Effect of Core Size on Temperature Reactivity Feedback of Indonesia Experimental Power Reactor (RDE)

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Abstract. BATAN (the National Nuclear Energy Agency) and its national stakeholders are now developing an experimental power reactor, so called Reaktor Daya Eksperimental (RDE) 10 MW thermal (MWth) and the reactor is a high temperature gas cooled reactor (HTGR) Gen IV-type power reactor. The RDE is a graphite-moderated and helium-cooled pebble bed reactor and uses uranium with the enrichment of 17%. There are a lot of safety analysis regarding RDE reactor, but there has not yet been a neutronic analysis focused on the effect of core size to influence the temperature reactivity feedback in the RDE reactor core. To begin with, RDE core reactor should be modeled in such 4 regions, fuel pebble and dummy, coolant, radial refelctor and cone and axial refelctor and shield. For all computation, continuous energy-nuclear data library ENDF/B-VII were then employed by differing the 4-region model and the famous Monte Carlo Neutron Perturbation 6 (MCNP6) was applied. The calculated temperature reactivity feedback dealing with Doppler temperature coefficient (DTC), moderator temperature coefficient (MTC) and reflector temperature coefficient (RTC) of reactivity has been utilized as well. For this simulation, it is assumed that an accident in the RDE core was defined if the core has the temperature in the range of 800 0K (526.85 0C) to 1,800 0K (1,526.85 0C). The KCODE and KSRC, a main part of the MCNP6 code, were then applied to generate cross section (XS) using the nuclear data library ENDF/B-VII.0 in the temperature ranges of 800 0K (526.85 0C) to 1,800 0K (1,526.85 0C). For whole calculations, instead of defining four regions, dry air and helium coolant were also implemented. The RDE core depth has also been decided starting from 79.023 cm as bottom core to 201.16 cm as full core. The simulation results showed the total of temperature reactivity feedback in the RDE reactor core is negative and hence the RDE reactor core is totally safe during the defined accident takes place.

Keywords: Core size, temperature reactivity feedback, RDE, MCNP6, ENDF/B-VII.

1. Introduction

After the direction of President of the Republic of Indonesia, during the plenary meeting of DEN (Dewan Energi Nasional, National Energy Chamber) in June 2016, BATAN (the National Nuclear Energy Agency) and its national stakeholders has been developing the RDE which is a HTGR Gen-IV type power reactor [1]. The RDE having power of 10 MWth can be utilized not only for electricity production but also for industrial steam application, such as, water desalination, hydrogen production, coal liquefaction etc. The RDE reactor applies uranium fuel with 17% enrichment and is expected to be constructed in Puspiptek area, Serpong, Banten and operable by 2030. The RDE reactor is a very unique reactor due to having a very small power but very powerful both for electricity production and for industrial heat application and the RDE reactor is contemplated as qualified as a new China HTR-PM firstly constructed in 2012. The HTR-PM classified as a small modular nuclear reactor is a high-temperature gas-cooled (HTGR) pebble-bed Gen-IV reactor partly based on the earlier HTR-10 prototype reactor [2,3]. The two reactors each having power of 250 MW thermal are connected to a single steam turbine to generate 210 MW of electricity and the HTR-PM, the first Gen-IV reactor in the Globe, will enter operation in 2019 [3].

There are a lot of RDE safety analysis aspects which have been established, such as, neutronic and thermal hydraulic, reactor pressure vessel and its materials, reactor core cooling system (RCCS) etc. [4-11]. Unfortunately, there has not yet been a safety analysis focused on how reactor core temperature change and core size influence the reactivity coefficient of RDE core.

As seen in figure 1, nuclear chain reaction takes place in the reactor pressure vessel (RPV) of the RDE core and heat produced in the reactor core makes hot water to generate steam turbine with the average temperature of 520 ^{0}C. The resulted steam then produces not only heat for industrial application but also electricity. What happens in the RPV is a very complicated one, because nuclear heat originally comes from the nuclear reaction containing 17%-enrichment uranium. The all fueled pebbles are spread out randomly with packing fraction of 0.61 [10] and the RDE reactor core is compacted with those fuels and moderators with the ratio of 57/43 and each fueled pebble contains 8,335 TRISO coated particles dispersed within the graphite matrix. The modelling of the RDE reactor core is the most complicated one among whole calculation processes.

To begin with the calculation, Monte Carlo transport code, MCNP6, is very powerful to accurately estimate all scientific matters including nuclear safety aspects in a nuclear reactor. Continuous energy nuclear data library ENDF/B-VII were utilized by varying six core size models (4 regions) to support XS generation and those data are requested in the nuclear diffusion computation [13-16]. The calculated temperature reactivity feedback includes DTC, MTC and RTC of reactivity. Effective multiplication factors (k_{eff}) of neutrons generated in the RDE core should be firstly estimated. The generation of MCNP6 has been implemented based on all reactor inputs, such as, core size, fuel enrichment and temperature etc. and all of those inputs are automatically processed by the code MCNP6. To generate the results, as arranged for defaults and the model of the axially, horizontally core, the KCODE and KSRC codes utilizing the nuclear data library ENDF/B-VII.0 have been implemented for the temperature ranges of 800 ^{0}K (526.85 ^{0}C) to 1,800 ^{0}K (1,526.85 ^{0}C). For whole calculations, four regions have been well-defined, such as, fueled pebble and dummy, coolant, radial reflector and cone, and axial reflector and shield. The RDE core depth has also been decided starting from 79.023 cm to 201.16 cm or full core. Finally, for whole simulation, dry air and helium coolant were accomplished. For the scenario of the RDE accident, the temperature ranges of 800 ^{0}K (526.85 ^{0}C) to 1,800 ^{0}K (1,526.85 ^{0}C) have been considered.

