Sensitivity of heat transfer parameters on the Reaktor Daya Eksperimental - RDE core

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Abstract. Center for Nuclear Reactor Safety and Technology (PTRKN) has tasks to perform research and development on the conceptual design of gas cooled reactor (RDE) with small power level of 10 MWt. In line with the development of RDE conceptual design, an analysis on the effects of thermal flow on TRISO fuel temperature distribution in RDE core has been performed. The objective of this research is to analyze the effects of variation of power level, coolant mass flow rate, and pressure on the temperature distribution of TRISO fuel in RDE core that meet safety requirements. This research employs VSOP code, by which the reactor core is divided into 50 components to represent the positions of various material compositions and to model TRISO fuel into 5 layers. The analysis is conducted at the following conditions: power level of 3 MW – 10 MW, flow rate of 1.5 kg/s – 4.32 kg/s, and system pressure of 1 MPa – 3 MPa. For the modelling, reactor parameters, core specification, and TRISO fuel specification as well as TRISO layer data of RDE are used. Based on the analysis results on the effect of helium gas flow, pressure, and reactor power variable on TRISO fuel temperature distribution, it can be concluded that, among these three variables, reactor power gives the most significant effect. The maximum temperatures at kernel and fuel outer layer is 740 °C and 736.4 °C, respectively. Compared to the temperature distribution resulted between VSOP’94 code and fuel temperature limitation as high as 1600 °C, there is enough safety margin from melting or disintegrating. Therefore, it can be concluded that TRISO fuel is able to contain all radioactive fission products.

Keywords: sensitivity, heat transfer, Reaktor Daya Eksperimental, Triso fuel, modelling

1. Introduction
High temperature reactor receives lots of attention nowadays. Its inherent safety features and economic electricity generation raise interests of many countries in the world, especially in Asia. Currently, Asia is one of the regions that is interested very much in developing high temperature gas-cooled reactor (HTGR), as indicated by the development of high temperature-test reactor (HTTR) in Japan [1] and HTR-10 in China [2], and the involvement of Asian countries including Indonesia in a Working Group and joint research on HTGR.

Development of conceptual design of experimental power reactor (RDE, Reaktor Daya Eksperimental) core was carried out at the National Nuclear Energy Agency of Indonesia (BATAN) at, as the first strategic milestone for the introduction of large scale nuclear power plant in the country. The main objective is to demonstrate reliable and safe generation of electricity and heat process [3,4].
This RDE design is similar to 10 MWth high-temperature gas-cooled reactor (HTR-10) with low enriched fuel of TRISO UO$_2$ and low power density. HTR-10, which is high-temperature gas-cooled test module reactor built in China [5], has many characteristics which are different from those of pressurized water reactor (PWR), i.e. special type of fuel, core construction, helium coolant. Many researchers have performed on thermo hydraulic of HTR-10 [2]. Previous research on design basis accident and beyond design basis accident shows that the fuel element temperature will not exceed the threshold temperature of 1230°C [6]. The validation and verification of safety analysis resulted in core transient data and cooling system for safety analysis code validation, as well as development of coupled neutronic and thermo hydraulic simulation of the 400 MWth modular pebble-bed reactor using VSOP diffuse code for fuel cycle has been completed [7].

The thermo hydraulic evaluation and calculation of HTR-10 is the most important indication to assess the reactor performance under the considered design conditions [8]. Simulation on temperature distribution in the pebble bed, coolant temperature in the inlet and outlet, coolant mass flow rate at steady state and transient [9]. A code of 3-D transient compressible CFD model has been developed to investigate the thermo hydraulic characteristics in the core under steady state and accident condition [10] Having inherent safety performance and high conversion efficiency, the high-temperature gas-cooled reactor becomes a potential candidate for the next generation of energy sources. Therefore, the configuration benchmarking at radial and axial direction of 2-D modelling of reactor core thermo hydraulics using analysis and design code [11] and sensitivity analysis are performed. Uncertainty of the maximum power density and power distribution on the pebble flow randomness [12]. Sensitivity of heat transfer parameters on the RDE core is the most indicator for evaluating the reactor performance under design condition. Power distribution, temperature distribution, and flow rate distribution of RDE are calculated for initial core and equilibrium core in this paper.

From the various analyzes that have been performed, it is necessary to perform an independent analysis of the sensitivity of heat transfer parameter on the Reaktor Daya Eksperimental, based on the RDE reactor data and the methods that have been successfully performed by previous researcher. In order to obtained the characteristic of TRISO fuel heat transfer in the RDE reactor core is in equilibrium condition.

