STUDY ON KINETIC PARAMETERS CHARACTERISTICS OF PEBBLE BED REACTOR USING HTR-PROTEUS FACILITY

by

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The inherent safety feature of a pebble-bed reactor can be observed from its kinetic parameters. Proper modeling for calculating the reactor kinetic is also a concern for safe operation during normal and transient conditions. This study is intended to investigate the kinetic parameters characteristics of a pebble bed reactor using HTR-Proteus. A series of calculations were conducted using MCNP6 code and ENDF/B-VII library. The calculation results show that the negative value on core temperature reactivity is affected dominantly by the Doppler broadening effect. Prompt neutron lifetime ℓ and mean generation time are slightly changed due to an increase in fuel temperature, moderator, and reflector that changed the neutron moderation and absorption over this part of the reactor. For (Th, U)O_2, UO_2, and PuO_2 cores, the effective delayed neutron fraction β_{eff} values are more influenced by ^{233}U, ^{235}U, and ^{239}Pu, respectively. In terms of stability during reactivity insertion, the UO_2 core is more stable and easier to control because its β_{eff} value is the largest compared to (Th, U)O_2 and PuO_2 cores. It can be concluded that changing temperature must be controlled because it does not only affect the reactivity but also kinetic parameters as part of developing inherent safety features on the pebble-bed reactor.

Key words: kinetic parameter, pebble bed reactor, HTR-proteus, MCNP6, ENDF/B-VII

INTRODUCTION

The increase in world population is predicted to double global energy demand by 2050. Traditional energy sources from fossil fuels such as oil, natural gas, and coal still provide the largest share of the world's energy today. However, fossil fuel is the main contributor to carbon emissions which causes climate change and endangers the world population present and future. Meanwhile, generating energy through nuclear power emits a small amount of CO_2, thus making it a promising option as a solid and reliable energy generation [1]. Since 2000, the Generation IV International Forum (GIF) has conducted a lot of effort in international collaboration to develop next-generation nuclear energy systems. The GIF has provided the basis for identifying and selecting six nuclear energy systems for further research and development of the Generation IV reactor. The Generation IV reactor is expected to be available for commercial deployment around 2030 with more efficient fuel utilization, less waste generation, being economically competitive, and could meet the requirement for safety and proliferation resistance [2].

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The pebble bed reactor, a type of high temperature gas-cooled reactor, is one of the six types of Generation IV nuclear reactors with graphite moderator and helium coolant. This reactor is an attractive choice for nuclear energy production due to several advantages, such as the inherent safety features characterized by a strong negative temperature coefficient of reactivity, large thermal inertia from the large graphite mass of the core, and the fuel designed to retain all fission products within the tri-structural isotropic (TRISO) coated particles. These advantages ensure that core meltdown is impossible, and the core remains intact in any accident scenario that causes the reactor temperature increases up to 1600 °C [3]. The pebble bed reactor possesses the flexibility to utilize various fuel cycles, including thorium [4-6], plutonium [7-9], and rock-like oxide [10].

The inherent safety feature of the pebble-bed reactor depends on the calculated kinetic parameters. Accurate calculation of the reactor kinetic is the main concern for safe operation and transient analysis [11]. The purpose of this study is to investigate the characteristics of kinetic parameters for pebble bed reactors using HTR-Proteus [12]. A series of calculations with various temperatures were performed by using the Monte Carlo transport code MCNP6 [13] and the con-

tinuous energy nuclear data library ENDF/B-VII [14]. The calculation of reactor kinetic parameters was conducted in the configuration of core 4.1 with a fuel-to--moderator pebble ratio of 1:1. Three fuel options for the design consisting of UO_2, PuO_2, and (Th, U)O_2 were adopted to present the calculation inter-comparison of kinetic parameters of pebble bed reactor between uranium, thorium, and plutonium cores. The analysis was performed in the core safety aspect because it can affect the behavior of transients in fatal accident situations.

THE HTR-PROTEUS FACILITY

Proteus is a zero-power research reactor located in the Paul Scherrer Institute, Switzerland. The basic geometry of Proteus consists of a cylindrical graphite annulus with a central cylindrical cavity. The graphite annulus is essentially unchanged for all experimental programs, but the contents of the central cavity can be replaced to adjust the type of reactor to be investigated. Proteus has represented light water reactors throughout its operational history, but from 1992 to 1996, Proteus was configured as a pebble bed reactor critical facility. Consequently, it was denominated as the HTR-Proteus. During this period, seventeen critical assemblies were configured and various experiments of nuclear reactor physics were performed such as criticality, differential, and integral control rod and safety rod worth, kinetics, reaction rates, water ingress effects, and small sample reactivity effects [15].

The HTR-Proteus was constructed to increase confidence in predicting the neutronic behavior of high-temperature gas-cooled reactors. The reactor program was conducted in HTR-Proteus to provide experimental benchmark data. The computational models were reviewed and investigated as a part of the HTR-Proteus program. The integral data obtained from the experimental benchmarking program is intended to validate various physics methods for pebble bed reactor core designs.

The HTR-Proteus facility is cylindrical graphite of 3.262 m in diameter and 3.3 m in height, with a central cylindrical cavity. This cavity has a diameter of 1.25 m and a height of 1.764 m, located 0.78 m above the lower axial reflector. The pulsed neutron source is placed on the bottom of the lower axial reflector. Symmetrically located 160 borings with a diameter of 2.743 cm are also on the lower axial reflector, where at least 127 borings are filled with 2.65 cm diameter graphite rods.

