Burnup Calculation Study of Pebble Bed Equilibrium Core

L. Suparlina, T. Setiadipura, Suwoto
Center for Nuclear Reactor Technology and Safety, National Nuclear Energy Agency of Indonesia (BATAN), Kawasan Puspiptek Gd. 80, Serpong, Tangerang Selatan, Indonesia

Email: lilyrsg@batan.go.id

Abstract. Reaktor Daya Eksperimental (RDE) is a high temperature gas-cooled reactor (HTGR) producing a 10 MW thermal with a pebble bed fuels which being developed by BATAN. The purpose of this paper is to study the burnup distribution and characteristic in the equilibrium core for different multipass recirculation method. Understanding the reactor physics, in particular the burnup, is important for optimum design and safety analysis of nuclear reactor. Related with the design approval phase of RDE, this study provides a design data which needed for the RDE’s safety analysis report, e.g. fuel pebble performance analysis. Analysis in this study was performed using PEBBED diffusion code. PEBBED is designed to solve the neutronics and thermalhydraulics parameter cases for high temperature pebble bed reactors for different fuel recirculation including once-through-then-out (OTTO) and multipass scheme. The reactor core calculation was performed by applying multipass scheme with variation from 5 passes up to 15 passes. With energy and power as inputs, the calculations produce the burnup fraction at the end of the cycle and the fast and thermal neutron fluxes in 8 energy groups. The calculation results showed that the lowest 5 passes fuel recirculation pattern has the highest and lowest minimum discharged burnup value. This is related to the average power distribution in the core which means more passes will flatter the burnup distribution including the power distribution and also seen in the value of flux and power peaking factor produced.

Keywords: burnup calculation, RDE, equilibrium, PEBBED code

1. Introduction

HTGR with its inherent safety and extensive utilization has abroad application prospect, and it is chosen as one of the promising candidates of the next generation nuclear power system technologies[1][2]. The pebble bed reactor (PBR) nuclear reactor is one of the most powerful reactors with various features. Various designs of this reactor are being developed for immediate commercialization, such as Star Core in Canada, Xe-100 in America.

High temperature gas cooled reactor (HTGR) is one of the six Generation IV reactor concepts that offer promising performance characteristics. This reactor concept generates sustainable energy, offers better proliferation resistance, promises high burn-up operations and large fuel failure margins with excellent fission product retention through the TRISO fuel design. The very high operating temperatures enable the reactor to support industrial process heat application[3][4].
Reaktor daya eksperimental (RDE) is an experimental facility to demonstrate the safety parameters of a nuclear power plant pebble bed type HTR. The attention of nuclear technology and nuclear technology scientists in the world to HTGR has been increasing in the last decade. The inherent safety features and capability of generating energy economically are the main factors that interest many parties to study by developing HTGR. The 10 MW Experimental Power Plant is an HTGR type reactor to be built in the Serpong Puspiptek nuclear area which is planned to operate in 2022.

In designing a nuclear reactor, some neutronic parameter safety analyzes need to be carried out in accordance with safety standards. One of the bases that need to be done is the scenario of the basic accidents of RDE 10MW core design. The HTR-10 reactor core which had been operating in early 2000[5][6] was used as a reference in the analysis of calculation results using So that, it can be believed that the design of the RDE10 MW will meet all the standard of similarity as other HTGRs [5,6]. PEBBED is designed to solve the problem with the equations of diffusion-neutronic-thermal-hydraulics for high-temperature reactors pebble bed fueled. The HTR-10 is built to test and develop fuel, verify the safety features of pebble bed reactors and demonstrate electrical production combined with process heat generation and to provide design, operation and construction experience of pebble bed reactors[7]. The HTR-10 core has a diameter of 180 cm, a mean height of 197 cm and is surrounded by a graphite reflector with a radial thickness of 100 cm and a total axial thickness of 351 cm. A total of 27,000 pebble fuels with U235 enrichment of 17% occupy the reactor core. The HTR-10 core can be operated up to an average burnup of 80,000 MWD / tU.

In this study, a fuel burnup calculation result of equilibrium core, neutron fluxes and power peaking factors parameters is discussed. The purpose is to study the burnup distribution in the equilibrium core for different multipass recirculation method. Calculations are performed using the PEBBED package program. PEBBED is a reactor physics code designed to solve the problem with the equations of diffusion neutronic thermal-hydraulics for high temperature reactors pebble bed fueled. PEBBED also designed, to solve the asymptotic burnup state of pebble bed reactors in conjunction with a generic algorithm to obtain a core with acceptable properties, particularly to simulate the moving core reactor of PBR and able to predict the equilibrium core design of PBR.