2. Conceptual design of RDE

RDE is a conceptual design of high temperature gas-cooled reactor developed by BATAN. High temperature gas-cooled reactor is one of nuclear plant that has the highest energy efficiency, the most economic, clean and high inherent safety margin. The conceptual design of RDE core can significantly increase total thermal efficiency of nuclear energy system due to its graded heat application. This reactor is development of conceptual design of cogeneration reactor with medium power level and helium coolant.

The conceptual design of RDE core is similar to Chinese High Temperature Gas-cooled Reactor Pebble bed Module (HTR-10). This reactor basically consists of a reactor pressure vessel (RPV), steam generator pressure vessel (SGPV), and coaxial-horizontal hot-gas duct pressure vessel (HDPV), and other internal components of RPV and SGPV installed in a concrete containment. Main helium blower is installed above SGPV. Helium transfer heat generated in the core to secondary loop in the steam generator to produce high pressure superheated steam, which then drives the steam turbine to generate electricity of about 4 MWe. During normal operation, residual heat removal system (RHRS), designed as a passive system, will remove decay heat from the core to a heat sink in order to ensure the thermal integrity of nuclear fuel, RPV, and steam generator vault. In addition, in the concrete containment and steam generator vault, an air cooling system is installed to maintain wall temperature below 100°C so that the integrity and strength of the containment is secured.

The RDE core has 180 cm in diameter and 197 cm in height. The RDE has 27,000 uranium fuel pebble randomly distributed in the core. The core volume is 5.015 m$^3$ with power density of 2 W/cm$^3$. Each fuel pebble contains 8335 kernel of coated fuel particle. The fuel kernel with 0.91 mm in diameter is dispersed in graphite matrix of 5.0 cm in diameter to form a fuel zone, and outer shell of
0.5 cm thick, which is fuel free zone. Fuel loading into the core is carried out continuously when the reactor is in operation. Fuel pebbles enter the vessel and fuel pebbles that are still feasible are returned through the top to the reactor vessel. Therefore, fuel pebbles are not static, but move dynamically and slowly from the top to bottom of the vessel.

2.1. VSOP computer code

VSOP (Very Superior Old Program) computer code is a computer code system for the comprehensive numerical simulation of neutronic and a heat transfer computation code initially developed by KFA-Julich. The correlation and main parameters of all different material in VSOP code have been tested through an experiment in Germany and have been improved for application in several high temperature reactors such as AVR, THTR, HTR-500, and HTR Module. In addition, VSOP code was also used in the development of South Africa PBMR design and Chinese HTR-10 [13]. The structure of VSOP code is a heat transfer calculation with conduction and convection mechanism at steady state and transient using basic equations and solution techniques of VSOP code. VSOP code consists of 12 modules, 5 of which are TRIGIT, BIRGIT, LIFE, and VSOP as well as ZUT. This code requires input data of reactor and fuel modelling, core specification, fuel pebble and TRISO coated fuel particle. Validation and verification VSOP'94 has been done by Reitsma, the result of the comparison verification between Data.exe, Birgit.exe, VSOP.exe Original and Data.exe, Birgit.exe, VSOP.exe modified are the same.

To identify sensitivity of fuel temperature against flow of helium gas as coolant of RDE, calculation of heat transfer in fuel pebble is performed. The variables used are helium flow rate, core pressure, and core power. The thermal flow rates of 1.5 kg/s, 3.0 kg/s, and 4.32 kg/s are used. The pressures used are 1 MPa, and 3 MPa. Meanwhile, the reactor powers as high as 3 MW, 7 MW, and 10 MW are employed. Analysis on the effect of flow on TRISO fuel temperature distribution in RDE core as a function of position at core height is carried out.

RDE fuel modelling is based on the fuel design consisting of low enriched uranium-triple coated isotropic (LEU-TRISO) contained in a graphite-layered pebble. These layered particles contain uranium dioxide kernel coated with four layers to form a fuel pebble of 6 cm in diameter. RDE fuel pebble comprise a number of TRISO fuel (in form of UO$_2$ kernel coated with porous carbon buffer (C) as the fourth layer, inner pyrolitic carbon (IPyC) as the third layer, silicon carbide (SiC) as the second layer, and outer pyrolitic carbon (OPyC) as the first layer, as shown in Figure 1.

