Criticality Study on Different Pebble Arrangement inside HTR Reactor Core

L Wahid*, T Setiadipura, Zuhair, Suwoto, S Bakhri

Centre for Nuclear Reactor Technology and Safety, 80th Building of Center for Science and Technology, South Tangerang

E-mail: *wahid-luthfi@batan.go.id

Abstract. Simplification on modeling of high temperature reactor core (HTR) of pebble bed type has been widely developed before. The last calculation that writer develop on modeling and simplification for HTR modelling has been done on TRISO and single pebble, especially on it is KINF and burnup calculation. From that calculation, it is known that TRISO modeling that using fuel kernels and cover (homogenized buffer, PyC and SiC) gives K-INF values that are not (much) different than the complete TRISO modeling (fuel kernel, buffer, PyC and SiC on each different cell). Then the purpose of this study was to analyze the effect on KEFF and calculation time of combined TRISO particle arrangement modeling in the HTR fuel pebble and this pebble arrangement inside reactor core using MCNPX. The modeling variations that will be carried out include modeling of HTR fuel pebble using simplified TRISO (fuel kernel and homogenized TRISO coating layers) that uniformly dispersed inside pebble using HCP, SC, FCC and BCC lattice, that arranged inside reactor core (also) using HCP, SC, FCC and BCC lattice. For all variations mentioned above, K-EFF calculations has been done for each fuel height variation from 90-190 cm inside reactor core, with 50% fuel pebble to fuel-moderator pebble ratio, in 61% pebble volume fraction ratio except Simple Cubic (SC) lattice (max. 52.36%). Whole modelling gives K-EFF that have not much deviation except all modelling using SC pebble arrangement inside reactor core, because its low packing fraction. SC-type TRISO dispersion mode inside pebble always need more calculation time than other model. The modeling using HCP TRISO unit inside HCP pebble unit inside reactor core gives consistently short calculation time, same as almost all calculation using FCC TRISO unit inside pebble always have shortest calculation time compare to other TRISO unit. FCC and BCC pebble unit inside reactor core using less calculation time compare to HCP at most calculation.

Keywords: TRISO, Pebble, Core, Modelling, MCNPX, K-EFF, calculation time.

1. Introduction
Previously on finding simpler way to modelling pebble bed high temperature reactor (HTR) core, Indonesia has found that the homogenized TRISO cover model (homogenized buffer, PyC and SiC) can be used as an initial approach for TRISO modeling of HTR full-core. Then selection of TRISO unit types that can facilitate full core modeling still requires further research, but SC (simple Cubic) type modeling can be chosen as initial approach [1, 2, 3, 4, 5, 6, 7, 8, 9]. As part of modeling of HTR to calculate equilibrium condition, the initial approach to see the effect of modeling and simplification that will be used in full-scale HTR modeling can start to be done on the next level, the reactor core itself.

The criticality calculation of HTR-10 has been done by INET as part of HTGR Test Module Core Physics Benchmarks using VSOP 2D and MCNP [10]. Tsinghua University has also been done the criticality calculation of HTR-10 using Random geometry capability in RMC code [11]. That last calculation is an improvement from previous calculation using RMC code on benchmarking HTR-10 [12].
Previous calculation has been done using main parameters of HTR-10 like default TRISO geometry, 8335 TRISO per fuel pebble (5grU/pebble), 61% packing fraction, approximately 57:43 ratio of fueled pebbles and dummy pebbles and 27000 pebble on 5m³ full core. Some calculation has been done on helium and dry air as coolant, with some correction on boron concentration inside reactor. The conclusion from mentioned calculation before is modelling using random geometry on RMC or using MCNP didn’t give much deviation from INET calculation using VSOP or MCNP, and also experimental result. Then modelling fueled pebble and dummy pebble dispersion inside reactor using something that not so random will be interesting enough, especially if this not so random modelling gives us less code lines, less computing time with enough accuracy.

RDE (Reaktor Daya Eksperimental – Experimental Power Reactor) as HTR-kind reactor from Indonesia is one of national program to support the RPJMN (National Medium-Term Development Plant) [13]. So, neutronic calculation of RDE is close enough to HTR-10 cause it share same type of pebble bed HTR. Because of that, writer mentions the reactor that is used in this study as HTR, to make it general to pebble bed type HTGR (High Temperature Gas-cooled Reactor).

