Fast Neutron Irradiation Influence Analysis in Thermal-Hydraulics Aspect of HTR-10 Reactor Using Modified PEBBLE Program

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Abstract. Pebble Bed Reactor is a Gen-IV reactor that uses spherical fuel loaded into an active core. This reactor uses graphite that can be found on fuel and reflectors as a neutron moderator. The fast neutron can damage the atomic structure of fuel because the neutron with high energy can displace the graphite lattice. As its effect, the value of fuel thermal conductivity is influenced. PEBBLE is the program used for thermal-hydraulic calculation for pebble bed reactor type (PBR), and mPEBBLE was developed based on PEBBLE. The main difference between the two is that the mPEBBLE can take into account the fast neutron factor in the calculation. In this study, the thermal-hydraulics calculation for HTR-10 was performed using the mPEBBLE code. The result obtained is compared to the results from two different programs; THERMIX and WIMSTER. The comparison between the mPEBBLE and THERMIX has a temperature difference, which is relatively high at 63.3°C at the near-wall position. For the comparison between mPEBBLE and WISMTER, the noticeable difference happens in pebble center temperature, which is 65.3°C for the temperature difference.

1. Introduction
The latest generation of a nuclear fission reactor is called the Gen-IV type reactor, which has a better safety capability than the previous generation [1]. There are six selected systems for Gen-IV reactors, including the gas-cooled reactors system. Many kinds of research have been conducted for Gas-cooled Fast Reactor \cite{2,3}, Prismatic-type of High-Temperature Gas Reactors \cite{4,5}, and Pebble-type High-Temperature Gas Reactor \cite{6,7}. The pebble-bed reactor, known as PBR, has some capabilities that the other reactor doesn't have. One of the PBR abilities is the online refueling capability. The online refueling capability makes the shutdown procedure unnecessary for the refueling process because it can be refueling when the core is still active.

HTR-10 is one of the reactors classified as PBR type. This reactor was designed and developed by the Institute of Nuclear Energy Technology (INET) for research purposes. The core has a small geometry size; the diameter is 1.8 m, and the height 1.875 m. HTR-10MW is operated on 10 MWth. Like all of
the PBR types, HTR-10 uses spherical fuel or pebble fuel. The fuel scheme used on the HTR-10 is the conventional German fuel type. It has a temperature limitation of 1230°C[8]. The HTR-10 specifications can be seen in Table 1.

**Table 1. HTR-10 specifications[9]**

| Specifications | Value |
|----------------|-------|
| Coolant Mass Flow | 4.32 kg/s |
| Coolant Mass Flow through Pebble Bed | 3.77 kg/s |
| Inlet Plenum Coolant Pressure | $4.0 \times 10^6$ Pa |
| Mixed Mean Inlet Plenum Coolant Temp. | 553 K |
| Radius Bed Dimension | 0.9 m |
| Axial Bed Dimension | 1.875 m |
| Nominal Bed Void Fraction | 0.39 |

**Fuel Element**

| Specification | Value |
|---------------|-------|
| Pebble Diameter | 0.06 m |
| Outer Radius of fueled/un-fueled Interface | 0.025 m |

In general, the pebble fuel consists of UO$_2$ (called the kernel), which coated with three layers; from inner to outer: PyC, SiC, and PyC, it is called coated fuel particle (CFP), then CFPs are collected and wrapped by graphite, so it is called pebble fuel. German fuel has two different schemes; shell and conventional. In the shell fuel, the middle area contains no CFP and is filled only with graphite. Meanwhile, in a conventional type, the CFPs are distributed from the pebble fuel center to a certain radius, then wrapped by the graphite.

