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EFFECTS OF FUEL DENSITY ON REACTIVITY COEFFICIENTS AND KINETIC PARAMETERS OF PEBBLE BED REACTOR

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ABSTRACT

EFFECTS OF FUEL DENSITY ON REACTIVITY COEFFICIENTS AND KINETIC PARAMETERS OF PEBBLE BED REACTOR. Few decades ago a large number of nuclear reactors were designed to use HEU as the fuel. But the use of HEU is being discouraged since it can be used as a nuclear explosive material which makes its proliferation potential. Most of the HEU-fueled nuclear reactors in the world are either closed or converted into other types that have LEU fuel with ²³⁵U enrichment below 20%. To extend lifetime, LEU fuel with high density is developed. The change in fuel density from low to high will also change core neutronics and thermal-hydraulics of the reactor, and as a result, it affects the transient response of the reactor. This paper studies the effects of fuel density on reactivity coefficients and kinetic parameters of pebble bed reactor through several calculations with MCNP6 code combine with ENDF/B-VII.1 continuous energy cross-section nuclear data library. The overall calculation results show that the Doppler temperature coefficient (DTC) increases with increasing fuel density, but the moderator temperature coefficient (MTC) decreases due to hardening of neutron spectrum. Kinetic parameters such as effective delayed neutron fraction (β_{eff}), prompt neutron lifetime (ℓ) and neutron generation time (Λ) which significantly reduced with increasing fuel density will strongly affect the reactor control and safety. The results of this work conclude that the selection of 9–15 g/cm³ fuel density should be considered carefully given that its effect on reactor controllability.

Keywords: Fuel density, reactivity coefficients, kinetic parameters, MCNP6, ENDF/B-VII.1.

ABSTRAK

PENGARUH DENSITAS BAHAN BAKAR TERHADAP KOEFISIEN REAKTIVITAS DAN PARAMETER KINETIKA REAKTOR PEBBLE BED. Beberapa dekade yang lalu sejumlah besar reaktor nuklir didesain untuk menggunakan HEU sebagai bahan bakar. Namun penggunaan HEU sedang tidak dianjurkan karena dapat digunakan sebagai bahan peledak nuklir yang membuat potensi proliferasinya. Sebagian besar reaktor nuklir berbahan bakar HEU di dunia ditutup atau diubah menjadi jenis lain yang memiliki bahan bakar LEU dengan pengayaan ^{235}U di bawah 20%. Untuk memperpanjang masa pakai, bahan bakar LEU dengan densitas tinggi dikembangkan. Perubahan densitas bahan bakar dari rendah ke tinggi juga akan mengubah neutronika dan termohidraulika teras reaktor, sehingga mempengaruhi respon transien reaktor. Makalah ini mempelajari pengaruh densitas bahan bakar terhadap koefisien reaktivitas dan parameter kinetik reaktor pebble bed melalui beberapa perhitungan dengan program MCNP6 yang dikombinasikan dengan pustaka data nuklir tampang lintang energi kontinu ENDF/B-VII.1. Hasil perhitungan secara keseluruhan menunjukkan bahwa koefisien temperatur Doppler (DTC) meningkat dengan meningkatnya densitas bahan bakar, tetapi koefisien temperatur moderator (MTC) menurun karena pengerasan spektrum neutron. Parameter kinetik seperti fraksi neutron kasip efektif (β_{eff}), waktu hidup neutron serempak (ℓ) dan waktu generasi neutron (Λ) yang berkurang secara signifikan dengan meningkatnya densitas bahan bakar akan sangat mempengaruhi pengendalian dan keselamatan reaktor. Hasil dari pekerjaan ini menyimpulkan bahwa pemilihan densitas bahan bakar 9-15 g/cm³ harus dipertimbangkan dengan hati-hati mengingat pengaruhnya terhadap pengendalian reaktor.

Kata kunci: Densitas bahan bakar, koefisien reaktivitas, parameter kinetika, MCNP6, ENDF/B-VII.1

INTRODUCTION

Few decades ago a large number of nuclear reactors were designed to use high enriched uranium (HEU) as the fuel. But the use of HEU is being discouraged since it can be used as a nuclear explosive material which makes its proliferation potential. After burned in the reactor, the fuels generally contain about 70% fissile ^{235}U which is still raising proliferation concerns related to the back end of the fuel cycle. Therefore, the international trade of HEU fuel is highly restricted and to get the fresh supply of HEU fuel is almost impossible. As a result, most of the HEU-fueled nuclear reactors in the world are either closed, or being converted to other types having low enriched uranium (LEU) fuel with ^{235}U enrichment of less than 20%. This limit on enrichment is considered to be an isotopic barrier for the use of nuclear weapons in conflict [1,2].

Lower uranium enrichment will shorten the lifetime of the fuel. To extend its lifetime, LEU fuel with high density was developed under the Reduced Enrichment for Research and Test Reactor (RERTR) project [3]. The change in fuel density from low to high will change core neutronics and thermal-hydraulics of the reactor, and as a result, affects the transient response of the reactor. The work presented in this paper focuses on the effects of fuel density on reactivity coefficients and kinetic parameters of Indonesian Experimental Power Reactor (*reaktor daya eksperimental*, RDE) pebble Bed Reactor [4].