The purpose of this study was to analyze the effect of TRISO particle dispersion pattern inside the pebble (TRISO unit) combined with pebble dispersion pattern inside reactor core (pebble unit) to K-EFF value of HTR core fuel height variation, its computing time and code lines. Dispersion pattern that will be use in this study is HCP (Hexagonal Close Packed), SC (Simple Cubic), FCC (Face-Centered Cubic) and BCC (Body-Centered Cubic). Constraint on this calculation is on ratio of fueled pebbles and dummy pebbles that fixed in 50:50 to make it easier to modelling inside MCNPX remembering that number of pebbles inside each lattice will be even HCP: 6, FCC: 4, BCC: 2, except SC: 1. In the future, these calculations can help in simplifying the HTR core modeling and reducing the calculations time needed to solve HTR's neutronic problems.

2. Methods
2.1. Main Parameter
The main parameter of HTR that will be used inside this study could be seen on Figure 1 and its radial dimension on Figure 2. On Figure 2, we could see that hexagonal lattice has been used as part of HCP pebble dispersion inside core. Other pebble dispersion mode will be used like square lattice for SC, FCC and BCC and this type of lattice will also be used for TRISO dispersion inside pebble.
TRISO modelling that chosen from pervious study is TRISO which all coating layers is made into one homogenized cover region. This fuel kernel cover is made up of the buffer material, PyC and SiC with the mass of each component and the overall size of TRISO unchanged. Dimension of TRISO modelling that used in this study could be seen in Figure 3. Density of UO2 is set to 10.4 gr/cc (17% $^{235}\text{U}$) and homogenized TRISO cover has density for about 1.929 gr/cc from combination of buffer material (1.04 gr/cc), PyC (1.88 gr/cc) and SiC (3.15 gr/cc).

In this study, reactor using helium as coolant paired with 1.73 gr/cc dummy pebbles density and reactor using dry air as coolant paired with 1.84 gr/cc dummy pebble density will calculated as 2 bonus variation beside TRISO or pebble dispersion mode and loading height. Temperature of all cell set to 27°C with default MCNPX cross section library, calculated using 2.5GHz dual core processor, 8GB RAM, 500 GB HDD.

2.2. Fueled Pebble and Dummy
TRISO unit variation that used inside pebble's fuel zone are HCP using hexagonal lattice, SC, FCC and BCC using square lattice. To maintain the number of TRISOs in a pebble of 8335 particles, the dimensions of each unit will be adjusted to achieve the desired packing fraction (5.0248%vol of TRISO inside the fuel zone). The dimensions for each TRISO unit can be seen in Figure 4.

The number of TRISO particles in HCP, SC, FCC and BCC-shaped unit are 6, 1, 4 and 2 TRISO particles respectively. Then TRISO unit is auto-fill to fuel region of fueled pebble that have dimension as seen on Figure 5. Dummy pebble has same dimension like fueled pebble, 3 cm pebble radius, but its only filled with graphite with uniform density, without fueled zone.
2.3. Pebble dispersion inside core

Pebble unit variation that used inside reactor core are HCP using hexagonal lattice, SC, FCC and BCC using square lattice. The dimensions of each unit will be adjusted to achieve the desired pebble packing fraction 61%, except SC that only has maximum packing fraction 52.36%. The dimensions for each TRISO unit can be seen in Figure 6.

Figure 6. Dimension of pebble unit type HCP, SC, FCC and BCC

For this calculation, 3 type of pebble configuration has been done. First configuration is configuring the position of “pebble unit that filled with fueled pebble only” and “pebble unit that filled with dummy pebble only” that makes 4 variation of pebble unit will fill the reactor core as shown in Figure 7 to Figure 10. Within simulation, we named it X-version.

Second variation of pebble configuration that selected is variation in positioning fueled pebble and dummy pebble inside each pebble unit. Because SC unit consist of 1 pebble per unit, so SC unit mode wasn’t included in this variation. Then because HCP unit consist of 6 pebble per unit that has more than 1 configuration mode that available, so HCP unit has 2 variation of fueled pebble and dummy pebble inside its unit, and we called it “HCP 3 center” and “HCP 2 center” to define number of pebbles on its center that variated. Within simulation, we named second variation as Xa-version and it could be seen in Figure 11.