From all simulation results, all temperature reactivity feedback (*Rho*/ρ) in the fueled pebble and dummy region are negatives due to negative reactivity feedback from fuel temperature. Moreover, in the coolant region, *Rhos* are also negatives and flat since the coolant uniformly distributes in the RDE core. In the radial reflector and cone and in the axial reflector and shield, all *Rhos* tend increased but still negatives. The total *Delta Rho/*$\Delta\rho$ of the RDE core, which is the summation of all *Rhos* in every region in the RDE core, showed completely negative. Indeed, it can then be deduced that the RDE reactor core is safe although the reactor has an accident due to temperature reactivity feedback.

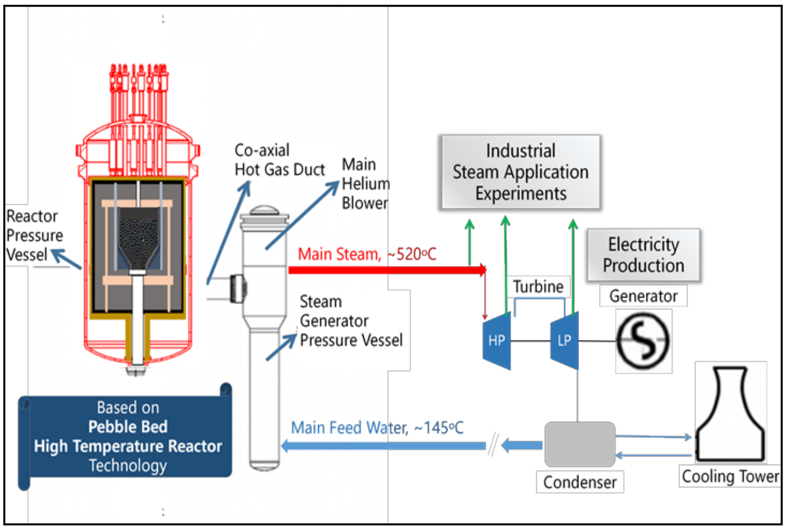

FIGURE 1. The diagram process of RDE reactor

2. Methodology of Calculation

As mentioned formerly, the MCNP6 code was applied to model the RDE reactor and the calculation was begun by modelling TRISO particles in a fueled pebble and the cross section of RDE core can be grasped in figure 2. In addition, figure 3 and figure 4 arrange TRISO particles in a graphite matrix using a simple cubic lattice (SC) and a pebble model applying body centered cubic (BCC) lattice, respectively. The modelling of TRISO particle, fueled pebble and RDE core have been implemented based on the transport code of Monte Carlo MCNP6 as mentioned earlier.

For this analysis, each fueled pebble consists of 5 grams shaped from 8,335 TRISO-layer particles in graphite matrix dispersion and each TRISO particle makes up of UO_2 kernel consuming 10.41 gr/cm^3 density and 0.0250 cm radius. The TRISO coating encompasses 4 layers, firstly, a porous carbon buffer layer (C) with 1.14 gr/cm^3 density and 0.0340 cm radius. Secondly, inner pyrolytic carbon (IPyC) layer consumes 1.89 gr/cm^3

density and 0.0380 cm radius and thirdly, a silicon carbide (SiC) layer devises 3.20 gr/cm^3 density and 0.0415 cm radius. Lastly, outer pyrolytic carbon (OPyC) layer produces 1.87 gr/cm^3 density and 0.0455 cm radius. Specific coating is devoted to withstand and contain gaseous and metallic fission product and hence to maintain the integrity of TRISO particle. A 6 cm diameter fueled pebble contains fueled zone with 5 cm diameter in which the composition of graphite matrix consists of TRISO and graphite shell with 0.5 cm thick. The graphite shell as a moderator surrounding fuel is detached to protect fueled zone during pebble movement. In the following paragraphs, there are mainly some following steps to accomplish the simulation for this research analysis.

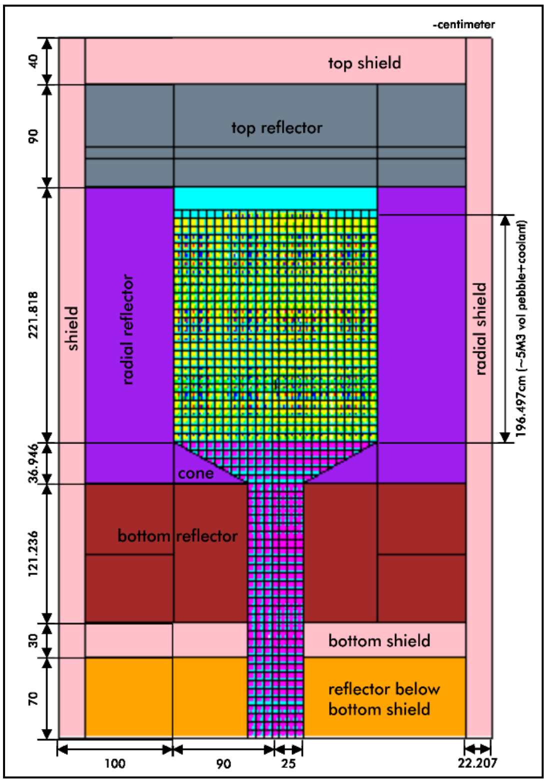

FIGURE 2. Cross section of RDE reactor core and size in cm [10].

