Full Core Optimization of Small Modular Gas-Cooled Fast Reactors Using OpenMC Program Code

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Abstract. Indonesia has many small regions and islands with low electrification ratio that needs small power plants. Gas-cooled Fast Reactors (GCFR) is one of the fourth generations of an advanced nuclear power plant with an improved safety system and optimum electricity production that match Indonesia’s energy needs. The neutronic analysis study and optimization of small modular GCFR has been performed with Monte Carlo method OpenMC code that use computational parallelization to speed up calculation time. The full core reactor design is cylindrical with a radius 100 cm and height is 120 cm. Additional 50 cm of radius and 40 cm for the height for the reflector. The core using several types of fuel composed of natural Uranium mixed with spent fuel Plutonium. The variation in fuel fraction pin and percentages of Plutonium in fuel to achieved optimum core design. The design of core reactor has flattened flux and power distribution.

1. Introduction

Technological developments in producing electricity are important factors in solving world problems today. The increasing number of the world’s population will directly increase the world's energy needs. But this energy source technology must be limited to the security of the community and the surrounding environment. Especially in Indonesia with a low electrification ratio, so that it requires a large but flexible power plant because Indonesia has many remote islands. These remote islands need a power plant with little electrical power up to a hundred MWe [1-2].

Nuclear power plants (NPPs) are one solution to the problem of energy shortages. This plant utilizes fission reactions in fissile material whose numbers are still many in the world. Now nuclear power plants have achieved technology with the fourth generations that is designed to have a security system, energy production, burn-up, and economic factors that are better than the previous generation. Gas-Cooled Fast Reactor (GCFR) is one of the fourth generations of NPPs design which operate in high temperature using helium gas as a coolant [4-6]. The small modular reactor design can achieve better safety and economy factor. In this research, the reactor uses natural uranium mixed with Plutonium as fuel to reduce cost production of uranium enrichment and also for proliferation factor [7].
In this research, a parameter study was carried out on Gas-cooled fast reactor with small modular design, using several types of fuels and ratio of volume fuel to cell pins. The neutronic calculation using the OpenMC program code. The OpenMC program [8] is developed by members of the computational physics reactor (CRPG) group at the Massachusetts Institute of Technology (MIT) since 2011. This program simulates neutron characteristic in reactors using Monte Carlo method and using a continuous cross-section energy library. Thus, the purpose of this research to design small modular reactors with survey parameter to obtain optimum results in neutronic analysis, which is evenly distributed flux and power distribution.

2. Calculation Method

In the calculation of neutronic analysis, parameters such as effective multiplication factor (K-eff), flux, and powers are important factors in designing nuclear reactors. Therefore, these parameters will be obtained through parameter survey study using the OpenMC program.

![Figure 1 Geometri Pin Sel Hexagonal](image)

Figure 1 show the geometry of the pin using hexagonal cell design and three sub-region area which is fuel, gap, and coolant. In this study, the value of the pitch pin was fixed. Figure 2 shows the design of the assemblies on the reactor core at vertical and horizontal cross views. Total assembly at the reactor is 127 assemblies, while the total one pin on the assembly is 127 pins. This number is quite small because the design we want to achieve is a small modular reactor.

![Figure 2 Configuration of assembly in reactor core in XY dan ZY plane](image)

In the Parameters design, variety of the fuel fraction and type of fuel was carried out. Using different nuclide fissile percentages in a different type of fuels to show the criticality of core and flattening power and flux distribution. The design geometry and calculation neutronic analysis were performed using computing OpenMC code program with parallelization method. Data nuclides provided by library ENDF/B-VII.1.
3. Results and Discussion

Table 1 displays the general parameters of the reactor core design with survey parameters on the type of fuel that can be seen in table 2, the fuel fraction of the cell pin in table 3, and the division of regions in the reactor to obtain a uniform flux and power distribution in table 4.