Meanwhile, the upper axial reflector is placed above the core cavity, suspended. It extends beyond the top of the radial reflector. This part is made of a complex structure consisting of graphite, steel, and aluminum as well as including inner and outer aluminum tanks, an aluminum safety ring to prevent the reflector from falling onto the pebble bed core during an accident, and a steel lid, support plate, and flanges.

The radial reflector starts from the radial boundary of the core cavity and extends to the outer radial boundary of the reflector, from the bottom of the reflector expanding upwards to a height of 330.4 cm. In this reflector, there is a reactor shutdown and control system, consisting of symmetrically located four boron-steel shutdown rods around the core at a radius of 68.4 cm, and 4 stainless-steel control rods with a radius of 90.6 cm. A schematic top and side view of the HTR-Proteus facility is shown in figs. 1 and 2, respectively.

Loading the HTR-Proteus core is carried out by dropping fuel pebbles into the core through a loading tube suspended above the core. Each fuel pebble is formed by a 5 cm diameter fueled zone and a graphite shell with a thickness of 0.5 cm. The moderator pebbles made of pure graphite with the same diameter as fuel pebbles are also simultaneously dropped in specified proportion to the fuel pebbles. The HTR-Proteus core configuration has different packing fractions because the pebbles are loaded in different ways. In core 4.1 fuel pebble and moderator pebble are loaded in parallel where each pebble is entered into the core from its respective channel. The second method is used for core loading of 4.2 and 4.3 where the fuel pebble and moderator pebble are entered in combination through the same channel. The pebble bed is then flattened after each loading step is completed and the height of the pebble bed core is measured. In the calculation of kinetic parameters, the configuration of core 4.1 was chosen with a fuel and moderator pebbles ratio of 1:1 [17].

In this study, the fueled zone is filled with 15 000 TRISO coated particles dispersed within the graphite matrix. The TRISO coated particles consist of a UO_2 fuel kernel with 18.4 % ^{235}U enrichment and four coat-

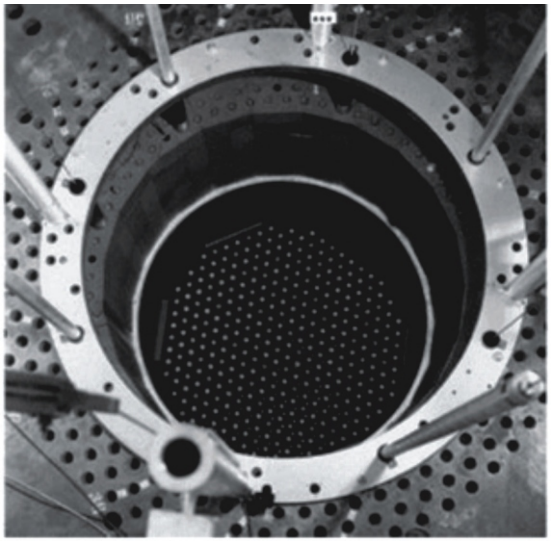

Figure 1. Top view of an HTR-Proteus deterministic core [16]

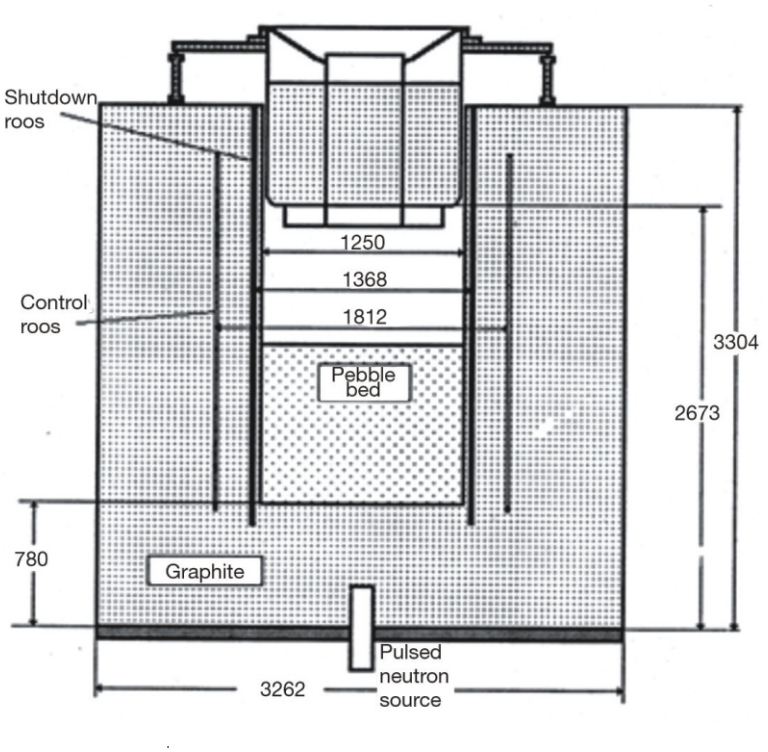

Figure 2. Schematic side view of the HTR-Proteus facility (dimensions in mm) [16]

