Steady State Temperature Distribution Investigation of HTR Core

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Abstract. Reactor operation safety is highly related to fuel temperature parameter in the reactor core. To maintain the fuel in good integrity (no crack or melting), fuel temperature should be continuously within licensing criteria. Fuel temperature parameter is one of safety parameters in nuclear reactor operation. Fuel temperature is determined by local heat flux. High heat flux generation will cause a change in heat equilibrium and consequently result a change in fuel temperature. In the present study, steady state temperature distribution investigations of pebble bed for HTR-10 have been performed. The calculation is performed by using VSOP’94 code to do the calculation by which the core is divided into 50 components to represent the positions of various material compositions and to model fuel into 5 layers. The analysis is carried out based on the input data of reactor parameters, core specification, and fuel specifications as well as layer data of HTR-10. The results of this simulation in HTR-10 core at steady state indicated that the maximum temperature is 969.9°C at the solid material and 1031.3°C in the fuel at the steady state condition. These temperatures are much lower than that of the maximum safety margin of fuel pebble, i.e. 1600°C, therefore, it can be concluded that TRISO fuel is able to contain all radioactive fission products.

Keywords: HTR-10 core, TRISO fuel temperature, solid material temperature, steady state

1. Introduction
Following the failure of heat removal system in the boiling water reactor (BWR) of Fukushima, Daiichi, Japan, professionals in nuclear reactor technology give more attention to high temperature gas-cooled reactor. It is believed that this reactor has high inherent safety feature due to its fuel characteristics, which withstands at relatively high temperature, so that it is categorized as an advanced nuclear reactor design. In order to implement BATAN’s vision in 2015 – 2019, BATAN has to develop and operate an experimental power reactor with capacity of 10 MWth using high temperature gas-cooled reactor (HTGR) technology, which is called Experimental Power Reactor-10 [1].

Currently, the analyses on this reactor type are being carried out and the supporting documents for construction license are being prepared. Many studies on core physics design and heat transfer in HTGR have been performed. F. Chen et al simulated anticipated transient without scram (ATWS) on HTR-10 at power level of 3 MW using VSOP’94 computer code. This analysis was aimed to verify
inherent safety characteristics in modular HTGR. The simulation results show that the maximum temperature at the fuel center is always less than 1600°C [2].

A transient three-dimensional compressible CFD model has been developed to investigate the thermal-hydraulic characteristics within the core under steady-state and accident conditions. Thermal-hydraulic characteristics and hydrogen production following steam generator rupture were investigated by Y.M. Ferng et al using CFD. In a postulated accident, water that is released into the core reacts with graphite on fuel surface, causing H₂ and CO generation. His calculation results show that H₂ concentration, generated by the chemical reaction between carbon and water, is not sufficient to induce hydrogen explosion in a postulated accident. In addition, the cooling peak temperature during transient is estimated lower than the specified limit margin. This study confirms the safety of HTR-10 core [3]. Experiments on UO₂ pellet treatment to produce HTR-10 fuel were performed by Wuhua Duan et al [4]. Heat removal analysis on HTR-10 spent fuel using natural convection mode was carried out by WANG Jin-hua et al. His study indicates that fuel spent and tank temperature is still within the permitted margin. Moreover, his study provides options in residual heat removal method during fuel loading and interim storage [5]. Meng-Jen Wang et al investigated material homogenization effect on criticality of HTR-10 using MCNP5 v11.51 and SCALE6 computer code. His study indicates that MCNP5 v11.51 and SCALE6 give good agreement results for geometry homogenization [6]. Meanwhile, Rainer Reimerta et al investigated heat supply process of modular HTR in aluminum calcination industry. His investigation show that industries requiring power as high as 100 MW and temperature between 950 – 1000°C are better supplied by HTR with modified process. Technically, this study was considered feasible [7]. Many studies on heat removal in high temperature gas-cooled reactor have also been conducted by BATAN’s researchers. Sudarmono carried out heat removal analysis on RGTT200K solid material [8]. In addition, investigation on thermal flow characteristics in HTGR core using VSOP’94-KONVEK and VSOP’94 has been performed [9]. This paper is aimed to identify the effect of coolant flow rate on TRISO fuel temperature distribution in HTR-10 core. There are several factors influencing the fuel temperature distribution, i.e. generated power, helium flow rate, and operational pressure. This study is aimed to investigate significant factors affecting HTR-10 fuel temperature performance using VSOP’94 computer code.