Then, third variation of pebble configuration is also a combined version of fueled pebble and dummy pebble inside each unit, but the different is only on reversed version of second variation. So, every dummy pebble in Xa-version will changed to fueled pebble and vice versa, as shown in Figure 12. We name it with Xb-version.
Figure 7. HCP X-version pebble dispersion mode

Figure 8. SC X-version pebble dispersion mode

Figure 9. FCC X-version pebble dispersion mode

Figure 10. BCC X-version pebble dispersion mode
Figure 11. Second variation of pebble unit, Xa-version

Figure 12. Third variation of pebble unit, Xb-version

For second and third variation, they don’t need any further configuration within core, so lattice input for this variation is simpler than the first one. Figure 13 to Figure 16 will show you an axial and radial cutaway of HTR reactor using two configuration that mentioned before.

Figure 13. HCP 3 center, Xa (left) and Xb (right) pebble dispersion mode
All TRISO unit variation (4) will combined with pebble unit variation (4), and make this study have 16 combination that will be used to calculate K-EFF of difference loading height of HTR from 90-190 cm with 10 cm increment. KCODE is used on this case that use 1000 neutron per cycle with 50 cycle skipped (inactive) from 200 total cycle. KSRC that used in this calculation is set to the middle of zero lattice element of each pebble unit.

3. Results and discussion

3.1. Helium as coolant and 1.73 gr/cc dummy pebble density

In this section, Helium coolant and 1.73 gr/cc dummy pebble density used to calculate K-EFF of different loading height from 16 variation that mention before. The K-EFF data for X-version of pebble unit (consist of HCP, SC, FCC, and BCC TRISO unit that combined with HCP, SC, FCC and BCC pebble unit) could be seen in Figure 17. Then, data for Xa and Xb-version of pebble unit (consist of HCP, SC, FCC, and BCC TRISO unit that combined with HCP 3 center, HCP 2 center, FCC and BCC pebble unit) could be seen in Figure 18 and 19 respectively. Its KEFF deviation from INET VSOP 2D could be seen in Figure 20 to 22.
Figure 17. K-EFF of different loading height for X-version pebble dispersion, He as coolant, 1.73 gr/cc dummy

Figure 18. K-EFF of different loading height for Xa-version pebble dispersion, He as coolant, 1.73 gr/cc dummy

Figure 19. K-EFF of different loading height for Xb-version pebble dispersion, He as coolant, 1.73 gr/cc dummy
Figure 20. %deviation of K-EFF for X-version pebble dispersion, He as coolant, 1.73 gr/cc dummy

Figure 21. %deviation of K-EFF for Xa-version pebble dispersion, He as coolant, 1.73 gr/cc dummy

Figure 22. %deviation of K-EFF for Xb-version pebble dispersion, He as coolant, 1.73 gr/cc dummy
Number of code lines and computing time of X-version, Xa-version and Vb-version under He coolant and 1.73 gr/cc dummy could be seen in Table 1, 2 and 3 respectively.

### Table 1. Computing time (minutes) for X-version pebble dispersion, He as coolant, 1.73 gr/cc dummy

| TRISO unit | Pebble unit | Code lines | Loading Height | Average |
|------------|-------------|------------|----------------|---------|
| HCP        | HCP         | 1533       | 17.48, 17.97, 17.87 | 18.42, 17.94 |
|            | SC          | 2816       | 17.44, 17.23, 17.54 | 20.75, 17.74 |
|            | FCC         | 1614       | 17.93, 17.31, 17.45 | 18.10, 17.87 |
|            | BCC         | 2230       | 18.30, 17.36, 17.98 | 17.00, 18.72 |
| SC         | HCP         | 1439       | 17.10, 19.19, 19.26 | 19.15, 19.41 |
|            | SC          | 2722       | 18.26, 16.17, 15.05 | 18.78, 17.87 |
|            | FCC         | 1520       | 18.46, 17.94, 18.53 | 16.72, 19.04 |
|            | BCC         | 2136       | 15.59, 18.09, 16.65 | 15.39, 18.68 |
| FCC        | HCP         | 1514       | 18.26, 17.70, 17.71 | 15.88, 18.24 |
|            | SC          | 2797       | 18.53, 16.72, 14.82 | 18.56, 18.73 |
|            | FCC         | 1595       | 18.18, 17.89, 17.96 | 17.41, 18.49 |
|            | BCC         | 2211       | 18.09, 18.09, 18.09 | 18.29, 18.93 |
| BCC        | HCP         | 1489       | 18.85, 18.92, 19.20 | 18.94, 18.89 |
|            | SC          | 2772       | 18.53, 18.00, 15.09 | 18.65, 18.53 |
|            | FCC         | 1570       | 18.39, 14.91, 14.82 | 18.56, 18.73 |
|            | BCC         | 2186       | 18.57, 18.01, 15.24 | 18.72, 18.84 |

