Neutronic Analysis of Modular Gas-cooled Fast Reactor for 5-25% of Plutonium Fuel using Parallelization MCNP6 Code

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Abstract. Modular Gas-cooled Fast Reactor (GFR) is one of six advanced reactor concepts set by the generation IV international forum. Modular GFR has the potential for use actinide recycling and closed fuel cycle as well as applying fast reactor, using helium gas as the main coolant, high working temperature and low void reactivity effect. The neutronic analysis of nuclear reactor means behavior study of subatomic particles that interact with matter. In this paper, the feasibility of plutonium fuel in modular Gas-cooled Fast Reactor (GFR) was investigated. The Monte Carlo method has advantages in full-scale and heterogeneous three-dimensional (3D) geometry modeling using Evaluated Nuclear Data File (ENDF/B-VIII.b5) nuclear data but requires a highly computation time. Since the progress of high performance computing, the reactor physicist community began proposing to use Monte Carlo method for nuclear reactor simulation through the parallelization of calculations. The GFR feasibility design study will carried out with plutonium fuel as fuel cycle inputs with 5-25% of fissile contain. The most important neutronic parameters characterizing of GFR core are determined for beginning of life (BOL) and during burnup calculation conditions. The results of calculation series in parallel computing give the good agreement will be faster of calculation time when more threads. Materials of (U-Pu)C and (U-Pu)N fuel are the good candidates to be chosen in GFR research that give keff more than 1.2 in fissile contain 20%Pu. The variation fissile contain gives the linearity with keff. In depletion simulation, the core reactor still in critical during 20 years operation, burn up values linear with operation time and mass evolution of plutonium and uranium from start-up core to equilibrium core.
1. Introduction

The Gas-cooled Fast Reactor (GFR) was selected by the generation IV international forum as one of six advanced reactor concepts for further investigation and possible future development (GIF, 2014). The modular reactors are very prospective for remote areas in Indonesia with small to medium power consumption levels. The modular GFR has the potential for use actinide recycling and closed fuel cycle as well as applying fast reactor can utilize the natural uranium during operation as the fuel, using helium gas as the main coolant, high working temperature and low void reactivity effect (Zaki Su’ud, 2017; Zaki Su’ud, 2013). The main advantages of modular GFR compare another advanced reactor concept is using helium gas as main coolant (Poette, 2015; R. Stainsby, 2011) due to necessity of understanding of GFR fuel design through simulation and modeling. The advantages for the GFR included favourable properties related to safety, sustainability, economics, proliferation resistance that are declared in the GIF (GIF, 2014).

The neutronic analysis of nuclear reactor means behavior study of subatomic particles that interact with matter. The development of modular GFR concept includes neutronic analysis of fuel pin, assembly and core of GFR to determine quantitatively of the particle behavior is needed the understanding about particle interaction through simulation of moving particle and mathematical description of particle distribution time dependent. The approach to determine particle distribution using the Monte Carlo method has profit in realistic 3D geometry modeling but needs high time computing (Romano, 2013). In this analysis, the investigation of several crucial aspects of modular GFR such types of material fuel and percentage of fissile contain include the capability understanding of parallelization of MCNP6 code. The research goal is to determine characteristic of plutonium fuel as fuel cycle inputs in modular gas-cooled fast reactor. The design study used the MCNP6 (Monte Carlo N-Particle) code is based on the Monte Carlo method for criticality calculation and capable of simulating complex physical phenomenon in the detailed 3D model and continuous energy cross section representation. Description of the fuel pin, assembly and core shown in table 2, figure 1, figure 2, and figure 3 respectively, these figures was generated by Vised MCNP that the fuel is a cylindrical rod region, the gap is an annular region cylindrical region that is empty and surround the fuel, the cladding is an annular cylindrical region that is a barrier for the dispersion of fission product and coolant is the outermost region that surrounds the cylindrical rod and has a hexagonal outer surface.

2. Design and Calculation Method

The modular GFR system combined the advantages of fast spectrum system with long-term availability of fuel and waste minimize through fuel reprocessing and fission products of long live actinide (R. Stainsby, 2011). In table 1. Presented fuel assembly characteristics of GFR reactor system that is analyzed. We used the MCNP6 (Monte Carlo N-Particle) code is based on the Monte Carlo method for criticality calculation and capable of simulating complex physical phenomenon in the detailed 3D model and continuous energy cross section representation. Description of the fuel pin, assembly and core shown in table 2, figure 1, figure 2, and figure 3 respectively, these figures was generated by Vised MCNP that the fuel is a cylindrical rod region, the gap is an annular region cylindrical region that is empty and surround the fuel, the cladding is an annular cylindrical region that is a barrier for the dispersion of fission product and coolant is the outermost region that surrounds the cylindrical rod and has a hexagonal outer surface.
### Table 1. Fuel Basic Cell Characteristic

| Parameter           | Fuel         | Gap            | Cladding       | Coolant       | Cell          |
|---------------------|--------------|----------------|----------------|---------------|---------------|
| Geometry            | Cylindrical rod | Cylindrical tube | Cylindrical tube | Hexagonal prism | Hexagonal prism |
| External radius (cm)| 0.4256       | 0.4285         | 0.4785         | -             | -             |
| Apothem (cm)        | -            | -              | -              | 0.64          | 0.64          |
| Side (cm)           | -            | -              | -              | 0.74          | 0.74          |
| Height (cm)         | 120          | 120            | 120            | 120           | 120           |
| Perimeter (cm)      | 2.6741237    | 2.6923449      | 3.0065042      | 4.44          | 4.44          |
| Area (cm²)          | 0.5690535    | 0.0077814      | 0.1424712      | 0.7014939     | 1.4208        |
| Volume (cm³)        | 68.28642     | 0.933768       | 17.096544      | 84.179268     | 170.496       |
| Volume fraction     | 0.4005163    | 0.0054768      | 0.1002754      | 0.4937316     | 1             |
| Density (gr/cc)     | 11           | 0.037          | 7.874          | 0.037         | -             |
| Mass (g)            | 751.15062    | 0.034549416    | 134.6181875    | 3.114632916   | -             |
| HM mass (g)         | 600.920496   | 0              | 0              | 0             | 600.920496    |