2. Theory

HTR-10 is a high temperature reactor with capacity of 10 MWₑ. The reactor achieved its first criticality in December 2000. Its main system consists of pebble bed, steam generator, hot gas duct and helium gas circulator. The major structure of HTR-10 comprises fuel pebbles. The 98.6-cm thick graphite structure covers the reactor core and the cavity above the reactor core is 41.698 cm high. Fuel pebble enters the core through the inlet at the vessel and fuel pebble that has good integrity is transferred back to the core through the upper part of reactor vessel. Therefore, it is apparent that fuel pebble is not static, but dynamically and slowly moves from the top and bottom of reactor vessel. The graphite reflector is placed on top, side, and bottom part of reactor vessel. In the side reflector, there are 10 control rods, 7 channels for absorber spheres, 3 experimental pipes, and 20 channels for cold helium coolant. This reactor type has two independent shutdown systems: control rod system and small absorber sphere system. These two shutdown systems are placed in channel located on the side of pebble bed. These systems run based on natural circulation cooling mechanism [10]. The helium temperature at the inlet and outlet of the core can reach from 250°C up to 700°C. The testing plant adopted a sub-C steam turbine cycle for energy conversion. The primary helium circulation and the second steam turbine circulation were coupled by the steam generator (SG) that serves as the heat exchanger. The reactor core was designed to be installed in the reactor pressure vessel while the steam generator, the helium blower with its driving motor were installed in another separate pressure vessel, called SG pressure vessel. These two pressure vessels were arranged side by side and were connected by the horizontal coaxial hot gas duct. The hot helium from the reactor core passes through the gas
duct and is fed into the SG and flows around the heating tube bundles downward. During this process, heat the water/steam on the other side, while the hot helium is cooled. Steam generated in the SG enters the inlet of a steam turbine and drives it to do work. The testing plant reached its full power in January 2003, and the outlet temperature is 700°C. The SG provides the steam turbine with water steam temperature of 435°C and inlet pressure of 3 MPa at a mass flow rate of 4.3 kg/s. Figure 1 describes the schematic diagram of the side-by-side arrangement of pressure vessels and the flow path of the primary loop coolant. A series of arranged tests and experiments has been performed on HTR-10 to verify its inherent safety features and to obtain operational characteristics. It also survived a power supply shutdown accident.

VSOP’94 is Design and Safety Analysis Code For Pebble Bed Reactor [11]. VSOP’94 was originally written with a simple 1-D thermal fluid solver to estimate local fuel and coolant temperatures in the core. That solver is still available but the 2-D (R-Z) THERMIX-KONVEK code has since been coupled to VSOP’94 to provide a more accurate and flexible thermal fluid analysis capability. THERMIX-KONVEK treats the pebble bed as a porous medium but also has an internal pebble fuel model to estimate peak fuel temperatures.

THERMIX-KONVEK code is heat transfer calculation code developed by KFA-Julich. The main correlation and parameters of different materials available in the Thermix code have been evaluated in many studies in Germany and improved for wide uses in other high temperature reactors, such as HTRs, HTR-PM and HTR-10 [12,13,14]. In addition, Thermix code was also used in the development of HTR-PM design for thermohydraulic transient studies [15]. The structure of Thermix code includes calculation of heat transfer based on conduction and convection mechanism at steady state and transient condition using basic and technical solution. Thermix code consists of 4 modules i.e. GASTEM, KONVEK, STROEM, and TFELD. These codes require reactor data and fuel modelling, core specification, fuel pebble, and TRISO fuel [16].

3. Methodology

To identify of solid material and fuel temperature on thermal flow of helium gas as coolant of HTR-10, temperature distribution investigation of Pebble Bed For HTR-10 in Steady State is performed. The variables used are helium thermal flow rate, core pressure, and core power. During the normal operation of the testing plant, the loop pressure of the primary coolant circulation is 3.0 MPa with a mass flow-rate of 4.32 kg/s, while the inlet temperature of the reactor core is 250°C. The lower structure of pebble bed is cone-shaped and has 1.8 m in diameter and 1.97 m in height. The fuel sphere has diameter of 50 mm and 5-mm graphite cladding. The pebble bed is filled with about 27,000 spherical fuel elements of 6 cm diameter, each of which consists of 12,000 coated fuel kernels. These fuel pebbles are loaded continuously into the core whose volume is 5.015m³ and power density is 2W/cm³. Steady State solid material and fuel temperature distribution investigation of Pebble Bed For HTR-10 as a function of position at core height is carried out.

HTR-10 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. HTR-10 fuel pebble comprise a number of fuel (in form of UO₂ 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.
For the temperature distribution investigation of Pebble Bed For HTR-10 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, are required.