The effects of fuel density with a range of 1 g/cm^3 to 15 g/cm^3 will be studied through a series of calculations of reactivity coefficients and kinetic parameters of pebble bed reactor. Monte Carlo transport code MCNP6 [5] was utilized in all calculations combining with ENDF/B-VII.1 continuous energy cross-section nuclear data library [6]. MCNP6 represents a merger of MCNP5 [7] and MCNPX [8] developed at Los Alamos National Laboratory (LANL) to improve its reliability at higher energies. Analysis was carried out on the calculation results as a function of fuel density. The results of the analysis are expected to be the basis for determining the specific fuel density for use in the pebble bed reactor.

DESCRIPTION OF PEBBLE BED REACTOR

RDE is a small type of high temperature pebble bed reactor planned to be constructed

in Puspipstek Complex, Serpong, Indonesia. The reactor is based on design and technology of HTR-10 China. RDE uses graphite moderator and helium coolant which produce thermal power of 10 MW and core power density of 2 MW/m^3 . The reactor is designed not only for supplying electricity but also for supplying high temperature steam or gas for cogeneration purposes such as hydrogen production, seawater desalination, coal gasification, enhanced oil recovery (EOR).

RDE is a cylindrical core with 90 cm radius and 197 cm effective height surrounded by graphite reflector radially and axially. The reactor shutdown control system consists of 10 control rods and 7 small absorber balls are placed on the reflector side. The 3 irradiation experiment position channels are similarly placed on the reflector side. The 20 helium channels are symmetrically placed on the reflector side.

Helium coolant is an inert gas, so it does not react chemically with fuel and any materials. In addition, helium gas is transparent to neutron exposure unlike most other possible coolants. The helium coolant in the primary system is designed at the pressure of 3.0 MPa, enters from top reactor core at temperature of $250\text{ }^\circ\text{C}$, flows from the top to the bottom through the fuel pebbles, and heated it the reactor core up to temperature of $700\text{ }^\circ\text{C}$ at outlet of reactor core. The main technical data parameters and the core schematic of RDE are shown in Figure 1 and Table 1.

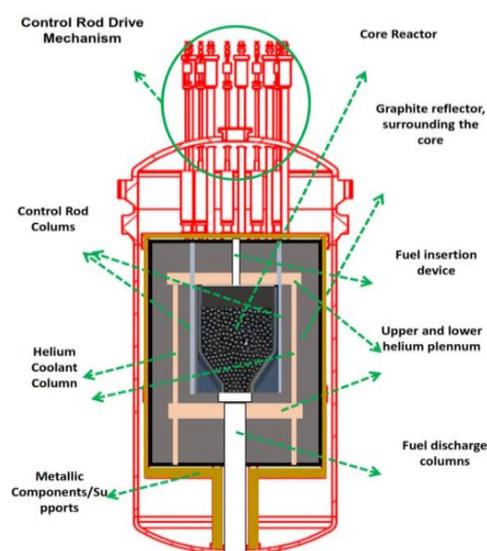


Figure 1. The schematic of RDE pebble bed reactor core [4].

Table 1. Main technical data parameters of RDE pebble bed reactor [4].

Technical data parameters of reactor	
The thermal power of reactor, MW	10
Helium coolant temperature of inlet, °C	250
Helium coolant temperature of outlet, °C	700
The pressure of helium gas, MPa	3
Mass flow rate of helium gas, kg/s	4.3
Control rods number	10
SAS (small absorber sphere) number	7
Technical data specification	
Active Height of the core, cm	197
Diameter of the core, cm	180
Power density of the core, MW/m ³	2
Pebble number in the core	27000
Pebble packing fraction	61%
Average of discharge burnup, MWd/t	80000
Scheme of fuel cycle	Multipass

The core loading in a multi-pass cycle scheme begins with dropping the moderator pebbles into the cone located at the bottom of the core with 0.61 fuel pebble fraction packing. Then a mixture of 57% fuel pebbles and 43% moderator pebbles is dropped gradually until the core is full so that the reactor can be operated at full power. The full core is estimated to have a volume of 5 m³ and contains of 27000 pebbles arranged with the same pebble packing fraction. Pebble loading is carried out from the central loading tube above the core and discharging pebbles through extraction pipes at the bottom of the core. The discharged pebbles are examined for their burnup level at burnup measurement facility one by one. They will be moved into the spent fuel storage tank if their designed burnup of 80000 MWd/t is reached, otherwise reinserted into the core.