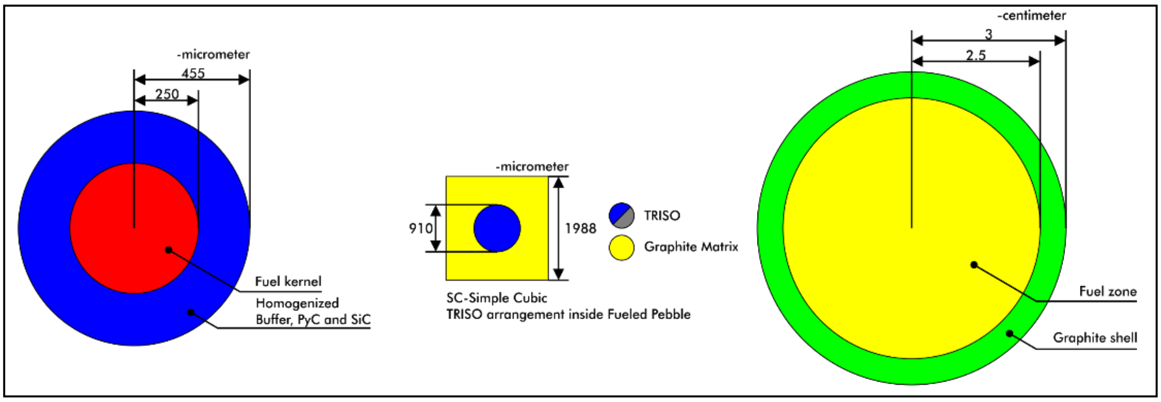

FIGURE 3. Modelling of a simple cubic lattice (SC) [10].

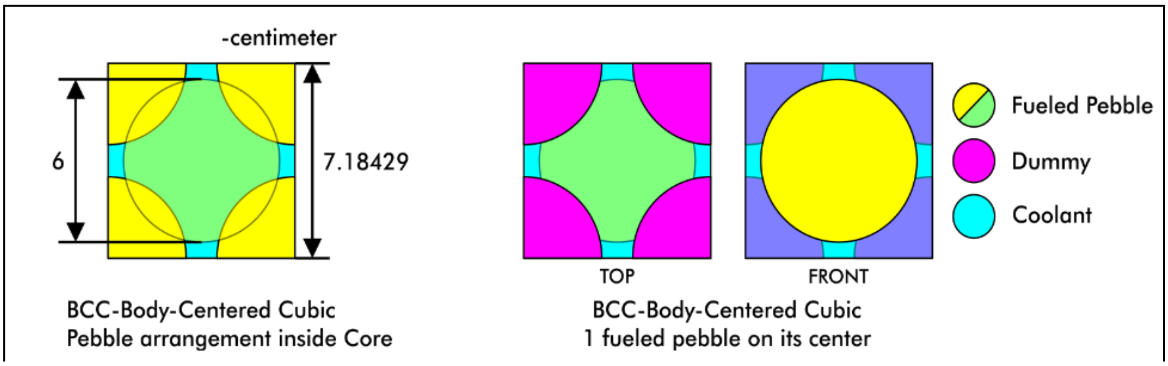

FIGURE 4. A pebble model using body centered cubic lattice (BCC) [10].

Firstly, the RDE core has been patterned to regions of fueled pebble and dummy, coolant, radial reflector and cone, and axial reflector and shield. During the RDE operation, there are two coolants applied, namely, dry air and helium gas. The RDE reactor employs helium to cool the reactor core and consumes dry air to cool the reactor core under accident condition. In this accident scenario, the temperature ranges from 800 ^{0}K (526.85 ^{0}C) to 1,800 (1,526.85 ^{0}C) have been applied. For detail simulation, temperatures of 800 ^{0}K (526.85 ^{0}C), 1,000 ^{0}K (726.85 ^{0}C), 1,200 ^{0}K (926.85 ^{0}C), 1,400 ^{0}K (1,126.85 ^{0}C), 1,600 ^{0}K (1,326.85 ^{0}C) and 1,800 ^{0}K (1,526.85 ^{0}C) have been accomplished. Furthermore, the height of the RDE core is 201.16 cm, called full core, in which the all fuel control rods are totally at the top of the reactor core. The core height of 79.0273 cm was firstly taken, and by using the around 7.0 cm step, the core calculation has been carried out till the RDE full core. After all well-defined inputs carefully chosen, KCODE as well as KSRC, a part of MCNP6 code, generated the results as arranged for defaults of the horizontally and axially models taking into account the nuclear data library ENDF/B-VII.0.

Secondly, the simulation results deal with the effective multiplication factors (k_{effs}) of the RDE core at every region earlier designated, and for the varieties of the RDE core sizes taking into account the temperature steps previously defined. To estimate the temperature reactivity feedback (*Rho*, ρ) in the RDE reactor during the events of temperature varieties in regions taking into account dry and helium coolant, the following formulas for *Rho* and $\Delta\rho$ were then smeared:

$$Rho = \rho = (k_{eff}-1) / k_{eff} \quad (1)$$

$$\Delta\rho = (k^n_{eff} - k^0_{eff}) / (k^n_{eff} \times k^0_{eff}) \quad (2)$$

where:

ρ (*Rho*)	=	temperature reactivity feedback,
$\Delta\rho$	=	reactivity coefficient of RDE core during the accident,
k^n_{eff}	=	effective multiplication factor in the RDE core at condition n and
k^0_{eff}	=	effective multiplication factor in the RDE core at room temperature.