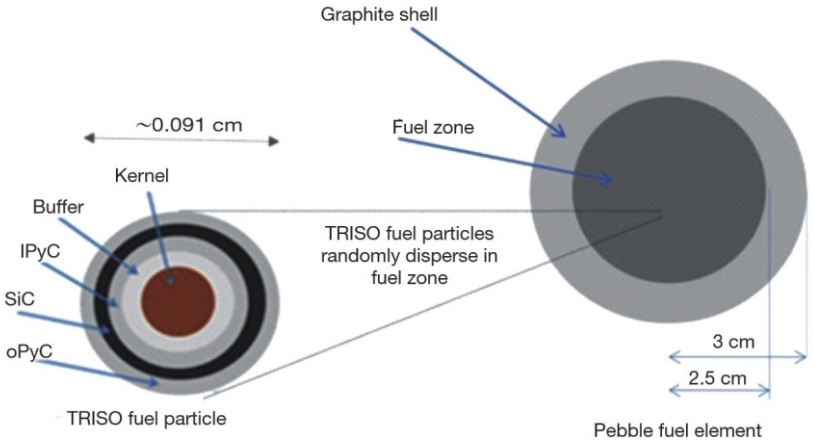

Figure 3. Schematic view of a fuel pebble and a TRISO particle [18]

ing layers. Other TRISO coated particles are formed by $(Th,U)O_2$ kernel with 12.48 % ^{233}U enrichment and PuO_2 kernel with plutonium isotopic vector of 0.0259/ 0.5385/ 0.2366/ 0.1313/ 0.0677 corresponding to plutonium isotopes of ^{238}Pu/ ^{239}Pu/ ^{240}Pu/ ^{241}Pu/ ^{242}Pu. Four protective TRISO layers consist of porous carbon buffer (C), inner pyrolitic carbon (iPyC), silicon carbide (SiC), and outer pyrolitic carbon (oPyC). These layers effectively retain the radioactive fission products up to the temperature of 1600 °C. Figure 3 shows a schematic view of a fuel pebble and a TRISO particle. Fuel pebble and coated fuel particles with UO_2, PuO_2, and $(Th, U)O_2$ kernels have the same design and specifications. Detailed specifications are described in tab. 1.

CALCULATION MODEL

Calculations of kinetic parameters of pebble bed reactor were performed using Monte Carlo transport code MCNP6 and continuous energy nuclear data library ENDF/B-VII. In the modeling of a pebble bed reactor, special attention must be paid to taking into account the double heterogeneity in the core region. It consists of TRISO fuel particles in the fueled zone of the pebble and pebble lattice containing fuel and moderator pebbles in the reactor core.

The core modeling is starting from the modeling of the TRISO particle using a simple hexagonal lattice. This lattice has a hexagonal pitch of 0.171456 cm. Next, the fuel pebble is modeled by constructing a regu-

Table 1. Fuel pebble and coated particle specifications

Fuel pebble	
Diameter [cm]	6
Radius of the fueled zone [cm]	2.5
Thickness of graphite shell [cm]	0.5
Density of graphite shell [gcm^{-3}]	1.75
Impurity of natural boron in graphite matrix [ppm*]	0.5
Density of graphite matrix [gcm^{-3}]	1.75
Impurity of natural boron in graphite shell [ppm]	0.5
Number of coated particles in pebble	15000
Mass of fuel per pebble [g]	10.210
Coated particle	
Kernel	
Radius [cm]	0.025
Density [gcm^{-3}]	10.4
Impurity of natural boron in the kernel [ppm]	0.5
Coatings	
Material	C/iPyC/SiC/oPyC
Thickness [cm]	0.095/0.04/0.035/0.04
Density [gcm^{-3}]	1.05/1.9/3.18/1.9
Packing fraction of coated particle [%]	9.043

*parts per million

lar array of lattice particles within the fueled zone of the pebble. Dispersing the 15 000 TRISO particles in each repetitively structured fuel pebble will result in the TRISO particles being cut in the boundary between the fueled zone and graphite shell. However, this condition may be considered negligible due to the insignificant impact it imposes on the calculation results. The MCNP6 model of fuel pebble is illustrated in fig. 4. The

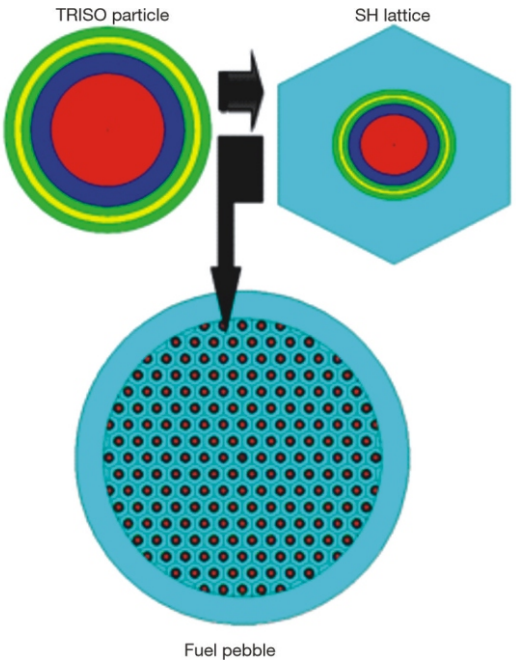

Figure 4. The MCNP6 model of fuel pebble

Table 2. Isotopic composition of TRISO particle

Kernel UO_2		Kernel (Th, U)O_2	
^{235}U	4.32074 10^{-2}	^{232}Th	2.07618 10^{-2}
^{238}U	1.89195 10^{-3}	^{233}U	2.94769 10^{-3}
O	4.64805 10^{-2}	O	4.74189 10^{-2}
^{10}B	1.14694 10^{-7}	^{10}B	1.14694 10^{-7}
^{11}B	4.64570 10^{-7}	^{11}B	4.64570 10^{-7}
Kernel PuO_2		Buffer	
^{238}Pu	6.01178 10^{-4}	^{12}C	5.26449 10^{-2}
^{239}Pu	1.24470 10^{-2}	iPyC/oPyC	
^{240}Pu	5.44599 10^{-3}	^{12}C	9.52621 10^{-2}
^{241}Pu	3.00965 10^{-3}	SiC	
^{242}Pu	1.54539 10^{-3}	^{28}Si	4.39872 10^{-2}
O	4.60983 10^{-2}	^{29}Si	2.24780 10^{-3}
^{10}B	1.14694 10^{-7}	^{30}Si	1.48899 10^{-3}
^{11}B	4.64570 10^{-7}	^{12}C	4.77240 10^{-2}