### Table 2. Computing time (minutes) for Xa-version pebble dispersion, He as coolant, 1.73 gr/cc dummy

| TRISO unit | Pebble unit | Code lines | Loading Height | Average |
|------------|-------------|------------|----------------|---------|
| HCP 3      | HCP         | 1505       | 17.51, 17.81, 17.52 | 18.17, 17.87 |
|            | HCP 2       | 1513       | 18.67, 17.89, 16.56 | 16.57, 17.61 |
|            | FCC         | 1594       | 17.64, 17.21, 17.74 | 16.15, 17.27 |
|            | BCC         | 2214       | 17.65, 17.10, 17.65 | 17.26, 17.77 |
| SC         | HCP 3       | 1411       | 19.11, 21.03, 18.67 | 17.77, 23.68 |
|            | HCP 2       | 1419       | 19.16, 18.37, 18.60 | 18.63, 22.86 |
|            | FCC         | 1500       | 19.13, 18.28, 19.07 | 18.87, 21.36 |
|            | BCC         | 2120       | 18.84, 18.18, 18.90 | 18.39, 19.78 |
| FCC        | HCP 3       | 1486       | 18.15, 17.68, 18.10 | 18.17, 18.29 |
|            | HCP 2       | 1494       | 18.13, 16.46, 17.99 | 18.00, 18.20 |
|            | FCC         | 1575       | 17.83, 17.43, 17.95 | 17.54, 18.00 |
|            | BCC         | 2195       | 18.00, 17.42, 17.89 | 17.69, 18.04 |
| BCC        | HCP 3       | 1461       | 18.86, 18.25, 18.79 | 18.32, 18.79 |
|            | HCP 2       | 1469       | 18.68, 18.38, 18.82 | 18.29, 18.91 |
|            | FCC         | 1550       | 18.15, 16.52, 18.02 | 18.63, 18.65 |
|            | BCC         | 2170       | 18.59, 17.80, 16.63 | 18.69, 18.69 |
In this section, Dry air is chosen as coolant and 1.84 gr/cc dummy pebble density used to calculate K-EFF of different loading height from 16 variation that mention before. The K-EFF data for X-version of pebble unit that has shortest average computing time when combined with FCC and BCC TRISO unit on maximum load but on the other minute it’s on normal load. So, it’s glad to see that there is some trend on TRISO unit level, but it’s pretty normal if there are no explicit trend within some variation, even after averaging its value. Generally, HCP, FCC and BCC pebble unit give us shortest average calculating time, but only on specific combination, like HCP pebble unit with HCP unit or FCC TRISO unit. FCC pebble unit has second short average computing time when combined with FCC and BCC, close enough to BCC pebble unit that has shortest average computing time when combined with FCC and BCC TRISO unit on Xb-version.

