Neutronic Analysis of Lead208-Bismuth Eutectic-Cooled Modified CANDLE Reactor with Core Geometry Variations

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Abstract. Lead208-Bismuth Eutectic (LBE)-cooled reactor is one of the Generation IV reactors. The fourth-generation has several objectives: economic competitiveness, inherent safety, minimize radioactive waste, and non-proliferation. Modified CANDLE burnup scheme is one solution to fulfil these objectives. The scheme does not need fuel enrichment and reprocessing Pu from LWR. Lead208-Bi eutectic was employed as a coolant of the reactor due to its low neutron absorption cross-section. However, it is necessary for surveying the neutronic core design. In this study, we compared the core neutronic among the variations of core geometry with equal volume of Pb208-Bi eutectic-cooled Modified CANDLE reactor. The calculation is performed by PIJ and CITATION of SRACs module. The Pancake cylindrical (larger diameter) has the highest K-eff and the lowest-peaking factor among of balance and tall cylindrical.

Keywords: Generation IV, Lead208-Bi eutectic, Modified CANDLE, neutronic, core geometry, pancake cylinder, balance cylinder, tall cylinder.

1. Introduction

Six reactor designs have been selected to be Generation IV reactors. The six designs are VHTR (Very High-Temperature Reactor), SFR (Sodium Fast Reactor), SCWR (Super Critical Water Reactor), GFR (Gas Fast Reactor), LFR (Lead Fast Reactor), and MSR (Molten Salt Reactor). Currently, Generation IV is still in the Research and Development stage. There are several objectives of Generation IV, economic competitiveness, inherent safety, minimizing radioactive waste, and non-proliferation. There are several studies about the burnup scheme of the reactor design to fulfil the objectives of Generation IV. Three of them are CANDLE reactor (Sekimoto, 2006), modified CANDLE (2010), and breed and burn reactor (Zheng et al, 2016).

One of the burnup schemes which is quite interesting is the modified CANDLE scheme in the eutectic Pb-Bi cooled fast reactor. The reactor can operate in a critical condition even though it utilizes natural uranium as fuel directly. (Zaki, 2010). Initially, the modified CANDLE burnup scheme only divided the core in the axial direction into several regions with equal volume. However, current studies have been performed to divide the core in the axial and radial direction (Zaki, 2017). The modified CANDLE design in the axial and radial directions provides better neutronic performance than only in the axial
direction (Zaki, 2017). The larger the reactor size, the more fuel is available, hence, the reactor criticality value will increase. However, if the volume remains equal but the core geometry is different, will it have a significant impact on neutronic performance in reactors with the burnup scheme.

In this study, neutronic performance on each core with the equal volume but different geometries will be performed. It is to determine the effect of core geometry on modified CANDLE burn schemes in the axial and radial directions.

2. Modified CANDLE burnup scheme
Modified CANDLE burnup scheme is a slight modification of the CANDLE burnup scheme. Initially, the core is divided into axial and radial directions with equal volume. Figure 1 shows the CANDLE burnup scheme and figure 2 shows the modified CANDLE burnup scheme.

![Figure 1. CANDLE Burn up Scheme](image1)

![Figure 2. Modified CANDLE axial-radial reshuffling combination scheme.](image2)
CANDLE reactor divided core into two regions in the axial direction. The lowest region is filled up with natural uranium or depleted uranium while the upper region is filled up with enriched uranium or LWR spent fuel. The modified CANDLE axial-radial scheme divides the core into twenty regions. The first Region is filled with natural uranium. After 10 years burnup, it is moved on to the second region then fuel from the second region is moved on to the third region and it is applied to all regions.

One of the interesting topics of this scheme is the effect of core geometry on the neutronic aspect. In this study, the significant impact of core geometry to the neutronic aspect will be analysed. We compared the neutronic performances of three considerable core geometry with equal volume. They are pancake cylinder, balance cylinder and tall cylinder. The types of core geometry are shown in figure 3.