Table 3. Isotopic composition of graphite matrix and graphite shell

Graphite matrix		Graphite shell	
^{12}C	8.77414 10^{-2}	^{12}C	8.77414 10^{-2}
^{10}B	9.64977 10^{-9}	^{10}B	9.64977 10^{-9}
^{11}B	3.90864 10^{-8}	^{11}B	3.90864 10^{-8}

isotopic composition of TRISO coated fuel particle (in atom per barn per cm; 1 barn = 10^{-28} m^2) is listed in tab. 2. The identical isotopic composition of graphite matrix and graphite shell (in atom per barn per cm) is listed in tab. 3.

The reactor core filled with thousands of pebbles was modeled using body centered-cubic (BCC) lattice with repetitive structures. This lattice is the most representative with a core characterized by fuel and moderator pebbles with the ratio of 1:1 due to the BCC lattice consisting of two pebbles. In addition, despite the pebbles arrangement on the pebble bed core is expected to approach the hexagonal close-packed (HCP) lattice, the BCC lattice is more often a choice, thanks to its ability to provide packing size typically found in pebble bed reactors. The lattice pitch of 7.224957 cm was obtained from the correlation between the pebble volume in the lattice and the specified packing fraction of 0.60.

The appearance of a number of clipped pebbles on the core wall surface as a result of the use of repetitive structures, called partial pebbles, was corrected by applying an exclusive zone of 1.5 cm thick helium around the reactor core. This is undertaken to compensate for the partial pebbles which may be affecting the calculation accuracy. Core components and structures, such as axial and radial reflectors, *etc*., were modeled in a simpler way. A detailed description of this procedure was first introduced by Lebenhaft [19] and found in several publications [20-28]. The whole facility modeling of HTR-Proteus is illustrated in fig. 5. The isotopic composition of moderator pebble (in atom per barn per cm) is given in

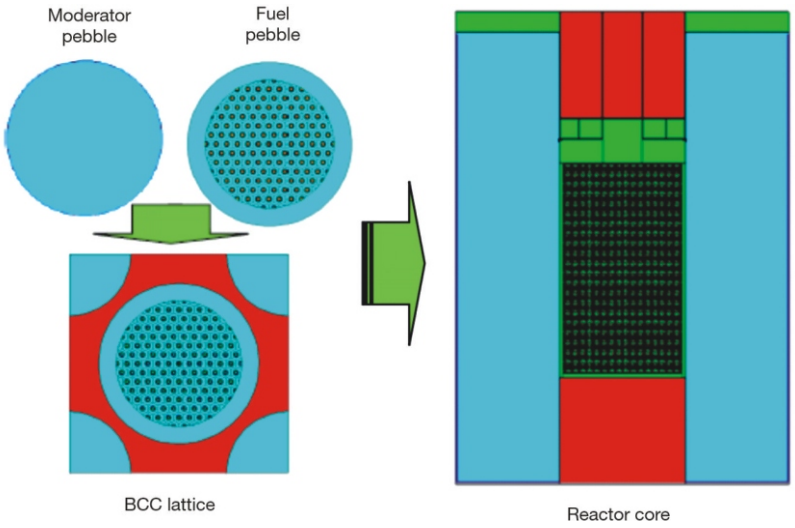

Figure 5. The MCNP6 model for HTR-Proteus

Table 4. Isotopic composition of moderator pebble

Moderator pebble	
^{12}C	$8.38302\ 10^{-2}$
^{10}B	$2.40326\ 10^{-8}$
^{11}B	$9.73442\ 10^{-8}$

Table 5. Isotopic composition of axial and radial reflectors

Axial reflector		Radial reflector	
^{12}C	$8.61000\ 10^{-2}$	^{12}C	$8.84000\ 10^{-2}$
^{10}B	$9.00000\ 10^{-9}$	^{10}B	$9.20000\ 10^{-9}$
^{11}B	$3.60000\ 10^{-8}$	^{11}B	$3.70000\ 10^{-8}$

tab. 4. The isotopic composition of axial and radial reflectors (in atom per barn per cm) is presented in tab. 5.

RESULTS AND DISCUSSION

The most important kinetic parameters of a reactor consist of the effective delayed neutron fraction β_{eff}, prompt neutron lifetime ℓ, and mean generation time [29]. These parameters were analyzed in this study. The core multiplication factor k_{eff} was also analyzed since the calculation of kinetic parameters is strongly connected to criticality calculations. To run the criticality problems, KCODE and KSRC cards are required in addition to the geometry description and material cards. The KSRC card which specifies the location of the initial spatial fission point was defined at the center of the fuel kernel and the KCODE card which determines the reactor multiplication factor was simulated with 25 000 particles per neutron life cycle. A total of 5 million neutron histories were used with discarding of the first 50 cycles of 250 cycles before averaging k_{eff}. The calculation of kinetic parameters was conducted by activating the KOPTS card in the MCNP6 input data. The control rods were placed in a fully withdrawn position.

