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MODELING AND ANALYSIS OF FLUX AND POWER DISTRIBUTION FOR HTR-10 REACTOR CORE

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Abstract: MCNP6 computer code is used to model HTR-10 core reactor. UO_2 fuel is used. We predict the Flux and power distribution for normal core loaded by UO_2 fuel pebbles of the reference HTR-10 reactor. The MCNP model consisted of the reactor structure which included the graphite reflector, the borated carbon bricks surrounding it and the pebble-bed core. The results show an analogue between the thermal neutron flux distribution and the power distribution, where the thermal neutrons are responsible for causing the fission, and hence power generation. The thermal neutron flux and power generation have its maximum value at the core center and decreases as we move away from the center to core boundary. The thermal flux is increased near the reflector because the neutron reflector scatters back (or reflects) into the core many neutrons that would otherwise escape. The neutrons reflected back into the core are available for chain reaction (reflector savings).

Keywords: Pebble-bed, HTR-10, Flux distribution, power distribution, thorium-based fuel

INTRODUCTION

High Temperature Reactors (HTRs) and Very High Temperature Reactors (VHTRs), grouped as V/HTRs, are thermal-spectrum reactors, cooled by circulating helium under pressure (50 to 90 bars). Graphite is used both as a moderator and a neutron reflector. In V/HTRs, helium is heated by the fuel in the core (at ~ 500°C) and exit with a temperature between 750°C and 850°C for HTRs and over 900°C in future VHTRs. These high temperature means that the thermodynamic efficiency can reach 50%, which is 30 – 40 % higher than PWRs and 20% higher than SFRs [1].

The HTR-10 high temperature gas cooled reactor was built as a safer, cheaper and more efficient than other designs of nuclear reactors. This reactor produces 10MW thermal power, using helium gas coolant that enters the reactor at 250¤C and 3MPa pressure and is heated to 700¤C. The HTR-10 uses graphite to moderate the neutrons. The fuel is made of TRISO particles with kernels of UO2 (17% enrichment) embedded in a graphite matrix.

The reactor fuel is packed into spherical particles surrounded by layers of ceramic [2]. The coolant outlet temperature in HTR-10 is much higher than PWRs (700°C - 950°C compared to 300°C) [3]. Therefore, the reactor can be used in a number of industrial heat applications, efficient electrical power generation and also hydrogen generation as a byproduct [3]. The spherical fuel elements with carbon coated particles are poured in the reactor from the top and are allowed to move downwards by gravity in a multi pass pattern (Figure 1) [4]. This prevents reactor meltdown even if there is a total loss of coolant [3].

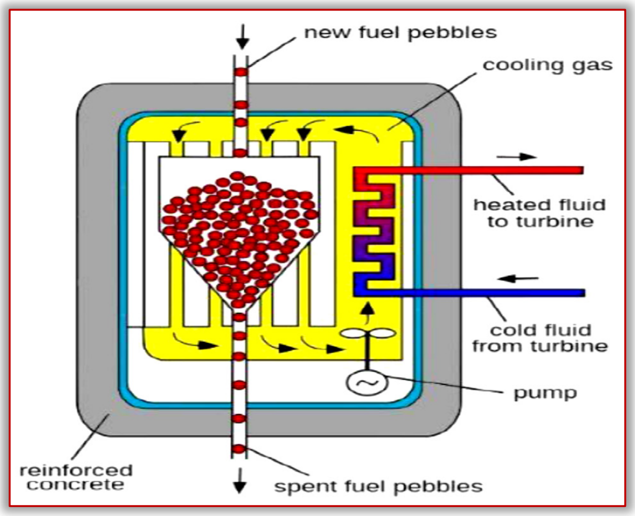

Figure 1: Schematic of the pebble bed reactor [4].

The neutron flux distribution in the internal parts of the reactors is an important parameter which affects the absorbed dose, temperature, and gas production of materials. Therefore, the good knowledge of neutron flux distribution is important for estimation of the radiation-induced swelling and activation of this internal component. The power distribution in the periphery fuel pebbles has considerable influence on neutron and gamma flu in the internal reactor elements. This paper aims to calculate the axial and radial distribution for each of neutron flux and power [5, 6].