Finally, all of figures 5 to 13 have been made related to the correlations between (*Rho*, ρ) at every core temperature and region previously defined and the core height or core sizes. The relationship between *Delta Rho* (the total reactivity coefficient) of the RDE core as function of helium and dry air coolant as well as core depth/core size is displayed in figure 14. In the following section, results and discussions for every condition previously delineated during the accident are briefly discussed.

3. Research and Discussions

3.1. General

For this research calculation, the world nuclear data library of cross section (XS), ENDF/B-VII.0, have been utilized and the varieties of fuel temperatures have also been taken into account from 800 ^{0}K (526.85 ^{0}C) up to 1,800 ^{0}K (1,526.85 ^{0}C) with the 200-degree step. While the former temperature has been applied due to reactor temperature operation, the latter temperature is respected to be the highest temperature in the fuel during the reactor accident. It is also noted that ENDF/B-VII.1 library applied is the latest revision to the United

States' Evaluated Nuclear Data File (ENDF). The revision expands upon that library, including the addition of new evaluated files from 393 to 423. Continuous energy cross section libraries which are very suitable for use with the MCNP6 Monte Carlo transport code have been practical to a suite of nearly one thousand critical benchmark assemblies distinct in the International Related Standards [17].

The calculations were performed with the latest release of the continuous energy Monte Carlo neutronic code MCNP, i.e. MCNP6. The results deal with the RDE core k_{eff} computation which allows for the varieties of fuel temperatures as well as the core size changes or core depths. Scheming of effective multiplication factors *(k_{eff})* has been adopted for regions of fueled pebble and dummy, coolant, radial reflector and cone and axial reflector and shield. For the case of RDE reactor calculations, dry air and helium coolant have been pertained. In a high temperature reactor 10 MW (HTR-10) as a reference of RDE design, while helium coolant was applied during the HTR-10 operation, dry air coolant was utilized for its experiments. Once the effective multiplication factors *(k_{eff})* accomplished, the temperature reactivity feedback (*Rho*) for every condition and region can be approximated using Equations 1 and 2 previously mentioned in Section 2. The following sub-section expresses the temperature reactivity feedback (Rho, ρ) which depends on the temperatures of the regions of fueled pebble and dummy, coolant, radial reflector and cone, and axial reflector and shield. Helium and dry air are utilized to cool the RDE core during reactor operation.

3.2. *Rho/ρ* in the fuelled pebble and dummy region

Now, we will see the temperature reactivity feedback (Rho, ρ) at the region of fueled pebble and dummy using dry air and helium coolant. From figure 5, when core depth starts from 129.3174 cm to 201.16 cm full core using dry air coolant, *Rho* of the RDE core increases due to the volume of the core becomes bigger. Providentially, as the temperature of the fueled pebble and dummy increases, *Rho* of the RDE core decreases due to the influence of negative reactivity feedback of temperature increase. For every core size or core depth, it is concluded the higher temperature of fueled pebble and dummy is, the less temperature reactivity feedback will be. This phenomenon is also the same as helium coolant applied as seen in figure 6, because the characteristic of dry air is very similar to that of helium. From those figures 5 and 6, although some temperature reactivity feedback are positives, but for the total Rho of the RDE core, all of those at all 4 regions should be simultaneously added and hence the total reactivity of the RDE core is believed to be negative meaning that the RDE core is safe.

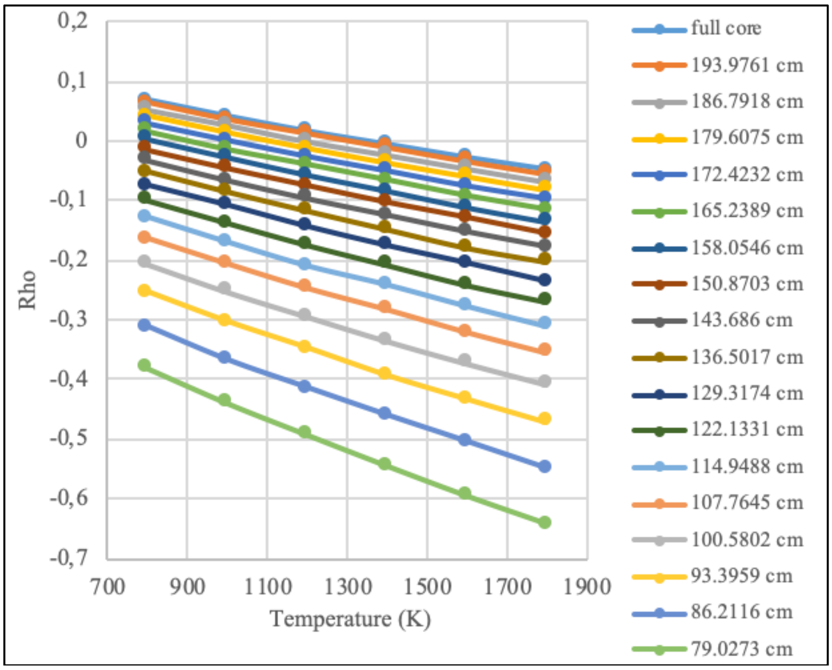

FIGURE 5. *Rho* versus fueled pebble and dummy temperatures using dry air coolant.

