E)C_i(r, t) \frac{1}{T(t)} = \frac{1}{v} \frac{\partial \Psi}{\partial t} + \frac{1}{v} \Psi(r, E, \Omega, t) \frac{1}{T(t)} \frac{dT}{dt}$$

In order to solve Eq. (4), one normalization condition is introduced:

$$\int \int \int \frac{1}{v} \Psi(r, E, \Omega, t) W(r, E, \Omega) dV dE d\Omega = \text{const}$$

Where $W$ is the weighting function. In our method, the adjoint flux is chosen as the weighting function. The adjoint flux can be easily obtained by iterative fission probability method for Monte Carlo code, which is also implemented in RMC.

Using the normalization condition, the kinetic equation (4) can be simplified to a point-reactor equation, and the kinetic parameters can be deduced:

$$\rho(t) = \frac{F(t) - \langle L\Psi + T\Psi + S\Psi, W \rangle}{F(t)}$$

$$A = \frac{1}{F(t)} \langle \frac{\Psi}{W}, W \rangle$$

Where

$$\int \int \int dV dEd\Omega \frac{2(E)}{4\pi} \int dE' d\Omega'\nu\Sigma_f \Psi(r, E', \Omega', t)$$

Also, after applying the implicit differential equation:

$$\frac{\partial \phi}{\partial t} \approx \frac{\Phi_n + 1 - \Phi_n}{\Delta t}$$

The kinetic equation will become a fixed source equation, which can also be easily solved by the Monte Carlo method.
Carlo simulation, and then the predicted neutron flux $\Phi_{n+1}$ can be obtained.

Finally, the amplitude function $T(t)$ will be got by solving the point-reactor equation, and the neutron flux can be obtained by the predicted flux:

$$\Phi = \Phi_{n+1}T(t) \frac{<\frac{\Phi_n}{\nu}, W>}{<\frac{\Phi_{n+1}}{\nu}, W>} \quad (10)$$

However, as the original RMC results[4] shows, obvious oscillation of lumped parameters will occur if only PCQS method is used, due to the stochastic property of the Monte Carlo method. Therefore, a parameter fitting method is further applied to solve this problem. The whole calculation process is divided into several stages. In every stage, the kinetic parameters at relative large time step sizes will be obtained by the PCQS method, and the kinetic parameters at relative small time step sizes will be get using least-square fitting method. Then the relative power will be calculated by solving the point-reactor equation with the fitted kinetic parameters. The fitting method can not only eliminate the oscillation but also decrease the time cost for the whole transient calculation.

**SPECIFICATIONS AND CONFIGURATIONS**

**Benchmark specifications**

The CSG7TD benchmark is based on the well-studied steady-state CSG7 benchmark. The reactor is a quarter-core with 2 uranium assemblies and 2 MOX assemblies, surrounded by a water reflector. Every assembly follows the $17 \times 17$ configuration. In the 3-D configuration, the height of the assembly is increased, and the control rods are inserted into the top reflector. Fig. 1 shows the 2-D configuration plotted by RMC.

The 7-group macroscopic cross sections and 8-group delayed neutron kinetics parameters are provided, which are generated by the code DRAGON and WIMS-ACEL 69 group library.

The benchmark consists of 28 cases in total. The cases are divided into six series of exercises, including 19 two-dimensional (2-D) transient problems from exercises 0 (TD0) to 3(TD3), and 9 three-dimensional (3-D) problems from exercises 4 (TD4) to 5(TD5). Either control rods movement or moderator density change is applied in these cases.

The initial states for all exercises should be made critical by adjusting the neutron production, so different cross section libraries will be used separately for 2-D and 3-D exercises. The benchmark specification [0] and the organizers’ paper [5] provide more details.

**RESULTS AND COMPARISON**

By far 8 participants have submitted their results to the organizer. However, some submitted only 2-D results. We compared our 2-D results with SUHAM and 3-D results with nTRACER. Good agreements were found for most of the cases, but small differences also appeared in some cases and the reason was discussed.

