Pebble Bed High Temperature Reactor for Electric and Cogeneration Application

T. Setiadipura¹, D. Irwanto², Suwoto¹, Zuhair¹

¹Center for Nuclear Reactor Technology and Safety – BATAN
Puspiptek Complex, OB No. 80, Serpong, Tangerang Selatan 15310, Indonesia
Tel. +62-21-756-0912, Fax. +62-21-756-0913

²Nuclear Physics and Biophysics Research Group, Physics Department
Bandung Institute of Technology (ITB), Jl. Ganesha 10, Bandung 40132, Indonesia
Tel. +62-21-756-0912, Fax. +62-21-756-0913
tsdipura@batan.go.id

Abstract. Specific energy demand of Indonesia with its distributed energy demand required a special energy supply solution. The energy supply solution should be able to fulfil the electric demand of huge and growing population which spread in many different islands also to fulfil the energy demand to process abundances yet distributed natural sources. This paper proposes a pebble bed high temperature reactor as an energy supply in the form electric and/or cogeneration application. A parametric survey of the core geometry of a 150MWt Pebble Bed Reactor called PeLUIt is performed, follow by an equilibrium analysis of the optimized design. An accident analysis of depressurized loss of forced cooling (DLOFC) is performed to show the strong passive safety features of the design. Finally the heat-mass balance of the plant is also presented.

Keywords: pebble bed high temperature reactor, cogeneration application, passive safety.

1. Introduction (copas dr Equilibrium Core Design of RDE)

Specific energy demand of Indonesia with its distributed energy demand required a special energy supply solution. This solution should be able to supply the electric demand of huge and growing population which spread in many different islands and energy demand to process natural resources. A small modular reactor (SMR) concept with the pebble bed high temperature gas-cooled reactor (HTGR) design is considered to be one of the best solutions for this specific energy demand. As an initial step, a 10MWt experimental reactor of this type called Reactor Daya Eksperimental (RDE) was proposed and designed [1]. Site license of RDE in the PUPIPTEK Area at Serpong was already achieved, and currently it is in progress to achieve the design permit from BAPETEN as the national regulatory body. The RDE design development is mainly following the HTR-10 design [2] and also to help a fast progress, without
the need of test of a new fuel design, the exact HTR-10 pebble bed TRISO-based fuel design [3] was also adopted. As the preparation of the follow-up step of RDE, a 150MWt pebble bed reactor, called ‘Pembangkit Listrik dan Uap-panas Industri’ or simply PeLUIt is being designed. This power level is considered to be the appropriate size for the Indonesian electricity and energy demand and appropriate to supply the small unit electricity demand part of Indonesia, as can be seen in Figure 1.

The purpose of this paper is to perform an initial conceptual design of a 150MWt pebble bed reactor. A parametric survey of the core geometry of a 150MWt Pebble Bed Reactor called PeLUIt is performed, followed by an equilibrium analysis of the optimized design. An accident analysis of depressurized loss of forced cooling (DLOFC) is performed to show the strong passive safety features of the design. Heat-mass balance of the plant is also performed.

![Figure 1. Indonesian electricity demand map divided into large unit electricity demand and small unit electricity demand.](image-url)
2. Reactor Model

The configuration of Pebble Bed type HTGR from the general in-vessel component including the active core down to its TRISO coated fuel particle can be seen in Figure 2. A ceramic based material including its fuel guarantee the capability to withstand a high temperature condition. In addition, the high heat conductivity and high heat capacity of the graphite ceramic make a good thermal hydraulic performance of the core. The diameter of the pebble bed type HTGR generally limited to 300cm also to assure the capability of the core in releasing the heat outside passively. The PeLUIt design development is based on the HTR-PM design including its pebble fuel design of 7g/pebble and 8.5% enrichment. The HTR-PM design then downscale to have an optimum design of PeLUIt 150MWt.

| Reactor parameter                                      | Value       |
|--------------------------------------------------------|-------------|
| Thermal power (MW)                                     | 150         |
| Helium inlet/outlet temperature (°C/°C)                | 250/700     |
| Helium pressure (MPa)                                  | 7           |
| Helium mass flowrate at full power (kg/s)              | 96          |

| Core specification                                      | Value       |
|--------------------------------------------------------|-------------|
| Core diameter/height (cm/cm)                           | Optimized   |
| Average core power density (MW/m³)                     | Optimized   |
| Number of pebble in full load                          | Optimized   |
| Packing fraction of pebble                             | 0.61        |
| Target Average discharge burnup (MWd/t)                | 90.000      |
3. Calculation Model

The equilibrium core analysis of the pebble bed type HTGR in this study was performed using PEBBED code [4,5]. It covers the neutronic analysis for eigen-value and depletion analysis of the moving core. In general, computational method to analyse equilibrium core is divided into two methods. Equilibrium analysis is important as it represent the general performance of the core over the entire range of its operation. Physically, the moving core reactor will have an initial loading, running-in phase, and finally reach the equilibrium condition [6]. However, PEBBED code directly calculate the equilibrium core as the BATAN-MPASS code [7]. On the other way, VSOP [8] code, adopt a non-direct approach by following the physical change of the moving core up to its equilibrium. VSOP code use diffusion method for the neutron transport simulation. A Monte Carlo based analysis with non-direct method can be done by MCPBR [9] software.