The core has been modeled with different fuel compositions and different temperatures to examine their effects on the core multiplication factor k_{eff} and its kinetic parameters. Calculated k_{eff} results of the HTR-Proteus reactor are presented in tab. 6. From this table, it can be observed that the increase in fuel temperature T_F, moderator temperature T_M, and reflector temperature T_R simultaneously causes a decrease in the k_{eff} value. The largest decrease in k_{eff} value was found in the core with UO_2 fuel, followed by the core with (Th, U)O_2 and PuO_2 fuels. The calculation results of the temperature reactivity coefficient are calculated from the data in tab. 6 and presented in tab. 7 show that within a temperature range of 900 K-1200 K, the value of the total core temperature reactivity coefficient of UO_2 and (Th, U)O_2 is the most negative while in the temperature range of 1200 K-2500 K, the position was taken over by the PuO_2 core. This means that at operating temperature, the HTR-Proteus core has an adequate safety factor.

Table 6. Core multiplication factor k_{eff}

Temperature [K]	UO_2	(Th, U)O_2	PuO_2
$T_F = 293$, $T_M = 293$, $T_R = 293$	1.06737 0.00041	1.06778 0.00035	1.06749 0.00034
$T_F = 600$, $T_M = 600$, $T_R = 600$	1.04472 0.00035	1.04483 0.00037	1.07228 0.00033
$T_F = 900$, $T_M = 900$, $T_R = 900$	1.02588 0.00038	1.02945 0.00033	1.06774 0.00034
$T_F = 1200$, $T_M = 1200$, $T_R = 1200$	0.99548 0.00037	1.00739 0.00037	1.05368 0.00038
$T_F = 2500$, $T_M = 2500$, $T_R = 2500$	0.93593 0.00037	0.97874 0.00034	0.98223 0.00033

Table 7. Total temperature coefficient of reactivity (k $k^{-1}K^{-1}$)

Temperature range [K]	UO_2	(Th, U)O_2	PuO_2
293-600	$-6.6163\ 10^{-5}$	$-6.70065\ 10^{-5}$	$-1.36309\ 10^{-5}$
600-900	$-5.85954\ 10^{-5}$	$-4.76633\ 10^{-5}$	$-1.32179\ 10^{-5}$
900-1200	$-9.92255\ 10^{-5}$	$-7.09057\ 10^{-5}$	$-4.16572\ 10^{-5}$
1200-2500	$-4.91657\ 10^{-5}$	$-2.2352\ 10^{-5}$	$-5.31052\ 10^{-5}$

Table 9. Fuel temperature coefficient of reactivity (k $k^{-1}K^{-1}$)

Temperature range [K]	UO_2	(Th, U)O_2	PuO_2
293-600	$-8.65901\ 10^{-5}$	$-9.10308\ 10^{-5}$	$-2.61194\ 10^{-5}$
600-900	$-6.89657\ 10^{-5}$	$-6.03986\ 10^{-5}$	$-2.23847\ 10^{-5}$
900-1200	$-1.07223\ 10^{-4}$	$-1.05196\ 10^{-4}$	$-3.26238\ 10^{-5}$
1200-2500	$-4.93204\ 10^{-5}$	$-3.83392\ 10^{-5}$	$-1.98315\ 10^{-5}$

The k_{eff} calculation results and kinetic parameters as a function of fuel temperature are summarized in tab. 8. In this case, the fuel temperature is varied while the moderator and reflector are maintained at a temperature of 293 K. Similar to tab. 7, tab. 8 shows that the increase in fuel temperature caused a significant decrease in the k_{eff} value and the largest one was found in the core with UO_2 fuel followed by (Th, U)O_2 and PuO_2. The decrease in the k_{eff} value is caused by the Doppler broadening effect in the resonance region of the fuel which affects the amount of neutron absorption by isotopes in the fuel. Compared with the value of the reactivity coefficient in tab. 7, the reactivity effect of fuel temperature, tab. 9, appears to be more negative, especially for UO_2 and (Th, U)O_2 cores. The same thing was experienced by the PuO_2 core but at a temperature range of less than 900 K. From this observation, we could say that the negative value on core temperature reactivity is affected dominantly by the Doppler broadening effect of fuel temperature.

Table 8 confirms that the change in fuel temperature has a significant effect on the ℓ and but this change hardly affects the value of the β_{eff}. The increase in fuel temperature causes the value of ℓ and of the UO_2 core and (Th, U)O_2 core to increase by 1.32-8.79 % and 1.35-6.20 %, respectively. Different things are experienced by the PuO_2 core, the increase in fuel temperature actually decreases the value of ℓ even though the decrease is still below 0.25 %, while the value of the still increases from 0.77-3.11 %. Looking back at tab. 8, it can be found that the UO_2 core is easier to control because the β_{eff} value is the largest one, in contrast to (Th, U)O_2 and PuO2 which are almost half of the UO_2 fuel system.

The effect of the temperature moderator on kinetic parameters is summarized in tab. 10. The moderator temperature was varied while the fuel and reflector temperatures were kept constant at 1200 K and 293 K, respectively. Table 10 shows that increasing the graphite moderator temperature causes the k_{eff} value to decrease, but not as significant as increasing fuel temperature. The k_{eff} value decreases slightly as the moderator temperature increases because of an increase in neutron absorption from materials other than fuels. The largest decrease in k_{eff} was experienced by the UO_2 core, followed by the (Th, U)O_2 and PuO_2 cores. Table 10 represents a recurring trend as the moderator temperature increases for the ℓ and of UO_2 and (Th, U)O_2 cores, which increase within the range 0.70-2.23 % and 0.58-0.67 %, respectively. The same trend is also experienced by the PuO_2 core, with the increase in fuel temperature actually decreasing the ℓ value even though the decrease is very small (<0.15 %), while the value of the increases by 0.49 % at a moderator temperature of 1200 K and decreases by 0.33-0.78 % at a moderator temperature of 600 K and 900 K. Similar to tab. 8, the β_{eff} value does not change as the moderator temperature increases. Compared to the total temperature coefficient of reactivity (k $k^{-1}K^{-1}$) in tab. 7 and fuel temper-