Table 1. Input Data [10]

| PARAMETER                                              | VALUE            |
|--------------------------------------------------------|------------------|
| Core Geometry                                          |                  |
| Core height(cm)                                        | 197              |
| Number of control rods in side reflector               | 10               |
| Number of absorber ball units in side reflector        | 7                |
| Core diameter(cm)                                      | 180              |
| Enrichment of fresh fuel element, (%)                  | 17               |
| Number of fuel elements in equilibrium core            | 27,000           |

| Pebble Geometry                                        |                  |
| Diameter of ball (mm)                                  | 60               |
| Diameter of fuel zone (mm)                             | 50               |
| Density of graphite in matrix and outer shell (g/cm³)  | 1.73             |
| Enrichment of $^{235}\text{U}$ (weight),%             | 17               |
| Equivalent natural boron content of impurities in graphite (ppm) | 1.3            |
| Volumetric filling fraction of balls in the core       | 0.61             |

| TRISO Fuel Geometry                                    |                  |
| Kernel material                                        | UO$_2$           |
| UO$_2$ density (g/cm$^3$)                              | 10.40            |
| Kernel diameter(µm)                                    | 500              |
| Coating layer thickness,(µm)                           | 90 /40 /35/40    |
| Coating layer density(g/cc)                            | 1.1/1.9/3.18/1.9 |
| Coating material                                       | Buffer/I-PyC/SiC/O-PyC |

Heat transfer in fuel pebble in the HTR-10 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 temperature distribution investigation of Pebble Bed For HTR-10, 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 under the reactor vessel. This is similar to the modelling of conceptual design developed for HTR-10[10].

### Table 2. Output Observation Points[8,9]

| Position | Observation Points |
|----------|--------------------|
| Radial   | Solid material and Fuel pebble at 0 to R=90 cm (center) |
| Axial    | 0 to 197 cm        |
| Zone     | 3 zone             |

Zone 1: at middle of the reactor core as a function of position (R,Z) at radial direction is performed at the middle of core R= 0 cm (centerline); R=7 cm; R=14 cm; R=21 cm; R=28 cm; and R=35 cm.

Zone 2: at between middle and side of the reactor core as a function of position (R,Z) at radial direction is performed at the between middle core and side core R= 38.5 cm; R=45.5 cm; R=52.5 cm; R=59.5 cm; R=65.5 cm; and R=70.5 cm

Zone 3: at side of the reactor core as a function of position (R,Z) at radial direction is performed at the side core R= 73 cm; R=78 cm; R=82 cm; R=85 cm; R=87 cm; and R=89 cm

The analysis is conducted using VSOP’94 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 solid material and fuel temperature as a function of position (R,Z) at radial direction is performed during the normal operation steady state condition for as a function of position (R,Z) at radial direction in the middle core (zone 1), between middle core and side core (zone 2) and in side core (zone 3). Selection of the data coincides done in order to obtain a good image.

### 4. Results and Discussion

Solid material and Fuel temperature distribution as a function of reactor core height is observed for during the normal operation, the loop pressure of the primary coolant circulation is 3.0 MPa with a mass flow-rate of 4.32 kg/s, while the inlet temperature of the reactor core is 250°C. 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. 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. In addition to solid material and temperature of fuel in the core, temperature for as a function of position (R,Z) at radial direction is also obtained. To identify fuel reactor core and solid material temperature of HTR-10, analysis on temperature characteristics at steady state condition, at which a reactor runs normally, was carried out.

The results could not be obtained immediately, but data selection should be carried out first. The data are then analyzed to obtain the simulation results in form of chart, as shown in Figure 2 to Figure 4. The axial direction is core height, while x direction is temperature in fuel.

The geometrical design of HTR-10 has been carried out with logical approach. It is assumed that absorber sphere is inserted to the reactor core and at position z=0 inlet helium coolant is located. Next, z = 125 cm is located in the helium coolant region, between the inlet and outlet, while z = 197 cm is located at the coolant outlet where it leaves the core. It is different from the one shown in Figure 2 since in point 193 cm is located near the outlet. The difference is due to different visual design in
interpreting VSOP'94-THERMIX, but the real meaning is that point 0 cm is inlet point, as simulated. The results of calculation of fuel temperature and solid material temperature distribution during the normal operation at steady state condition for as a function of position (R,Z) at radial direction in the zone 1 are shown in Figure 2.