Each fuel pebble consists of a 2.5 cm radius of fueled zone and coated by 0.5 cm thickness of graphite outer shell. The latter acts as a moderator surrounding the fuel as well as to protect the fueled zone during pebble movements. Moderator pebbles are made of pure graphite with the same diameter as fuel pebbles. The fueled zone contains 8335 TRISO coated fuel particles wrapped within the graphite matrix. TRISO particle is comprised of UO₂ fuel kernel with 17 % ²³⁵U enrichment and four coating layers. i.e: porous carbon buffer (C) layer, inner pyrolytic carbon (iPyC) layer, silicon carbide (SiC) layer, and

outer pyrolytic carbon (oPyC) layer. These layers effectively retain all radioactive fission products in normal and accident condition. The failure rate of TRISO particle is very low for all accident conditions. Therefore, the possibility of fuel degradation is physically eliminated and impossible to occur [10]. The detailed characteristics and the configuration of fuel pebble are shown in Table 2 and Figure 2. The characteristics of the moderator pebble is given detailed in Table 3.

Table 2. Detailed characteristics of fuel pebble[4].

Fuel pebble			
Fuel kernel type	UO ₂		
Radius of fuel pebble, cm	3		
Radius of fueled zone, cm	2.5		
Thickness of graphite outer shell, cm	0.5		
²³⁵ U enrichment, %	17		
Number of TRISO particles per fuel pebble	8,335		
HM (heavy metal) loading per fuel pebble, g	5		
Density of graphite in fuel matrix/shell, g/cm ³	1.73		
Equivalent natural boron impurity in fuel pebble/graphite, ppm	1.0/1.3		
TRISO coated fuel particle			
Fuel kernel		IPyC/oPyC	
Radius, cm	0.0250	Thickness, cm	0.0040
Density, g/cm ³	10.41	Density, g/cm ³	1.90
Carbon Buffer		SiC	
Thickness, cm	0.0090	Thickness, cm	0.0035
Density, g/cm ³	1.10	Density, g/cm ³	3.18

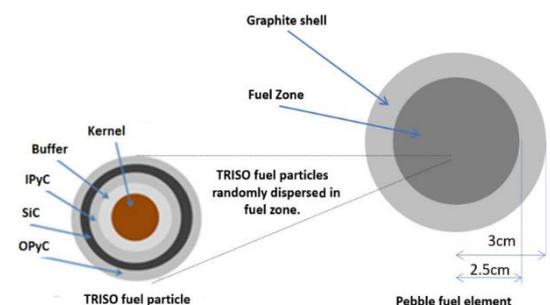


Figure 2. The configuration of the RDE fuel pebble[9].

Table 3. Detailed characteristics of moderator pebble [4].

Radius of moderator pebble, cm	3
Graphite moderator pebble density, g/cm ³	1.84
Boron impurity in graphite, ppm	1.3

METHODOLOGY

Calculations of reactivity coefficients and kinetic parameters of RDE were performed using MCNP6 code and ENDF/B-VII.1 continuous energy cross-section nuclear data library. Modeling of pebble bed reactor is considerably big different compared to conventional light water reactors (LWRs) because its core configuration exhibits a large amount of volumes stochastically distributing the TRISO particles inside fuel pebble and the pebbles in the core. This is known as double heterogeneity problem. MCNP6 code is capable to solve the double heterogeneity problem with detailed and accurate model. The double heterogeneity model in MCNP6 was built in a regular lattice for TRISO coated fuel particle and pebble arrangement.

In this calculation, a number of neutron histories per cycle of 10000 with 50 cycle to be skipped from 250 total number of cycle were simulated. The number of skipped cycles was selected to convergence the calculation. The statistical errors is estimated to be less than 0.07%. The initial fission source as an important point was located in the center of the fuel pebble in the reactor. The thermal scattering library $S(\alpha, \beta)$ was used to consider the molecular binding effect of the thermal neutron interactions with graphite in all region of the reactor at the energy below ~4 eV for temperature of 293K, 600K, 900K, and 1200K. The outer boundary of the RDE reactor system was assumed as vacuum condition.

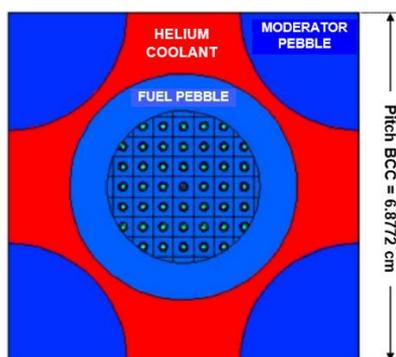


Figure 3. Fuel and moderator pebbles in BCC lattice.

TRISO inside fuel pebble modeling

The 3-D simple cubic (SC) lattice was used to model TRISO coated particles inside the fuel pebble. Fuel kernel enclosed by four coating layers was placed at the center of the lattice. The packing fraction was set in such way that the graphite matrix outside the TRISO coated fuel particle has a volume of $6.227025 \times 10^{-3} \text{ cm}^3$. The lattice length was 0.1988 cm. The repeated structure geometry with LATTICE and UNIVERSE options provided in MCNP6 code was used to model the fuel pebble. Regularly distributing the 8335 TRISO particles inside the fuel pebble will produce clipped coated particles at the boundary between the fueled zone and graphite shell. However, the excess of clipped particle in fueled zone does not affect significantly the calculation results due to the low packing fraction of the coated particle.