2. Methodology

2.1 Core Design and Pebble Fuel

In the initial core, a pebble moderator of pure graphite with a diameter of 3 cm is placed first in the cone located at the bottom of the core. The pebble fuel mixture and the pebble moderator are then loaded from the top of the core gradually with a ratio of 57:43 to the first criticality achieved. A pebble mixture of the same ratio is further loaded into the core to allow the reactor to operate at full power. The full core has a nominal volume of 5 m$^3$. The helium coolant derived from twenty circular canals in the side reflector enters the reactor core following the flow pattern from top to bottom through the sidelines of a randomly arranged pebble pile with 0.61 packing fraction. The main design parameters of RDE can be seen in Table 1.

| Table 1. Main design parameter of RDE[4]. |
|------------------------------------------|
| Reactor thermal power (MW) | 10 |
| Reactor diameter / height (cm) | 180 / 197 |
| Primary coolant pressure (MPa) | 3.0 |
| Average coolant Inlet/outlet temperature (°C) | 250 / 700 |
| Coolant mass flowrate (kg/s) | 4.3 |
| Outlet steam pressure (MPa) | 4.0 |
| Steam generator inlet temperature / outlet (°C) | 104 / 400 |
| Steam flowrate (tons/hr) | 12.5 |
| Number of pebble fuels in equilibriumcore | 27,000 |
| Fuel loading mode | Multi-pass |
The pebble fuel with a diameter of 6 cm is composed of 8,335 TRISO coated fuel particles. Each TRISO particle consists of a UO₂ kernel and four layers of coating. Coating 1: porous carbon buffer, designed to provide space for gas-shaped fission products. Coating 2: inner pyrolytic carbon (iPyC), has a low density and acts as a diffuse barrier for fission products. Coating 3: silicon carbide (SiC), has a high density and becomes a focal strength of fuel particles. Coating 4: outer pyrolytic carbon (oPyC), serves as a protective SiC coating and further diffusion barrier.

The RDE fuel management pattern follows a multi-pass scheme with a pulsed pneumatic fuel handling system utilized for continuous loading and fuel removal. Burnup fuel is individually measured and if it has not reached the desired burn up target, the pebble fuel will be recirculated pneumatically onto the reactor core. Table 2 and Table 3 show the fuel characteristics of pebble and pebble moderators respectively while Figure 1 illustrates the schematic of pebble fuel.

### Table 2. Fuel specification of RDE[4].

| Fuel pebble                                      |
|--------------------------------------------------|
| Pebble diameter (cm)                              | 6 |
| Graphite shell thickness (cm)                     | 0.5 |
| Heavy metal loading per pebble (g)               | 5 |
| Number of coated fuel particles in a pebble      | 8,300 |
| Graphite matrix and graphite shell (g/cm³)       | 1.75 |
| Natural boron impurity in the graphite matrix and graphite shell (ppm) | 1.3 |

**TRISO coated particles**

**Fuel kernel**

Kernel material: UO₂

| Enrichment of U²³⁵ (%) | 17 |
| Kernel diameter (µm)  | 500 |
| Kernel density (g/cm³) | 10.4 |
| Natural boron impurity in the kernel (ppm)  | 4.0 |

**Coating Layers**

Coating layer materials (starting from kernel): C/PyC/SiC/PyC

| Coating layer thickness (µm) | 90/40/35/40 |
| Coating layer density (g/cm³) | 1.04/1.88/3.15/1.88 |

### Table 3. Pebble moderator characteristics of RDE[4].

| Pebble diameter (cm) | 6.0 |
| Graphite density (g/cm³) | 5.0 |
| Natural boron impurity equivalent inside graphite | 1.3 |
2.2 Computation Method

2.2.1. Fuel Modelling
Each TRISO particle consists of a UO$_2$ kernel and four layers of coating. Coating 1: porous carbon buffer, designed to provide space for gas-shaped fission products. Coating 2: inner pyrolytic carbon (iPyC), has a low density and acts as a diffuse barrier for fission products. Coating 3: silicon carbide (SiC), has a high density and becomes a focal strength of fuel particles. Coating 4: outer pyrolytic carbon (oPyC), serves as a protective SiC coating and further diffusion barrier. Table 4, summarizes the densities of the nuclide atoms in the TRISO particles, graphite matrix and identical graphite shell, reflector, helium cooler and the RDE core cavity.