REFERENCE CORE

We used the HTR-10 reactor core composition as our reference case. The fuel particles contain kernels coated with different layers of SiC and PyC, with low-enriched uranium (17% 235U) whose design burnup is 80,000 MWd/t [2]. Detailed core parameters are given in Table 1 [2]. There are 27,000 pebbles randomly packed in the full core. The core has a cylindrical cavity, 1.97m high, with a 1.8 m diameter and 5 m3 volume [2]. There is a graphite reflector around the core and a borated carbon shield. The 100 cm thick radial reflector contains penetrations for ten control rods, seven absorber ball units, three irradiation sites and twenty coolant channels.

Table 1. Parameters of HTR-10 core [2].

Parameter	Value	Unit
Density of graphite in matrix and outer shell	1.73	g/cm^3
Uranium loading per fuel pebble	5.0	g
Enrichment of 235U	17	wt.%
Equivalent natural boron content of impurities in uranium	4	ppm
Equivalent natural boron content of impurities in graphite	13	ppm
Volumetric filling fraction of balls in the core	0.61	
Coated Fuel Particle		
Radius of fuel kernel	0.025	cm
UO$_2$ density	10.4	g/cm^3
Thickness of first pyrolytic carbon coating	0.009	cm
Thickness of second pyrolytic coating	0.004	cm
Thickness of silicon-carbide coating	0.0035	cm
Thickness of third pyrolytic carbon coating	0.004	cm
Density of first pyrolytic coating	1.1	g/cm^3
Density of second pyrolytic coating	1.9	g/cm^3
Density of silicon-carbide coating	3.18	g/cm^3
Density of third pyrolytic coating	1.9	g/cm^3

Helium gas flows up these coolant channels before reversing direction at the top of the core and flowing downward into the pebble bed. The core inlet and outlet coolant temperatures are 2500C and 7000C, respectively, at a pressure of 3.0 MPa [2].

The moderator pebbles fill both the discharge tube and the cone at the bottom of the core before adding a mixture of fuel and moderator pebbles randomly until the critical core height (defined as the minimum active core height required to achieve the first criticality) is reached with the control rods fully withdrawn. The ratio of fuel to moderator pebbles used in the reactor is 57% to 43%, and the initial loading is carried out at room temperature and in atmospheric air [2].

With inserting the control rods, the core is then pressurized and completely filled using the same mixture of fuel and moderator balls. The initial critical core height is chosen so as to limit the maximum excess reactivity held down by the control absorber rods to the amount required to provide sufficient xenon override. The excess reactivity margin is controlled subsequently by the continuous refueling of the reactor [2].

A number of deterministic codes are used for HTGR neutronic calculations, such as VSOP94, PANGU and PEBBED. VSOP94 is a general purpose code used for reactor physics and fuel cycle simulation using 2-D and 3-D diffusion calculations [7]. PANGU was developed by the Institute of Nuclear and New Energy Technology (INET), Tsinghua University and is used for physics analysis and fuel cycle simulations of pebble bed HTGR [8]. PEBBED is used for the design and analysis of pebble-bed high temperature reactor (PBR) cores [9].

REACTOR MODEL

We used MCNP6.1 code [10] for the calculations, which is capable of doing burnup calculations and can give the composition of burnt materials at different time periods among the irradiation cycle of the reactor. The MCNP model consisted of the reactor structure which included the graphite reflector, the borated carbon bricks surrounding it and the pebble-bed core. Figure 2 shows a vertical cross sectional view of the modeled reactor.