Pebbles in core modeling

The 3-D body centered cubic (BCC) lattice was used to model fuel and moderator pebbles in the core. This unit cell of the lattice consists of one fuel pebble at the center and eight one-eighth moderator pebble at each corner of the lattice so that two pebbles are obtained in a lattice. Such configuration makes it easy to change the radius of the pebble moderator in order to control the ratio of fuel and moderator pebbles at 57/43%. Fuel pebble radius was kept constant to take into account the effect of double heterogeneity problem. The lattice size was readjusted to 6.8772 cm in order to compensate for reduction in radius of moderator pebble from 3 cm to 2.7310 cm and maintain a fixed packing fraction of 0.61. The fuel and moderator pebbles in BCC lattice and TRISO coated fuel particle in SC lattice are depicted in Figures 3 and 4, respectively.

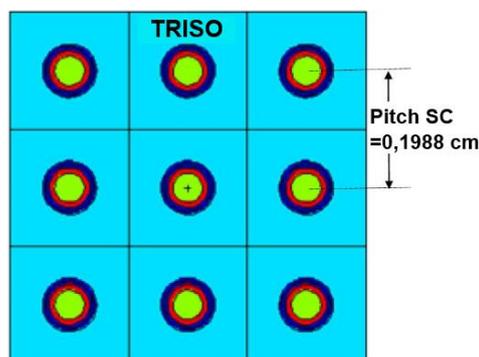
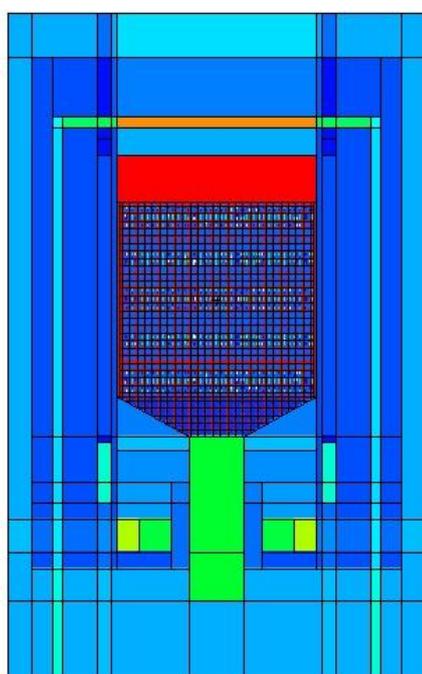
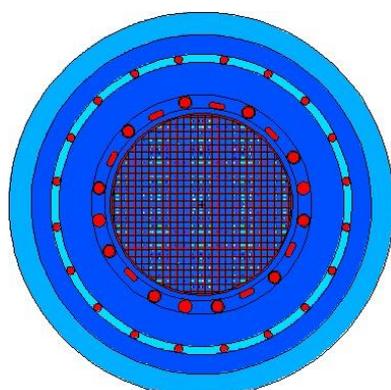


Figure 4. TRISO coated fuel particle in SC lattice

The repeated structure geometry with LATTICE (LAT) and UNIVERSE (U) options is used again to model pebbles in the reactor core. Regularly distributing 27000 pebbles in reactor cores using repeated structure geometry will result in clipped pebbles in the boundary between pebbles and pressure vessel wall of the core. The excess of clipped pebbles in the core is one of the most critical factors in pebble bed type reactor which should be eliminated by making correction. Correction was made by applying an exclusive zone of helium with 1.71 cm thickness around the reactor core. The whole reactor model of RDE is illustrated in Figure 5.



(a). Side view



(b). Top view

Figure 5. Full core modelling of RDE pebble bed reactor.

The structural components of the reactor core such as graphite reflectors were easily modeled while the coolant in the reflector side and especially, the reactor shutdown and control systems require special effort in modeling. The modeling and calculations performed in this study were demonstrated successfully in various publications [11-22].

RESULTS AND DISCUSSION

The calculation results of the effective multiplication factor (k_{eff}) are shown in Figure 6. The k_{eff} is defined to denote the relative number of neutrons produced in successive fission events. In effect, k_{eff} is the ratio of number of neutrons produced by fission in one generation to the number of neutrons lost through absorption and leakage in the preceding generation. From Figure 6, it can be seen that an increase in fuel density increases the effective multiplication factor (k_{eff}) since the fuel content in the reactor increases. The curve is not linear due to reduced moderation caused by a decrease in the ratio of graphite/fuel in the reactor core. It can also be seen that by increasing the fuel density from 9 g/cm³ to 15 g/cm³ the k_{eff} value increases from 1.00000 to 1.08649. This means that 67% change in the density will be followed by 8% change in the k_{eff} . In other words, a 40% increase inventory of uranium in the reactor causes a rise in k_{eff} of 8% only. In this calculation, the temperature in core is 900K.