**Results of 2-D problems**

The RMC used 200 inactive cycles and 400 active cycles with 1 million histories per cycle, and the standard deviation of the eigenvalue is about 5pcm. For most cases, this deviation can be ignored, but in some cases the reactivity change during the whole transient process is only tens of pcm, so 10 million histories per cycle was chosen specially for these cases. Fig. 2 shows the reactivity values of different codes at 1.0s for case TD1-3. It's obvious that the 10 million result (the red dot) of RMC is much closer to the average value than the 1 million one (the left first black dot).
The 2-D problems consist of four sets of cases. The TD0, 1, and 2 sets of cases are problems with different control rods insertion/withdrawal specified either a step change or a linear change in the material XS. The TD3 set of cases involve different linear moderator density changes.

The fission rate profiles for TD0 are shown in Fig. 7. Abrupt rod insertion/withdrawal was utilized to introduce the reactivity variation, and the shape of step change is clearly depicted in Fig. 7. The comparison between RMC and SUHAM shows very good agreement, with maximum difference of the normalized core fission rate less than 0.01.

![Fig. 7. Normalized Core fission rate of RMC and SUHAM for TD0 cases.](image)

Fig. 8 and Fig. 9 show the fission rate results of TD1 and TD2 cases. Both sets were using linear control rods movement, but the maximum depth of the control rods insertion in TD1 cases was only 1% while it was 10% in TD2 cases. Similarly, the two codes show good agreement, especially for the TD2 cases for which the curves almost completely overlap.

A little discrepancy at 2 seconds for TD1-2 is observed. As is shown in Fig. 2, the maximum inserted reactivity is tens of pcm for TD1-3, and it is also the case for TD1-2. For such small reactivity condition, even 1 pcm variation of reactivity will lead to obvious fission rate change.

![Fig. 8. Normalized Core fission rate of RMC and SUHAM for TD1 cases.](image)

![Fig. 9. Normalized Core fission rate of RMC and SUHAM for TD2 cases.](image)

Fig. 10. shows the fission rate profiles of TD3 cases. The minimum moderator densities for the four cases are different. Obviously, the results of RMC and SUHAM are in great agreement.

![Fig. 11. Normalized Core fission rate of RMC and SUHAM for TD3 cases.](image)

Results of 3-D problems

The 3-D problems consist of two sets of cases: TD4 and TD5, involving CRs movement and moderator density change respectively. For TD4, the control rods movement was modeled by adjusting the rod positions rather than the XS changes, and the rise/drop of the control rods was not synchronous for different assemblies. As for TD5 cases, the moderator density changes are synchronous for different assemblies.

Fig. 13 shows the fission rate results of RMC and nTRACER. Obviously, the agreement between the two codes are not that good, especially for the TD4-4 and TD4-5 cases. As the method section shows, we chose the adjoint flux as our weighting function, while the nTRACER was using the constant as the weighting...
function. This difference led to discrepancies for the kinetic parameters, and the fission rates eventually diverged from each other. We have tried substituting the kinetic parameters in our calculation with the nTRACER’s results, and then the fission rates were in good agreement. The SUHAM was using the adjoint flux, and this is the reason why we compared SUHAM results for the 2-D cases.

Fig. 13. Normalized Core fission rate of RMC and SUHAM for TD4 cases.

The fission rate profiles for TD5 cases were depicted in Fig. 15. This agreement is better than the TD4 results, but a little discrepancy is still observed after 4 seconds. Weighting function difference is also the reason, but whether or not other factors also affect the calculation remains to be studied.

Fig. 15. Normalized Core fission rate of RMC and SUHAM for TD5 cases.

CONCLUSIONS

All the C5G7-TD benchmark Phase-I problems are solved by the RMC code using the improved predictor-corrector quasi-static method. The RMC results agree well with those of SUHAM for 2-D problems, but shows a little discrepancy against the results of nTRACER for 3-D results. Future work will focus on the impact of the weighting function. The calculation and comparison of C5G7-TD benchmark validated the universality, flexibility, robustness and accuracy of the kinetic capability for RMC.

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REFERENCES