Table 8. Effect of fuel temperature T_F on kinetic parameters (T_M = 293 K, T_R = 293 K)

Fuel temperature T_F [K]		k_{eff}		ℓ [s]		[s]		β_{eff}	
UO_2	293	1.06737	0.00041	$3.2507\ 10^{-3}$	$1.5126\ 10^{-6}$	$1.6789\ 10^{-3}$	$1.2600\ 10^{-5}$	0.00665	0.00038
	600	1.03792	0.00038	$3.3108\ 10^{-3}$	$1.4263\ 10^{-6}$	$1.7710\ 10^{-3}$	$1.3080\ 10^{-5}$	0.00629	0.00039
	900	1.01610	0.00038	$3.3545\ 10^{-3}$	$1.5732\ 10^{-6}$	$1.8369\ 10^{-3}$	$1.3820\ 10^{-5}$	0.00663	0.00040
	1200	0.98394	0.00039	$3.4364\ 10^{-3}$	$1.4784\ 10^{-6}$	$1.9507\ 10^{-3}$	$1.5470\ 10^{-5}$	0.00620	0.00038
	2500	0.92555	0.00033	$3.5639\ 10^{-3}$	$1.4588\ 10^{-6}$	$2.1222\ 10^{-3}$	$1.6860\ 10^{-5}$	0.00639	0.00039
$(Th,U)O_2$	293	1.06778	0.00035	$3.6369\ 10^{-3}$	$1.4876\ 10^{-6}$	$1.8651\ 100^{-3}$	$1.3890\ 10^{-5}$	0.00369	0.00029
	600	1.03684	0.00037	$3.7054\ 10^{-3}$	$1.4998\ 10^{-6}$	$1.9249\ 10^{-3}$	$1.4510\ 10^{-5}$	0.00345	0.00027
	900	1.01772	0.00036	$3.7553\ 10^{-3}$	$1.5723\ 10^{-6}$	$1.9621\ 10^{-3}$	$1.5160\ 10^{-5}$	0.00274	0.00025
	1200	0.98605	0.00037	$3.8476\ 10^{-3}$	$1.5206\ 10^{-6}$	$2.0629\ 10^{-3}$	$1.6480\ 10^{-5}$	0.00299	0.00028
	2500	0.93986	0.00038	$3.9776\ 10^{-3}$	$1.6016\ 10^{-6}$	$2.1909\ 10^{-3}$	$1.8360\ 10^{-5}$	0.00299	0.00029
PuO_2	293	1.06749	0.00034	$2.0983\ 10^{-3}$	$1.2841\ 10^{-6}$	$9.6555\ 10^{-4}$	$8.9429\ 10^{-6}$	0.00357	0.00028
	600	1.05843	0.00038	$2.0976\ 10^{-3}$	$1.2887\ 10^{-6}$	$9.7797\ 10^{-4}$	$9.5914\ 10^{-6}$	0.00285	0.00024
	900	1.05096	0.00033	$2.0929\ 10^{-3}$	$1.2343\ 10^{-6}$	$9.8606\ 10^{-4}$	$9.4730\ 10^{-6}$	0.00334	0.00027
	1200	1.04026	0.00035	$2.0901\ 10^{-3}$	$1.3359\ 10^{-6}$	$9.9368\ 10^{-4}$	$9.3932\ 10^{-6}$	0.00280	0.00022
	2500	1.01309	0.00036	$2.0850\ 10^{-3}$	$1.3816\ 10^{-6}$	$1.0246\ 10^{-3}$	$9.9400\ 10^{-6}$	0.00299	0.00025

Table 10. Effect of moderator temperature T_M on kinetic parameters (T_F = 1200 K, T_R = 293 K)

Moderator temperature T_M [K]		k_{eff}		ℓ [s]		Λ [s]		β_{eff}	
UO_2	293	0.98394	0.00039	$3.4364\ 10^{-3}$	$1.4784\ 10^{-6}$	$1.9507\ 10^{-3}$	$1.5470\ 10^{-5}$	0.00620	0.00038
	600	0.97396	0.00035	$3.4633\ 10^{-3}$	$1.4965\ 10^{-6}$	$1.9942\ 10^{-3}$	$1.5550\ 10^{-5}$	0.00726	0.00043
	900	0.96531	0.00037	$3.4876\ 10^{-3}$	$1.4458\ 10^{-6}$	$1.9987\ 10^{-3}$	$1.6150\ 10^{-5}$	0.00626	0.00040
	1200	0.94935	0.00038	$3.5342\ 10^{-3}$	$1.3584\ 10^{-6}$	$2.0333\ 10^{-3}$	$1.6350\ 10^{-5}$	0.00710	0.00043
$(Th,U)O_2$	293	0.98605	0.00037	$3.8476\ 10^{-3}$	$1.5206\ 10^{-6}$	$2.0627\ 10^{-3}$	$1.6480\ 10^{-5}$	0.00299	0.00028
	600	0.97635	0.00036	$3.8732\ 10^{-3}$	$1.4584\ 10^{-6}$	$2.0629\ 10^{-3}$	$1.6330\ 10^{-5}$	0.00303	0.00027
	900	0.96861	0.00037	$3.8955\ 10^{-3}$	$1.4583\ 10^{-6}$	$2.0765\ 10^{-3}$	$1.6800\ 10^{-5}$	0.00352	0.00033
	1200	0.95427	0.00037	$3.9360\ 10^{-3}$	$1.4482\ 10^{-6}$	$2.0833\ 10^{-3}$	$1.6570\ 10^{-5}$	0.00338	0.00031
PuO_2	293	1.04026	0.00035	$2.0901\ 10^{-3}$	$1.3359\ 10^{-6}$	9.9368 10-4	$9.3932\ 10^{-6}$	0.00280	0.00022
	600	1.03684	0.00036	$2.0897\ 10^{-3}$	$1.2734\ 10^{-6}$	9.8594 10-4	$9.3016\ 10^{-6}$	0.00292	0.00024
	900	1.03365	0.00034	$2.0875\ 10^{-3}$	$1.2762\ 10^{-6}$	9.8271 10-4	$9.4513\ 10^{-6}$	0.00309±0.00024	
	1200	1.02652	0.00036	$2.0848\ 10^{-3}$	$1.3670\ 10^{-6}$	9.8749 10-4	$9.7416\ 10^{-6}$	0.00374	0.00028