Basically, to simulate a moving core of pebble bed reactor, the governing equation need to be solved [10]

\[ \frac{\partial N_k}{\partial t} + \frac{\partial N_k}{\partial z} u = \Phi \sum_{i=1}^{m} N_i \sigma_{fi} y_{ik} + \Phi \sum_{s=1}^{q} N_s \sigma_{as} y_{sk} + \sum_{j=1}^{p} N_j \lambda_j \alpha_{jk} - N_k \lambda_k - \Phi N_k \sigma_{ak} \]  

1

where

- \( N_k \) = atomic concentration of isotope k,
- \( u \) = axial ball velocity
- \( \Phi \) = flux of the core region
- \( \sigma_{fi} \) = fission cross section of isotope i
- \( \sigma_{as} \) = absorption cross section of isotope s
- \( \lambda_j \) = decay constant of isotope j
- \( y_{ik} \) = yield of isotope k due to fission of isotope i
- \( y_{sk} \) = probability that neutron absorption of isotope s produces isotope k
- \( \alpha_{jk} \) = probability that decay of isotope j produce isotope k

In solving the above equation, PEBBED converges directly to the equilibrium (or asymptotic) core solution and thus assumes that the first term on the left in Eq. 1 vanishes. By solving that new equation and the diffusion equation iteratively until burnup convergence is achieved which represent the static nuclide distribution in the core. The thermal-fluid and spectrum equations are also solved in in this loop to yield a fully consistent core solution [1,5]. Flowchart of the PEBBED code is shown in Figure 3.
4. Results and Discussions

Parametric survey considering the possible core geometry of the PeLUIt based as a downscale of HTR-PM are given in Table 2.

| Core Radius (m) | Core Height (m) | Power Density 1.9 W/ce | Power Density 2.7 W/ce | Power Density 3 W/ce | Power Density 3.2 W/ce |
|----------------|-----------------|------------------------|------------------------|----------------------|------------------------|
| 1.0            |                 | 24.75                  | 17.68                  | 15.91                | 14.92                  |
| 1.1            |                 | 20.45                  | 14.61                  | 13.15                | 12.33                  |
| 1.2            |                 | 17.19                  | 12.28                  | 11.05                | 10.36                  |
| 1.3            |                 | 14.64                  | 10.46                  | 9.42                 | 8.83                   |
| 1.4            |                 | 12.63                  | 9.02                   | 8.12                 | 7.61                   |
| 1.5            |                 | 11.00                  | 7.86                   | 7.07                 | 6.63                   |

Results of the parametric survey are shown in Figure 4. As can be seen from Figure 4, discharge burnup is increasing for bigger core radius, while the maximum power generated per fuel is decreasing. The optimum condition is the design with power density 3.2 W/cm3, active core radius 1.5m, and core height 6.63m.

**Figure 3.** Computational scheme for equilibrium cycle analysis of pebble bed reactor in the PEBBED code.[1]
Figure 4. Results of parametric survey for maximum power fuel and discharge burnup.

Results of the pass recirculation parametric survey is shown in Figure 5. From the axial power density profile, it can be seen that increasing the pass will decrease the power density peak up to certain number of pass. The results in Figure 5 shows that the 15-pass is the optimum pass for the design.

Figure 5. Individual control rod worth (%Δk/k).
Variation of U-235 enrichment for the optimum discharge burnup is shown in Figure 7. The maximum discharge burnup include in this study is 150 MWd/Kg, based on this limit, the optimum discharge burnup of 147.81 MWd/Kg can be achieved by enrichment 13.5%. However, this discharge burnup value might be too high, several option with lower discharged burnup is possible as given in Figure 7. The enrichment value of 8.5% as in the HTR-PM is used in further optimized equilibrium design.

![Figure 6. Discharge burnup parametric survey.](image)

Result of the conceptual design based on the PEBBED calculation are as following. The parameter of the optimized equilibrium core is given in Table 3.

| Reactor Core Parameter                                           | Nominal   | Units   |
|-----------------------------------------------------------------|-----------|---------|
| Diameter                                                        | 300       | cm      |
| Height                                                          | 650       | cm      |
| Void above the core                                             | 30        | cm      |
| Top reflector thickness                                         | 150       | cm      |
| Side reflector thickness                                        | 115       | cm      |
| Bottom reflector thickness                                      | 150       | cm      |
| Core residence time                                             | 1043      | EFPD    |
| Fuel element in active core                                     | 247.813   | FE      |
| Fuel element discharged                                         | 3565      | FE/day  |
| Fresh FE per day                                                | ~238      | FE/day  |
| Average Discharge BU                                            | 87.69     | MWd/Kg-HM|
| Avg. power density                                              | 3.26      | W/cm³   |
| Max. power density                                              | 5.12      | W/cm³   |
| Max. power per fuel ball                                         | 1.447     | kW/FE   |
| Primary coolant flow rate                                        | 57        | Kg/s    |
| Reactor operating pressure                                      | 7         | MPa     |
| Core coolant inlet temperature                                  | 250       | °C      |
| Core coolant outlet temperature                                 | 750       | °C      |
| Avg. Fuel Temp under normal operation                           | 540.8     | °C      |
| Max. Fuel Temp. under normal operation                          | 903.7     | °C      |
Among the acceptance criteria of the design is that the maximum fuel temperature after hypothetical DLOFC accident is below 1620°C. The fuel temperature transient after DLOFC as calculated by PEBBEN is shown in Figure 7 which shows that current design have an acceptable peak fuel temperature even after DLOFC accident.

