A SIMULATION OF A PEBBLE BED REACTOR CORE BY THE MCNP-4C COMPUTER CODE

by

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Lack of energy is a major crisis of our century; the irregular increase of fossil fuel costs has forced us to search for novel, cheaper, and safer sources of energy. Pebble bed reactors – an advanced new generation of reactors with specific advantages in safety and cost – might turn out to be the desired candidate for the role. The calculation of the critical height of a pebble bed reactor at room temperature, while using the MCNP-4C computer code, is the main goal of this paper. In order to reduce the MCNP computing time compared to the previously proposed schemes, we have devised a new simulation scheme. Different arrangements of kernels in fuel pebble simulations were investigated and the best arrangement to decrease the MCNP execution time (while keeping the accuracy of the results), chosen. The neutron flux distribution and control rods worth, as well as their shadowing effects, have also been considered in this paper. All calculations done for the HTR-10 reactor core are in good agreement with experimental results.

Key words: HTR-10, MCNP-4C, neutron flux, pebble bed, shadowing effects

INTRODUCTION

Gas cooled nuclear reactors, especially pebble bed nuclear reactors, have many significant advantages compared to other types of reactors, making them a focal point of attention for researches as possibly one of the best novel energy resources. Their inherent safety stems from their exceptionally small excess reactivity [1]; on line refueling, the absence of cladding which nullifies the clad melting issue at high temperatures, hydrogen production, a short construction period and provision of high temperature tests, are just a few of the advantages of the said reactors [2]. High efficiency and relatively low construction costs are an added advantage. Using helium noble gas as a coolant allows us not only to avoid radiation hazards to reactor equipment, but also to reach high temperatures without increasing the pressure. For above mentioned reasons, and other features already dealt with in scientific literature, nuclear scientists and engineers have lately concentrated more on this particular type of reactors. The HTR-10 is a pebble bed reactor operated by the Tsinghua University in China [3]. As already pointed out in references, the configuration of this reactor is quite different from other conventional types of reactors. The HTR-10 fuel and moderator are in the form of spherical balls and are distributed randomly throughout the reactor core.

In this paper, the HTR-10 reactor core is simulated by use of the MCNP-4C computer code [4]. Because of the spherical nature of the fuel, moderator and even the core of the reactor itself, as well as the Cartesian nature of the MCNP computer code, the modeling of the core by usual MCNP-4C computer codes is not that straightforward. Moreover, the Monte Carlo method is inherently slow and time-consuming and one has to use various variance reduction techniques in order to achieve a reasonable execution time [5]. Such as applying the computer clustering technique for the simulation of the reactor core, if one is to provide LATTICE and UNIVERSE options. We have tried to present a new simulation scheme for the HTR-10 reactor core which reduces time consumption during MCNP execution. This new scheme

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also allowed us to reduce the size of the input deck, as well as the required time for MCNP execution; meaning that variance reduction techniques are not the only option. Our paper is structured as follows: in the section on HTR-10 gas cooled reactor, we present a brief description of the HTR-10 reactor core and its specifications. Simulations of fuel and moderator balls, as well as those of the reactor core, are given in the section on HTR-10 modeling by the MCNP-4C code. In section Calculation of the effective multiplication factor (K_{eff}), we also present the calculations of the effective multiplication factor for various heights of the reactor core. In the section of sensitivity analysis, the variation in the effective multiplication factor of different arrangements of kernels in the fuel pebbles will be presented. In the section on control rods, the distribution of neutron flux in the core and calculation of control rods worth are presented. Finally, the main conclusions are drawn.

