Study on Control Rod Reactivity of Small Pebble Bed Reactor with Wallpaper Fuel Design

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Abstract. The control rod reactivity is a crucial reactor parameter designed to shut down the reactor and to control the safety of reactor core under any operation conditions. This paper discusses the control rod reactivity of small pebble bed reactor with wallpaper fuel design. The geometric configuration of RDE was selected for the reactor core model. A number of simulations with Monte Carlo n-particle transport code MCNP6 based on evaluated nuclear data library ENDF/B-VII were employed to investigate the total and individual control rod worth and reactivity in stuck rod condition. In the simulation model, the total amount of uranium per pebble was kept constant at 5 g by varying the hexagonal lattice pitch calculated for different radius of the central graphite zone. The simulation results show that the total control rod achieves the best effectiveness on the central graphite radius of 1.0 cm. The highest worth of individual rods in the wallpaper fueled core are almost greater than that of standard fueled core. The stuck rod criterion in all simulation results confirm that the failure of one rod with highest worth will not prevent the control system from shutting down the reactor. These results conclude that selecting a central graphite radius of wallpaper fuel is one of the strategies to be carefully considered and a radius of 1.0 cm is the best one in controlling reactor safety and ensuring the control system could shut down the reactor safely.

Keywords: control rod reactivity, small pebble bed reactor, wallpaper fuel design, MCNP6, ENDF/B-VII

1. Introduction
The human population which is estimated to have grown to around 10 billion individuals by 2050 has consequences on rapidly increasing energy consumption in the world. So far, the share of the energy
produced by fossil fuels as the main contributor to global warming is still very high. With the concern of climate change due to the emission of CO₂, nuclear energy is an unavoidable choice as an important source to fulfill the rising energy demand in the future [1,2].

One of the goals of the Generation IV International Forum (GIF) establishment is to anticipate the increasing energy needs in the world. A collaboration between 14 countries in the GIF has been developing the nuclear energy which has highest score in sustainability, economics, safety and reliability, proliferation resistance, and physical protection. The pebble bed reactor, as a type of HTGR reactor, is one of the six promising candidates for the Generation IV nuclear power plants [3,4].

The reactor is designed to be inherently safe by making the fuel pebbles can withstand the increasing reactor temperature up to 1600°C without releasing any fission products. In the case of accident, an active cooling system is not required and the heat can be removed passively from the reactor core. The pebble bed reactor has a flexibility to utilize a series of comprehensive fuel cycles, including thorium [5], plutonium [6], and rock-like oxide (ROX) [7].

This paper discusses the control rod reactivity of small pebble bed reactor with wallpaper fuel design. The control rod reactivity is a crucial reactor parameter designed to shut down the reactor and to control the safety of reactor core under any operation conditions. The wallpaper fuel is developed to replace the standard fuel so that the peak fuel temperature at the center of fuel pebble is reduced. The fuel design was based on the inclusion of a spherical central graphite zone at the center of fuel pebble by positioning the TRISO fuel particles in the spherical region outside the central graphite zone [8,9].

In this study, the geometric configuration of 10 MWth Experimental Power Reactor (Reaktor Daya Eksperimental, RDE) [10] was selected for the reactor core model. A number of simulations with Monte Carlo n-particle transport code MCNP6 [11] based on evaluated nuclear data library ENDF/B-VII [12] were employed to investigate the total and individual control rod worth and reactivity in stuck rod condition. In the simulation model, the total amount of uranium per pebble was kept constant at 5 g by varying the hexagonal lattice pitch calculated for different radius of the central graphite zone. The control rod reactivity of wallpaper fuel was compared with those of standard fuel to complete the safety analysis of small pebble bed reactor with wallpaper fuel design.

2. Reactor Model

The RDE is a pebble bed reactor with graphite moderator and helium coolant which refers to China's HTR-10 design and technology [13]. Like HTR-10, the reactor was designed to demonstrate the inherent safety essentiality and technical viability of a modular HTGR under normal and accident conditions. The RDE is being prepared to build at Puspiptek, Serpong, Indonesia. The primary system of the reactor operates at 3 MPa. The helium inlet and outlet temperatures of 250°C and 700°C, respectively, enable to generate nuclear high temperature for industrial heat applications such as hydrogen production, etc.