Figure 5 shows the temperature coefficient of reactivity (*Rho*, *ρ*) versus fueled pebble and dummy temperatures from 800 ^{0}K (526.85 ^{0}C) up to 1,800 ^{0}K (1,526.85 ^{0}C) using dry air coolant. From those relationships, it can be directly estimated the *Rho* at any core depth from 79.0273 cm to 201.16 cm or full core. Furthermore, there is actually a complete series of the relationship between those two values of temperatures and *Rho*, however there are only some relationships displayed in figure 6. This is due to very tight one graph to another graph and hence the graph can not be seen clearly. Furthermore, from figures 6 and 7, the minimum R^2 is 0.9969 or this equals to the curve fitting accuracy of 99.69%. The accuracy of 99.69% comes from all complete data resulted from the XS (cross section) calculation which mainly depends on the temperatures of the region adopted. It is also noted that the accuracy of 99.69% is very high for the simulation results. Finally, it may be concluded that the code MCNP6 is very suitable to be applied for neutronic calculation, especially for the RDE core.

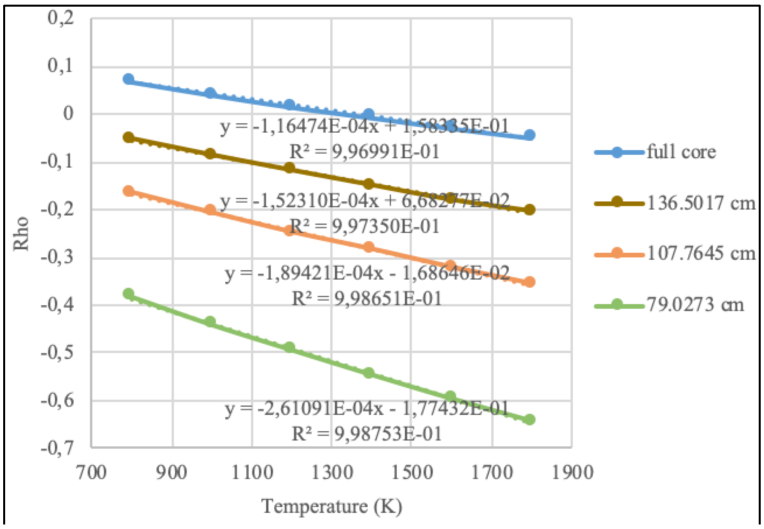

FIGURE 6. *Rho* versus fueled pebble and dummy temperatures using dry air coolant.

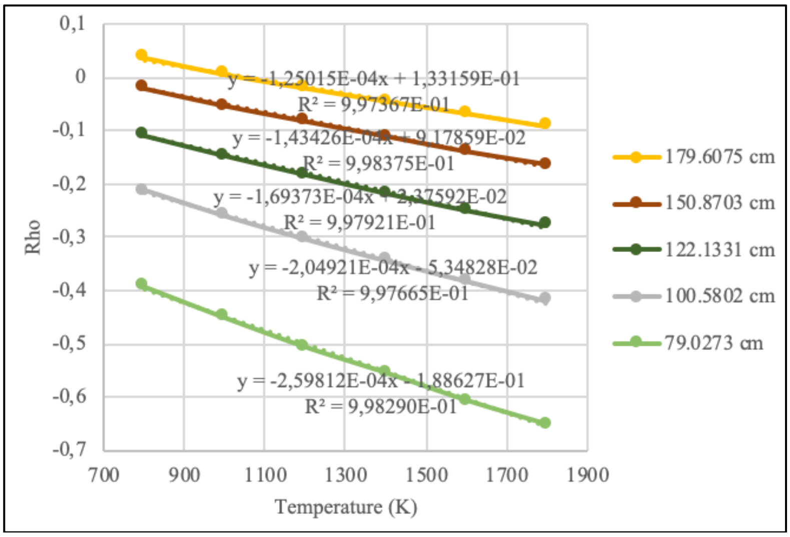

FIGURE 7. *Rho* versus fueled pebble and dummy temperatures using helium coolant.

3.3. *Rho/ρ* in The Coolant Region

The simulation results now derived from the region of coolant in the RDE core are displayed in figures 8 and 9. While figure 8 expresses *Rho* versus the core depth from 79.0273 to 201.16 cm or full core, figure 9 explores the association between *Rho* and the varieties of temperatures from 526.85 ^{0}C to 1,526.85 ^{0}C. It is noted that the densities of helium and dry air are vey low even the lowest among those of other regions. Therefore, it can be seen that at every depth of the RDE core, the temperature coefficient of reactivities are flat because the coolant distributes very uniformly to all of the reactor core and hence the coolant temperature is stable. It is also very evident from figures 8 and 9, those *Rhos* are all negative and will positively contribute to the total negative reactivity of the RDE core (*Delta-Rho*) and hence the RDE core is safe.