HTR-10 GAS COOLED REACTOR

HTR-10 is a high temperature gas cooled pebble bed reactor. Its core region is filled with fuel and graphite moderator spheres (60 mm in diameter). The reactor core with the height and diameter of 1.97 and 1.8 m, respectively, contains about 27000 pebbles. Each fuel pebble contains about 8000-9000 fuel microspheres bound in graphite. Each fuel microsphere is made up of an uranium dioxide kernel enclosed in a three-layer coating, *i. e.*, a layer of silicon carbide (SiC), sandwiched by two layers of pyrolotic carbon (PyC). This so-called TRISO fuel has exhibited good fission product retention. Each fuel pebble contains about 5 g of uranium enriched for 17% and the ratio of fuel to moderator pebbles in the core is about 57/43 [5]. The volume of the core is about 5 m^3 and it is surrounded by a meter thick side reflector. The reactor has 10 control rods, 7 absorber ball channels and 22 helium flow channels in the reflector region. Fuel discharge burn-up is 80000 MWd/T. The main characteristics of this reactor are listed in tab. 1.

HTR-10 MODELING BY THE MCNP-4C CODE

Fuel and moderator spheres modeling

As already mentioned, fuel spheres are made up of TRISO particles. TRISO particles are composed of uranium dioxide pellets enclosed in three layers of coating. The modeling of TRISO particles is easily done by the MCNP-4C computer code. Figure 1 shows a simulated TRISO particle. To get the exact weight of 5 g of heavy metal loaded into each fuel pebble, one has to assume about 8343 TRISO particles in a fuel pebble. Regular and random distribution of coated fuel particles (CFP) in each of the pebbles does not affect the results significantly, although a homogenous distribution of CFP in graphite is not recommended [5]. A fuel pebble simulated by the MCNP-4C computer code, with 8343 regularly distributed TRISO particles (fig. 2). The moderator pebbles are spheres with a 6 cm

Table 1. The main characteristics of HTR-10 reactor [5]

Reactor thermal power	10 MW
Reactor core height	197 cm
Reactor core diameter	180 cm
Number of control rods in side reflector	10
Number of absorbed ball units in side reflector	7
Number of fuel pebbles in the core	27000
Fuel material	UO_2
Heavy metal loading per fuel element	5 g
Fresh fuel enrichment	17 %
Diameter of spherical fuel elements	6 cm
Average discharge burn-up	80000 MWd/t
Active core volume	5 m^3
Average power density	2 MW/m^3

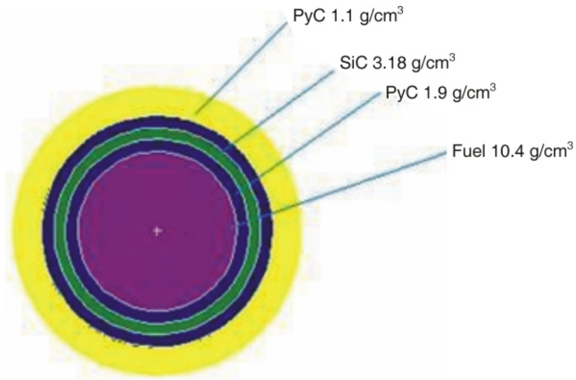


Figure 1. Horizontal cross-section view of a fuel kernel by the MCNP-4C computer code

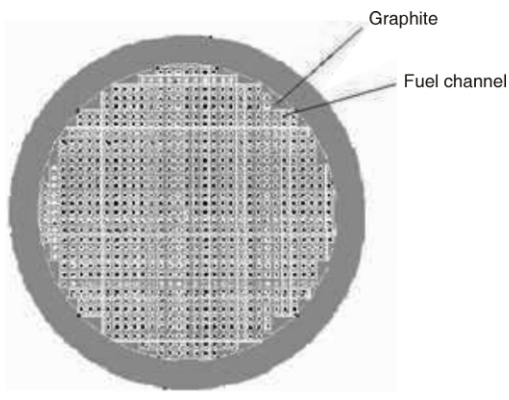


Figure 2. Horizontal cross-section view of fuel pebble with 8343 CFPs modeled by the MCNP-4C computer code

diameter, made up of net graphite, easily modeled by the MCNP-4C computer code.