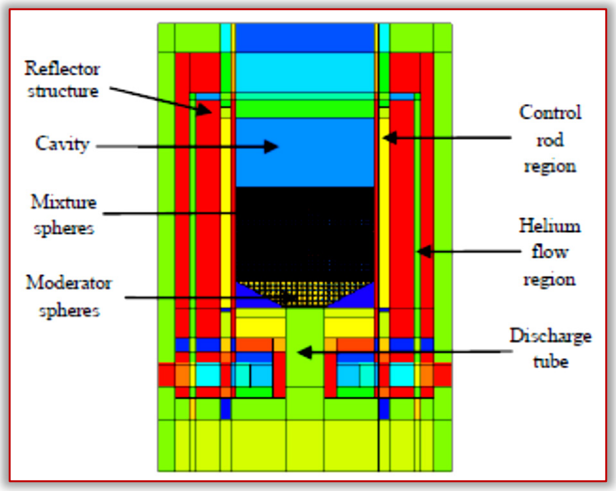

Figure 2. MCNP6 Model of HTR-10 (Vertical Cross Section)

Figure 3 shows the horizontal view of that model. Because online fuel pebble shuffling is a dynamic process which cannot be modeled using MCNP 6.1 code, instead, fixed pebble bed was used in this paper.

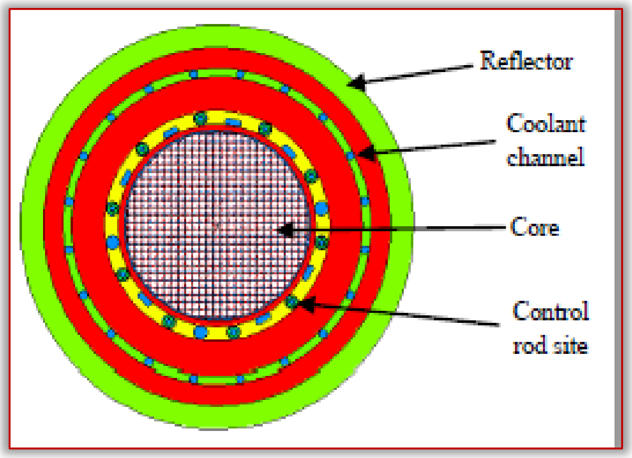

Figure 3. MCNP6 Model of HTR-10 (Horizontal Cross Section)

Assuming a body-centered cubic (BCC) lattice, the packing fraction of the fuel and moderator pebble inside the core zone was 0.61. The size of the graphite moderator sphere was reduced from 7.1843 cm to 6.8772 cm in order to preserve the packing fraction and to reproduce the specified fuel-to-moderator pebble ratio. We used the repeated-structure feature of MCNP6.1 to approximate the specification of a 57:43 fuel-to-moderator pebble percent ratio for the initial HTR-10 core loading. The MCNP6 model for BCC lattice, pebble-bed and triple isotropic coated particles (TRISO) are shown in Figure 4. Table 2 summarizes the geometry specifications used to model the pebble bed.

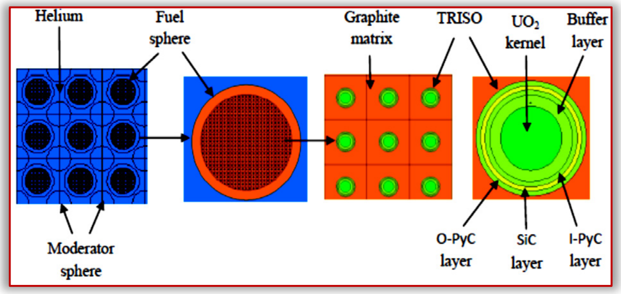

Figure 4. Pebble-bed and moderator ball in a BCC lattice and TRISO in the reactor core model.

Table 2. HTR-10 Pebble-bed model geometry

Specifications. Parameter	Value	Units
Fuel-to-moderator pebble volume ratio	1.3256	–
Radius of fuel pebble	3.0	cm
Radius of fueled region	2.5	cm
Packing fraction	0.61	–
Moderator pebble radius	2.7310	cm
BCC unit cell size	6.8773	cm

We used the standard ENDF/B-VII.1 cross-section data. The percentages of fissions caused by neutrons are 94.08% in the thermal range (<0.625 eV), 5.69% in the intermediate range (0.625 eV - 100 keV) and 0.23% in the fast neutron ranges (>100 keV).