This graph shows that the fuel temperature distribution at zone 1 as a function of axial direction and temperature difference is well observed in the core. At the outlet, the helium temperatures at the center (z = 193 cm; r = 0 cm), and edge (z = 193 cm; r = 35 cm) of the core are 1031.3°C, and 969.6°C, respectively. Moreover, at the region be the helium inlet and outlet, the temperatures at the center (z = 125 cm; r = 0 cm), and edge (z = 125 cm; r = 35 cm) of the core are 759.5°C, and 715.6°C, respectively. The graph of fuel temperature distribution indicates that the temperature obtained rises as a function of axial distance and a temperature difference in the core is well observed.

![Graph of fuel temperature distribution](image)

**Figure 2.** Temperature distribution of fuel and solid material in the middle of core (zone 1).

This graph also shows that the solid material temperature distribution at zone 1. At the outlet, the helium temperatures at the center (z = 193 cm; r = 0 cm), and edge (z = 193 cm; r = 35 cm) of the
Temperatures at point \((z = 193 \text{ cm}, r = 28 \text{ cm})\) is \(931.9^\circ\text{C}\). Moreover, at the region be the helium outlet, the temperatures at the center \((z = 125 \text{ cm}; r = 0 \text{ cm})\), and edge \((z = 125 \text{ cm}; r = 35 \text{ cm})\) of the core are \(706.2^\circ\text{C}\), and \(666.2^\circ\text{C}\), respectively.

The results of calculation of fuel and solid material temperature distribution during the normal operation steady state condition for as a function of position \((R, Z)\) at radial direction is performed in between the middle and side core (zone 2) are shown in Figure 3. The results of calculation of fuel temperature distribution during the normal operation steady state condition for as a function of position \((R, Z)\) at radial direction is performed at \(R = 38.5 \text{ cm}; R = 45.5 \text{ cm}; R = 52.5 \text{ cm}; R = 59.5 \text{ cm}; R = 65.5 \text{ cm};\) and \(R = 70.5 \text{ cm}\).

![Figure 3. Temperature distribution of fuel and solid material in the between middle core and side core (zone 2).](image)

This graph shows that the fuel temperature distribution at between middle and side of the reactor core as a function of axial direction and temperature difference is well observed in the core, as shown in Figure 6. At the outlet, the helium temperatures at the center \((z = 193 \text{ cm}; r = 38.5 \text{ cm})\), and edge \((z = 193 \text{ cm}; r = 70.5 \text{ cm})\) of the core are \(957.6^\circ\text{C}\) and \(836.7^\circ\text{C}\), respectively. Temperatures at
point \((z = 193\text{ cm}, r = 65.5\text{ cm})\) is 854.1°C. Moreover, at the region be the helium inlet and outlet, the temperatures at the center \((z = 125\text{ cm}; r = 38.5\text{ cm})\) and edge \((z = 125\text{ cm}; r = 70.5\text{ cm})\) of the core are 707°C, and 620.4°C, respectively.

This graph also shows that the solid material temperature distribution at zone 2 of the reactor core as a function of axial direction and temperature difference is well observed in the core. At the outlet, the helium temperatures at the center \((z = 193\text{ cm}; r = 38.5\text{ cm})\), and edge \((z = 193\text{ cm}; r = 70.5\text{ cm})\) of the core are 900.7°C, and 788°C, respectively. Temperature at point \((z = 193\text{ cm}, r = 65.5\text{ cm})\) is 804.2°C. Moreover, at the region be the helium inlet and outlet, the temperatures at the center \((z = 125\text{ cm}; r = 38.5\text{ cm})\), and edge \((z = 125\text{ cm}; r = 70.5\text{ cm})\) of the core are 658.4°C, and 577.9°C, respectively.

The results of calculation of fuel temperature and solid temperature distribution during the normal operation steady state condition for as a function of position \((R,Z)\) at radial direction is performed at \(R= 73\text{ cm}; R=78\text{ cm}; R=82\text{ cm}; R=85\text{ cm}; R=87\text{ cm}\) and \(R=89\text{ cm}\) in side core (zone 3) are shown in Figure 4.

![Figure 4. Temperature distribution of solid material in the side core (zone 3).](image)