Reactor core modeling

The HTR-10 reactor core is comprised of fuel and graphite pebbles. In the modeling of the reactor core, aside from its heterogeneity, the ratio of fuel to graphite spheres should be kept at 57/43. The usual scheme of the MCNP computer code, *i. e.*, LATTICE and UNIVERSE, models the reactor core by means of the computer clustering technique [5]. In order to free ourselves of the clustering technique, we have tried to come up with a different scheme. In our model, the reactor core is meshed by several concentric cubes which have already been filled by rectangular lattices, including the spherical fuel or moderator elements. This could reduce the execution time and even the size of the input significantly but, at the same time, increase the time needed for plotting the geometry. The calculation of the effective multiplication factor, neutron flux distribution and other parameters would be noticeably faster with this scheme, in comparison to that proposed by ref. [5]. The HTR-10 reactor core [6] is modeled by this scheme by using a PC equipped by a 3 GHz CPU speed. Horizontal and vertical cross-section views of the HTR-10 reactor core modeled by the MCNP-4C are shown in figs. 3 and 4, respectively. Results obtained show good agreement with the experimental results reported in [5].

CALCULATION OF THE EFFECTIVE MULTIPLICATION FACTOR (K_{eff})

Using the above proposed scheme, the calculation of the effective multiplication factor of the HTR-10 reactor without the use of the computer clustering technique or other variance reduction techniques, such as time or energy cutoff which obviously contribute to the increase in statistical errors, can be achieved. The required time to calculate the effective multiplication factor for 1000 neutrons in 100 cycles is about 2 hours by a PC with mentioned specifications. The variation in the effective multiplication factor versus core loading height at room temperature is listed in tab. 2, as calculated by the MCNP-4C computer code. As can be seen in tab. 2, the first criticality occurs at about 120 cm of the core loading height, in good agreement with that reported in [7], *i. e.*, 123.06 cm.

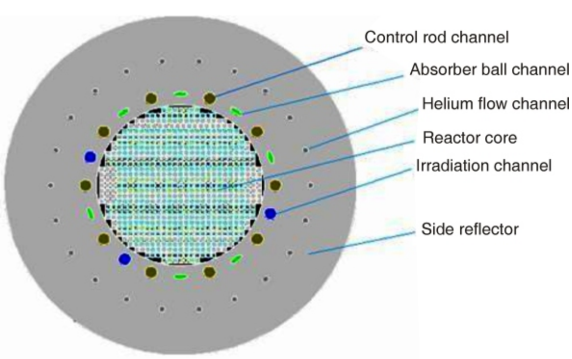


Figure 3. Horizontal cross-section view of the HTR-10 reactor core modeled by the MCNP-4C computer code

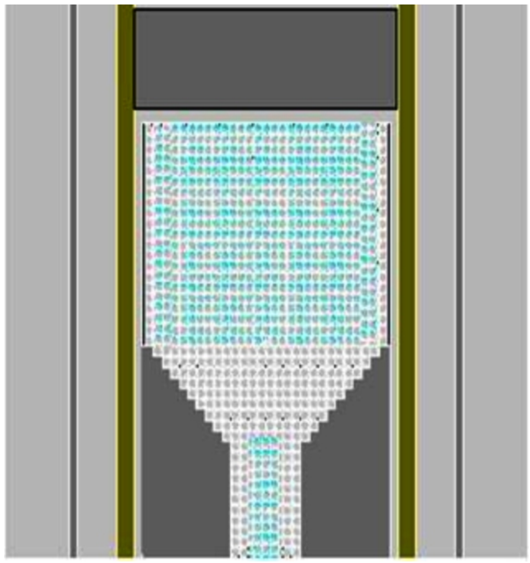


Figure 4. Vertical cross-section view of the HTR-10 reactor core modeled by the MCNP-4C computer code

SENSITIVITY ANALYSIS OF THE EFFECTIVE MULTIPLICATION FACTOR (K_{eff}) TO DIFFERENT ARRANGEMENTS OF KERNELS IN FUEL PEBBLES

