Static Structural Analysis of Ceramic Internals Experimental Power Reactor (RDE)

Farisy Yogatama Sulistyo\textsuperscript{a}, Roziq Himawan\textsuperscript{a}, Ari Nugroho\textsuperscript{b}, Syaiful Bakhri\textsuperscript{a}

\textsuperscript{a} Centre for Nuclear Reactor Technology and Safety - National Nuclear Energy Agency of Indonesia, Building No. 80 PUSPIPTEK Area, Serpong, South Tangerang, 15310, Indonesia

\textsuperscript{b} Centre for Nuclear Energy System - National Nuclear Energy Agency of Indonesia, Building No. 3C, Kuningan Barat, South Jakarta, 12710, Indonesia

e-mail: farisy-yogatama@batan.go.id

Abstract. In 2018, BATAN propose detail engineering design of Experimental Power Reactor (RDE). An important issue of RDE is Ceramic Internals or Reactor Pressure Vessel (RPV). Ceramic Internals is pathway of helium gas, control rod, absorber ball and also pebble fuel. Its structural component must sustain by the load of 27000 pebbles fuel. A preliminary static structural analysis of bottom reflector, a part of Ceramic Internals, has been studied before, the result was satisfying and could be scale-up to analyse the Ceramic Internals with same methods. Design and static structural simulation are performed by using Solidworks software to study the factor of safety distribution in Ceramic Internals. The design was made in 16 layers with small dowel as the component to endure the movement. Factor of safety was obtained in static simulation using single simplified parts. The preliminary result show that the minimum factor of safety can handle the load of Ceramic Internals structural. This result show that the model is suitable for RDE design.

Keywords: RDE, HTR-10, Ceramic Internals, static, factor of safety

1. Introduction

Experimental Power Reactor (RDE) is a modular pebble-bed type reactor and similar to High Temperature Gas-Cooled Test Reactor (HTR-10) that has been built in China. RDE is designed for cogeneration of 10 MW thermal, which is equal to 3MW electric. RDE nuclear island system consist of main components and auxiliary system. Main components consist of pressure vessel Unit, main helium circulator, steam generator, hot gas duct, and reactor internals. Auxiliary system consist of fuel handling system, Helium purification system, Helium auxiliary system, spent fuel storage and transport [1]. In 2018, BATAN propose detail engineering design of RDE. An important issue of detail engineering design is reactor internal. The reactor internal failure would impair the barrier function [2].

Reactor internal includes reactor core, Ceramic Internals, and metallic internals. The Ceramic Internals is pathway of Helium gases, control rod protection system, absorber ball protection system, and also pebble balls. The Ceramic internal include the graphite reflector and the carbon brick. The graphite reflector is used as the neutron reflector and the carbon brick is used as the thermal insulation.

The Ceramic Internals should able to endure and ensure the integrity of its component for any conditions happened. The Ceramic Internals experience load due to self-weight, weight of the pebbles,
pressure differences, steady-state and transient thermal load, seismic load, load due to radiation and oxidation [3]. The arrangement of the components should maintain a stable core geometry and ensure continued core cooling by circulating helium in the coolant circuit. Fuel element flow design has to be maintained to avoid the stagnation of fuel elements. The Ceramic Internals configuration is shown in figure 1. The graphite reflector includes top, side and bottom reflector. The boronated carbon brick are enclosed by the graphite reflector. The Ceramic Internals are designed as layers structures. Each layer of graphite reflector and boronated carbon brick are divided into 20 segmental brick and the lower side of bottom reflector have only 10 segmental brick. In the bottom reflector, there is a hot gas chamber which is a helium gases mixing and connected to hot gas duct. The total height of Ceramic Internals is about 6100 mm and 3800 mm in diameter [4].

![Figure 1. Section View of Ceramic Internals](image)

Design of Ceramic Internals has been reported in IAEA technical document [5]. The model should be simulated to ensure the structure integrity of each parts. This study focusing in 3D design of the ceramic internals and structural simulation to determine the safety factor and stress distribution in parts. The design and simulation of ceramics internal using Solidworks sofware.

2. Methodology

2.1. 3D Design
The design of HTR-10 China become reference for the RDE design. The Ceramic Internals structure depend on the structural design integrity and reliability. The 3D design of Ceramic Internals show in figure 2. The structural features of Ceramic Internals are divided into top reflector, side reflector, and bottom reflector. The reflector consist of graphite brick and carbon brick that have different boron contain and function.
Figure 2. Ceramic Internals isometric view

2.1.1. Graphite and carbon brick

The graphite brick in the side reflector has 775 mm in length, 300 mm in thickness and 283 mm at the small side end. There are three types form of the channel that locate in 96 mm from the core, they are control rod guide channel, absorber ball channel and the experimental channel. The graphite sleeve are inserted into the holes to ensure the guide function and also prevent the helium gas leakage. The Helium gas channel locate in 141 mm from the core.

Carbon brick has a function as thermal insulator and neutron absorbent. Carbon brick has 22 mm in length and 300 mm in thickness. Carbon brick locate in the outside of the graphite brick and the swallow key endure the movement of carbon brick due to graphite brick. The brick layers are connected vertically with dowels. The key are designed as radial connected to prevent brick movement. The graphite brick and carbon brick show in figure 3 and figure 4 [4] [5].