![Figure 1. German fuel type scheme](image)

Graphite is the element that can be found in the pebble fuel of the PBR type. The use of graphite is for the neutron moderation process. However, the moderation process of degrading neutron energy can damage the atomic structure of graphite. The fast neutron irradiation can cause the fuel's lower thermal...
conductivity because the neutron with high energy can displace the graphite atom's position. Atomic depletion caused by fast neutrons can be seen in Figure 2. However, the temperature can influence the fuel thermal conductivity value [10]. For the German fuel type, there is the equation for fuel thermal conductivity, which depends on temperature and fast neutron dose,

$$k_s = 127.68 \left( \frac{0.06829 - 0.3906 \times 10^{-4}T}{DOSIS + 1.931 \times 10^{-4}T} + 1.228 \times 10^{-4}T + 0.042 \right)$$  \hspace{1cm} (1)$$

Several methods can be used for thermal-hydraulics analysis PBR type. PEBBLE is a computer code used for the thermal-hydraulics calculation of the PR-3000 reactor [12]. PEBBLE uses the finite-different method and FORTRAN language.

Several studies regarding the thermal-hydraulic aspect of PBR have been done [13, 14]. In the present study, the objective is to include fast neutron irradiation on the thermal-hydraulics calculation by modifying the PEBBLE program, called the mPEBBLE. The mPEBBLE has several modifications, as shown in Table 2.

**Table 2.** PEBBLE and mPEBBLE features

| Features            | PEBBLE          | mPEBBLE          |
|---------------------|-----------------|------------------|
| Calculation method  | Finite-Difference| Finite-Difference|
| Language            | FORTRAN         | python           |
| Program Input       | On Script       | Dynamic Input    |
| $k_s$ Fuel          | KFA-Jülich      | KFA-Jülich, German Fuel |
| $k_{se}$ Fuel       | Kunii-Smith     | Kunii-Smith      |
| Core porosity       | Homogenous      | Point Input      |
2. Governing Equations and Calculation Procedures

The fast neutron irradiation influence is related to heat transfer, especially in pebble fuel. The core is filled with pebble fuel that has a gap in between it. The gap is used for the coolant flow path. Therefore, many studies conclude that the PBR core can be assumed as a porous medium. The porous medium that generates heat within it has been studied by Daizo Kunii and J. M. Smith (1960) for the heat transfer mechanism.

Because the pebble generates heat and the void can be found in between pebble fuel, there are heat transfer mechanisms despite the convection that happened in flowing fluid:

a. Pebble (Conduction) – Void (Radiation) – Pebble (Conduction)
b. Pebble (Conduction) – Fluid (Conduction) – Pebble (Conduction)
c. Pebble (Conduction) – Pebble (Conduction)
d. Pebble (Conduction) – Fluid Film (conduction) – Pebble (Conduction)
e. Pebble (Conduction) – Pebble (Radiation)

All of the heat transfer, despite the convection, can be simplified, stated as one quantity. It called effective conductivity thermal of solid (solid means that the pebble fuel because the porous medium, in this case, consists of solid and void which filled with fluid),

\[
\frac{k_{se}^0}{k_f} = \phi(1 + \beta \text{Nu}_{rv}) + \beta(1 - \phi)\left\{ 1 + \frac{k_f}{k_s} + \frac{1}{\phi + \text{Nu}_{rs}} \right\}
\] (2)

Where \(k_{se}^0\) is the static effective thermal conductivity of solid, \(k_f\) is the fluid thermal conductivity, \(\phi\) is the porosity value, \(\beta\) and \(\gamma\) are the geometrical factors; the spherical has \(\beta = 0.95\) and \(\gamma = 2/3\), \(\phi\) is the empirical factor which can be expressed as

\[
\phi = \phi_2 + (\phi_1 - \phi_2)(\phi - 0.260)/0.216
\] (3)