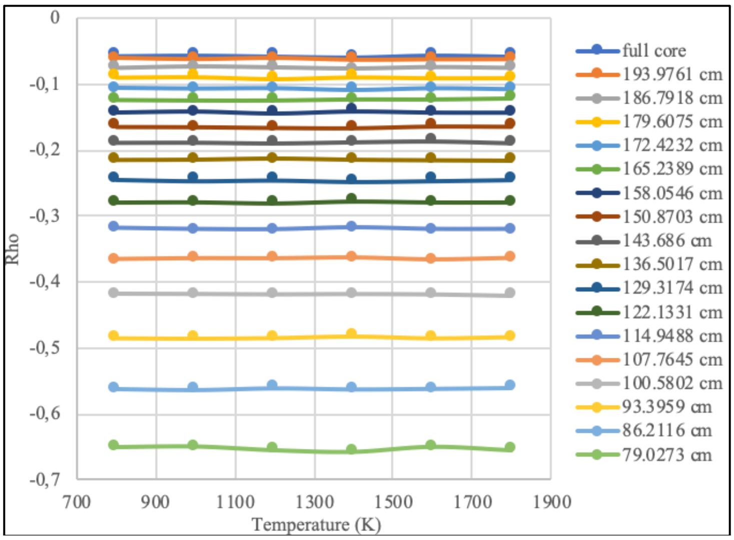

FIGURE 8. *Rho* versus coolant temperatures using helium coolant.

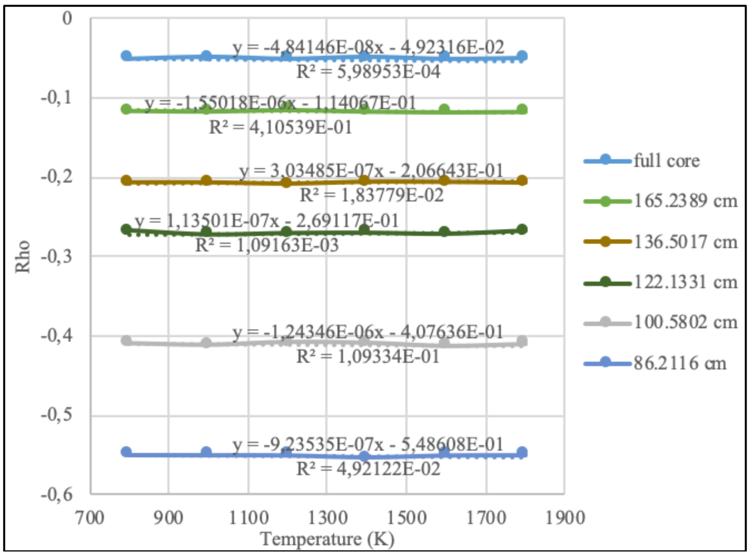

FIGURE 9. *Rho* versus coolant temperatures using helium coolant.

3.4. *Rho/p* in the Radial Reflector and Cone Regions

The simulation results derived from the region of radial reflector and cone in the RDE core are shown in figures 10 and 11. While figure 10 deploys *Rho* versus the core depth from 79.0273 (bottom core) to 201.16 cm (full core), figure 11 explores the relationship between *Rho* and the temperature varieties of the region from 526.85 ^{0}C (800 ^{0}K) to 1,526.85 ^{0}C (1,800 ^{0}K). For every depth of the RDE core, *Rho/ρs* are bit increased, because as the temperature increases, the amount of neutrons in the region is a bit increased as well. *Rho* is also a bit increased, but they are mostly negatives meaning that the RDE core is safe. It is noted that the reflector is a place in the RDE core in which all neutrons are all collected together and the amount of all neutron increases k_{eff} and hence the temperature reactivity feedback (*Rho*) in that area goes up as well.

In addition to the previous mention, figure 11 displays the relationship between *Rho* and the region temperatures of radial reflector and cone from 800 ^{0}K (526.85 ^{0}C) up to 1,800 ^{0}K (1,526.85 ^{0}C). By using dry helium coolant during the RDE operation and in the temperature range of simulation, although *Rho* in this region increases slowly for whole temperatures, but they are mostly negatives. In the case of *Rho* positive in the range of 10^{-5} (0.00001) as seen in figure 11, it is compensated by negative *Rho* resulted from the fuel and dummy region in which *Rho* is in the range of 10^{-4} (0.0001) meaning 10 times as much. Since the total *Rho* of the RDE core is the summation from all reactivity core changes from each region in the RDE core, it may be concluded that the total *Rho* of RDE core is negative and hence the RDE reactor core is totally safe.

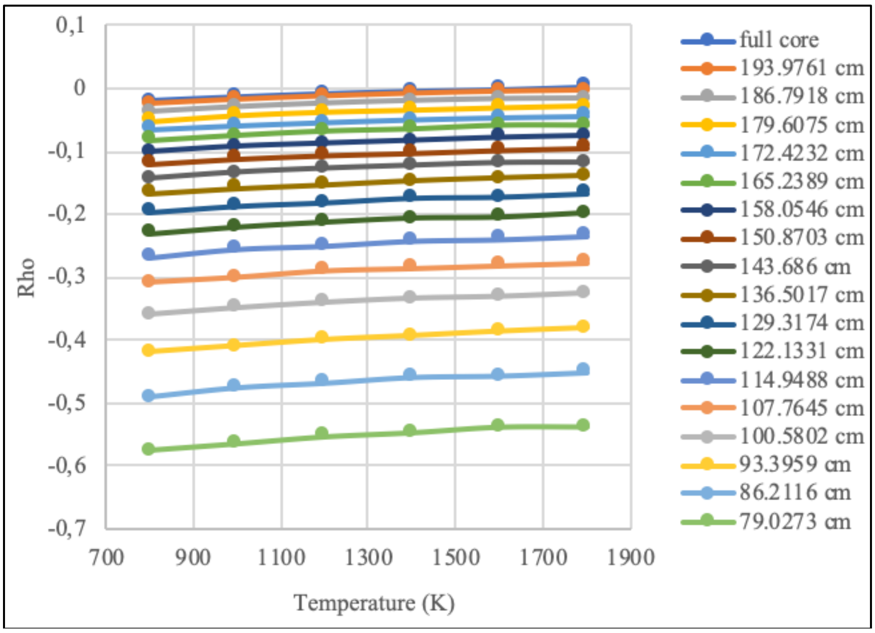

FIGURE 10. Rho versus radial reflector and cone temperatures using helium coolant.

