Monte Carlo Benchmark Calculations for 400MW$_{th}$ PBMR Core

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Abstract – Benchmark calculations for the core of the 400MW$_{th}$ Pebble-bed Modular Reactor (PBMR), being developed in South Africa, were carried out by using MCNP5 code as a part of establishing Monte Carlo computation system for HTGR core analysis. After the detailed MCNP modeling of the whole facility, two neutronic benchmark problems, for fresh fuel and cold conditions(Case F-1), and first core loading with given number densities(Case F-2), proposed by the IAEA CRP5 was pursued. The resulting k$_{eff}$ was calculated to be 1.2795±0.00052 and 1.1401±0.00055 for Case F-1 and F-2, respectively. It was found that these results were different with the results from other research group using MCNP4b, because 3 bottom cone regions and de-fueling chutes were assumed as the surfaces flattened in MCNP4b calculations while these were modeled explicitly in this study. This study can be contributed and utilized directly in the establishment of benchmark problems to develop deterministic neutronics analysis tools and methods, which lagged behind the state of the art compared to other reactor technologies, to design and analyze PBMR.

I. INTRODUCTION

Hydrogen is an environmentally attractive fuel that has a significant potential to displace the fossil fuels. In order for significant expansion of hydrogen production, nuclear energy can become a good source to provide sufficient heat for that purpose.

For the reasons of the above, pebble-bed and other high temperature gas-cooled reactor (HTGR) designs are in vogue in connection with hydrogen production. It is the most important to design precisely core using the reliable computational code. The existing computational code such as VSOP(1) had been developed to analyze the HTGR cores. The VSOP code was adopted for use in both the South African PBMR and the Chinese HTR-10 reactor projects. It is, however, known that the code is old fashioned, poorly documented and not very “user friendly”. Thus, efficient code systems have been needed for the core analysis of HTGR. A computational code system is also, in Korea, under development for the HTGR core analysis.

In order to validate the computer codes for the HTGR core analysis which will be developed in near future, Monte Carlo analysis of the core is necessary for the code benchmark. With rapid improvement in computer technology, Monte Carlo method is highlighted in the area of reactor core analysis as well as code benchmark.

In this study, as a part of work for establishing Monte Carlo computation system for HTGR core analysis, some benchmark calculations for pebble-type HTGR were carried out using MCNP5 code(2). As for Korea, the experiences for the commercial reactor of pebble-type to be developed for hydrogen production are poorly accumulated. Therefore, the core of the 400MW$_{th}$ Pebble-bed Modular Reactor (PBMR) was selected as a benchmark model.

Recently, the IAEA CRP5 neutronics and thermal-hydraulics benchmark problem was proposed for the testing of existing methods for HTGRs to analyze the neutronics and thermal-hydraulic behavior for the design and safety evaluations of the PBMR. This study deals with the neutronic benchmark problems, for fresh fuel and cold conditions (Case F-1), and first core loading with given number densities (Case F-2), proposed for PBMR. After the detailed MCNP modeling of the whole facility, benchmark calculations were performed. Results to benchmark problems have been obtained by MCNP5 code(3).

II. DESCRIPTION OF PBMR

II.A.Design Criteria

The PBMR has a vertical steel reactor pressure vessel (RPV), 6.2 m in inner diameter. The reactor pressure vessel contains a metallic core barrel, which supports the annular pebble fuel core and the graphite neutron reflector in the center and on the outside of this fuel annulus, presented in Figures 1 and 2. The PBMR reactor core is basically a long right circular cylinder with a fuel effective height of 10.117m and a diameter of 3.7m, and is comprised of about 452,000 fuel spheres. Table I describes key core characteristics of the PBMR. Vertical borings in the center and outer reflectors are provided for the reactivity central elements. Two diverse systems are provided for shutting the reactor down, one being control rods inserted into the borings in the side reflector and the other being small neutron absorbing spheres which are dropped into borings in the central reflector. The followings are the most important characteristics of the PBMR.

- A continuous power rating of 400 MW_{th}
- An annular core with an outer diameter of 3.7 m and a ‘fixed central reflector’ with an outer diameter of 2 m
- An effective cylindrical core height of 11 m
- A graphite side reflector of ~90 cm
- The reactivity control system (RCS) consisting of 24 partial length control rod positions in the side reflector, with 12 upper and 12 lower rods, when fully inserted. The rods have an effective length (neutron absorbing material) of 6.5 m.
- The reserve shutdown system (RSS) consisting of eight small absorber sphere (SAS) systems positioned in the fixed central.
- Three fuel loading positions and three fuel unloading tubes, positioned equidistant in the center of the fuel annulus.