The reactor core, with 180 cm in diameter and 197 cm in effective height is composed of a 57% fuel pebbles and 43% moderator spheres, with packing factor of 61%. During full load, 27000 pebbles in total fill the core which is surrounded by the graphite reflectors consisting of the bottom, top and side reflectors. There are ten control rods, seven small absorber spheres and three experimental channels in the inner zone of the side reflector, as well as twenty helium flow channels in the outer zone of the side reflector which are equally spaced azimuthally. The main parameters of RDE reactor is summarized in Table 1 and its schematic view is described in Figure 1.

The control rod has an active absorbing medium of B₄C contained in five ring segments located between the inner and outer sleeves of stainless steel. These segments are connected by tubular iron joints whose upper and lower ends are capped with iron. A radial gap between the control elements and each sleeve is 0.05 cm. When the control rod is fully withdrawn, its lower end is at the axial position of 10.8 cm above the upper surface of the cavity. When the control rod is fully inserted, its lower end is at the axial position of 5.436 cm below the lower surface of the cone region. The geometric representation of the control rod is shown in Figure 2. The detailed dimensions of the
control rod components can be found in RDE Internal Report [10]. The composition of the control rod components is given in Table 2.

Table 1. The main parameters of RDE reactor [10].

| Reactor parameter                                      | Value   |
|--------------------------------------------------------|---------|
| Thermal power (MW)                                     | 10      |
| He inlet temperature (°C)                              | 250     |
| He outlet temperature (°C)                             | 700     |
| He inlet pressure (MPa)                                | 3       |
| Mass flow rate of He at full power (kg/s)              | 4.3     |
| No. of control rods                                    | 10      |
| No. of small absorber spheres                          | 7       |

| Core specification                                      | Value   |
|--------------------------------------------------------|---------|
| Core diameter (cm)                                     | 180     |
| Core height (cm)                                       | 197     |
| Power density (MW/m³)                                  | 2       |
| No. of pebble in full load                             | 27000   |
| Packing factor of pebble                               | 61%     |
| Fuel discharge burnup (MWd/t)                          | 80000   |
| Fueling scheme                                         | Multipass|

Figure 1. The schematic view of RDE reactor [14].
Table 2. Compositions of control rod components [10].

| Component                  | Composition | Density     |
|---------------------------|-------------|-------------|
| Control elements          | B₄C         | 1.7 g/cm³   |
| Stainless steel           | Cr          | 0.18        | 7.9 g/cm³ |
|                           | Fe          | 0.68        |
|                           | Ni          | 0.10        |
|                           | Si          | 0.01        |
|                           | Mn          | 0.02        |
|                           | C           | 0.001       |
|                           | Ti          | 0.008       |
| Joints and end caps       | Fe          | (atom density) |
|                           |             | 0.04 atoms/barn-cm |

Figure 2. The control rod of RDE [10].

The fuel pebble can be continuously renewed and recycled in Multipass scheme by removing used fuel through the discharge tube. If the target burnup of 80000 MWd/t has not been reached, the fuel pebble is then returned into the core. The fuel pebble consists of a graphite matrix with a diameter
of 5 cm covered by a 0.5 cm thick shell graphite. Each graphite matrix in the pebble contains 8335 TRISO coated fuel particles corresponding to 5 g uranium with 17% U\textsuperscript{235} enrichment.

The TRISO particle is comprised of a spherical fuel kernel of uranium dioxide (UO\textsubscript{2}) and four coating layers of isotropic materials. The coating layers are assigned to prevent the fission products from releasing into environment and maintain structural integrity. These fuel particles are randomly dispersed in the fuel pebble. The moderator pebbles containing nothing other than graphite with the same radius as fuel pebble of 3 cm occupy a conical area located at the bottom of the core. The detailed characteristics of the RDE fuel pebble is listed in Table 3 and its configuration is depicted in Figure 3.