The fuel temperature coefficient of reactivity or Doppler temperature coefficient (DTC) and the moderator temperature coefficient (MTC) are the two most dominant reactivity coefficients in the pebble bed reactor. Other reactivity coefficients such as the void coefficient do not significantly affect gas-cooled reactors since it uses gas phase coolant which already has a void fraction of 100%. Its coolant also did not act as a moderator like a light water reactor. The temperature coefficient of reactivity act on the reflector does not show a big change compared to changes in the fuel temperature. Since reflector temperature is dominated by the coolant temperature inside the coolant channel within the reflector, when combined with a large heat capacity of graphite, its significance is even less discernible.

Figure 7 shows the effect of increased DTC as a function of fuel density caused by increased absorption to fission ratio of ²³⁸U within the resonance region. The DTC value changes from $-1.65543 \times 10^{-5} \Delta k/kK^{-1}$ for fuel

density of 9 g/cm³ to $-1.91873 \times 10^{-5} \Delta k/kK^{-1}$ for fuel density of 15 g/cm³, an increase of 16%. This condition makes the role of the Doppler coefficient in the reactor control increase. In contrast, reduced MTC as increased fuel density in Figure 8 is found due to the effect of neutron spectrum hardening. The value of MTC changes from

$-1.49930 \times 10^{-4} \Delta k/kK^{-1}$ for fuel density of 9 g/cm³ to $-8.91400 \times 10^{-5} \Delta k/kK^{-1}$ for fuel density of 15 g/cm³, showing a decrease of 41%. These results may affect reactor control when combined with other reactivity feedback since higher fuel temperatures happen while the reactor operates, i.e. under hot full power (HFP) conditions.

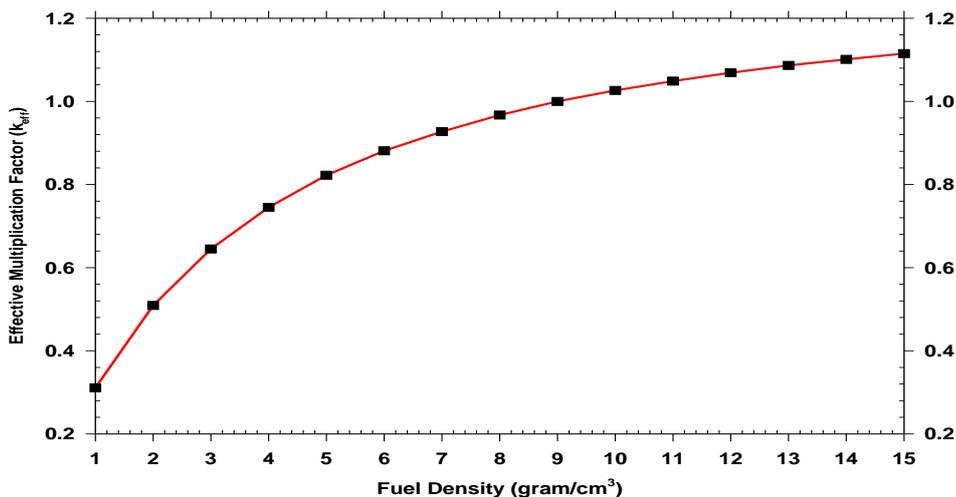


Figure 6. Effective multiplication factor (k_{eff}).

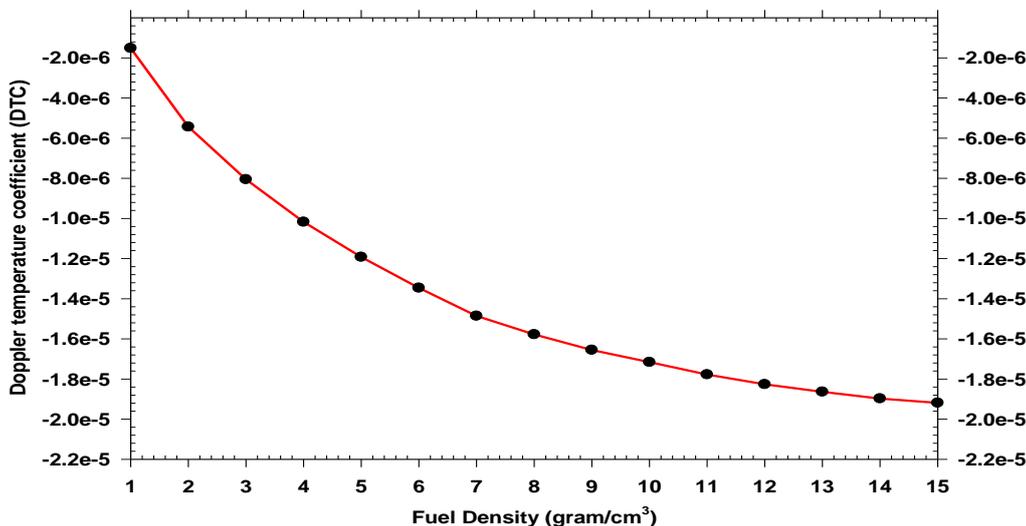


Figure 7. Doppler temperature coefficient (DTC).

