HTR-10 full core first criticality analysis with MCNP

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Abstract
Experimental facilities like HTR-10, HTTR, and ASTRA serve as the source of information for the currently designed high temperature gas-cooled nuclear reactors. It is also desired to verify the existing codes against the data obtained in such facilities. In this study, first criticality calculations of a pebble bed gas-cooled reactor, HTR-10, is performed with MCNP-4B, a code system for Monte Carlo particle transport simulation. HTR-10 has rather unique characteristics in terms of the randomness in geometry as in the case of all pebble bed reactors. The geometrical model of the full reactor is obtained by using lattice and universe facilities provided by MCNP. Modeling details are discussed with necessary simplifications. Results obtained by Monte Carlo simulations are compared with available data. It is observed that Monte Carlo simulations yield sufficiently accurate results in terms of initial criticality of the HTR-10 reactor.

1. Introduction

Gas-cooled nuclear reactors have been receiving significant attention due to many desired characteristics such as inherent safety, modularity, relatively low cost, short construction period, and easy financing. There are a number of current design studies for different type of gas-cooled power reactors. There is a lack in the operational experience and data for this type of reactors. Therefore, information about behavior and characteristics of such reactors is an invaluable asset. Therefore, a number of small experimental facilities and reactors have been developed to gather such information. HTR-10 is such a reactor operated by the Institute of Nuclear Energy Technology (INET), Tsinghua University, China. It is a pebble bed type, helium-cooled, and graphite-moderated reactor with 10 MW thermal power. Schematic view of HTR-10 is given in Fig. 1. The first criticality of HTR-10 was achieved on December 1, 2000.

The initial core configuration of HTR-10 and criticality calculations for this configuration are reported by Jing et al. (2002). Reported calculations are performed by the VSOP code which was specifically developed for pebble bed reactors (Teuchert, 1994). It is basically a diffusion code, however, considers peculiarities relevant to pebble bed reactors. For instance, double heterogeneity and anisotropy in diffusion parameters are taken into account.

Monte Carlo method is applied for criticality problems for many diverse systems. Golsev et al. (1997) used MCU-RFFI code to study coated particle utilization in WWER type pressurized water reactors. Another study deals with the investigation of the criticality upon water ingress to a pebble bed assembly, HTR-PROTEUS experimental facility, which is performed by MCNP-4A (Rooselet, 1999). Bende and Hogenbrink (1999) performed Monte Carlo simulations...
for kernels in a fuel sphere and a lattice formed by spheres with MCNP-4A to generate Dancoff factors and compare them with their analytical estimations. In the present study, criticality analysis based on transport calculations with the Monte Carlo code MCNP-4B is performed for full core HTR-10 reactor. Since direct particle paths, energies, and reactions are followed in Monte Carlo simulations, no simplification or assumption is necessary. Other advantages provided by MCNP are to allow flexible geometrical modeling and extensive cross section libraries. Every single geometrical detail is included in the model as much as possible. However, it is not possible to obtain the criticality values for the same elevations as in the reported cases (Jing et al., 2002) due to modeling differences. Meanwhile, results are compared as close as possible.

The configuration of HTR-10 is a quite different than conventional reactors. Fuel and dummy balls are randomly distributed in the core. Another dimension of randomness is encountered in the distribution of coated fuel particles as embedded in the inner zone of fuel balls. It is necessary to represent coated fuel particles in order to see the effect of double heterogeneity. It is possible to create a geometrical model by means of MCNP using repeated structures. Such a model is prepared using lattice and universe options of MCNP for coated particles inside the fuel and for fuel and moderator balls inside the core. Thus, the development of full core HTR-10 model becomes tractable. A disadvantage of this method is to exclude the randomness encountered in the arrangement of fuel and moderator balls in the core as well as inside a fuel ball in the arrangement of TRISO particles as mentioned earlier.

2. HTR-10 gas-cooled pebble bed reactor

HTR-10 is a helium-cooled and graphite-moderated pebble bed reactor. Main design characteristics of the reactor is given in Table 1. An important advantage of HTR-10 is to allow on-line refueling. Therefore, the reactor can be operated with a little excess reactivity since adjustment of reactivity is possible during the operation. Table 2 shows characteristics of HTR-10 fuel and moderator balls. TRISO particle fuel is made of uranium dioxide kernel coated by three pyrolytic carbon (PyC) and a silicon carbide layers. Density
of PyC layers are different. The one next to the kernel has a lower density than that of the other layers to accommodate fission products. SiC layer serves as cladding to avoid radioactivity release due to fission products.

3. Criticality analysis with MCNP

MCNP is a general-purpose, continuous-energy, generalized-geometry, time-dependent, coupled $n$ particle, neutron, photon and electron, Monte Carlo transport code (Briesmeister, 1997). MCNP is also capable of calculating the multiplication factor of fissile systems. A system is defined by generating cells bounded by surfaces in three dimensions. Any kind of geometry can be defined as a cell and this cell can be rotated and moved to anywhere in the space. Simulations can be performed by either discrete (multigroup) or continuous energy cross sections. ENDF/B-VI continuous energy cross sections are used in calculations for all materials except graphite. Cross sections for graphite are taken from TMCCS library.