### Table 3. The detailed characteristics of the RDE fuel pebble [10].

| Fuel pebble       |          |          |
|-------------------|----------|----------|
| Radius of pebble (cm) | 3        |          |
| Radius of fuel zone (cm) | 2.5      |          |
| Mass of uranium in fuel pebble (g) | 5        |          |
| U\textsuperscript{235} enrichment (%) | 17       |          |
| Density of graphite matrix/shell (g/cm\textsuperscript{3}) | 1.73     |          |
| Impurity of natural boron in fuel/graphite (ppm/ppm) | 4/1.30   |          |

#### TRISO coated particle

| Material                | Density (g/cm\textsuperscript{3}) | Outer radius (cm) |
|-------------------------|------------------------------------|-------------------|
| Kernel UO\textsubscript{2} | 10.41                              | 0.0250            |
| Porous carbon buffer    | 1.14                               | 0.0340            |
| Inner pyrolytic carbon  | 1.89                               | 0.0380            |
| SiC layer               | 3.20                               | 0.0415            |
| Outer pyrolytic carbon  | 1.87                               | 0.0455            |

![Figure 3. The configuration of the RDE fuel pebble [15].](image-url)
3. Simulation Model

The modeling of pebble bed reactor requires a different effort compared to the conventional reactors such as PWR, BWR, etc. This presents a major challenge for traditional reactor simulation methods. Two-level randomness of TRISO particles arrangement in fuel pebble and fuel pebbles distribution in the core, which is well-known as double heterogeneity, should be modeled using particular treatment. The MCNP6 code is able to overcome this challenge with its geometrical representation capability in modeling the pebble bed reactor.

3.1. Fuel Pebble Model

The fuel pebble consisting of spherical fueled zone and an outer graphite shell was modeled using repeated structure of simple hexagonal lattice of TRISO particle. The fuel particle was located at the center of the lattice. The graphite matrix was modeled in the remaining volume of the lattice.

In the fuel pebble model, the total amount of uranium per pebble was kept constant at 5 g by varying the hexagonal lattice pitch calculated for different radius of the central graphite zone. The following formula is used to calculate the pitch in the hexagonal lattice (p),

\[ p = \frac{2 \times r_k}{\sqrt{3}} \sqrt{\frac{4 \pi^2}{3} \times \frac{\rho_U}{m_U} \times (r_0^3 - r_i^3)}, \quad i=1,2,\ldots,n \]  

where,

- \( r_k \) is fuel kernel radius (cm),
- \( \rho_u \) is uranium density (g/cm\(^3\)),
- \( m_U \) is total amount of uranium/pebble (g),
- \( r_0 \) is fueled zone radius of standard fuel pebble (cm),
- \( r_i \) is central graphite radius of wallpaper fuel design (cm).

The uranium density (\( \rho_U \)) is calculated using the formula,

\[ \rho_U = \frac{A_U}{A_U + 2 \times A_O} \times \rho_{UO_2} \]  

where,

- \( A_U \) is uranium atomic weight,
- \( A_O \) is oxygen atomic weight,
- \( \rho_{UO_2} \) is UO\(_2\) density (g/cm\(^3\)).

| Central graphite zone | Hexagonal lattice pitch (cm) |
|----------------------|-----------------------------|
| 0                    | 0.198789115                 |
| 0.6                  | 0.198755182                 |
| 1.0                  | 0.191172877                 |
| 1.4                  | 0.170120967                 |
| 1.8                  | 0.156506558                 |
| 2.2                  | 0.135761034                 |

The calculated pitch of TRISO particle in hexagonal lattice is collected in Table 4. The central graphite zone of zero indicates the standard fuel pebble which is regularly used in the pebble
bed reactors. The MCNP6 model of fuel pebble is presented in Figure 4. It can be observed from this figure, that the incomplete TRISO particles appear in the boundary zones of graphite shell and central graphite. However, this situation does not affect the accuracy of the simulation results because of the small TRISO packing factor.