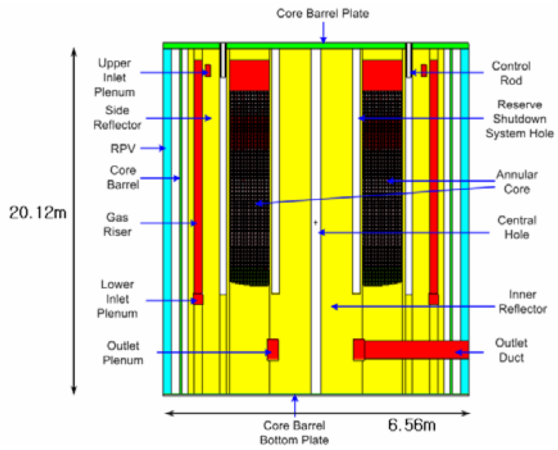

Fig. 1. Vertical View of the PBMR

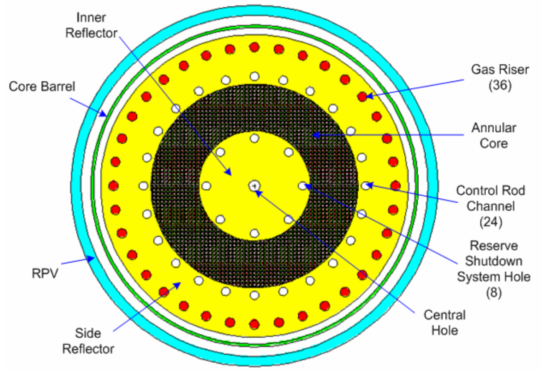

Fig. 2. Horizontal View of the PBMR

TABLE I

Core Characteristics

Characteristic	**Value**
Total Fuel Volume	83.7156 m^3
Core Outer Diameter	3.7 m
Outer Diameter of Central Reflector	2.0 m
Fuel Effective Cylindrical Height	10.117 m
Fuel Enrichment	9.6% UO_2 for Equilibrium Core
Target Burn-up	>90,000 MWd/tU
Average Pebble-bed Packing Fraction	0.61
Number of Spheres in Core	451,555

II.B.Reactivity Control and Shutdown System

Two reactivity control systems are provided to compensate for excess reactivity, to ensure an adequate shutdown margin, and to control changes in reactivity that occur during operation. The first system, called the RCS, consists of 24 active control elements divided into two groups of 12 (with every other control rod belonging to a group). The RCS are positioned in borings in the side reflector. The second system, the RSS, consists of eight reserve shutdown units making use of small absorber spheres (SAS). The RSS are positioned in borings in the inner reflector.

II.C.Fuel and Moderator Pebbles

The diameter of fuel pebble is 6.0cm. Each fuel pebble contains about 15,000 coated particles in a graphite matrix. The coated particles are distributed in the fuel region, of which diameter is 5.0cm, in a stochastic sense. These particles consist of an oxide fuel kernel with coating layers of pyrocarbon (PyC) and silicon carbide (SiC), the so-called TRISO coating. Both PyC layers prestress the SiC and act to relieve the pressure buildup in the SiC due to internal gas pressure. The low density carbonaceous buffer layer provides the necessary free volume for fission gases. The physical properties of the fuel pebbles are given in Table II.

The diameter of moderator pebble is also 6.0cm and consists of only graphite. Its mass is 195g.

TABLE II

Main Specifications of the Fuel Pebble

Description	**Value**
Fuel Pebble	
Fuel Pebble Outer Radius	3.0 cm
Thickness of Fuel Free Zone	0.5 cm
Density of Matrix Graphite and Graphite in Fuel Free Zone	1.74 g/cm^3
Total Heavy Metal Loading per Fuel Pebble (Equilibrium Fuel)	9 g
Total Heavy Metal Loading per Fuel Pebble (Start-up Fuel)	9 g
Enrichment for Equilibrium Fuel (Weight Percentage)	9.6 wt/o
Enrichment (N_{U235} / N_U) for Start-up (Weight Percentage)	5.76 wt/o
Coated Particle	
Fuel Kernel Diameter	500 ㎛
Particle Material Type	UO2
UO_2 Density	10.4 g/cm^3
Coating Material	C/C/SiC/C

III. Description of Benchmark Problems

The benchmarks pursued in this study are Case F-1 and Case F-2 which are the problems for steady state without any control rod insertion.