![Figure 1. RDE TRISO Fuel](image)
For the analysis of heat transfer in RDE fuel at steady state, fuel specification and geometry data of TRISO fuel and fuel pebble as well as core geometry data, as tabulated in Table 1, is required.

| Material                        | Value              |
|---------------------------------|--------------------|
| Kernel material                 | UO₂                |
| UO₂ density (g/cm³)             | 10.40              |
| Kernel diameter(µm)             | 500                |
| Outer layer thickness (cm)      | 0.5                |
| Coating thickness,(µm)          | 90 /40 /35/40      |
| Coating layer density(g/cc)     | 1.1/1.9/3.18/1.9   |
| Fuel matrix                     | graphite           |
| Coating material                | Buffer/I-PyC/SiC/O-PyC |

| Fuel Geometri                   |                    |
|---------------------------------|--------------------|
| Sphere outer diameter (mm)      | 60                 |
| Sphere inner diameter (mm)      | 50                 |
| Density of graphite in matrix and outer shell (g/cm³) | 1.73 |
| Enrichment(%)                   | 17                 |
| Equivalent natural boron content of impurities in graphite (ppm) | 0.5 |

| Core Geometry                   |                    |
|---------------------------------|--------------------|
| Core height(cm)                 | 197                |
| Number of control rods in side reflector | 7 |
| Core diameter(cm)               | 180                |
| Graphite Density(g/cm³)         | 1.70               |
| Number of fuel elements in equilibrium core | 27,000 |

| Thermal Flow                    |                    |
|---------------------------------|--------------------|
| Flow rate(kg/s)                 | 1.5; 3.0; 4.32     |
| Inlet gas temperature(°C)       | 250                |
| Thermal power(MWth)             | 3; 7; 10           |
| The pressure of the primary (MPa) | 1; 3               |

Heat transfer in fuel pebble in the RDE core consists of conduction heat transfer at radial and axial direction (pebble-pebble), convection heat transfer between pebble surface and flowing gas (helium coolant) and radiation heat transfer among fuel pebbles.

To identify the characteristics of heat transfer in TRISO fuel, several observation points are selected as shown in Table 2. The position of TRISO fuel in the core is considered as a layer with particular radius.

The assumption used is that fuel sphere is located in the reactor core at position of point z = 0 cm, which is in the helium coolant inlet to reactor core. Moreover, point z = 197 cm is located at the helium coolant outlet or bottom of the reactor vessel [15].
Table 2. Output Observation Points

| Position | Observation Points |
|----------|--------------------|
| Radial   | Fuel pebble at R=90 cm (center) |
| Axial    | 0 to 197 cm |
| Zone     | 5 zonal layers of shielding Z=1 to Z=5  
Z=1; O-Pyc layer; Z=2; SiC layer  
Z=3; IPyC layer; Z=4; Buffer layer  
Z=5; UO$_2$ kernel |

The analysis is conducted using VSOP calculation code, in which material properties such as helium density, dynamic viscosity, specific heat capacity, TRISO fuel material heat conductivity, are integrated into the code. Analysis on calculation results is carried out for the hottest position in the core. Observation on fuel temperature as a function of position (R,Z) at radial direction is performed at R=90 cm at the core center, while at axial direction the observation is at Z= 0 cm, Z= 32 cm, Z= 63 cm, Z= 94 cm, Z= 125 cm, Z= 156 cm, Z= 175 cm, Z= 183 cm, Z= 191 cm, Z= 197 cm.

3. Results and Discussion

TRISO fuel temperature sensitivity as a function of reactor core height is observed for the effect of helium gas flow rate, operation pressure and reactor power. The fuel outer layer is directly in contact with thermal flow. Based on the calculation results, fuel temperature distribution at each fuel sphere layer. Kernel temperature and the outer layer of TRISO fuel is discussed. Kernel is the nucleus of fuel pebble material and made of UO$_2$. Kernel has 500 µm in diameter. Number of fuel element in equilibrium core 27,000 and each pebble consists of 12,000 kernels. Kernel is not directly in contact with thermal flow. Heat generated by fission product of kernel is cooled through graphite layer of 0.5 cm thick that become fuel sphere shielding. Heat transfer in the reactor core occurs through conduction to axial and radial direction, i.e. between pebble and pebble, pebble and reflector, and whole graphite. Fuel outer layer is all material located inside and outside the fuel pebble. The heat generated by fission reaction in the core is directly transferred to fuel outer layer material. Convection heat transfer occurs among pebble bed particles and helium gas coolant mass flow rate[16], while radiation heat transfer occurs between pebble and pebble, pebble and reflector wall, and core barrel and reactor pressure vessel. The variation of input data used in this analysis include thermal power of 10 MW$_{th}$, 7 MW$_{th}$, and 3 MW$_{th}$, and coolant mass flow rates used are 1.5 kg/s, 3.0 kg/s, and 4.32 kg/s, and pressure variation includes 3 MPa and 1 MPa. The observation of fuel outer layer temperature as a function of position (R, Z) in the radial direction is carried at R = 0 (centreline), to R= 90 cm (near outer annular core), while axial direction is from axial position (Z= 0 cm, Z= 32 cm, Z= 63 cm, Z= 94 cm, Z= 125 cm, Z= 156 cm, Z= 175 cm, Z= 183 cm, Z= 191 cm, Z= 197 cm). Heat generated by fission product is transferred by conduction mechanism through buffer, IPyC, SiC, OPyC and graphite layers. Observation on the analysis results is also carried out for temperature of the fuel outer layer or OPyC. The results of sensitivity calculation of fuel outer layer temperature on variables of coolant flow rate, pressure, and reactor power are depicted in Figure 2.