Criticality evaluations are done based on the principle of neutron balance. The number of neutrons in each generation is taken into account and comparison is made with the number of neutrons in the consequent generation. All possible mechanisms for the birth and loss of neutrons are accounted in bookkeeping. Thus, effective multiplication factor is evaluated for a given cycle. Each fission neutron is generated randomly out of possible locations containing fissile material. In order to generate statistical basis, simulations are repeated as many times as desired. Variance reduction techniques may be incorporated in order to increase the accuracy of calculations without performing long- and time-consuming simulations.

4. MCNP model of HTR-10

HTR-10 reactor model for MCNP is generated in a way that all reactor components are designed in detail. The initial step is to model the fuel ball having a diameter of 6 cm and containing 17% enriched $^{235}\text{U}$. Fuel balls have 5 g of heavy metal content which...
corresponds to 8335-coated particles. First, a single TRISO particle with UO$_2$ kernel and four outer layers (two inner graphite, an SiC buffer zone, and an outer graphite layers) is created. A lattice in a cubic array in a three-dimensional space is formed with these particles. This lattice is embedded into a spherical volume such that only full TRISO particles are permitted inside the sphere. Volume not occupied by TRISO particles within the sphere is filled with graphite. Then, this spherical volume is covered with a 0.5 cm thick spherical shell made of graphite as in the case of fuel balls. The number of full fuel particles inside a fuel ball is verified to be 8335 as in the case of the original reactor fuel. Fig. 2 shows MCNP model for a fuel ball. Graphite moderator balls are also created simply by solid spheres with 6 cm of diameter.

The next step in the modeling is to arrange spherical elements in the core. This is accomplished by creating hexagonal prism unit cells. These cells are then assembled as layers. The height of a layer is 9.798 cm. Top and bottom planes of hexagonal prisms are flat and contain half-spheres. There are seven balls at these faces, one at the center of the basal plane and six surrounding spheres. These six spheres are not centered at the corners of the hexagons, but rather, hexagonal prism side surfaces surround these balls. The intermediate section of each hexagonal prism contains three full balls as well as partial contributions from the neighboring hexagonal prism cells from all six sides. When neighboring hexagonal prisms are attached to each other, these partial spheres are completed and make full scale balls. Fuel and moderator balls are

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Fig. 3. Cross sectional view of HTR-10 cell model, basal and central planes. Light colored balls are fuel and dark colored ones are moderator balls.

Fig. 4. Horizontal cross sectional view of HTR-10 model.
selected in each layer such that 0.57:0.43 ratio is established. Typical structure of cells are shown in Fig. 3. These hexagonal prism are then assembled to form an array to be placed into the core. Outer boundary of the array is the inner surface of the side reflector. If any ball intersects with the reflector surface, it is rejected. Complications arise at the top layer and in the cone region below the reactor core. The top layer is formed by adding half spheres to each ball present in this layer. Once the model of core region is completed, it is verified that the filling fraction of ball in this region is 61%. The cone region and discharge tube are formed by only graphite balls as directed by Jing et al. (2002). These regions are also made by balls arranged in hexagonal geometry. Balls intersect with cone or discharge tube surface are rejected. In addition to fuel and moderator balls, there are side, top, and bottom reflectors included in the model. Top and side reflectors house control rods, small absorber balls, helium flow channels, and irradiation channels. Horizontal and vertical cross sectional views of HTR-10 model are shown in Figs. 4 and 5.

5. Results

In this section, results of MCNP simulations will be given for a number of representative cases. These examples deal with the criticality as a function of different fuel-loading and control rod-insertion conditions.

5.1. Criticality for different fuel loading conditions

This case deals with the evaluation of the effective multiplication factor for different amount of fuel loading. Since the model prepared for MCNP is made of layers, the step size of fuel addition is selected as the height of a layer i.e. 9.798 cm in order to avoid fractional fuel or moderator balls. Calculations are performed for vacuum, air, and helium. All materials are specified to be 27°C. Air is saturated to moisture at this temperature and atmospheric pressure (101.33 kPa). All control rods are fully withdrawn from the reflector. Results of calculations are shown in Table 3. Among three cases, the lowest effective multiplication factors are obtained for the case in which air is employed as coolant. On the other hand, the case with helium results in the highest $k_{eff}$ values. This is attributed to relatively high neutron absorption by air compared to air and slightly high neutron moderation in helium compared to air.

Fig. 6 shows MCNP simulation results for vacuum together with the results reported by Jing et al. (2002) for the same conditions. When results are compared, it is seen that diffusion calculations yield slightly higher $k_{eff}$. However, the difference between diffusion and Monte Carlo calculations converge to each other as the loading height increases.

Jing et al. (2002) also report $k_{eff}$ for air at two different loading heights such that 1.010562 and 0.992149 at 126 and 120 cm, respectively. Corresponding $k_{eff}$ values in this study are 1.002420 and 0.981912, respectively.