The power of the reactor was 10 MW_{th} and the number of neutron histories allowed to scan the reactor core and accumulate the tallies is 210 cycles with 40000 neutrons per cycle, with 10 cycles skipped. While for burnup calculations, we used 110 cycles and 10000 neutrons for each cycle, with 10 cycles skipped.

We found from the MCNP6 simulations that the HTR-10 reference core achieved the first criticality in the active core height of 127.259 cm calculated from the bottom of the active core. The minimum UO_2 fuel pebbles needed to achieve initial criticality was 9,581 fuel pebbles and 7,228 moderator pebbles.

MODEL VALIDATION

Table 3 shows the critical height of the core (the height at which the core is critical) at fresh fuel conditions as loaded with UO2 fuel. The second column represents the critical height of the experimental measurements (123.06 cm). The third column shows the theoretical results of Ref. [2]. The fourth column is our model results (127.259 cm). There is a good agreement between the experimental measurements and the present model with 3.4% error.

Table 3. Comparison between present model and published results

Parameter	Experimental Measurements	Ref. [2] Results1	Present Model2
Critical height	123.06 cm	126.116 cm	127.952 cm
Critical loading	--	16,821 pebbles	16,809 pebbles

CALCULATED PARAMETER

All calculations were performed using the standard ENDF/B-VII.1 cross-section data, helium gas coolant, full core (core height is 197 cm, number of fuel pebbles is 15390, number of moderator pebbles is 11610 with a total number of 27000 pebbles) except for cases used to determine the initial criticality (critical height, number of moderator pebbles and number of fuel pebbles). The results were based on 8.4 million (active) neutron histories per case, which reduced the standard deviation to about 0.0003. Ten non-active cycles, with 40000 neutrons per cycle, were used to establish a uniform source distribution.

POWER DISTRIBUTION

▦ Radial power distribution

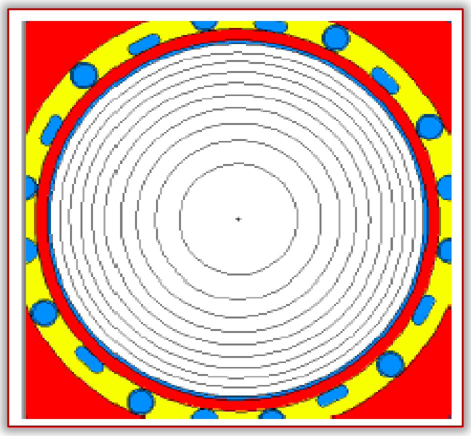

Figure 5. Radial zones for HTR-reactor

Figures 6 illustrates the radial thermal flux distribution for HTR-10 versus core radius, thermal flux has its maximum value at the core center and decreases by increasing the core radius to reach its minimum value at 80 cm then increases again. The thermal flux is increased near the reflector because the neutron reflector scatters back (or reflects) into the core many neutrons that would otherwise escape. The neutrons reflected back into the core are available for chain reaction (reflector savings).

Figure 7 shows the general effect of reflection in the thermal reactor system. Note that a reflector can raise the power density of the core periphery and thus increase the core average power level without changing the peak power.