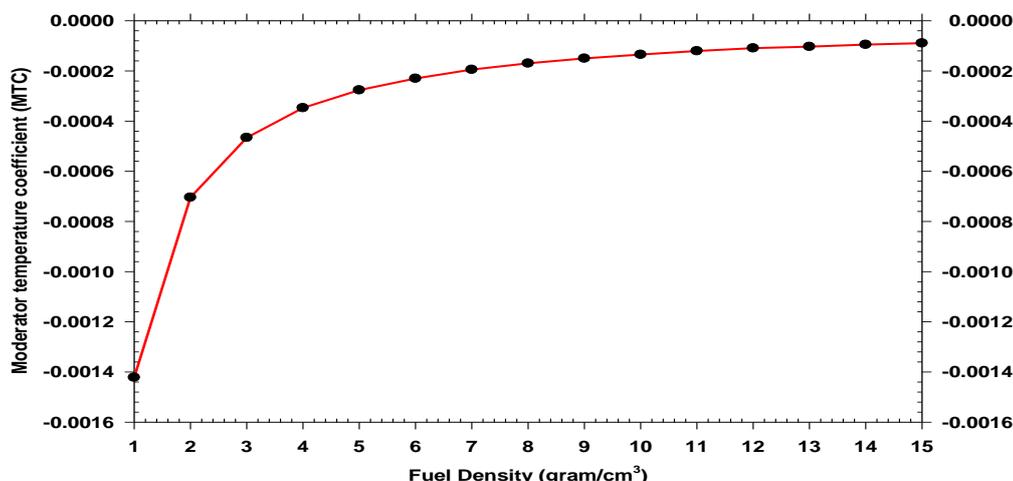


Figure 8. Moderator temperature coefficient (MTC).

Accurate estimation of kinetic parameters is one of the main concerns in the safety analysis of nuclear reactors. The effective delayed neutron fraction (β_{eff}) is the most important kinetic parameter since it corresponds to the maximum reactivity that can be inserted in a critical system without becoming prompt-critical. In this study, the calculation result of β_{eff} is illustrated in

Figure 9. It can be observed that an increase in fuel density decreases effective delayed neutron fraction (β_{eff}) since the ratio of density number of ^{238}U to density number of ^{235}U increases with fuel density. The value of β_{eff} insignificantly decreases from 0.00608 for fuel density of 9 g/cm³ to 0.00579 for fuel density of 15 g/cm³.

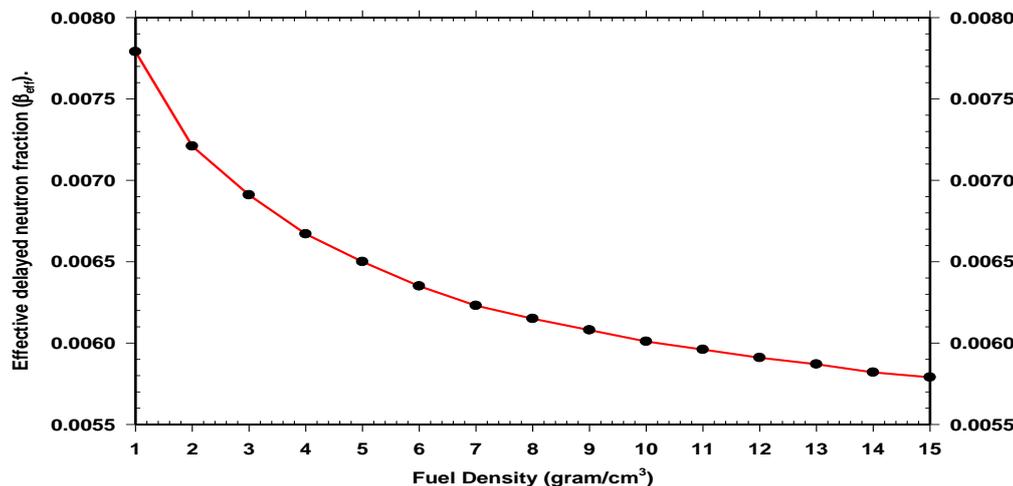


Figure 9. Effective delayed neutron fraction (β_{eff}).

The prompt neutron lifetime (ℓ) and neutron generation time (Λ) are other important kinetic parameters. The calculation results of these parameters are illustrated in Figures 10 and 11. Both parameters decrease as fuel density increases. The increased fuel

amount in the reactor due to the increase in fuel density results in decreased thermalization which has a consequence of increased average neutron velocity. These combinations led to decreasing ℓ and Λ . The values of ℓ and Λ decrease from

2.06530×10^{-3} s and 1.52874×10^{-3} s for fuel density of 9 g/cm³ to 1.61870×10^{-3} s and 9.77024×10^{-4} s for fuel density of 15 g/cm³. A decrease of about 22% on ℓ and 36% on Λ is experienced for an increase of 40% in the inventory of uranium on reactor core. This

amount of change in ℓ and Λ is need to be checked with several transient simulations since there are reactivity feedbacks and kinetic parameters that affect each other in response to reactor perturbation.