III.A. Case F-1

As this benchmark problem is the one for fresh fuel and cold conditions, the following conditions are used.

- The core is filled with fresh first core fuel (9 grams HM and 5.768 $^w/_o$ enriched). – use ND-set1 presented in Table III
- Number densities can be used for homogeneous material or volume weighted and applied to heterogeneous fuel specifications.
- Cold condition (300K) is employed for all materials.
- Use of own cross sections

TABLE III

Number-densities for ND-set1

Isotope	Central column	Fuel regions	Graphite (reflector)	Control
U-234	0.0	6.22417E-08	0.0	0.0
U-235	0.0	7.0860E-06	0.0	0.0
U-238	0.0	1.1570E-04	0.0	0.0
O-16	0.0	2.4570E-04	0.0	0.0
SI	0.0	2.77203E-04	0.0	0.0
C	8.9747E-02	5.2626E-02	9.0248E-02	7.2472E-02
B-10	0.0	0.0	0.0	3.20E-06

III.B. Case F-2

As this benchmark problem is the one for first core loading with given number densities, the following conditions are used.

- Employ a homogeneous mixture of 33.3 % first core fuel (9 grams HM and 5.768 $^w/_o$ enriched) and 66.6% graphite spheres (no fission products or higher elements). – use ND-set2 presented in Table IV
- Number densities can be used for homogeneous material or volume weighted and applied to heterogeneous fuel specifications.
- Constant temperature conditions (300K) for all materials
- Use of own cross sections

TABLE IV

Number-densities for ND-set2

Isotope	Central column	Fuel regions	Graphite (reflector)	Control
U-234	0.0	2.07472E-08	0.0	0.0
U-235	0.0	2.3620E-06	0.0	0.0
U-238	0.0	3.85673E-05	0.0	0.0
O-16	0.0	8.19001E-05	0.0	0.0

SI	0.0	9.24009E-05	0.0	0.0
C	8.9747E-02	5.3203E-02	9.0248E-02	7.2472E-02
B-10	0.0	0.0	0.0	3.20E-06

IV. MCNP MODELING OF PBMR

IV.A. Random Packing Core Modeling

It is not possible to exactly describe the feature to be randomly packed using Monte Carlo code or any other codes. It is, therefore, easy to be that the feature is assumed to be a specified lattice model. Several choices of lattice are possible, including simple cubic, body-centered cubic (BCC), face-centered cubic (FCC), or hexagonal closed packed (HCP). Although the pebbles tend to pack towards an HCP lattice at the bottom of the core, the BCC lattice was found to work well for the loose packing typically encountered in pebble-bed reactor cores(3).

The random packing cannot be modeled directly with MCNP5 code, because of the large number of pebbles in the core. The PBMR annular core consists of approximately 452,000 pebbles in the benchmark problems. Therefore, the core model must rely on the repeated-structure feature of the code, in which a unit cell is expanded throughout the volume of the core.

In Case F-1 where the core was filled with only fresh fuel pebble, a BCC(body-centered-cubic) lattice model was employed in order to achieve the random packing core with the packing fraction of 0.61. At this time, the BCC lattice pitch to conserve the fuel quantity within one BCC cell was calculated to be about 7.18cm and the number of pebbles for full core was obtained to 415,531. The BCC lattice was also employed with the size of the moderator pebble increased in a manner that reproduces the specified F/M ratio of 1:2 while preserving the packing fraction of 0.61 in Case F-2.

IV.B. Fuel Pebble Modeling

The fuel pebble has two concentric spherical shells. The outer region has an outer radius of 3.00cm and inner radius of 2.5cm and is comprised of graphite. The inner spherical region of 2.5cm in radius is the fuel region. In order to model a fuel pebble which contains on average 15,000 CFPs (Coated Fuel Particles), spherical fuel region of a fuel pebble is divided into cubic lattice element. Each element contains one CFP at its center. But, in a real fuel sphere, the CFP are distributed in the fuel region in a stochastic sense. Therefore, conservation of the fuel quantity in the fuel region is required. In this study, the side length of each cubic lattice element to have the same amount of fuel was calculated to be 0.1635 cm by Monte Carlo method(4). The remaining volume of each lattice element was filled with graphite.