Table 11. Moderator temperature coefficient of reactivity (k $k^{-1}K^{-1}$)

Temperature range [K]	UO_2	(Th, U)O_2	PuO_2
293-600	$-3.39221\ 10^{-5}$	$-3.28193\ 10^{-5}$	$-1.03284\ 10^{-5}$
600-900	$-3.06681\ 10^{-5}$	$-2.72813\ 10^{-5}$	$-9.92166\ 10^{-6}$
900-1200	$-5.80522\ 10^{-5}$	$-5.17139\ 10^{-5}$	$-2.23989\ 10^{-5}$

Table 13. Reflector temperature coefficient of reactivity RTC (k $k^{-1}K^{-1}$)

Temperature range [K]	UO_2	(Th, U)O_2	PuO_2
293-600	$9.32431\ 10^{-5}$	$9.85160\ 10^{-5}$	$5.73674\ 10^{-5}$
600-900	$2.89788\ 10^{-5}$	$3.59327\ 10^{-5}$	$1.66267\ 10^{-5}$
900-1200	$3.83083\ 10^{-5}$	$4.74434\ 10^{-5}$	$8.36861\ 10^{-6}$

ature coefficient of reactivity (k $k^{-1}K^{-1}$) values in tab. 9, the moderator temperature coefficient of reactivity (k $k^{-1}K^{-1}$) in tab. 11 is slightly smaller for all three HTR-Proteus cores considered.

The effect of reflector temperature T_R on kinetic parameters (T_F = 1200 K, T_M = 1200 K) is summarized in tab. 12. Unlike other previously mentioned cases, when the reflector temperature increases, the k_{eff} value increases. The increase in k_{eff} value is quite significant compared to the decrease of the k_{eff} value when the moderator temperature is increased. Therefore, the reflector temperature coefficient of reactivity is positive, as shown in tab. 13. This means that the number of neutrons coming out of the reactor is reduced which is most likely due to the backscattering of neutrons into the reactor core that occurs in the reflector. Because the material used as neutron moderator and reflector is the same graphite material, it can be said that this backscattering phenomenon can also occur inside the reactor core. Increasing the moderator temperature causes the k_{eff} value to increase due to the increasing number of moderated neutrons, but on the other hand, the effect of neutron absorption from non-fuel materials whose temperature increases due to the Doppler effect is predicted to be more dominant when inside the reactor core, different from the radial and axial reflector that positioned on the edge of the core.

The UO_2 and (Th, U)O_2 cores have a higher reflector temperature coefficient of reactivity than PuO_2 core because there is a greater increase in k_{eff}. The calculation results of the kinetic parameters shown in tab. 12 give the impression that the value of the ℓ and are

Table 12. Effect of reflector temperature T_R on kinetic parameters (T_F = 1200 K, T_M = 1200 K)

Reflector temperature T_R [K]		k_{eff}		ℓ [s]		[s]		β_{eff}	
UO_2	293	0.94935	0.00038	$3.5342\ 10^{-3}$	$1.3584\ 10^{-6}$	$2.0333\ 10^{-3}$	$1.6350\ 10^{-5}$	0.00710	0.00043
	600	0.97587	0.00035	$2.9834\ 10^{-3}$	$1.3754\ 10^{-6}$	$1.7763\ 10^{-3}$	$1.3180\ 10^{-5}$	0.00668	0.00042
	900	0.98422	0.00038	$2.7518\ 10^{-3}$	$1.1517\ 10^{-6}$	$1.6795\ 10^{-3}$	$1.1970\ 10^{-5}$	0.00752	0.00046
	1200	0.99548	0.00037	$2.4433\ 10^{-3}$	$1.0271\ 10^{-6}$	$1.5508\ 10^{-3}$	$1.1030\ 10^{-5}$	0.00717	0.00043
$(Th,U)O_2$	293	0.95427	0.00037	$3.9360\ 10^{-3}$	$1.4876\ 10^{-6}$	$2.0833\ 10^{-3}$	$1.6570\ 10^{-5}$	0.00338	0.00031
	600	0.98263	0.00034	$3.3424\ 10^{-3}$	$1.3384\ 10^{-6}$	$1.8855\ 10^{-3}$	$1.4510\ 10^{-5}$	0.00260	0.00025
	900	0.99315	0.00034	$3.0898\ 10^{-3}$	$1.2130\ 10^{-6}$	$1.97574\ 10^{-3}$	$1.2860\ 10^{-5}$	0.00299	0.00028
	1200	1.00739	0.00037	$2.7523\ 10^{-3}$	$1.1410\ 10^{-6}$	$1.6099\ 10^{-3}$	$1.1460\ 10^{-5}$	0.00317	0.00029
PuO_2	293	1.02652	0.00036	$2.0848\ 10^{-3}$	$1.3670\ 10^{-6}$	$9.8749\ 10^{-4}$	$9.7416\ 10^{-6}$	0.00374	0.00028
	600	1.04542	0.00033	$1.6812\ 10^{-3}$	$1.0354\ 10^{-6}$	$8.3326\ 10^{-4}$	$7.6371\ 10^{-6}$	0.00298	0.00024
	900	1.05090	0.00037	$1.5180\ 10^{-3}$	$1.0616\ 10^{-6}$	$7.6837\ 10^{-4}$	$6.8161\ 10^{-6}$	0.00320	0.00026
	1200	1.05368	0.00038	$1.3032\ 10^{-3}$	$8.6296\ 10^{-7}$	$6.7693\ 10^{-4}$	$5.8807\ 10^{-6}$	0.00301	0.00023

