Preliminary Design Study of Small Power 30-50 MWt Experiment Power Reactor based on High Temperature Pebble Bed Gas Cooled Reactor Technology

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Abstract. Pebble Bed Reactor (PBR) is one of the most promising nuclear power plant. It has advantages in terms of high thermal efficiency, economic and its safety features. To build an experimental power reactor based on PBR technology, it is important to understand all the aspects related to the neutronic, thermal hydraulic and safety features of this reactor type. In the present study, a set of calculations have been performed to find characteristics of selected parameters of the PBR design that significantly contributed to the neutronic aspect, such as number of uranium enrichment, pebble fuel speed, fuel loading scheme and burnup. Calculation and analysis was performed for 30 MWt and 50 MWt power.

1. Introduction

Recently, nuclear power generation is an established part of the world's electricity mix providing a significant portion of world electricity. Continuous improvement to the reactor designs resulting Generation IV reactors (Gen IV) as a set of theoretical nuclear reactor designs that currently under intensive research in the world. Many reactor types were considered initially but the list was downsized to focus on the most promising technologies. These systems offer significant advances in safety and reliability, proliferation resistance, sustainability and economics.

The Very High Temperature Reactor concept utilizes a graphite-moderated core with outlet temperature of around 1000 °C is also one of the Gen-IV reactor that being researched. The high temperatures enable applications such as hydrogen production, desalination of sea water and some other industrial processes. The reactor core can be either a prismatic-block or a pebble bed reactor design. The Pebble Bed Reactor (PBR) has three fuel loading scheme: Multipass, Once Through Then Out and Peu a Peu or accumulative fuel loading scheme which have good neutronic aspect for both using uranium or thorium fuel [1-3].

Pebble bed reactor considered as a safety system because of the low power density of the reactor, which means that the amount of energy and heat produced is volumetrically low. The use of large amount of graphite as a moderator and reflector make this system has high heat capacity. Moreover, it is expected that natural mechanisms to remove the heat such as conductive and radiative heat transfer will works even if no convective core cooling is provided. This becomes important because the
temperature that is reached in a case of loss of coolant accident is far below the fuel damage threshold temperature and it takes long time to reach the peak temperature. So, that fuel damage will not occur and the core will not melt even in a severe accident [4].

Indonesia is now considering to build an Experiment Power Reactor based on PBR technology. In order to master this technology, it is important to understand all the aspects related to the neutronic, thermal hydraulic and safety features of this reactor type. The purpose of the present study is to analyze characteristics of selected parameters of the PBR design that significantly contributed to the neutronic aspect, such as number of uranium enrichment, pebble fuel speed, fuel loading scheme and burnup. Calculation and analysis are performed for 30 MWt and 50 MWt power.

2. Calculation Methods and Model

Pebble Bed Reactor has unique design and characteristic compared to other types of reactor. To accurately calculate Pebble Bed Reactor system, one have to consider double heterogeneity of PBR. The first heterogeneity is the randomly distributed coated fuel particle inside a pebble fuel ball. This pebble fuel balls itself are then randomly distributed inside the reactor core, that make it the second heterogeneity. A suitable computational method to simulate this system is the continuous energy Monte Carlo Method. This method can deal with reactor systems which have double heterogeneous structure. In Monte Carlo simulation of particle transport in the region where spherical fuel element exists, a particle enters a spherical fuel element, penetrates it and enters the next spherical fuel element. The whole particle transport history is made up of these basic processes. Therefore, it is not necessary to know the locations of all spherical fuel elements at the same time in the calculation. The position of the fuel particles itself is determined probabilistically from the Nearest Neighbor Distribution (NDD) in the process of the random walk. Those methods are implemented in the MVP/MVP-BURN code with JENDL 3.3 as nuclear data library which are used in this research. [5-7]

A reference design based on HTR-10 are implemented in the calculation [8]. In the present step, simplification to the actual reactor was done by created a cylindrical core loaded by pebble fuel ball. Figure 1 shows calculation model of the small Pebble Bed Reactor.