In initial criticality experiment, the first criticality was reached with 9627 fuel and 7263 graphite moderator balls at a loading height of 123.06 cm (IAEA, 2001). The atmosphere was air at 15°C. Simulations
Table 3
Criticality as a function of core loading height

<table>
<thead>
<tr>
<th>Height (cm)</th>
<th>Number of fuel balls</th>
<th>Total number of balls</th>
<th>$k_{eff}$ Vacuum</th>
<th>$k_{eff}$ Air</th>
<th>$k_{eff}$ Helium</th>
</tr>
</thead>
<tbody>
<tr>
<td>94.182</td>
<td>7321</td>
<td>12847</td>
<td>0.88456</td>
<td>0.87929</td>
<td>0.89044</td>
</tr>
<tr>
<td>103.880</td>
<td>8081</td>
<td>14193</td>
<td>0.93052</td>
<td>0.92405</td>
<td>0.93144</td>
</tr>
<tr>
<td>113.778</td>
<td>8855</td>
<td>15539</td>
<td>0.96998</td>
<td>0.95833</td>
<td>0.96973</td>
</tr>
<tr>
<td>123.576</td>
<td>9622</td>
<td>16885</td>
<td>1.00350</td>
<td>0.99489</td>
<td>1.00479</td>
</tr>
<tr>
<td>133.374</td>
<td>10399</td>
<td>18231</td>
<td>1.03366</td>
<td>1.02531</td>
<td>1.03233</td>
</tr>
<tr>
<td>143.172</td>
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<td>19577</td>
<td>1.05840</td>
<td>1.05023</td>
<td>1.06030</td>
</tr>
<tr>
<td>152.970</td>
<td>11923</td>
<td>20923</td>
<td>1.08512</td>
<td>1.07507</td>
<td>1.08276</td>
</tr>
<tr>
<td>162.768</td>
<td>12690</td>
<td>22269</td>
<td>1.10250</td>
<td>1.09099</td>
<td>1.10218</td>
</tr>
<tr>
<td>172.566</td>
<td>13457</td>
<td>23615</td>
<td>1.12237</td>
<td>1.11631</td>
<td>1.12248</td>
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<tr>
<td>182.364</td>
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<td>1.13904</td>
<td>1.13180</td>
<td>1.13783</td>
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<tr>
<td>192.162</td>
<td>14991</td>
<td>26307</td>
<td>1.15846</td>
<td>1.14764</td>
<td>1.15683</td>
</tr>
<tr>
<td>201.960</td>
<td>15758</td>
<td>27653</td>
<td>1.17193</td>
<td>1.16042</td>
<td>1.14973</td>
</tr>
</tbody>
</table>

at this temperature are not carried out since the cross section set for graphite is given for 27°C. However, only a slight decrease in criticality is expected at 27°C. This is also equivalent to a respective increase in core loading height. When Monte Carlo and diffusion results are compared, MCNP estimates the critical loading better than VSOP. However, the difference is not very significant.

5.2. Control rod effect

There are ten control rods of HTR-10 placed symmetrically in the side reflector and 102.1 cm away from the center of the reactor. Each hole housing control rods are 13 cm in diameter. Control rods are made of five B$_4$C ring segments enclosed in stainless steel sleeves. In these simulations, all ten control rods are...
simultaneously withdrawn from their channels with increments of 20 cm. Two cases are taken into consideration: core with critical loading (123.576 cm) and full loading (192.162 cm). Fig. 7 shows the effective multiplication factor as a function of control rod position for these cases. Simulations are carried out for helium and at 27°C temperature. Position of control rods are measured from the lowest level (z = 0 cm) which corresponds to fully inserted control rods.

A related simulation is performed for a single control rod for full and critical loading conditions. When all control rods are out, $k_{\text{eff}}$ is calculated to be 1.15683 and 1.00479, respectively. Effective multiplication factor decreases to 1.13889 and 0.98812, respectively when a single control rod is fully inserted into the core with full and critical loadings. Corresponding control rod worths are 1.362% for the core with full loading and 1.679% for the core with critical loading.

5.3. Temperature effect

In order to see the effect of temperature, reactivity values are evaluated at different temperatures for fully loaded core and helium coolant. Excess reactivity values are calculated to be 13.56, 11.58, 9.99, and 7.66% at temperatures of 300, 600, 800, and 1200 K, respectively. Calculations are only performed for these cases since cross sections for graphite are provided by TM-CCS library only for these temperatures.

6. Conclusions

Full core criticality analysis of HTR-10, a pebble bed gas-cooled reactor, is successfully performed by Monte Carlo simulations. Critical height and the reactivity effect of control rods and temperature are evaluated with MCNP-4B. Results are in good agreement with experimental evaluations and predictions with special purpose diffusion code VSOP. MCNP simulations yield better results compared to diffusion calculation when a comparison is made with experimental observation. It is seen that similar methodology can be extended to perform the neutronics design and criticality studies of similar power reactors. Another study is underway to perform burnup calculations for pebble bed gas-cooled reactors with Monte Carlo methods to see long-term reactivity variations.
References