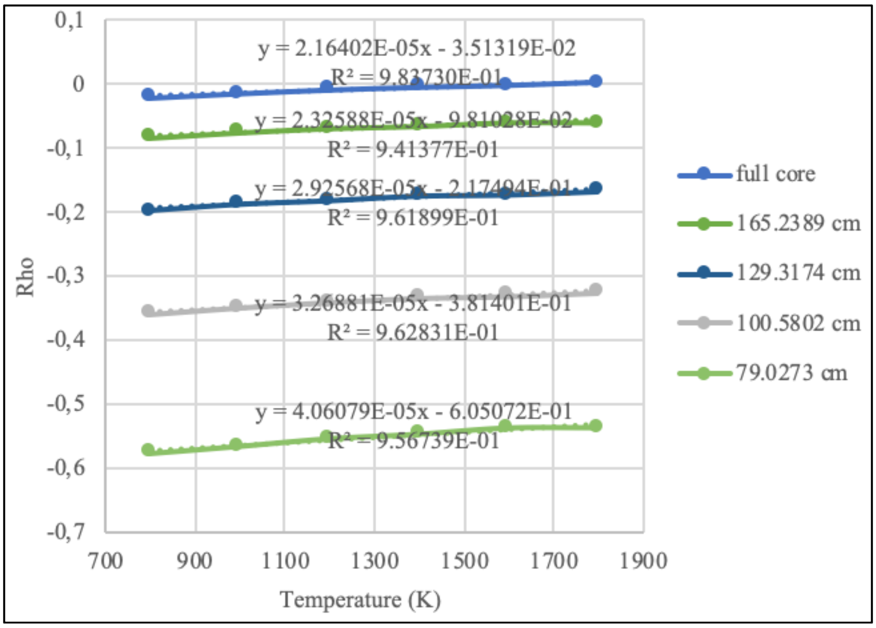

FIGURE 11. *Rho* versus radial reflector and cone temperatures using helium coolant.

3.5. *Rho/ρ* in the Axial Reflector and Shield Regions

Lastly, we are now arriving at the simulation results gained from the region of axial reflector and shield in the RDE core and those are displayed in figures 12 and 13. As figure 12 deploys *Rho* versus the core depth from 79.0273 cm (bottom of core) to 201.16 cm (full core), figure 13 displays the association between *Rho* and the varieties of the region temperatures from 800 ^{0}K (526.85 ^{0}C) up to 1,800 ^{0}K (1,526.85 ^{0}C). It is very evident for every depth of the RDE core, all *Rhos* are bit increased, because as the temperature increases, the amount of neutrons in the region intensifies as well. It is also noted from figure 13 when helium coolant used, starting from the core depth of 100.5802 cm to full core, *Rhos* are increased, but they are mostly negatives. However, in the case of *Rho* positive in the range of 10^{-6} (0.000001), it is then compensated by negative *Rho* from the fuel and dummy region in which the fuel, dummy *Rho* is in the range of 10^{-4} (0.0001) meaning 100 times as much. The total *Rho* of RDE core is then negative and hence the RDE reactor core is totally safe.

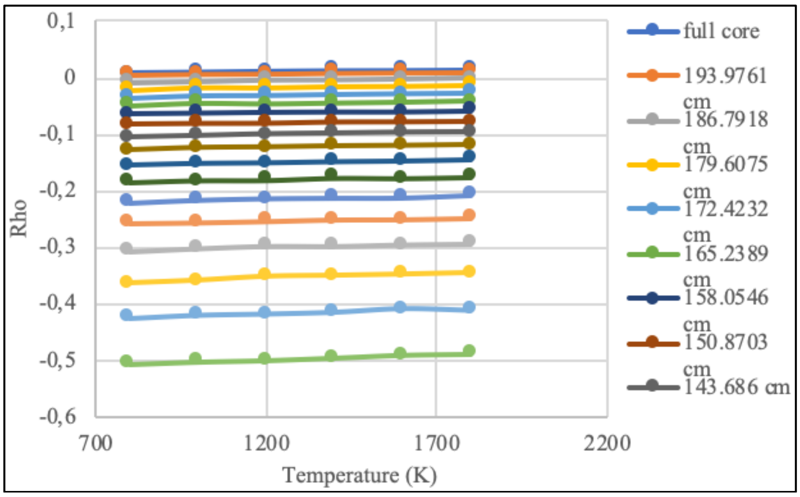

FIGURE 12. *Rho* versus axial reflector and shield temperatures using helium coolant.