Table 4. Atomic density TRISO particle, graphite matrices, graphite shell and pebble moderator

| Nuclide     | Atomic density (atom/barn-cm) |
|-------------|-------------------------------|
| Kernel      |                               |
| $^{235}$U   | 3.99207E-03                   |
| $^{238}$U   | 1.92445E-02                   |
| $^{16}$O    | 4.64733E-02                   |
| $^{11}$B    | 7.44502E-08                   |
| $^{10}$B    | 1.84964E-08                   |
| Coating 1   |                               |
| $^{12}$C    | 5.51513E-02                   |
| Coating 2   |                               |
| $^{12}$C    | 9.52614E-02                   |
| Coating 3   |                               |
| $^{28}$Si   | 4.77590E-02                   |
| C           | 4.77590E-02                   |
| Coating 4   |                               |
| C           | 9.52614E-02                   |
| Graphite matrix |                             |
| $^{11}$B   | 9.03242E-08                   |
| $^{10}$B   | 2.24401E-08                   |
| Graphite shell |                               |
| C           | 8.67417E-02                   |
| $^{11}$B   | 9.03242E-08                   |
| $^{10}$B   | 2.24401E-08                   |
| Pebble moderator |                             |
| C           | 9.22571E-02                   |
| $^{11}$B   | 9.24878E-09                   |
| $^{10}$B   | 2.28337E-09                   |

Figure 1. Illustration of TRISO pebble bed fuel[8]
The analysis in this study is performed using PEBBED code[8]. PEBBED is a reactor physics code specifically designed to solve for the asymptotic burnup state of pebble bed reactors in conjunction with a genetic algorithm to obtain a core with acceptable properties, particularly developed to simulate the moving core reactor of PBR and able to predict the equilibrium design of PBR. PEBBED is already used for the PBR benchmarking and code-o-code comparison. This code has a neutronic and thermal-hydraulic module, also additional code for spectral zone cross section called COMBINE-7[8][9]. Computational flow chart of the Pebbed code package is given in Figure 2. Provided the power density distribution data of the active core available from the Pebbed neutronic module.

![Figure 2. Computational flow chart of the PEBBED code package[8].](image)

### 2.2.2 Core modelling

The PBR core scheme is shown in Figure 3. The reactor core is fitted with a graphite reflector which also becomes the core support structure. Among the graphite reflectors, there is a control rod channel where there is a control rod that can be vertically shifted according to operational requirements. In general, the PBR core can be controlled with the position of the control rod from outside the core as long as the active core diameter is not more than 3 meters. There is a cold helium channel where cold helium flows from the steam generator unit to the top of the core. Then the helium will flow down on the reactor core to cool down and take heat from the core. Hot helium that has passed through the core, flowing to the steam generating unit through a coaxial hot gas duct. Ball-shaped pebble fuel with a diameter of 6 cm lies on the reactor's porch randomly and moves axially during operation until it exits from the bottom of the core. From the operating side, this fuel scheme allows refuelling even when the reactor is in operation. Geometrically, the core model in PEBBED is simplified given in Figure 3.
Figure 3. A simplified model of RDE in the analyses performed on PEBBEd[8]

The RDE core scheme is shown in Figure 3. The reactor core is fitted with a graphite reflector which also becomes the core support structure. Among the graphite reflectors, there is a control rod channel where there is a control rod that can be vertically shifted according to operational requirements. In general, the PBR core can be controlled with the position of the control rod from outside the core as long as the active core diameter is not more than 3 meters. There is a cold helium channel where cold helium flows from the steam generator unit to the top of the core. Then the helium will flow down on the reactor's core to cool down and take heat from the core. Hot helium that has passed through the core, flowing to the steam generating unit through a coaxial hot gas duct. Ball-shaped pebble fuel with a diameter of 6 cm lies on the reactor's porch randomly and moves axially during operation until it exits from the bottom of the core. From the operating side, this fuel scheme allows refuelling even when the reactor is in operation. Neutronically, this ability makes the reactivity of the core stable[8][10].

3. Results and Discussion
The reactor core calculation was performed by multipass variation model from 5 passes up to 15 passes. With energy and power as inputs, the calculations produce the burnup fraction at the end of the cycle and the neutron fluxes in 8 energy groups. The average and maximum discharged fuel burnup and the average core burnup fraction is shown in Figure 4. and the average fuel burnup fraction for 8 flow channels is shown in Figure 5. The reactor which operates at a certain power and cycle length, there will be a change in power distribution and neutron flux in the fuel position which will cause a change in the fuel burnup fraction. The axialthermal neutron flux distribution at the core center position for 5 multipass recirculation is shown in Figure 6, while the correlation of axial flux distribution and power distribution is shown in Figure 7.
Figure 4. Average and maximum discharge burnup of pebble bed equilibrium core for various circulations method.