![Figure 4. The MCNP6 model of fuel pebble.](image)

3.2. Core Model
The reactor core consisting of 27000 pebbles was modeled using the repeated structure of BCC lattice of mixed pebble. A mixed pebble consists of one fuel pebble placed at the center and eight one-eight moderator spheres located at the corners of the lattice. The radius of moderator sphere was rearranged from 3 cm to 2.730983784 cm to produce the specified F/M ratio of 57%:43%. The BCC lattice pitch was readjusted also to be 6.878189713 cm to preserve the fraction factor of pebbles in the core.

![Core Model](image)
The moderator spheres with density of 1.84 g/cm$^3$ occupying the conus at the lower part of the core was modeled using BCC lattice with packing factor of 61%. The modeling of reflectors and fuel discharge tube were employed in a simple manner. The major components of the reactor such as twenty circular channels of helium flow, seven elliptical channels of small absorber spheres and ten circular channels of control rod with their absorbers were modeled using special technique.

The whole facility modeling of RDE is illustrated in Figures 5a and 5b. Some intersecting pebbles with the boundary of the reactor vessel was eliminated by considering the exclusive zone of 1.73 cm thick helium around the reactor core. The modeling procedure in this study was first proposed by Lebenhaft [16] in 2001 and applied by reactor physicists in numerous publications [17-26].

4. Results and Discussions

In Monte Carlo simulation, the complexity of pebble bed reactor geometry requires high number of simulated particles. The simulation of control rod reactivity was performed using 25,000 particles per cycle with active cycle of 250 and inactive cycle of 50 to achieve sufficiently standard deviation of about 0.00020 on the effective multiplication factor ($k_{eff}$). The location of the initial neutron source was prepared in detailed using numerous points within the fuel pebble to accelerate the convergence of source distribution. The evaluated nuclear data library ENDF/B-VII was applied in all simulations at room temperature of 300 K. The binding of the scattering nucleus between thermal neutron and all graphite contained in each reactor material under energy of 4 eV was considered by applying the thermal scattering $S(\alpha,\beta)$ law of grph.01t.

| Table 5. Total control rod worth (%Δk/k). |
|-------------------------------------------|
| Standard fuel pebble                      | 15.34 |
| Wallpaper fuel design, $r_1=0.6$ cm       | 15.73 |
| Wallpaper fuel design, $r_2=1.0$ cm       | 16.32 |
| Wallpaper fuel design, $r_3=1.4$ cm       | 16.14 |
| Wallpaper fuel design, $r_4=1.8$ cm       | 15.31 |
| Wallpaper fuel design, $r_5=2.2$ cm       | 14.86 |
The total control rod worth is calculated as reactivity difference between the core with the condition of all control rods at fully inserted position and the core with the condition of all control rods at fully withdrawn position. Reactivity is determined by substituting the value of the $k_{\text{eff}}$ into an equation. Table 5 shows the simulation results of the total control rod reactivity of RDE core. In this study, the central graphite in the fuel pebble plays an important role on the control rod worth. As the central graphite radius increases, the total control rod becomes more effective and achieves the best effectiveness on the central graphite radius of 1.0 cm. This situation changes and decreases with increasing the central graphite radius. The role of central graphite starts to weaken and even at a radius of 2.2 cm the effectiveness of the total control rod is worse than that of the standard fuel.

A comparison of control rod reactivity between wallpaper fuel and standard fuel is plotted in Figure 6. This curve is constructed in a way: a partial length of control rod is inserted into the core from top to bottom and the reactivity difference is calculated step by step with interval of 27.5 cm. This procedure is repeated until the control rod is fully inserted to the core. It can be seen that, in insertion of each part of the control rod, the rod worth of the wallpaper fuel design with central graphite radius of 1.0 cm is consistently greater compared to the standard fuel.