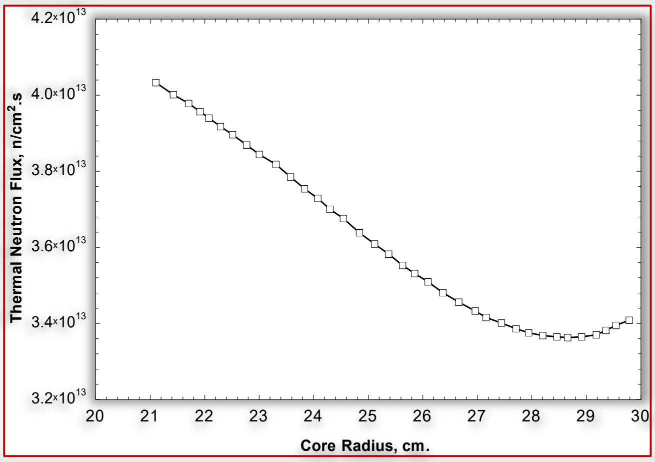

Figure 6. Radial thermal flux distribution for HTR-10 versus core radius

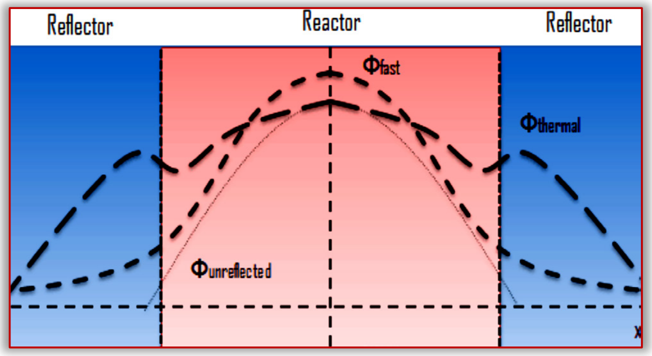

Figure 7. Effect of reflection in the thermal reactor

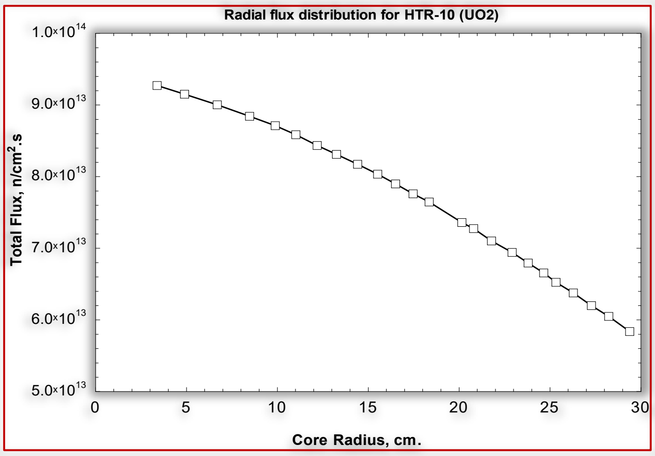

Figure 8. Radial total flux distribution for HTR-10 versus core radius

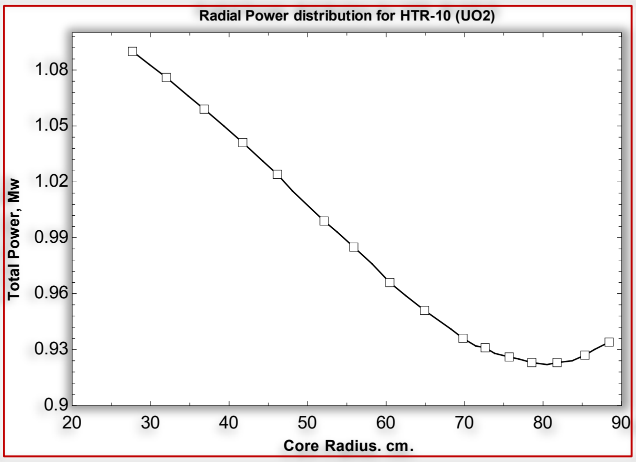

Figure 9. Radial total power distribution for HTR-10 versus core radius

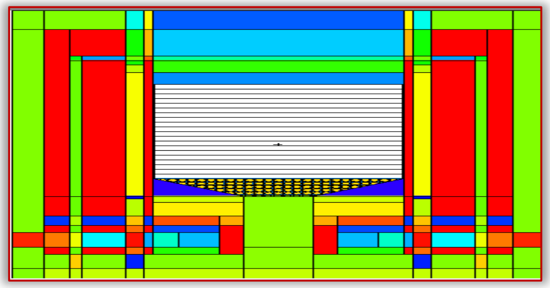

Figure 10. Axial zones for HTR-reactor

Thermal flux, total flux and total power calculated in each zone for reference case. Figures 11 - 13, below, present the axial thermal neutron flux, total flux and total power for different active core radius