Figure 4 shows that the scheme with recirculationless fuel will decrease the level of fuel fraction obtained. The maximum discharged and average core fuel burnup are between 69.196–72.34 MWD/kghm, and 38.68 – 38.85 MWD/kghm respectively. The 5 passes recirculation has the highest maximum discharge fuel burnup 72.34 MWD/kghm, while the 6 passes circulation shows the highest at the average core fuel burnup 38.85 MWD/kghm. Figure 6 shows the radial discharged burnup fraction of pebble fuel in 8 fuel flow zones for fuel loading recirculation 5, 7, 9, 11 and 15 passes. PEBBLED performs a two-dimensional core calculation R-Z direction, so the determination of the fuel zone starts from the middle of the core to the outside. It is seen that the lowest 5 passes fuel recirculation pattern has the highest and lowest minimum discharged burnup value. This is related to the average power distribution in the core which means more passes will flatter the burnup distribution including the power distribution[9].

Figure 5. Radial discharge burnup distribution for different multipass circulation.
Figure 6 presents the axial thermal neutron flux for different active core distance. It is shown that the highest thermal neutron flux is at 63 cm from the core center and the lowest is at the outer core. The correlation of power distribution, thermal neutron flux and fuel burnup as presented in Figure 7 showed that the higher the flux, the higher the power density and the higher the fuel burnup in equilibrium core.

4. Conclusion
The result of RDE fuel burnup calculation using a multipass method using pebbled program package shows that the lowest 5 passes fuel recirculation pattern has the highest and lowest minimum discharged burnup value. This is related to the average power distribution in the core which means more passes will flatter the burnup distribution including the power distribution and also seen in the value of flux and power peaking factor produced.

Acknowledgements
The authors would like to thank Manager and staffs of Reactor Physics and Technology Division, Director of PTKRN-BATAN for giving support in the implementation of this study. This research was funded by the INSINAS-Flagship – Kemenristekdikti program in 2018.

References
[1] Zhang Z, Wu Z, Wang D, Xu Y, Sun Y, Li F and Dong Y 2009 Current status and technical description of Chinese 250 MWth HTR-PM demonstration plant Nucl. Eng. Des.239 1212–9
[2] Li J, She D and Shi L 2018 Burnup characteristics analyses of graphite impurities in HTGR fuel element Ann. Nucl. Energy118 165–9
[3] Kadak A C 2016 The Status of the US High-Temperature Gas Reactors Engineering2 119–23
[4] Terry W K, Kim S S, Montierth L M, Cigliati J J and Ougouag a. M 2006 Evaluation of the HTR-10 Reactor as a Benchmark for Physics Code QA Physor 2006 Paper D113
[5] IAEA 2013 Evaluation of High Temperature Gas Cooled Reactor Performance: Benchmark Analysis Related to the PBMR-400, PBMM, GT-MHR, HTR-10 and the ASTRA Critical Facility vol 53
[6] IAEA 2008 Accident analysis for nuclear power plants with modular high temperature gas cooled reactors Saf. Reports Ser. 54
[7] Au werda G J, Kloosterman J L, Lathouwers D and Van Der Hagen T H J J 2010 Effects of random pebble distribution on the multiplication factor in HTR pebble bed reactors Ann. Nucl. Energy 37 1056–66

[8] T. Setiadipura, D. Irwanto Z 2015 Preliminary Neutronic Design of High Burnup OTTO Cycle Pebble Bed Reactor Atom Indonesia 41 7–15

[9] Topan Setiadipura, Jupiter S. Pane Z 2016 Jurnal Pengembangan Energi Nuklir Studi Awal Desain Pebble Bed Reactor Berbasis HTR-PM Dengan Resirkulasi Bahan Bakar Once-Through-Then-Out 18 59–65

[10] Peng Hong LIEM, Hoai-Nam TRAM, Tagor Malem SEMBIRING, Bakri ARBIE I S 2017 Alternative Fueling Scheme for the Indonesian Experimental Power Reactor ScienceDirect Fueling Scheme for the Indonesian Experimental on District Heating and Cooling Power Reactor (10 MWth Pebble-Bed HTGR) Assessing the feasibility Energy Procedia 131 69–76