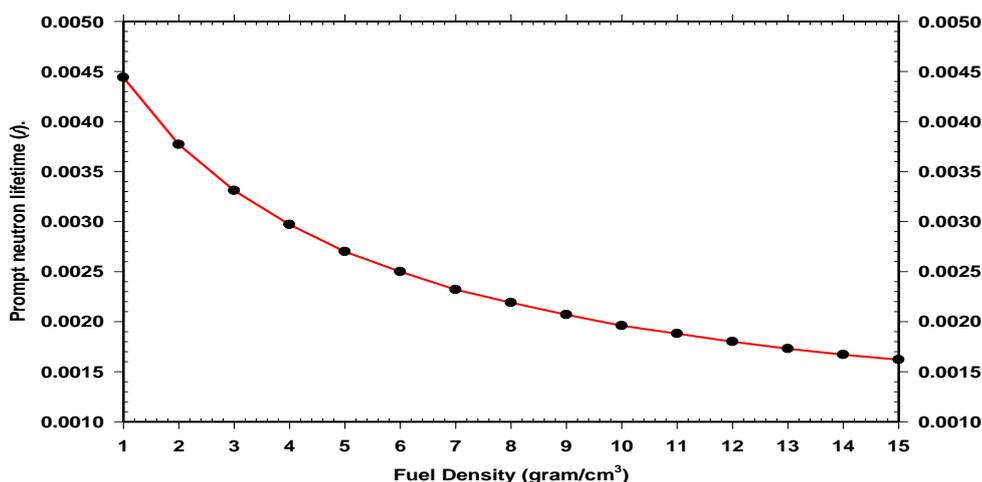


Figure 10. Prompt neutron lifetime (ℓ).

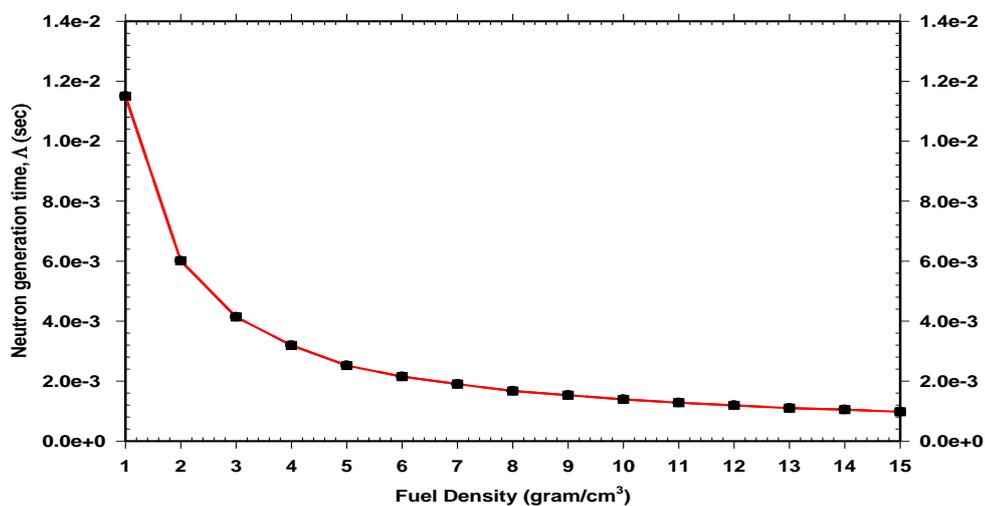


Figure 11. Neutron generation time (Λ).

CONCLUSION

Several calculations related to the effects of fuel density on reactivity coefficients and kinetic parameters of small pebble bed reactors have been done using MCNP6 code with ENDF/B-VII.1. The calculation results show that the Doppler temperature coefficient (DTC) increases with the increase of fuel density, but the moderator temperature coefficient (MTC) decreases due to the

hardening of the neutron spectrum. Kinetic parameters such as effective delayed neutron fraction (β_{eff}), prompt neutron lifetime (ℓ), and neutron generation time (Λ) significantly reduced as fuel density increased. The results of this work conclude that the selection of 9-15 g/cm³ fuel density should be considered carefully given its effect on reactor controllability.