The modeling of fuel pebbles is an issue that makes the simulation of the HTR-10 core either com-

Table 2. Effective multiplication factor as a function of the core loading height

Core loading height [cm]	Effective multiplication factor	Reference results	
		Core loading height [cm]	Effective multiplication factor
114	0.97657	113.778	0.96973
120	1.00435	123.576	1.00479
126	1.01849	–	–
150	1.07943	152.970	1.08270
156	1.08994	–	–
186	1.13815	182.364	1.13783
192	1.15541	192.162	1.15683

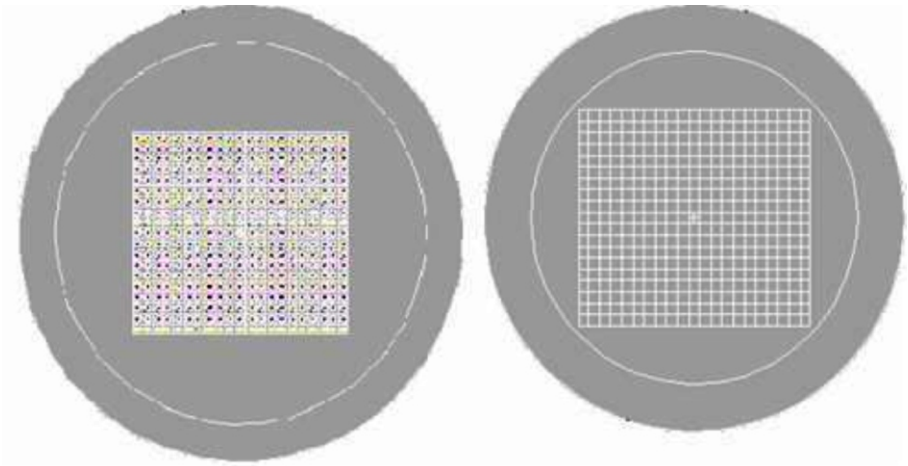


Figure 5. Horizontal cross- -section view of a fuel pebble in a cubic model

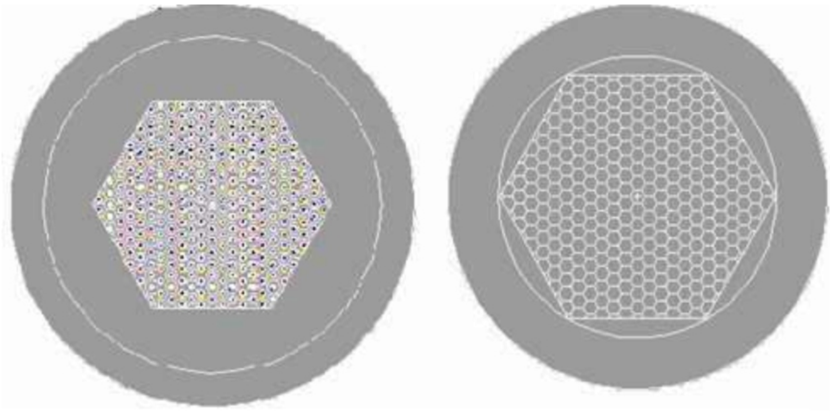


Figure 6. Horizontal cross- -section view of a fuel pebble in a hexagonal model

plicated or time consuming. We have tried to investigate the sensitivity of the effective multiplication factor to different types of kernel distribution in fuel pebbles. For this purpose, fuel pebbles have been modeled in three different arrangements of kernels: cubic (fig. 5), hexagon (fig. 6), and the model mentioned in section on fuel and moderator (fig. 2). The number of kernels in all three models was identical, *i. e.* 8343 TRISO Particles. The variation in the effective multiplication factor of the three different models is shown in fig. 7. Results obtained show that the difference in the effective multiplication factor for hexagonal and cubic models is negligible, while the same thing cannot be said for exact modeling.