![Figure 6. Comparison of total control rod worth.](image)

Table 6. Individual control rod worth (%$\Delta k/k$).

| Control rod (CR) | Standard fuel | Wallpaper fuel design | r₁=0.6 cm | r₂=1.0 cm | r₃=1.4 cm | r₄=1.8 cm | r₅=2.2 cm |
|------------------|---------------|-----------------------|-----------|-----------|-----------|-----------|-----------|
| CR1              | 0.99          | 1.52                  | 1.42      | 1.68      | 1.33      | 1.13      |
| CR2              | 1.36          | 1.49                  | 1.46      | 1.51      | 1.75      | 1.46      |
| CR3              | 1.48          | 1.79                  | 1.33      | 1.53      | 1.39      | 1.36      |
| CR4              | 1.21          | 1.56                  | 1.51      | 1.19      | 1.59      | 0.82      |
| CR5              | 1.66          | 1.42                  | 1.47      | 1.83      | 1.26      | 1.03      |
| CR6              | 1.43          | 1.00                  | 1.62      | 0.88      | 1.08      | 1.17      |
| CR7              | 1.51          | 1.41                  | 1.49      | 1.67      | 1.12      | 1.04      |
| CR8              | 1.26          | 1.52                  | 1.84      | 1.25      | 1.53      | 1.24      |
| CR9              | 1.65          | 1.64                  | 1.33      | 1.68      | 1.42      | 1.10      |
The worth of the individual control rod is calculated to find which rod has high neutron absorption in RDE. The individual rod worth is determined as reactivity difference between the core with the condition of one control rod at fully inserted position and the core with the condition of remaining control rods at fully withdrawn position. In RDE, all rods have the same configuration and are arranged in a circle with the same radius from center of the core, however, their worths in the same case are different as shown in Table 6. The highest worth of individual rod in the wallpaper fueled core are almost greater than that of standard fueled core. Their worth are 1.79, 1.84, 1.83, 1.75, and 1.46 %Δk/k corresponding to CR3, CR8, CR5, CR2, and CR2 for wallpaper fuel design with central graphite radius of 0.6, 1.0, 1.4, 1.8 and 2.2 cm, respectively. The highest worth rod in the standard fuel is CR5 (1.66 %Δk/k).

| Table 7. One stuck rod reactivity (%Δk/k). |
|------------------------------------------|
| Standard fuel pebble                     | 3.86 |
| Wallpaper fuel design, r₁= 0.6 cm        | 3.23 |
| Wallpaper fuel design, r₂= 1.0 cm        | 3.64 |
| Wallpaper fuel design, r₃= 1.4 cm        | 3.78 |
| Wallpaper fuel design, r₄= 1.8 cm        | 3.56 |
| Wallpaper fuel design, r₅= 2.2 cm        | 3.38 |

The simulation of stuck rod condition is usually based on the highest worth of individual rod. In stuck rod condition, the rod worth is calculated as reactivity difference between the core with condition of one highest worth rod at fully withdrawn position and the core with the condition of remaining control rods at fully inserted position. As shown in Table 7, the highest reactivity in stuck rod condition is found to be 3.78 %Δk/k in the wallpaper-fueled core with a central graphite radius of 1.0 cm corresponding to shutdown margin of 1.64 %Δk/k. This result is slightly different from standard fuel worth of 3.86 %Δk/k with a smaller shutdown margin of 1.08 %Δk/k. The stuck rod criterion in all simulation results confirm that, the failure of one rod with highest worth will not prevent the control system from shutting down the reactor.

5. Conclusion
Study on control rod reactivity of small pebble bed reactor with wallpaper fuel design has been performed by means of a number of simulations with MCNP6 code based on ENDF/B-VII library. The simulation results show that the total control rod achieves the best effectiveness on the central graphite radius of 1.0 cm. The highest worth of individual rod in the wallpaper fueled core are almost greater than that of standard fueled core. The stuck rod criterion in all simulation results confirm that, the failure of one rod with highest worth will not prevent the control system from shutting down the reactor. These results conclude that selecting a central graphite radius of wallpaper fuel is one of the strategies to be carefully considered and a radius of 1.0 cm is the best one in controlling reactor safety and ensuring the control system could shut down the reactor safely.

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