![Figure 1. Calculation Model](image)

Specification of the reactor core design is shown in Table 1. The core is 197 cm high with 90 cm radius. 180 cm of it height is filled with pebble fuel balls with homogen uranium enrichment. Parametric survey was performed for pebble bed fuel with uranium enrichment between 7% to 20%.
Table 1. Reactor Design Specification

| Design Specification |       |
|----------------------|-------|
| Reactor Power        | 30    |
|                      | 50    |
| Fuel                 | TRISO |
| Core radius          | 90    cm |
| Core Height          | 197   cm |
| Reflector width      | 100   cm |
| Uranium enrichment   | 7-20% |
| U loading            | 5     gram |

Number of uranium loaded per one ball set to be constant at 5 grams for each ball and enrichment. TRISO fuel configuration is used and its detail configuration including material and density of each layer is shown in Table 2.

3. Calculation Results and Analysis
Calculation are performed to investigate important parameters that affect neutronic characteristics of the reactor design. Uranium enrichment are varying from 7-20% for each reactor configuration with five bulk fuel loaded in the reactor core. Uranium enrichment effects to criticality of the reactor then examined for different approximated pebble fuel speed of 0.5, 0.75 and 1.0 cm/day through the reactor core to see its effects.

![Figure 2](image)

Figure 2. Characteristic of pebble fuel speed (1.0, 0.75 and 0.5 cm/day) with five passes fuel loading scheme and 7-20% uranium enrichment needed for 30 MWth power

Figure 2-3 shows characteristic of several aspects that contribute to neutronic parameters: number of uranium loaded to the pebble fuel and pebble fuel speed with five passes fuel loading scheme.
From series of performed calculations, one could understand that for five passes fuel loading with 1.0 cm/day fuel ball speed, minimum uranium required is 14% for 30 MWt power reactor. For the same configuration of 30 MWt power and five fuel ball passes, if fuel ball speed decreased to 0.75 cm/day then minimum uranium enrichment required increased to 15%. If fuel ball speed through reactor core further decreased to 0.5 cm/day, one would need 19% of uranium enrichment for the same 30 MWt power.

With the same scheme for 50 MWt, fuel speed of 0.5 cm/day had to have more than 20% of uranium enrichment. For 0.75 and 1.0 cm/day fuel ball speed, it is required 20% and 17% uranium enrichment, respectively.

Furthermore, it is also important to examined number of burnup for each reactor configuration with minimum uranium enrichment obtained from the previous analysis. Figure 4-5 shows the results of burnup and number of fissile material (U-235) used for each reactor configuration.

Figure 3. Characteristic of pebble fuel speed (1.0, 0.75 and 0.5 cm/day) with five passes fuel loading scheme and 7-20% uranium enrichment needed for 50 MWth power

Figure 4. Effect of fuel speed (0.5, 0.75 and 1.0 cm/day), uranium enrichment for five fuel passes loading scheme of 30 MWt power
Figure 5. Effect of fuel speed (0.5, 0.75 and 1.0 cm/day), uranium enrichment for five fuel passes loading scheme of 50 MWt power.

From performed calculation for different fuel speed of 1.0, 0.75 and 0.5 cm/day and minimum uranium required for each reactor configuration with 30 MWt power, one could get burnup of 41.7, 55.6 and 83.5 MWD/ton, respectively. Each of these reactor configurations also will burn 35.1, 43.4 and 51.4% U-235 as fissile material. For 50 MWt power with 1.0 cm/day speed and 20% uranium enrichment, burnup will be 69.5 MWD/ton and 47.8% fissile burned; meanwhile for 0.75 cm/day and 17% uranium enrichment, it will be 92.7 MWD/ton and 54.2% depleted U-235.

4. Conclusion
Parametric survey and design for small Pebble Bed Reactor have been performed in the present study for 30 and 50 MWt power by considering fuel speed and uranium enrichment for five passes loading fuel through the reactor core. Based on parametric surveys performed in the present study, considering uranium enrichment and fuel economics, configuration of reactor core with 15% enrichment and 0.75 cm/day for 30 MWt; 20% enrichment and 0.75 cm/day for 50 MWt have relatively good characteristics. From series of performed calculations, in general one could understand that faster fuel ball speed will required lower uranium enrichment but it will have relatively poor fuel economic. At the other hand, from the calculation it is shown that slower fuel ball speed will required higher uranium enrichment and resulting in relatively higher fuel economic for the same number of fuel passes.

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