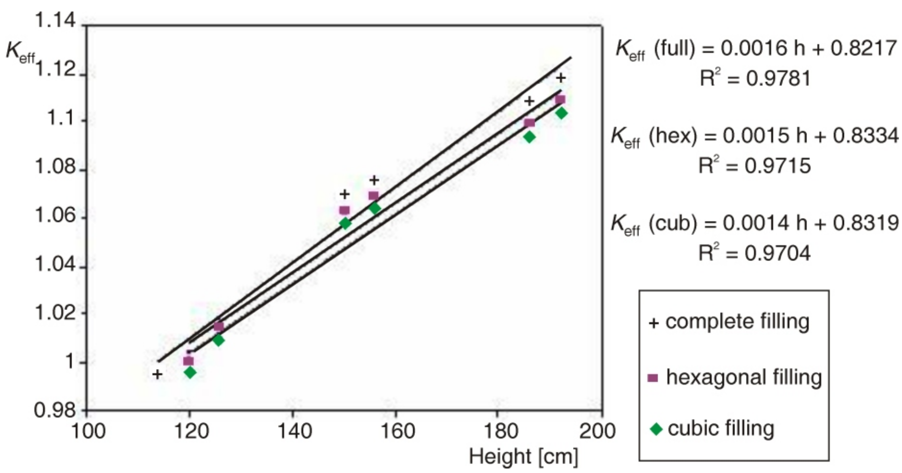


Figure 7. Effective multiplication factor as a function of different arrangements of kernels in a fuel pebble

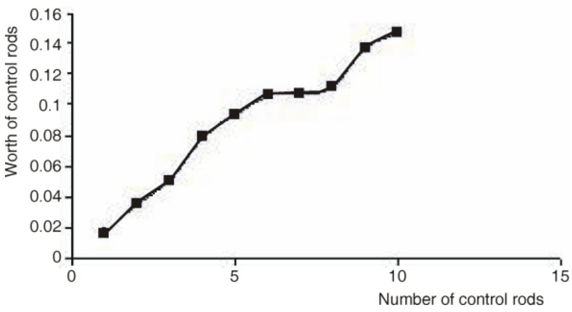


Figure 8. Worth of control rods as a function of their numbers

CONTROL RODS WORTH AND NEUTRON FLUX DISTRIBUTION

Unlike to conventional reactors, control rods in pebble bed reactors are located at the reflector side, as shown in fig. 1. Using the MCNP computer code, the integral worth for the critical loading condition of a single control rod is calculated (1.689%), showing a good agreement with results reported in reference [5]. In order to investigate their shadowing effects, the reactivity worth of each control rod is calculated during the existence of other rods. Figure 8 shows the worth of each control rod at the moment of its entering the core, one by one. As can be seen in fig. 8, there is a plateau region for control rods number 6 and 7. It may be interpreted as a shadowing of the worth of other control rods.

In the next phase, the neutron flux distribution has been calculated by the MCNP-4C computer code. Results obtained are shown in figs. 9 and 10. As can be seen, the radial neutron flux distribution is rather flat and the radial power peaking factor is calculated at about 1.21.

CONCLUSION

A criticality calculation of a pebble bed gas-cooled reactor, HTR-10, using the MCNP-4C computer code, is presented in this paper, with results