Table 1 the design parameter if the core reactors

| Parameter                  | Value                      |
|----------------------------|----------------------------|
| Reactor geometry           | Small cylindrical modular  |
| Fuels type                 | Mixed Uranium-Plutonium*    |
| Coolant type               | Helium gas                 |
| Assembly geometry          | Hexagonal                  |
| Pin and assembly layers    | 7                          |
| Assembly height            | 120 cm                     |
| Cladding material          | Stainless steel HT9        |
| Reflector material         | ZrSi₂                      |
| Plutonium percentages (%)  | 10-20                      |
| Volume fuel fraction (%)   | 40,50,60                   |

3.1. Variation of fuel type

Table 2 is a detailed parameter of the type of fuel used in this study. This data is taken from The GEN IV GCFR: Status of Studies, Pioneering Science and Technology [10].

Table 2. General parameters of the design core reactor [10]

| Pu 20% in U-Pu | MOX (U-Pu)₂ | Caride (U-Pu)C | Nitride (U-Pu)N | Metallic (U-Pu)Zr |
|----------------|-------------|----------------|-----------------|-------------------|
| Theoretical density (g/cm³) | 11          | 13.6           | 14.3            | 15.6              |
| Heavy atom density (g/cm³)   | 9.75        | 12.95          | 13.53           | 14                |
| Melting conductivity (°C)    | 2430        | 2420           | 2780            | 1080              |
| Thermal conductivity (W/m²k) | 2.9         | 16.5           | 14.3            | 14                |
3.2. Variation of fuel fraction

![Figure 3 Configuration of assembly in reactor core](image)

For survey parameters on fuel fraction, the geometry design of assembly can be seen in figure 3 above. It is seen that when the fuel fraction is raised, the pin cell was expanded and tightly the assembly because the volume of the pin also increases, therefore the fuel area was also increasing inside the assemblies. The detailed survey parameter for radius in each region in pin for different fuel fraction can be seen in table 3 below.

| Radius region in mm | Fuel fraction 40% | Fuel fraction 50% | Fuel fraction 60% |
|---------------------|-------------------|-------------------|-------------------|
| Fuel                | 4.25              | 4.75              | 5.205             |
| Gap                 | 4.276             | 4.78              | 5.232             |
| Cladding            | 4.751             | 5.31              | 5.581             |

![Figure 4 K-eff changes with an increase of Pu percentages, a variation of fuel fraction pin using MOX fuel](image)

![Figure 5 K-eff changes with an increase of Pu percentages, a variation of fuel fraction pin using carbide fuel](image)
Figure 4 shows changes in the K-eff value of reactor core, with the addition of the percentage of Plutonium from 10% to 20% in MOX fuel type, the addition of Plutonium’s percentages increases the value of k-eff. In the case of fuel fraction, the addition of the fuel fraction also increasing the keff value for all the percentages of Pu. In MOX fuel case, the reactor reached critical condition with the minimum value at 40% fuel fraction and 13% of Plutonium percentages.

Figure 5 shows changes in the K-eff value of reactor core with the same parameters as before but with carbide fuel type. With fuel fraction value at 40% and 11.5% of Plutonium percentages, the reactor reached the critical condition. The same pattern also appeared in case of nitride fuel type as shown in figure 6. The optimal value for critical condition of core reached when the reactor used 11.8% of plutonium. For the case of metallic fuel in figure 7, 10.5% of Plutonium was the minimum value for the reactor to reach it is critical.

Figure 8 shows the result of comparison between all type of fuels with fixed fuel fraction at the value of 40%. The metallic fuel (U, Pu)Zr gives the highest K-eff value compared to other fuels with a high enough difference, while the lowest K-eff value is obtained when using MOX fuel. It is seen that the value of K-eff is related to the density of each fuel. Seen in table 2, metallic fuel has the highest density while MOX fuel with the lowest density.
3.3. Variation of full core design

To obtain an evenly distributed flux and power distribution of the full core, a study parameter design was conducted. The core was divided into three regions in radial course where each region had a difference in the percentage of Plutonium. Seen in figure 9, the first region was placed at the center of the core, the middle region was the second region, and the outer area was the third region. The number of assemblies in the outer region is far more than the inner region.