This graph shows that the fuel temperature distribution at zone 3 as a function of axial direction and temperature difference is well observed in the core. At the outlet, the helium temperatures at the center \((z = 193\text{ cm}; r = 73\text{ cm})\) and edge \((z = 193\text{ cm}; r = 89\text{ cm})\) of the core are 828.5°C and 693.2°C, respectively. Temperatures at point \((z = 193\text{ cm}; r = 87\text{ cm})\) and \((z = 193\text{ cm}, r = 89\text{ cm})\) are 769.9°C and 758.7°C. Moreover, at the region be the helium inlet and outlet, the temperatures at the center \((z = 125\text{ cm}; r = 73\text{ cm})\) and edge \((z = 125\text{ cm}; r = 89\text{ cm})\) of the core are 615.4°C and 543.4°C, respectively.
This graph also shows that the solid material temperature distribution at side of the reactor core (zone 3) as a function of axial direction and temperature difference is well observed in the core, as shown in Figure 4. At the outlet, the helium temperatures at the center \((z = 193 \text{ cm}; r = 73 \text{ cm})\) and edge \((z = 193 \text{ cm}; r = 89 \text{ cm})\) of the core are 780.3°C and 664.4°C, respectively. Temperatures at point \((z = 193 \text{ cm}; r = 87 \text{ cm})\) and \((z = 193 \text{ cm}, r = 89 \text{ cm})\) are 723.4°C and 712.3°C. Moreover, at the region be the helium inlet and outlet, the temperatures at the center \((z = 125 \text{ cm}; r = 73 \text{ cm})\) and edge \((z = 125 \text{ cm}; r = 89 \text{ cm})\) of the core are 573.1°C and 514°C, respectively.

The fuel temperature distribution in the reactor core is affected very much by processes either inside the core. In the core, conduction heat transfer among pebbles and between pebble and the wall occurs directly. The temperature near the reactor wall is lower because there are some moderators surrounding the core so that the number of neutron decreases and heat flow from pebble to the wall occurs due to lower temperature of the wall. The highest temperature in the core is near the helium outlet due to continuous helium flow causing hot flow to go down to the outlet and it unlikely for helium to return to the inlet. In addition, radiation and convection heat transfer occurs. Radiation heat transfer between pebble and other pebble in distance is not influenced by coolant flow, while convection heat transfer between pebble and other pebble or between pebble and the wall in distance is affected by heat flow brought by the coolant.

The temperature distribution of fuel provides a temperature decrease in relation to its height. The farther temperature from the inlet, the lower the temperature. Based on the results, temperature difference in fuel in the reactor core is affected very much by effective thermal conductivity. Thermal conductivity is influenced very much by several properties, such as heat transfer coefficient between solid and gas, pebble zone surface area, and helium fluid temperature.

**Table 3. Comparison Results**

| Parameter                          | HTR 10 China [17] | HTR Core Using VSOP'94 |
|-----------------------------------|------------------|------------------------|
| Thermal power, MW                 | 10               | 10                     |
| Primary helium pressure, MPa      | 3.0              | 3.0                    |
| Average helium temp. at reactor inlet, °C | 250              | 250                    |
| Primary coolant flow rate, kg/s   | 4.32             | 4.32                   |
| Core volume, m³                   | 5.0              | 5.0                    |
| Effective core diameter, m        | 1.80             | 1.80                   |
| Core height, m                    | 1.97             | 1.97                   |
| Diameter of fuel element, cm      | 6                | 6                      |
| Number of fuel elements           | 27,000           | 27,000                 |
| Fuel kernel diameter, µm          | 500              | 500                    |
| Maximum fuel temp, °C             | 918.7            | 1031.3                 |
| Outlet helium temp, °C            | 700              | 759.5                  |
| Maximum coolant temp, °C          | 818              | 970                    |
| Maximum temp. of side reflector, °C | 666.9            | 666.2                  |
| Maximum temp. at bottom reflector, °C | 789.7            | 706.2                  |
| Limitation of fuel temperature, °C | 1600             | 1600                   |

Comparison of fuel and solid temperature calculation on HTR core using VSOP'94 and similar calculation of HTR-10 reactor core is shown in table 3. Compared with parameters of HTR reactor at 10 MW, the calculation results of fuel and solid material temperature in zone 1 position of HTR core reactor, seems in agreement, there are under limitation of fuel temperature. Therefore, it can be concluded that steady state temperature distribution of high temperature reactor determination has been verified.
5. Conclusion
The results of this simulation indicate several important points, i.e. the highest temperature in the solid material at the outlet, the helium temperatures at the center (z = 193 cm; r = 0 cm), and edge (z = 193 cm; r = 35 cm) of the core are 969.9°C and 911.9°C, respectively. The highest temperature in the fuel temperature distribution are 1031.3°C and 969.6°C, respectively. Moreover the temperatures resulted in this analysis are compared with that of the previous research and with the maximum safety margin of fuel pebble temperature. i.e. 1600 °C. This value is chosen as a limit so that fuel pebble integrity is maintained and no radionuclide such as Cs-137 causing hazard to human body is released. Therefore, the HTR-10 core design meets the safety criteria. Moreover analysis on the solid material and fuel temperature distribution in HTR-10 core using VSOP’94 code is very beneficial for considering the best and most suitable reactor type for BATAN.

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