3.2 Dry air as coolant and 1.84 gr/cc dummy pebble density

In this section, Dry air is chosen as coolant and 1.84 gr/cc dummy pebble density used to calculate K-EFF of different loading height from 16 variation that mention before. The K-EFF data for X-version of pebble unit could be seen in Figure 23. Then, data for Xa and Xb-version of pebble unit could be seen in Figure 24 and 25 respectively. Its KEFF deviation from HCP TRISO unit variance (this reference chosen because HCP input code complexity is higher than other TRISO unit type) could be seen in Figure 26 to 28.
Figure 23. K-EFF of different loading height for X-version pebble dispersion, air as coolant, 1.84 gr/cc dummy

![Graph](image)

Figure 24. K-EFF of different loading height for Xa-version pebble dispersion, air as coolant, 1.84 gr/cc dummy

![Graph](image)

Figure 25. K-EFF of different loading height for Xb-version pebble dispersion, air as coolant, 1.84 gr/cc dummy

![Graph](image)
Figure 26. %deviation of K-EFF for X-version pebble dispersion, air as coolant, 1.84 gr/cc dummy

Figure 27. %deviation of K-EFF for Xa-version pebble dispersion, air as coolant, 1.84 gr/cc dummy

Figure 28. %deviation of K-EFF for Xb-version pebble dispersion, air as coolant, 1.84 gr/cc dummy
Table 4. Computing time (minutes) for X-version pebble dispersion, air as coolant, 1.84 gr/cc dummy

| TRISO Code | Pebble Code | Code lines | Loading Height | Average |
|------------|-------------|------------|----------------|---------|
| HCP        | 1536        | 17.06      | 17.92          | 18.06   |
|            | 16.00       | 17.92      | 17.80          | 18.19   |
|            | 16.70       | 17.92      | 17.60          | 17.91   |
|            | 16.40       | 17.92      | 17.30          | 17.91   |
|            | 16.10       | 17.92      | 17.00          | 17.91   |
|            | 15.80       | 17.92      | 16.80          | 17.91   |
|            | 15.50       | 17.92      | 16.50          | 17.91   |
|            | 15.20       | 17.92      | 16.20          | 17.91   |
|            | 14.90       | 17.92      | 15.90          | 17.91   |
|            | 14.60       | 17.92      | 15.60          | 17.91   |
|            | 14.30       | 17.92      | 15.30          | 17.91   |
|            | 14.00       | 17.92      | 15.00          | 17.91   |
|            | 13.70       | 17.92      | 14.70          | 17.91   |
|            | 13.40       | 17.92      | 14.40          | 17.91   |
|            | 13.10       | 17.92      | 14.10          | 17.91   |
|            | 12.80       | 17.92      | 13.80          | 17.91   |
|            | 12.50       | 17.92      | 13.50          | 17.91   |
|            | 12.20       | 17.92      | 13.20          | 17.91   |
|            | 11.90       | 17.92      | 12.90          | 17.91   |
|            | 11.60       | 17.92      | 12.60          | 17.91   |
|            | 11.30       | 17.92      | 12.30          | 17.91   |
|            | 11.00       | 17.92      | 12.00          | 17.91   |
|            | 10.70       | 17.92      | 11.70          | 17.91   |
|            | 10.40       | 17.92      | 11.40          | 17.91   |
|            | 10.10       | 17.92      | 11.10          | 17.91   |
|            | 9.80        | 17.92      | 10.80          | 17.91   |
|            | 9.50        | 17.92      | 10.50          | 17.91   |
|            | 9.20        | 17.92      | 10.20          | 17.91   |
|            | 8.90        | 17.92      | 9.90           | 17.91   |
|            | 8.60        | 17.92      | 9.60           | 17.91   |
|            | 8.30        | 17.92      | 9.30           | 17.91   |
|            | 8.00        | 17.92      | 9.00           | 17.91   |
|            | 7.70        | 17.92      | 7.90           | 17.91   |
|            | 7.40        | 17.92      | 7.70           | 17.91   |
|            | 7.10        | 17.92      | 7.50           | 17.91   |
|            | 6.90        | 17.92      | 7.30           | 17.91   |
|            | 6.70        | 17.92      | 7.10           | 17.91   |
|            | 6.50        | 17.92      | 6.90           | 17.91   |
|            | 6.30        | 17.92      | 6.70           | 17.91   |
|            | 6.10        | 17.92      | 6.50           | 17.91   |
|            | 5.90        | 17.92      | 6.30           | 17.91   |
|            | 5.70        | 17.92      | 6.10           | 17.91   |
|            | 5.50        | 17.92      | 5.90           | 17.91   |
|            | 5.30        | 17.92      | 5.70           | 17.91   |
|            | 5.10        | 17.92      | 5.50           | 17.91   |
|            | 4.90        | 17.92      | 5.30           | 17.91   |
|            | 4.70        | 17.92      | 5.10           | 17.91   |
|            | 4.50        | 17.92      | 4.90           | 17.91   |
|            | 4.30        | 17.92      | 4.70           | 17.91   |
|            | 4.10        | 17.92      | 4.50           | 17.91   |
|            | 3.90        | 17.92      | 4.30           | 17.91   |
|            | 3.70        | 17.92      | 3.90           | 17.91   |
|            | 3.50        | 17.92      | 3.70           | 17.91   |
|            | 3.30        | 17.92      | 3.50           | 17.91   |
|            | 3.10        | 17.92      | 3.30           | 17.91   |
|            | 2.90        | 17.92      | 2.90           | 17.91   |
|            | 2.70        | 17.92      | 2.70           | 17.91   |
|            | 2.50        | 17.92      | 2.50           | 17.91   |
|            | 2.30        | 17.92      | 2.30           | 17.91   |
|            | 2.10        | 17.92      | 2.10           | 17.91   |
|            | 1.90        | 17.92      | 1.90           | 17.91   |
|            | 1.70        | 17.92      | 1.70           | 17.91   |
|            | 1.50        | 17.92      | 1.50           | 17.91   |
|            | 1.30        | 17.92      | 1.30           | 17.91   |
|            | 1.10        | 17.92      | 1.10           | 17.91   |
|            | 0.90        | 17.92      | 0.90           | 17.91   |
|            | 0.70        | 17.92      | 0.70           | 17.91   |
|            | 0.50        | 17.92      | 0.50           | 17.91   |
|            | 0.30        | 17.92      | 0.30           | 17.91   |
|            | 0.10        | 17.92      | 0.10           | 17.91   |
It can be seen from Figure 23 to 25, that K-EFF of different loading height of HTR core under dry air environment and 1.84 gr/cc dummy graphite are higher than core under helium environment with 1.73 gr/cc dummy graphite. SC pebble unit has lower K-EFF than other pebble unit type like before because it’s 52.67% packing fraction. From Figure 26 to 28 we could see that some variance from Xb-version has more deviation than X-version or Xa-version as mention before on He coolant and 1.73 gr/cc. There is higher deviation that X-version or Xa-version as mention before on He coolant and 1.73 gr/cc. There is higher deviation from HCP TRISO unit K-EFF value on Xb-version of TRISO and pebble unit variation. Yellow lines (SC TRISO unit var) and black lines (FCC TRISO unit var) gives more deviation than green lines (BCC TRISO unit), blue lines (HCP TRISO unit) always flat on 0% because it is selected as base for deviation calculation because its complexity in modelling HCP TRISO unit inside MCNPX.