Figure 9. Sideway view of the neutron flux distribution

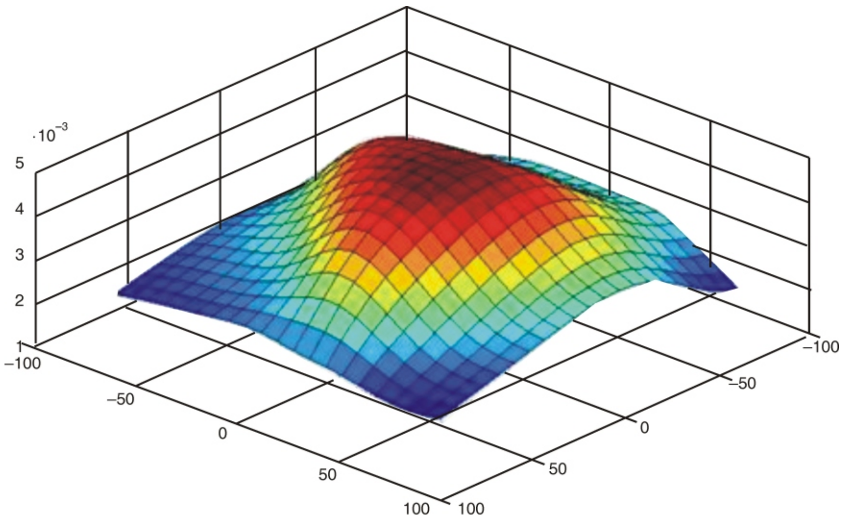
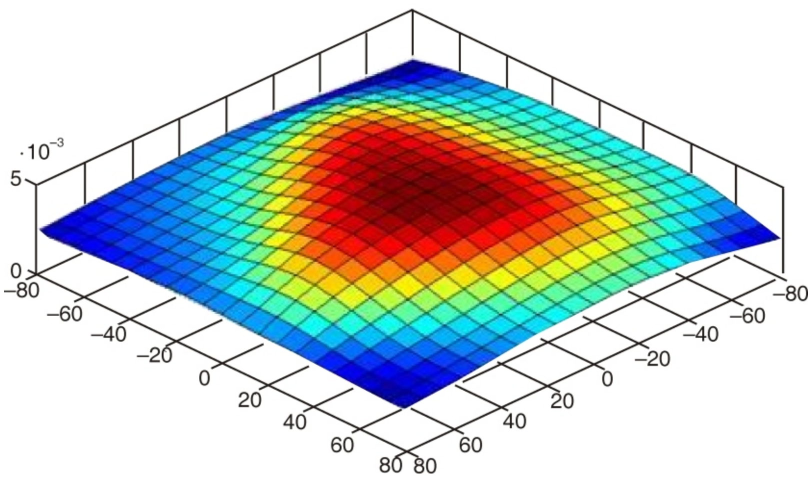


Figure 10. Uppermost view of the neutron flux distribution



showing good agreement with the experimental data. We have presented a new simulation scheme with a MCNP computer code which noticeably decreases CPU time consumption and is free of the computer clustering technique. Different arrangements of kernels in fuel pebbles are investigated. According to the results, it is possible to simplify the fuel pebble simulation with hexagon or cubic models instead of an exact one. The worth of control rods and radial neutron flux distribution were calculated, showing good agreement with the results reported in references.

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СИМУЛАЦИЈА ЈЕЗГРА РЕАКТОРА СА СФЕРНИМ ГОРИВНИМ ЕЛЕМЕНТИМА ПРОГРАМОМ MCNP-4C

Недостатак енергије је истакнуто питање нашег времена; непредвидљив раст цене фосилног горива приморава нас да тражимо нове, јевтиније и сигурније изворе енергије. Реактори са сферним горивним елементима – унапређена нова генерација реактора са посебним предностима у сигурности и цени – могли би се показати пожељним кандидатима за ову улогу. Основна намера овог рада је да се посредством рачунарског програма MCNP-4C одреди критични ниво реактора са сферним горивним елементима на собној температури. У циљу смањења времена прорачуна кода MCNP-4C, развијени су нови путеви симулације у односу на раније предвиђене поступке. Испитане су различите могућности распореда језгара у симулацији горивних кугли и изабрано је најбоље решење са гледишта умањења времена прорачуна – уз сачувану тачност резултата. Такође, у раду су размотрени расподела флукса неутрона и вредност контролних шипки, као и ефект њиховог заклањања. Сви прорачуни обављени за HTR-10 реакторско језгро сагласни су са експерименталним резултатима.

Кључне речи: HTR-10, MCNP-4C, неутронски флукс, сферни горивни елемент, ефект заклањања