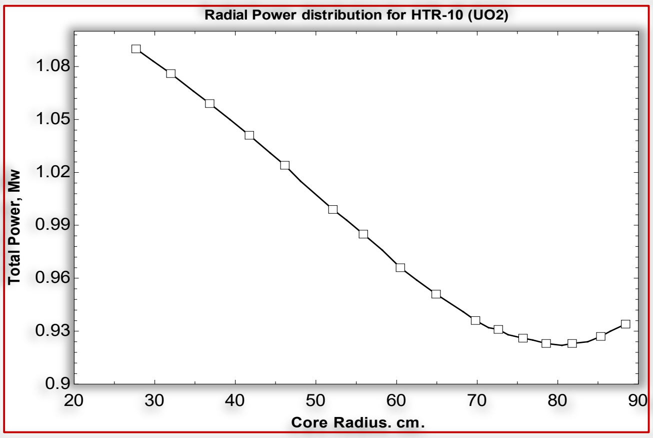

Figure 11. Axial thermal flux distribution for HTR-10 versus core height

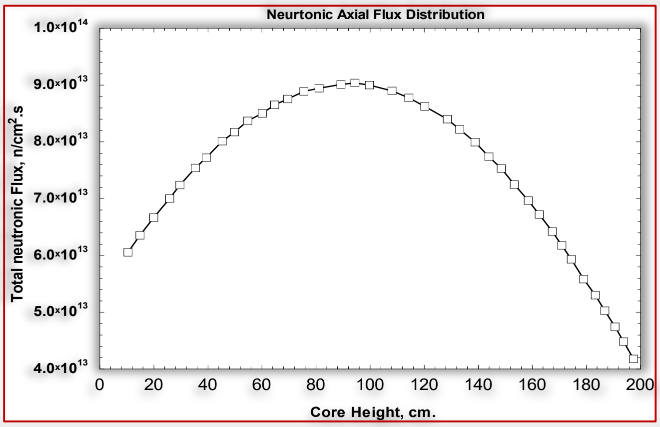

Figure 12. Axial total flux distribution for HTR-10 versus core height

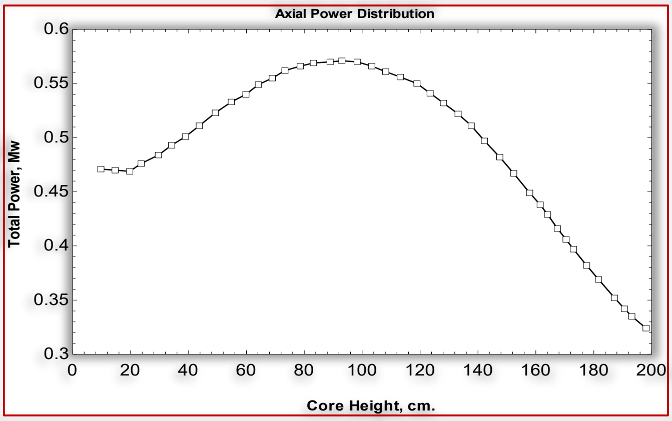

Figure 13. Axial total power distribution for HTR-10 versus core height

In general, there is an analogue between the thermal flux distribution and the power distribution, where the thermal neutrons are responsible on causing the fission, and hence production.

The thermal flux has its maximum value at the core center and decreases as we move away from the center. The thermal flux is increased near the reflector because the neutron reflector scatters back (or reflects) into the core many neutrons that would otherwise escape. The neutrons reflected back into the core are available for chain reaction (reflector savings).

CONCLUSION

The reactor core of HTR-10 pebble bed gas-cooled reactor was modeled using MCNP6.1, to study the flux and power distribution. The model was validated using benchmark problems. A good agreement between the present work and others published in benchmark was found, with 0.8% error, due to necessary assumptions to model double heterogeneity and random packing. The axial and radial flux distributions and the axial and radial power distributions have been investigated for normal core loaded by UO_2 fuel pebbles of the reference HTR-10 reactor. The results show that; the thermal flux has its maximum value at the core center and decreases as we move away from the center. The thermal flux is increased near the reflector because the neutron reflector scatters back (or reflects) into the core many neutrons that would otherwise escape. The neutrons reflected back into the core are available for chain reaction (reflector savings).

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