### Table 2. Fuel Assembly and Core Characteristics

| Parameter                          | Value                  | Units   |
|------------------------------------|------------------------|---------|
| Geometry                           | Hexagonal              | -       |
| Apothem (cm)                       | 11.16                  | cm      |
| Side (cm)                          | 12.88645801            | cm      |
| Height (cm)                        | 120                    | cm      |
| Perimeter (cm)                     | 77.31874805            | cm      |
| Heavy Metal (HM) Composition       | U/PU(90-97/3-10)        | % weight|
| Fuel Composition                   | HM/C/N/Zr/O₂ (80/20)   | % weight|
| Number of fuel pin in assembly     | 127 (7 rings)          | pin     |
| Number of assembly in core         | 127 (7 rings)          | assembly|
In table 3 shown related fuel candidates that investigated in GFR concept comprised the fuel material with carbide (U-Pu)C, nitride (U-Pu)N, oxide(U-Pu)O2, and metallic (U-Pu)Zr to obtain the good candidate. The fuel candidates that used material composition type with density value are 13.6 gr/cm3, 14.3 gr/cm3, 11 gr/cm3, and 15.6 gr/cm3, respectively.

| Table 3. Fuel Candidates |
|--------------------------|
| Theoretical density (gr/cc) | 13.6 | 14.3 | 11 | 15.6 |
| Heavy atom density (gr/cc) | 12.95 | 13.53 | 9.75 | 14 |
| Melting Point (°C) | 2420 | 2780 | 2430 | 1080 |
| Thermal conductivity (W/m/K) | 16.5 | 14.3 | 2.9 | 14 |

3. Results and Discussion

The simulation of GFR core model using MCNP6 code to get results and data calculation. Figure 4 and 5. The core GFR generated in YZ view-MCNP. In this research used hexagonal lattice for assembly that shown there are 7 rings of fuel pins and geometry of fuel meats, gaps and claddings total 127 pins and there are 7 rings of assemblies for full core with total 127 assemblies.
In figure 6. That shown about the number of threads is available in computer cluster that used in this paper. The availability of CPU (s) are 32 from 2 threads per core, 8 cores per socket and there are 2 sockets. In figure 7. That shown about the comparison of computing time versus number of threads that implemented OpenMP method which used the shared memory. The simulation time decrease from 37 to 3 minutes for 1 thread to 16 threads but if used more 16 threads then we can get the simulation time about 7 minutes. From this results, we got the optimum time for simulation is about 16 threads that used to calculation in advanced.

Figure 6. Fuel Assembly in YZ View-MNCP

Figure 7. Parallel Computing with OpenMP

The analysis of profile plutonium that applied such as U-PuC, U-PuN, U-PuZr and U-PuO2 (MOX). Figure 8 and 9 shown that the multiplication factor higher than 1.00 when the fissile contain higher than 14%. We used the variation of fissile contain start from 5 to 25% that shown the linearity between the increasing of plutonium and criticality value. The results of keff for MOX is 1.117290
with standard deviation 0.00048, U-PuC is 1.251450 with standard deviation 0.00057, U-PuN is 1.229570 with standard deviation 0.000452 and U-PuZr is 1.218380 with standard deviation 0.00054, respectively.

**Figure 8.** Variation of Fissile Contain

**Figure 9.** Variation of Fuel

In **figure 10 and 11** that shown the flux distribution of GFR core model in XY view and YZ view. We can know from this results that the highest flux in the center of core both of XY and YZ view obtained for 100% fresh fuel, homogeneous of fissile contain and simple configuration. The graph consistent with the expected behavior, the fast flux has a large peak in the center of core because the simulation used the fast neutron region and no flattening spectrum by variation of fissile contain.

**Figure 10.** Flux Profile XY View

**Figure 11.** Flux Profile YZ View

In figure 12 shows the comparison of the keff number and the linearity of burn-up (GWd/MTU) between operation times in days. From this results, concluded that the core reactor still in critical after 20 years during in operation that used the U-PuN fuel with 15% of fissile contain. In figure 13 shows the changing of plutonium vector composition (238Pu, 239Pu, 240Pu, 241Pu, and 242Pu isotopes) during 20 years in operation. The masses of plutonium isotopes especially for 239Pu and 241Pu decrease significant mainly by fission reaction. The masses of 238U changes become 239Pu isotopes beside that 234U, 236U, 237U, and 239U increase relatively mainly by transmutation reaction.
4. Conclusion

In this research, we got the results of calculation series in parallel computing gives the good agreement will be faster of calculation time when more threads. The material of \((U-Pu)C\) and \((U-Pu)N\) fuel are the good candidates to be chosen in GFR research that give keff more than 1.2 in fissile contain 20\%Pu. The variation fissile contain gives the linearity with keff. In depletion simulation, the core reactor still in critical during 20 years operation, burn up values linear with operation time and mass evolution of plutonium and uranium from start-up core to equilibrium core.

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