![Figure 3. Core geometry variations with the equal volume](image)

3. Computational method
In this paper, the calculation was performed by SRAC2006 and JENDL 4.0 was used as nuclear data. First, we used PIJ to calculate pin cell burn up with the collision probability method. From this calculation, we obtained eight energy groups macroscopic cross-section data. Then, the data is used to solve the diffusion equation for the core with CITATION. (Zaki, 2010).

4. Results and discussion
Table 1 shows the list of reactor design parameters used in this study. The reactor core volumes for all three geometries are equal.

| Parameter                        | Specification               |
|----------------------------------|-----------------------------|
| Thermal Power                    | 300 MWt                     |
| Refueling                        | 10 Years                    |
| Cladding Material                | HT-9 (2048)                 |
| Coolant Material                 | Pb-208 dan Bi eutectic      |
| Fuel Material                    | UN (15N 100%)               |
| Fuel-cladding-coolant volume Fraction | 60%-12.5%-27.5%         |
| Pin fuel geometry                | cylindrical                 |
| Core Volume                      | 6084571.43 cm³             |
| Core geometry                    | cylindrical                 |
| Pin pitch (cm)                   | 1.3                         |

Some core parameters that have been compared are the value of effective multiplication factor (k-eff), neutron leakage, neutron loss, and peaking factor.
4.1. The Effective Multiplication Factor (k-eff)

Figure 4 shows k-eff value of the reactor for 10 years. The core reactor with pancake cylinder geometry has the highest k-eff among all and the tall cylinder is the lowest. Initial k-eff for pancake, balance and tall core are 1.010, 1.004, and 1.002, respectively. It means core geometry has a significant effect on the k-eff. The reactor can operate for ten years for all geometries of the same volume.

4.2. Neutron leakages and losses

It can be explained by the number of neutrons leakage from the core and the neutrons losses on the core in figures 5 and 6. Figure 5 shows the number of neutron leakage from the core. The tall cylinder has the highest neutron leakage from the core and the lowest for the balance reactor. It is one of the advantages of a balance cylinder reactor, voids reactivity can be reduced by neutron leakage. (Ishiguro, 2017).

Figure 6 shows the number of neutron losses from the core for different core geometry. Tall cylinder core has the highest total neutron losses among all, and the pancake cylinder core is the smallest one. Neutrons loss in the core due to absorption and leakage. Hence, a tall cylinder core has the smallest k-eff.

Figure 6. the number of neutron losses from the core for different core geometry.

4.3. Peaking factor (Fq)
Table 2 shows the peaking factor value for different core geometry at the beginning of the cycle (BOC) and the end of the cycle (EOC). Peaking factors are necessarily related to nuclear safety. Decreasing power peaking factor also decreased the PCT (peak cladding temperature). The pancake cylinder has the smallest Fq value among all. It is recommended to using the pancake cylinder geometry to obtain more advantages, such as higher k-eff (related to neutron economy) and more safety for Modified CANDLE burnup scheme.

Table 2. shows the peaking factor value for different core geometry at the beginning of life (BOL) and end of life (EOL).

| Core geometry  | Pancake cylinder | Balance cylinder | Tall cylinder |
|----------------|------------------|------------------|--------------|
| Time           | BOL              | EOL              | BOL          | EOL          | BOL  | EOL  |
| Peaking Factor | 4.487            | 4.523            | 4.564        | 4.677        | 4.637| 4.889 |

5. Conclusions
We have compared some neutronic aspects of the reactor with core geometry variations. The pancake cylinder (larger diameter) has the highest K-eff among of all fuel material However, the balance cylinder is the lowest number of neutron leakage. The tall cylinder core has the highest total neutron losses among all, and the pancake cylinder core is the smallest one. The pancake cylinder core also has the lowest-peaking factor. The lower Peaking factor decreases the peaking cladding temperature (PCT) (related to reactor safety). Based on the results obtained, for the modified CANDLE scheme an optimum result will be obtained if the core geometry is a pancake cylinder or more "flat".
Acknowledgement
This research was supported by Nuclear and biophysical research of physics department ITB 2018 and 2019

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