decreasing while reflector temperature is increasing for all cores. This value is on the opposite trend of the ℓ and when the fuel and moderator temperatures increase. More specifically, the ℓ and of the PuO_2 core are also decreased as the moderator temperature increase. Again, it can be found that the UO_2 core is easier to control because its β_{eff} value is greatest when the reflector temperature increases. The β_{eff} values of (Th, U)O_2 and PuO_2 cores are almost half of the UO_2 core β_{eff} values.

Changes in the ℓ and due to changes in temperature of the fuel, moderator and reflector may be caused by factors related to neutron moderation and neutron absorption by fissile and fertile materials in the core. The β_{eff} value is very specific and only depends on the isotope used as a fissile and fertile material. That is why changes in temperature of the fuel moderator, and reflector do not have much effect on the β_{eff} value because the composition of the fissile and fertile material is practically the same or does not change as the temperature changes. For the (Th, U)O_2 core, the β_{eff} value obtained is dominated by the presence of ^{233}U while for the UO_2 and PuO_2 cores, the β_{eff} values are more influenced by the ^{235}U, and ^{239}Pu isotopes, respectively. If the fuel composition of the core is different, especially the fissile material, the β_{eff} will also be different.

CONCLUSION

A study on the characteristics of kinetic parameters for pebble bed reactor using HTR-Proteus has been conducted. A series of calculations with various temperatures were performed by using the Monte Carlo transport code MCNP6 and the continuous energy nuclear data library ENDF/B-VII. The calculation results show that the negative value on core temperature reactivity is affected dominantly by the Doppler broadening effect of fuel temperature. The moderator temperature coefficient is slightly smaller for all three HTR-Proteus cores considered. UO_2 and (Th, U)O_2 cores have a higher reflector temperature coefficient of reactivity than PuO_2 core. Changes in the ℓ and due to changes in temperature of the fuel, moderator and reflector may be caused by factors related to neutron moderation and neutron absorption by fissile and fertile materials in the core. For the (Th, U)O_2 core, the β_{eff} value obtained is dominated by the presence of ^{233}U while for the UO_2 and PuO_2 cores, the β_{eff} values are more influenced by the ^{235}U, and ^{239}Pu isotopes, respectively. The UO_2 core is easier to control because the β_{eff} value is the largest one, in contrast to (Th, U)O_2 and PuO_2 which are almost half of the UO_2 fuel system. It can be concluded, that changing temperature not only affects the temperature coefficient of reactivity but also kinetic parameters as an inherent safety feature of a pebble-bed reactor.

AUTHOR'S CONTRIBUTIONS

All authors contributed equally to this manuscript.

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ПРОУЧАВАЊЕ КАРАКТЕРИСТИКА КИНЕТИЧКИХ ПАРАМЕТАРА РЕАКТОРА СА СВЕРНИМ ГОРИВОМ КОРИШЋЕЊЕМ HTR-PROTEUS ПОСТРОЈЕЊА

Инхерентна сигурност карактеристика реактора са сверним горивом може се уочити из његових кинетичких параметара. Такође, брига за правилно моделовање кинетике реактора потребно је ради сигурног рада током нормалних и прелазних режима. Овај рад има за циљ да истражи карактеристике кинетичких параметара реактора са сверним горивом коришћењем HTR-PROTEUS постројења. Серија прорачуна спроведена је коришћењем MCNP6 кода и библиотеке ENDF/B-VII.1. Резултати прорачуна показују да на негативну вредност температурне реактивности језгра доминантно утиче ефекат Доплеровог ширења. Промптни животни век неутрона и средње време генерисања мало се мењају услед повећања температуре горива, модератора и рефлектора, који утичу на модерацију и апсорпцију неутрона у овом делу реактора. За језгра (Th, U)O_2, UO_2 и PuO_2, ефективне вредности фракције закаснелих неутрона више су под утицајем ^{233}U, ^{235}U и ^{239}Pu, респективно. У погледу стабилности током уношења реактивности, језгро UO_2 је стабилније и лакше га је контролисати јер је вредност његове фракција закаснелих неутрона највећа у поређењу са (Th, U)O_2 и PuO_2 језгрима. Може се закључити да се промена температуре мора контролисати јер не утиче само на реактивност већ и на кинетичке параметре као део тока својствених сигурносних карактеристика реактора са сверним горивом.

Кључне речи: кинетички параметар, реактор са сверним горивом, HTR-PROTEUS, MCNP6, ENDF/B-VII