Figure 7. Fuel temperature transient after DLOFC accident.

Steam Turbine for current PBR 150MWt is selected based on the target power rate of 150MWt or about 65MWe. For the cogeneration application, a live steam from steam generator is targeted to have a temperature of 540°C and pressure 140bar. This steam parameter used as the design parameter of the steam turbine which currently a Siemens SST400 steam turbine was chosen. Mass balance analysis of the coupled primary and secondary system of current PBR 150MWt was performed using ChemCAD software. Input to the ChemCAD is the livesteam parameter for the steam turbine (540°C and 140bar) also the helium parameter in the primary system. Data for the power conversion system is given in Table 4 and schematic results of the general mass balance analysis is given in Figure 10.

Table 4. Power Conversion System

| Power Conversion System                      | Nominal       | Unit   |
|---------------------------------------------|---------------|--------|
| Working medium                              | (superheated) Steam |        |
| Flow rate at nominal condition              | 59.5          | Kg/s   |
| Pressure (SG outlet)                         | 14            | MPa    |
| Temperature (SG outlet)                      | 540           | °C     |
| Feed water Temperature (input to SG)        | 200           | °C     |
| Feed water Pressure (input to SG)           | ~14.9         | MPa    |
| Feed water flowrate                         | 59.5          | Kg/s   |
5. Conclusion

Initial conceptual design of a 150MWt pebble bed reactor called PeLUIt is already performed. The design is based on HTR-PM, then downscaling of the geometry was performed. Currently, the optimum design geometry is with radius 1.5m, and height 6.50m, the power density 3.26 W/cm$^3$. Number of fuel recirculation pass is 15 passes with a discharge burnup of 87.69 MWd/Kg. With an outlet He from the core of 750 °C and steam output from the steam generator of ~540 °C, PeLUIt is a good option for electrical and cogeneration supply. A sound passive safety performance also shown as the fuel peak temperature of PeLUIt is still below the limit of 1620°C.

Acknowledgment

We would like to express our sincere gratitude to Dr. Geni Rina Sunaryo, M.Sc. for giving us support and motivation in completing this research. Moral encouragements from our colleagues in the division of reactor physics and technology are highly appreciated. This research work was financially supported by the Ministry of Research, Technology, and Higher Education, Republic of Indonesia through INSINAS-Flagship 2018 grant program.

References

[1] Topan Setiadipura, Syaiful Bakhri, Geni R. Sunaryo, Djarot S. Wisnusubroto, 2018. Cooling Passive Safety Features of Reaktor Daya Eksperimental, AIP Conference Proceedings 1984 020034.
[2] Wu Z, Lin D, Zhong D, 2002, The design features of the HTR-10, Nucl. Eng. Des. 218, 25-32.
[3] Tang C, Tang Y, Zhu J, Zou Y, Li J, Ni X, 2002, Design and manufacture of the fuel element for the 10 MW high temperature gas-cooled reactor, Nucl. Eng. Des. 218, 91-102.
[4] Terry W.K., Gougar H.D., Ougouag A.M, 2002, Direct deterministic method for neutronics analysis and computation of asymptotic burnup distribution in a recirculating pebble-bed reactor, Ann. Nucl. Energy 29, 1345-1364
[5] Gougar H.D., Ougouag A.M., Terry W.K., 2010, Automated design and optimization of pebble bed reactor cores, Nucl. Sci. Eng. 165, 245-269
[6] Gougar H.D., Reitsma F, Joubert W., 2009, A Comparison of Pebble Mixing and Depletion Algorithms Used in Pebble-Bed Reactor Equilibrium Cycle Simulation, Idaho National Laboratory
[7] Liem P.H., BATAN-MPASS: A general fuel management code for pebble bed high-temperature reactors, Ann. Nucl. Energy 21(5), 281-290
[8] Rutten H.J., Haas K.A., Brockman H., Scherer W, 2005, V.S.O.P. (99/05) Computer Code System for Reactor Physics and Fuel Simulation, Forschungszentrum Julich GmbH.
[9] Setiadiipura T, Obara T, 2014, Development of Monte Carlo-based pebble bed reactor fuel management code, Ann. Nucl. Energy 71, 313-321
[10] Massimo L., 1976, The Physics of High-Temperature Reactors, Pergamon Press, Oxford