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REFERENCES

- [1]. F. Muhammad, A. Majid, "Effects of high density dispersion fuel loading on the kinetic parameters of a low enriched uranium fueled material test research reactor", *Annals of Nuclear Energy*, vol. 35, pp. 1720–1731, 2008.
- [2]. A. Glaser, "About the enrichment limit for research reactor conversion: why 20%?", *The 27th International Meeting on RERTR, Boston, Massachusetts, 6–10 November, 2005*.
- [3]. J.M. Dix, A.B.D. Tigliole, F.M. Marshall, S.M. Tozser, "IAEA activities in support of HEU minimization", *36th International Meeting on Reduced Enrichment for Research and Test Reactors, Seoul, South Korea, October 11-14, 2015*.
- [4]. PTKRN-BATAN, "Detail engineering design of RDE," Internal Report, 2018.
- [5]. J.T. Goorley, et al., "Initial MCNP6 release overview - MCNP6 version 1.0," LA-UR-13-22934 Los Alamos National Laboratory, 2013.
- [6]. J.L. Conlin et al., "Release of ENDF/B-VII.1-based continuous energy neutron cross-section data tables for MCNP, LA-UR-13-24077," Los Alamos National Laboratory, 2013.
- [7]. F.B. BROWN, et al., "MCNP – A general monte carlo N-particle transport code, Version 5," LA-UR-03-1987, April 24, 2003.
- [8]. G. McKinney, J. Durkee, J. Hendricks, et al., "MCNPX 2.6x features, LA-UR-07-2053," Los Alamos National Laboratory, 2007.
- [9]. T. Setiadipura, D. Irwanto, Zuhair, "Preliminary neutronic design of high burnup OTTO cycle pebble bed Reactor", *Atom Indonesia*, vol. 41, no.1, pp. 7-15, 2015.
- [10]. C. Fang, R. Morris, and F. Li, "Safety Features of high temperature gas cooled reactor", *Science and Technology of Nuclear Installations*, Article ID 9160971, 2017.
- [11]. Suwoto, H. Adrial, T. Setiadipura, Zuhair and S. Bakhri, "Impact of different nuclear data library on control rod reactivity worth calculation of small pebble bed reactor", *Journal of Physics: Conference Series 2048 012029*, 2021. doi:10.1088/1742-6596/2048/1/012029
- [12]. O. Kabach, A. Chetaine, A. Benchrif, H. Amsil and F. El Banni, "A comparative analysis of the neutronic performance of thorium mixed with uranium or plutonium in a high-temperature pebble-bed reactor", *International Journal of Energy Research*, vol. 45, no. 11, pp. 1-18, 2021. doi: 10.1002/er.6935.
- [13]. Zuhair, R.A.P. Dwijayanto, Suwoto and T. Setiadipura, "The implication of thorium fraction on neutronic parameters of pebble bed reactor", *Kuwait Journal of Science*, vol. 48, pp. 1-16, 2021. doi:10.48129/kjs.v48i3.9984.
- [14]. Zuhair, Suwoto, T. Setiadipura, J.C. Kuijper, "Study on the characteristics of effective delayed neutron fraction (β_{eff}) for pebble bed reactor with plutonium fuel", *Iranian Journal of Science and Technology, Transactions A: Science*, pp.1-9, 2019. doi:10.1007/s40995-019-00772-8.
- [15]. Suwoto, H. Adrial, A. Hamzah, Zuhair, S. Bakhri, G.R. Sunaryo, "Neutron dose rate analysis on HTGR-10 reactor using monte carlo code", *Journal of Physics: Conference Series*, vol. 962, no.1, 012029, 2018. doi:10.1088/1742-6596/962/1/012029.
- [16]. S. A. Hosseini and M. Athari-Allaf, "Effects of the wallpaper fuel design on the neutronic behavior of the HTR-10", *Kerntechnik*, vol. 81, no.6, pp. 627-633, 2016.
- [17]. Zuhair, Suwoto, T. Setiadipura and Z. Su'ud, "Study on MCNP6 model in the calculation of kinetic parameters for pebble bed reactor", *Acta Polytechnica*, vol. 60, no. 2, pp. 175-184, 2020. doi:10.14311/AP.2020.60.0175.
- [18]. Zuhair, Suwoto, T. Setiadipura and J.C. Kuijper, "The effects of fuel type on control rod reactivity of pebble-bed reactor", *Nukleonika*, vol. 64, no.4, pp. 131-138, 2019. doi:10.2478/nuka-2019-0017.
- [19]. O. Kabach, A. Chetaine, A. Benchrif, and H. Amsil, "The use of burnable absorbers integrated into TRISO/QUADRISO particles as a reactivity control method in

- a pebble-bed HTR reactor fuelled with (Th,²³³U)O₂", *Nuclear Engineering and Design*, vol. 384, 111476, 2021. doi:10.1016/j.nucengdes.2021.111476.
- [20]. Zuhair, Suwoto, T. Setiadipura, Z. Su'ud, "The effects of applying silicon carbide coating on core reactivity of pebble-bed HTR in water ingress accident", *Kerntechnik*, vol. 82, no.1, pp. 92-97, 2017. doi:10.3139/124.110628.
- [21]. S.A. Hosseini and M. Athari-Allaf, "Implementation and benchmarking of ENDF/B-VII based library for PBM reactor analysis with MCNP4c", *Progress of Nuclear Energy*, vol. 60, pp. 27-30, 2012.
- [22]. Zuhair, Suwoto, Sidik Permana, Topan Setiadipura. "Study on control rod reactivity of small pebble bed reactor with wallpaper fuel design." *Journal of Physics: Conference Series*, vol. 1772, no.1, 012021. doi:10.1088/1742-6596/1772/1/012021.

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