A CFP consists of a UO_2 kernel, buffer layer, inner pyrolytic cabon (PyC) layer, silicon carbide (SiC) layer, and another outer PyC layer. All of these 5 concentric shells were modeled. Fuel pebble modeling is shown in Figure 3.

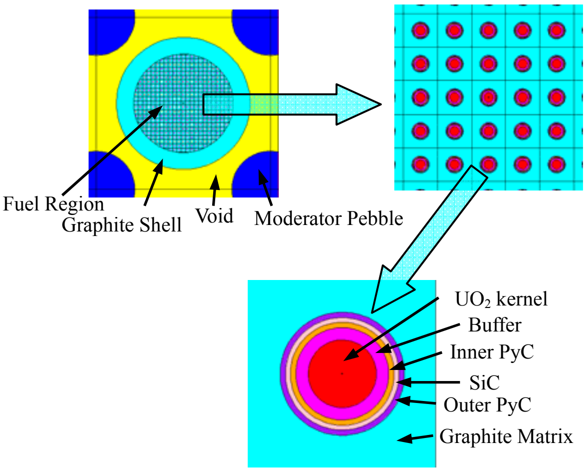

Figure 3. MCNP Modeling for Fuel Pebble

IV.C. Whole Facility Modeling

The major components of the reactor were also modeled, which are 24 reactivity control systems (RCS), 8 reserve shutdown systems (RSS), 3 de-fueling chutes, 36 gas risers, 2 inlet ducts, outlet duct, 2 inlet plenum, outlet plenum, and reflectors as well as the core. Whole facility modeling was shown in Figures 1, 2, and 4.

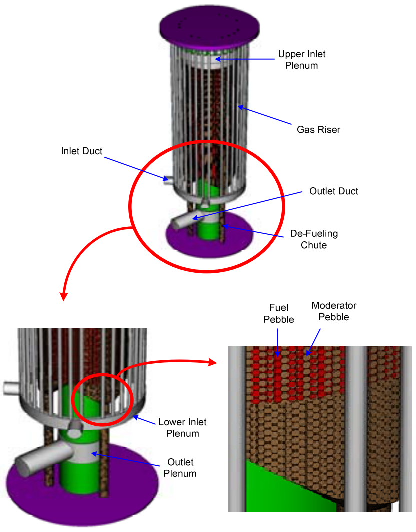

Figure 4. MCNP Modeling for Whole Facility

V. CALCULATION RESULT AND DISCUSSION

The calculations were pursued with ENDF/B-VI cross-section library and used sab2002 S(α, β) thermal cross-section library for graphite material. The results of this study and other research groups using MCNP4b were represented in Table V.

TABLE V

Calculation Results of Benchmark Problem

	k_{eff}	
	Case F-1	Case F-2
MCNP4b (Turkey)	1.2781	1.1533
MCNP5 (This Study)	1.2795±0.00052	1.1401±0.00055

The resulting k_{eff} was calculated to be 1.2795±0.00052 and 1.1401±0.00055 with the statistical error bounds associated with the 68% confidence interval for Case F-1 and F-2, respectively. Comparing with other previous results from MCNP4b code, these results gave an agreement of k_{eff} difference by 141 pcm and 1,315 pcm for Case F-1 and F-2, respectively. These results were caused by a different geometry modeled. While 3 bottom cone regions and de-fueling chutes were modeled explicitly in this study, these were assumed as the surfaces flattened in MCNP4b calculations.

VI. SUMMARY AND CONCLUSIONS

In this study, some Monte Carlo benchmark calculations were carried out for the PBMR with MCNP5 code. This calculation deals with the neutronic benchmark problems, for fresh fuel and cold conditions, and first core loading with given number densities, proposed for PBMR.

It was found that the resulting k_{eff} was different with the result from other research group using MCNP4b, because 3 bottom cone regions and de-fueling chutes were assumed as the surfaces flattened in MCNP4b calculations while these were modeled explicitly in this study.

This study can be contributed and utilized directly in the establishment of benchmark problems to develop deterministic neutronics analysis tools and methods, which lagged behind the state of the art compared to other reactor technologies, to design and analyze PBMR. It is also expected that this study would be utilized in the validation of a deterministic computer code for HTGR core analysis which will be developed in near future in Korea.

ACKNOWLEDGMENTS

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