When \(\phi \leq 0.260\), then \(\phi = \phi_2\) and for \(\phi \geq 0.476\) then \(\phi = \phi_1\). For \(10 \leq k_s/k_f \leq 300\), the values of \(\phi_1\) and \(\phi_2\) can be expressed as

\[
\phi_1 = 0.2770 \left( \frac{k_f}{k_s} \right)^{0.2426}
\] (4)

and

\[
\phi_2 = 0.1293 \left( \frac{k_f}{k_s} \right)^{0.3292}
\] (5)

and for \(\text{Nu}_{rv}\) and \(\text{Nu}_{rs}\) are the Nusselt number for heat transfer that occurred within the void and the surface, which expressed as

\[
\text{Nu}_{rv} = h_{rv} d_p / k_f
\] (6)
where

\[ h_{rv} = \frac{4\sigma t_s^3}{1 + \frac{\phi}{2(1-\phi)}} \left( \frac{1 - \epsilon_r}{\epsilon_r} \right), \]  

(7)

and

\[ \text{Nu}_{rs} = \frac{h_{rs}}{\nu} \frac{d_p}{k_f}, \]  

(8)

where

\[ h_{rs} = 4\sigma t_s^3 \left( \frac{\epsilon_r}{2 - \epsilon_r} \right), \]  

(9)

\( \epsilon_r \) is the surface emissivity solid surface, \( \sigma \) is the Stefan-Boltzmann constant, \( d_p \) is the pebble diameter, and \( t_s \) is the average solid surface temperature.

From equation (1), the value of \( k_s \) defined for a specific position with the temperature value \( T \) and fast neutron dose value \( \text{DOSE} \). For simplification, the calculation for \( k_s \) is done in three temperature positions; \( k_s \) at temperature \( t_1, t_2, \) and \( t_s \) (the temperature positions can be seen in Figure 1), the relaxation method is used for finding the \( k_s \) value. Although there are three different \( k_s \) values, it just one \( k_s \) value used as stated in equation (2), so from the three different temperatures acquired from the iteration process, the average temperature is used for the new \( k_s \). The implementation can be seen in Figure 3.
Figure 3. The flowchart for finding the $k_5$ value

The core power density for HTR-10 was obtained from HTR-10 benchmarks performed by the Institute of Nuclear and New Energy Technology (INET) [10]. The interpolation has been used to obtain more power density values at different positions. For the neutron dose distribution, the neutron dose distribution is obtained from the normalization of power density, which is multiplied by the maximum fast-flux neutron in the core ($2.77 \times 10^{13}$ neutron.cm$^{-2}$.s$^{-1}$). For the irradiation time, the average fuel residence time (1080.2 days) is used. The power density and neutron dose distribution can be seen in Figure 4 and Figure 5, respectively.
Figure 4. HTR-10 power density

Figure 5. HTR-10 fast neutron dose distribution
3. Results and Discussion
In this section, the result obtained from a calculation using mPEBBLE is compared with the result from three different programs; PEBBLE, THERMIX, and WIMSTER. All of them have different approaches in the calculation. The temperature comparisons are presented on the axial and/or radial position.

3.1. Result Comparison mPEBBLE – PEBBLE
The temperature profile comparisons between mPEBBLE and PEBBLE are observed in three different radial positions: 0 m, 0.45 m, and 0.9 m that can be seen in Figures 6, 7, and 8, respectively. The observations are only limited to the profile on the maximum fuel matrix temperature, average surface temperature, and coolant bulk temperature.

Although mPEBBLE uses a different approach for the $k_s$ value that taking into account the neutron irradiation compared to the PEBBLE that does not depend on the neutron irradiation, it can be seen from Figure 6, 7, and 8; the mPEBBLE temperature profiles are quite similar to the results from PEBBLE. The maximum difference in maximum fuel matrix temperature between mPEBBLE and PEBBLE is 14.23°C, and for the average surface temperature and coolant bulk temperature, the maximum differences are below 1°C (0.27°C and 0.66°C, respectively).