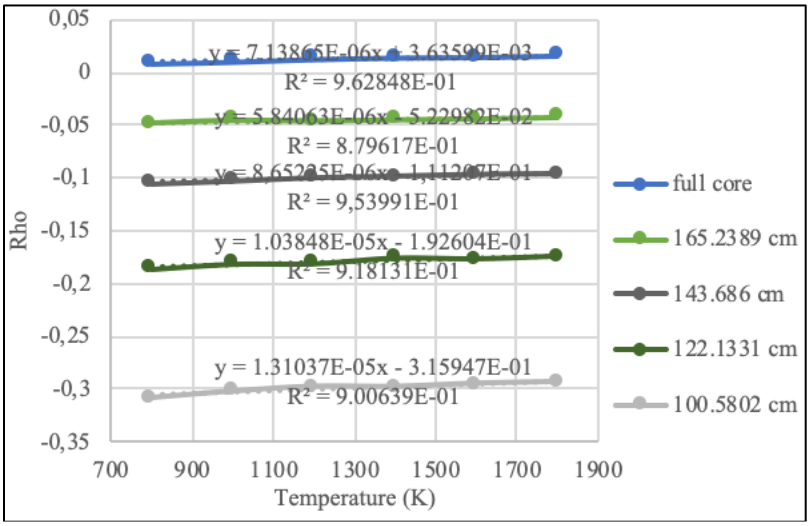

FIGURE 13. *Rho* versus axial reflector and shield temperatures using helium coolant.

3.6. The total *Delta Rho/Δρ* of the RDE Reactor Core

The total of core temperature reactivity feedback *(Delta-Rho/Δρ)* contemplates all regions of fueled pebble and dummy, coolant, radial reflector and cone as well as axial reflector and shield. The reactor temperature ranges of calculation deals with the temperatures of 800 ^{0}K (526.85 ^{0}C) to 1,800 ^{0}K (1,526.85 ^{0}C). The results as shown in figure 14 display temperature reactivity feedback (*Delta-Rho, Δρ*) as a function of core height from 79.0273 cm (bottom of core) to 201.1604 cm (full core). From figure 14, it is very evident that while the core height of 79.0273 cm, *Delta-Rho* using dry air coolant is around – 0.00020 ($\Delta\rho/\rho$), and when using helium coolant, the *Delta-Rho* is less than that using dry air coolant. It is also understandable when the core height increases, the *Delta-Rho of* RDE core is of course increased too, because the fueled pebble content in the reactor core becomes bigger. Furthermore, let us see, when the RDE core is full of fuels or with the depth of 201.16 cm, the temperature reactivity feedback (*Delta-Rho*) is the biggest or around – 0.0001, but that is still negative reactivity (– *Delta-Rho*/$\Delta\rho$). From all calculations taking into account the temperatures from 800 ^{0}K (526.85 ^{0}C) to 1,800 ^{0}K (1,526.85 ^{0}C), and core depth from 79.02773 cm (bottom core) to 201.1604 cm (full core), all *Delta-Rhos* ($\Delta\rho$) are all negatives which mean that the RDE core is totally safe. Indeed, from this point of view and from all simulation results accomplished, it can be again concluded that the RDE reactor core is totally safe when the previous defined accident occurs during the reactor operation.

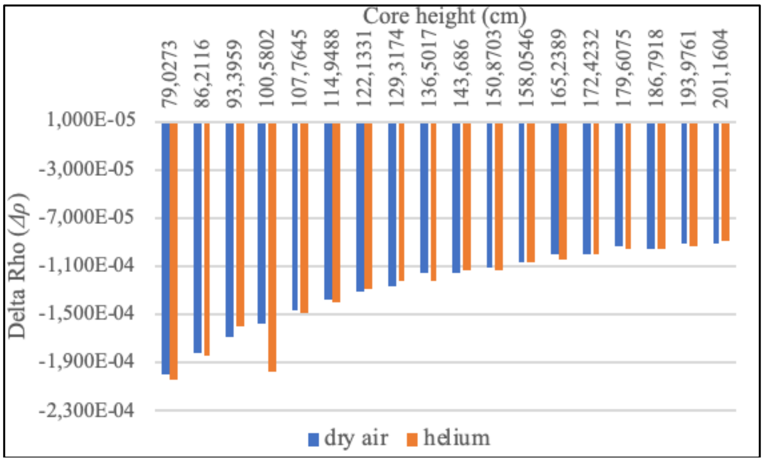

FIGURE 14. Total *Delta-Rho* ($\Delta\rho$) of RDE reactor core using dry air and helium coolant.

4. Conclusions

The Reaktor Daya Eksperimental (RDE), an HTGR Gen IV-type power reactor, is currently in the process of design approval by BAPETEN. The RDE reactor may be constructed in Puspiptek Area, Serpong, Banten and the reactor is expected to be operable by 2030. To assure the RDE reactor core safe, neutronic calculations focused on the core size influence to affect the temperature reactivity feedback of the RDE reactor have been done. For all calculations, continuous energy nuclear data library of ENDF/B-VII was employed by varying six core size models. The calculated temperature reactivity feedback includes DTC, MTC and RTC of reactivity. The KCODE and KSRC which are main parts of the MCNP6 codes utilizing the nuclear data library ENDF/B-VII.0 have been implemented to generate XS for the temperature ranges of 800 ^{0}K (526.85 ^{0}C) to 1,800 ^{0}K (1,526.85 ^{0}C). For whole simulations, four regions have been defined: fueled pebble and dummy, coolant, radial reflector and cone, and axial reflector and shield. The RDE core depth was decided starting from 79.023 cm (bottom of core) to 201.16 cm (full core) and dry air and helium gas coolant were utilized. The final results showed the total *Delta-Rho*/$\Delta\rho$ of the RDE reactor core is negative which means that the RDE reactor core is indeed safe although the defined accident occurs during the reactor operation.

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