Table 4 variation of percentages Plutonium each region

| % of Pu | Model I | Model II | Model III | Model IV |
|---------|---------|----------|-----------|----------|
| Region 1 | 11      | 15       | 15        | 13       |
| Region 2 | 13      | 13       | 11        | 11       |
| Region 3 | 15      | 11       | 13        | 15       |

Table 4 shows the percentage of Plutonium used in each region on the reactor core. Survey parameters are done by making several models with different settings, which is the difference for a percentage of Plutonium in each region.
Figure 10 shows the results of the flux distribution and fission rate on the reactor core without the division of regions. The Flux value shown in the figure is the total flux value for the entire assembly. Fission rate here can be interpreted by the total power in assembly, namely the core power obtained by multiplying the desired total power reactors with the power distribution. Seen in the picture of the case without dividing the terrace. There is a less uniform distribution of power and flux, where the center area of the core has a big difference in power compared to the edge of reactor. The maximum value of flux is around 0.01 and a fission rate is around 3.5E-5.
Figure 11 shows the results of the distribution of flux values in the case of survey parameters for full core design. The surveys are divided into four models which details can be seen in table 4. In this case, the core used 11%, 13%, and 15% of Plutonium in region I, II, and III respectively. With the same survey parameter as the previous case but different percentages of Plutonium, figure 12 shows the flux distribution but with 15%, 13%, and 11% of Plutonium. The most Plutonium percentage is in the center of the core, contrasts with figure 11.

Figure 13 shows the results of flux distribution in the core, with the percentages of plutonium in region I, II, and III are 15%, 11%, and 13% respectively, where the least Plutonium percentage is in the middle region of the core. Figure 14 shows the results of flux distribution in the core with same parameters as figure 13, but with most percentages for Plutonium was located in outer region.

The best model is obtained in model I with the percentage of Pu in regions I, II, and III are 11%, 13%, and 15% respectively. Seen in a model III, by putting the smallest percentage in the middle of region, which has the least number of assemblies, it will reduce the maximum power in the middle of the reactor. For the outer region with the most number of assembly, the highest percentage of Pu is given to get evenly distributed flux even on the edge of the reactor. Model II gives the highest peak of flux by 0.012.

Figure 15 shows the results of the distribution of fission rate values in the case of survey parameters for full core design. There are similarities in the case of flux distribution as before. The most evenly power distribution is obtained in a model I with the highest fission rate of 2.5E-5. This result gives good results for a reactor safety system where the power peak is low in the middle of the reactor. Region II as can be seen in figure 16, has the highest value of power peak comparing to the other model. Figure 17 also give the same results as figure 16, with more uniformly in the middle and outer region but has low peak. Figure 18 on the other hand, gives a good result almost the same as figure 15 but has lower power peak in middle region.

4. Conclusion

Design study of full core optimization of small modular gas-cooled fast reactor using Monte Carlo parallelization method with OpenMC program has been performed. The reactors are small, modular type with helium gas as a coolant, with hexagonal assembly and design. Using variation in fuel type, percentages of Plutonium, and the size of pin cell to achieve critical core. The core divided by three regions with different percentages of Plutonium to obtain a flat distribution of flux and power. In this research, 40%, 50%, and 60% fuel fraction pin with 10-20% percentages of Plutonium in a different type of fuel have been discussed. A higher value of the fuel fraction will obtain higher K-eff that has
been shown in figure 4 to figure 7. Metallic fuel (U, Pu)Zr fuel shows optimum K-eff of full core which has the highest value of K-eff. The increased percentages of fuel fraction will also increase the K-eff value of all types of fuel. The most uniform of flux and power distribution for the case in all model in the core was achieved with 11%, 13%, and 15% of Plutonium in region I, II, and III respectively that has been shown in figure 11 and figure 15 in model I.

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