Figure 2 shows fuel outer layer temperature as function of axial height experiences a stable rise at position of half of the core height, while for coolant flow rate of 3 Mpa/10.00 MWth/1.50 kg/s a temperature peak occurs with steep gradient before finally goes down slightly at position of the lower part of the core. Similar trends occur for variable of 2 MPa/10 MWth/4.32 kg/s; 3 Mpa/ 10 MWth/4.32 kg/s and 3 Mpa/10.00 MWth/1.50 kg/s . At lower part of reactor core, the temperature somewhat tends to increase again. The maximum kernel temperatures are 648.9°C, 687.3°C, and 735.7°C, respectively for the three coolant flow rate.

The results of calculation indicate that similar temperature distribution pattern along reactor core, where there is an increase trend of temperature at TRISO fuel at the inlet. The temperature achieves its peak at 48 cm of height and then decreases. This pattern is not precisely similar with that of temperature at fuel outer surface (OPyC)[17], because the temperature in the kernel is relatively
homogeneous, while TRISO surface experiences conduction heat transfer among pebbles. The effect of lower thermal flow rate results in higher OPyC layer temperature. The maximum temperatures at OPyC for the three variable of thermal flow values $3 \text{ MPa}/10 \text{MWth}/3.0 \text{ kg}^{-1}$; $3 \text{ MPa}/10 \text{MWth}/1.5 \text{ kg}^{-1}$ and $3 \text{ MPa}/10 \text{MWth}/4.32 \text{ kg}^{-1}$ are significantly different, i.e. $703.5^\circ\text{C}$, $736.3^\circ\text{C}$, and $687.7^\circ\text{C}$, respectively.

Figure 2. The Fuel Outer Layer temperature distribution as a function of reactor core height

The effect of thermal flow pressure results in OPyC layer temperature. The maximum temperatures at OPyC for the three variable of thermal flow values $3 \text{ MPa}/7 \text{MWth}/1.5 \text{ kg}^{-1}$; $1 \text{ MPa}/7 \text{MWth}/3 \text{ kg}^{-1}$ and $1 \text{ MPa}/3 \text{MWth}/3 \text{ kg}^{-1}$ are significantly different, i.e. $650.1^\circ\text{C}$, $631.1^\circ\text{C}$, and $637.4^\circ\text{C}$, respectively. The effect of thermal flow power, which are values $1 \text{ MPa}/3 \text{MWth}/1.5 \text{ kg}^{-1}$; $3 \text{ MPa}/7 \text{MWth}/3 \text{ kg}^{-1}$ and $2 \text{ MPa}/10 \text{MWth}/4.32 \text{ kg}^{-1}$ are significantly different, i.e. $534.4^\circ\text{C}$, $539.9^\circ\text{C}$, and $543.2^\circ\text{C}$, respectively. Observation on the analysis results is also carried out for the distribution temperature fuel kernel. The results of sensitivity calculation of the distribution kernel fuel temperature on variables of coolant flow rate, pressure, and reactor power are depicted in Figure 3.

Observation on the analysis results is also carried out for temperature of the TRISO fuel kernel. The effect variable of $2 \text{ MPa}/10 \text{MWth}/4.32 \text{ kg/s}$; $3 \text{ Mpa}/10 \text{MWth}/4.32 \text{ kg/s}$ and $3 \text{ MPa}/10.00 \text{ MWth}/1.50 \text{ kg/s}$ indicates similar temperature distribution pattern along reactor core, where there is an increase trend of temperature at TRISO fuel kernel at the inlet. The temperature achieves its peak at 48 cm of height and then decreases. This pattern is precisely similar with that of temperature at fuel kernel, because the temperature in the kernel is relatively homogeneous, while TRISO surface experiences conduction heat transfer among pebbles[18].
Figure 3. The kernel temperature distribution as a function of reactor core height

The effect of lower thermal flow rate results in higher fuel kernel temperature. The maximum temperatures at kernel for the three values of variable are significantly different, i.e. 649°C, 696°C, and 740°C, respectively.