Figure 6. The temperature profile comparison between mPEBBLE – PEBBLE at $r = 0$ m

Figure 7. The temperature profile comparison between mPEBBLE – PEBBLE at $r = 0.45$ m
The temperature profile comparison between calculation results of mPEBBLE and THERMIX are shown in Figure 9 and 10. The temperature value is the average value of three temperatures position: coolant, pebble surface, and pebble center temperature (temperature within the pebble bed). The temperature comparison for this case is presented on the axial and radial temperature distribution. Figures 9 and 10 show a notable difference between the two results in the near-wall position, with the maximum temperature difference is 63.3°C. The difference might be caused by a slight difference in power density input, inlet coolant mass flow, fast neutron dose, and calculation method. Although mPEBBLE using the power density obtained from INET, which might be utilized by THERMIX, the data end at 0.835 m in radial position; hence the data is extrapolated to obtain power density data in 0.9 m, the different power density near-wall position might contribute to the difference profile of temperature.

Differences between the mPEBBLE and THERMIX calculation result might happen because of the inlet coolant mass flow profile. In mPEBBLE, the inlet coolant mass flow is assumed as homogenous flow. However, in THERMIX, there is no explanation for the coolant mass flow distribution profile. Also, there is a possibility the inlet coolant mass flow is heterogenous because THERMIX calculates not only the core area but also other areas of the reactor.

Another factor that might make the difference in calculation results is the fast neutron dose distribution. The fast neutron dose input in mPEBBLE is not a real value from the measurement, but it just an approach using conversion from power density distribution. So, mPEBBLE and THERMIX might have a different fast neutron dose distribution. The fast neutron irradiation is time-dependent. The difference in observation time between programs might cause the different fast neutron dose distribution. Note that mPEBBLE is merely calculating the active core. THERMIX is the program that considers other reactor areas besides the active core, like a reflector, that can make different results. Other than that, the methods used by THERMIX for the calculation can contribute to this difference.
3.3. Result Comparison mPEBBLE – WIMSTER

The temperature profile comparisons between mPEBBLE and WIMSTER are observed in three different properties: coolant, pebble surface, and pebble center, in three radial positions; 0 m, 0.45 m, and 0.9 m. The calculation comparison can be seen in Figures 11, 12, and 13.
Figure 11. The temperature profile comparison between mPEBBLE – WIMSTER at $r = 0$ m

Figure 12. The temperature profile comparison between mPEBBLE – WIMSTER at $r = 0.45$ m

Figure 13. The temperature profile comparison between mPEBBLE – WIMSTER at $r = 0.9$ m
In general, the apparent difference between mPEBBLE and WIMSTER located at the pebble center with the highest temperature difference is 65.3°C at r = 0.45 m. The value of fuel thermal conductivity in mPEBBLE is influenced by the fast neutron dose. However, in the WIMSTER calculation, it is unclear whether the fuel thermal conductivity is influenced by a fast neutron or is just temperature-dependent or a constant value.

4. Conclusion
The fast neutron irradiation can influence the fuel thermal conductivity, which can induce the temperature distribution, especially fuel temperature. In the comparison between mPEBBLE and PEBBLE, even though the PEBBLE is not considering the fast neutron irradiation, the temperature difference is quite small compared to the mPEBBLE result at this particular calculation. For the comparison between mPEBBLE and THERMIX, although it has several similarities, both taking into account the fast neutron influence and the same power density, the difference is still there. It might happen because of inlet coolant mass flow profile, power density input, fast neutron dose, and calculation method. As for mPEBBLE and WIMSTER, it has a remarkable difference at the pebble center, which reached 65.3°C; it can be caused by the difference in how the fuel thermal conductivity value is determined. The fuel temperature is the important thing in nuclear reactor design which closely related to the safety aspect.

Acknowledgment
The authors express their gratitude to Institut Teknologi Bandung (ITB) for the Research and Innovation ITB Grant and the Ministry of Research Technology and Higher Education for the University’s Excellence Applied Research (PUPT) Grant.

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