From Table 4 to 6, we could see that SC TRISO unit are more often on red label (longer computing time) for computing time than other TRISO unit type, same like before. Then computing time of FCC TRISO unit is shortest on X-version combination, followed by HCP unit on Xa-version combination, and BCC unit on Xb-version combination.

Over all coolant and dummy graphite density variation, we could say that SC TRISO unit gives longest calculation time on K-EFF of different loading height, and FCC TRISO unit gives shorter calculation time than other TRISO unit type. Further calculation needed to determine what kind of pebble unit modelling that could be used to cut off calculation time.

4. Conclusion

The criticality calculation of pebble bed HTR core has been done using combination of 4 TRISO unit (HCP, SC, FCC, and BCC) and 4 pebble unit (HCP, SC, FCC, and BCC), with fuel kernels and cover (homogenized buffer, PyC and SiC) as TRISO modelling. With 50:50 fueled pebble and dummy ratio, almost whole modelling gives K-EFF that have not much different than previous calculation except all modelling that use SC pebble unit arrangement inside reactor core, because its low packing fraction, 52.67%. SC TRISO unit inside pebble always need more calculation time than other model. The modeling using HCP TRISO unit inside HCP pebble unit inside reactor core gives consistently short calculation time, compare to other TRISO unit. FCC and BCC pebble unit inside reactor core using less calculation time compare to HCP at most calculation. As a suggestion for next study, maybe a neutron flux distribution inside reactor core could be shown as a parameter that compared within study, beside computing time, code lines and K-EFF.
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