4. Conclusion
Based on the analysis results on the effect of helium gas flow, pressure, and reactor power variable on TRISO fuel temperature distribution, it can be concluded that, among these three variables, reactor power gives the most significant effect. The maximum temperature at the OPyC layer surface of TRISO fuel is 700°C. Compared to the temperature distribution resulted between VSOP’94 code and fuel temperature limitation as high as 1600 °C, there is enough safety margin from melting or disintegrating. Therefore, it can be concluded that TRISO fuel is able to contain all radioactive fission products.
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References
[1] Nakagawa S, Tachibana Y, Takamatsu K, Ueta S and Hanawa S 2004 Performance test of HTTR 233 291–300
[2] Yang C, Fang C and Cao J 2014 Progress in Nuclear Energy The design and thermohydraulics study of the HTR-10 High Temperature Helium Experimental Loop Prog. Nucl. Energy 77 329–35
[3] Setiadipura T and Obara T 2014 Annals of Nuclear Energy Development of Monte Carlo-based pebble bed reactor fuel management code Ann. Nucl. Energy 71 313–21
[4] Taryo T, Bakhri S, Sunaryo G R, Kegiatan R-D A N, Terkait R and Program N 2019 The On-Going Progress of Indonesia’s Experimental Power Reactor 10 MW and Its National Research Activities 57–67
[5] Wu Z, Lin D and Zhong D 2002 The design features of the HTR-10 Nucl. Eng. Des. 218 25–32
[6] Sudarmono 2015 Investigation on Thermal-Flow Characteristics of HTGR Core Using Thermix-Konvek Module and VSOP’94 Code Tri Dasa Mega 17 41–54
[7] Reitsma F, Strydom G, Haas J B M De, Ivanov K, Tyobeka B, Mphahlele R, Downar T J, Seker V, Gougar H D, Cruz D F Da and Sikik U E 2006 The PBMR steady-state and coupled kinetics core thermal-hydraulics benchmark test problems 236 657–68
[8] Zuying G and Lei S 2002 Thermal hydraulic transient analysis of the HTR-10 Nucl. Eng. Des. 218 65–80
[9] Sudarmono 2014 Analisis perpindahan panas solid material RGTT200K J. Teknol. Bahan Nukl. 10 43–53
[10] Fernd Y M and Chen C T 2011 CFD investigating thermal-hydraulic characteristics and hydrogen generation from graphite e water reaction after SG tube rupture in HTR-10 reactor Appl. Therm. Eng. 31 2430–8
[11] Dudley T, Bouwer W, Villiers P De and Wang Z 2008 The Thermal – Hydraulic model for the pebble bed modular reactor ( PBMR ) plant operator training simulator system 238 3102–13
[12] Chen H, Fu L, Jiong G, Ximing S and Lidong W 2015 Quantitative analysis of uncertainty from pebble flow in HTR 295 338–45
[13] Sudarmono 2013 Analisis karakteristika distribusi temperatur bahan bakar pebble di teras RGTT200K pada kondisi tunak Prosiding Seminar Nasional ke-19 Teknologi dan Keselamatan PLTN Serta Fasilitas Nuklir (Yogyakarta: BATAN) pp 210–21
[14] Setiadipura T, Irwanto D and Zuhair 2015 Preliminary Neutronic Design of High Burnup OTTO Cycle Pebble Bed Reactor Atom Indonesia. 41 7–15
[15] Sudarmono, Suwoto, Bakhri S and Sunaryo G R 2018 Steady State Temperature Distribution Investigation of HTR Core J. Phys. Conf. Ser. 962 (1), 012040. DOI: https://dx.doi.org/10.1088/1742-6596/962/1/012040
[16] Hastuti, E P; Tukiran, Surip Widodo S 2018 Abnormal control rod withdrawal analysis for innovative research reactor using PARET-ANL codes Kerniteknik 83 96–105
[17] Sudarmono, Suwoto and Adrial H 2013 Sensitivitas Pengayaan Uranium dan Fraksi Packing (3Th , U)O2 Terhadap k∞ Sebagai Dasar Desain Konseptual RGTT200K J. Urania 19 (1) 25–38
[18] Ekariansyah A S, Hastuti E P and Sudarmono 2018 Relap5 simulation for severe accident analysis of rsg-gas reactor J. Tek. Reakt. TRI DASA MEGA 20 23–34