Figure 3. Graphite brick model
Figure 4. Carbon brick model

2.1.2. Bottom Reflector

Bottom reflector is a cone-shaped graphite brick stack that have function as hot helium gas mixing chamber and a pathway out of helium gas to hot gas duct. The load of pebbles fuel in the reactor give a vertical and radial force to the bottom reflector that should be maintain by the structural integrity of
bottom reflector. The bottom reflector was made in 6 layers and each layer have 10 segmental bricks. The cone-shaped graphite in the first layer have 370 mm thickness and 650 mm length. 640 holes in circular pattern with 16 mm diameter are inserted in the middle. The second layer, a brick with 133 mm thickness and 650 mm in length, have a function as a pathway the hot helium gas to go the hot gas plenum. This layer have holes pattern same as the first layer. Below the second layer, there is graphite brick with 280 mm in thickness and it has a plenum with 150mm in height and 440 mm length. The plenum has 3 holes that distribute the hot gas to hot gas chamber downward. Before the ht gas duct, there is a layer with 200 mm thickness and continue to distribute the hot gas to gas chamber downward. The fifth and the sixth layer are hot gas chamber with 600 mm in thickness.

The hot gas chamber contribute in thermal mixing performance. The hot gas chamber design should be maintain the structural integrity and also thermal mixing degree of hot helium gas. Figure 5 show the hot gas chamber design and position in bottom reflector [4] [5].

![Figure 5. Bottom Reflector Models](image)

2.2. **Death load simulation**

Ceramic Internals was simulated using Solidworks Static Structural feature. The properties of unirradiated graphite show in Table 1. The static structural simulation depend on components material properties. In this case, a graphite brick material considered as a brittle material. Brittle materials have elastic deformation without plastic flow. To study about brittle material, one of most theory is used is Mohr-Coloumb theory. This theory give conventional method to determine the failure analysis of the material [6] [7]. The simulation result would describe the stress distribution, factor of safety, strain distribution, etc. The factor of safety shows material’s capability to sustain the load given. If the value less than the standard, it mean the load given to the structure reach the material maximum strength. It will cause failure in the structure integrity.

| Table 1. Properties of Graphite models, IG11 type [4] |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Mass Density    | Modulus Elasticity | Tensile Strength | Compressive Strength | Poisson ratio | Friction coefficient (µ) |
| (g/cm³)         | (GPa)            | (MPa)           | (MPa)             | -              | -                |
| 1.76            | 9.04             | 25.40           | 76.22             | 0.126          | 0.369            |

The Mohr-Coulomb stress criterion is used for brittle material that have tensile and compressive properties. The compressive strength is bigger than the tensile strength. This stress criterion is used to determine failure load by combine the Coloumb Friction and Mohr’s Cicle. The Coloumb Friction is
used to determine the stress applied in term of shear and normal stress, and the Mohr’s Cicle is used to determine the principal stress, either the first ($\sigma_1$), second ($\sigma_2$), and third ($\sigma_3$) principal. The third principal ($\sigma_3$) value is negative mean that the stress is dominated by the compressive stress. The Mohr-Coloumb Stress Criterion is following the case in Table 2.

**Table 2. Mohr-Coloumb stress criterion**

| State of Principal stresses                                                                 | Failure Criterion                                                                 | FOS                                                                 |
|--------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------|----------------------------------------------------------------------|
| Both minimum and maximum stresses is dominated by tension                                    | If $\sigma_1 > \sigma_{\text{Tensile Strength}}$, the model would be fail         | $\frac{\sigma_{\text{Tensile Strength}}}{\sigma_1}$                  |
| Both minimum and maximum stresses is dominated by compression                              | If $|\sigma_1| > \sigma_{\text{Compressive Strength}}$, the model would be fail     | $\frac{\sigma_{\text{Compressive Strength}}}{\sigma_1}$              |
| The minimum stresses is dominated by tension and the maximum stresses is dominated by compression | If $\frac{\sigma_1}{\sigma_{\text{Tensile Strength}}} + \frac{|\sigma_3|}{\sigma_{\text{Compressive Strength}}} > 1$, the model would be fail | $\frac{1}{\frac{\sigma_{\text{Tensile Strength}}}{\sigma_1} + \frac{|\sigma_3|}{\sigma_{\text{Compressive Strength}}}}$ |
| The minimum stresses is dominated by compression and the maximum stresses is dominated by tension | If $\frac{|\sigma_1|}{\sigma_{\text{Compressive Limit}}} + \frac{\sigma_3}{\sigma_{\text{Tensile Limit}}} > 1$, the model would be fail | $\frac{1}{\frac{|\sigma_1|}{\sigma_{\text{Compressive Limit}}} + \frac{\sigma_3}{\sigma_{\text{Tensile Limit}}}}$ |

2.2.1. Simplified models

The Ceramic Internals consists of 20 segmental brick that have same size. A model simplification by elimination of parts that have same characterization with others, should be useful. Through this process, the number of parts will be decreased [8]. The simulation had been divided and simplified into 2 segmental bricks. The chosen segmental brick is the segmental that has helium hot gas exit tunnel to the hot gas duct. In the helium gas exit tunnel, the structural is assumed to have high stress concentration that probably make the structural fail. The simplified model is show in figure 6.

2.2.2. Fixture modelling

Fixture point had been done to control the parameter as close as possible to the original model. There are two types fixture point that have been done. The first fixture is on the left side and right side as cyclic symmetry fixture. In this fixture, the simplified model are connected around with the fixture so it would...
restraint the simplified model to move freely in cylindrical movement. The second fixture is on the bottom side as planar to minus y-axis. This fixture will contribute as ground floor for the simplified models. The fixture point show in figure 7.

![Figure 7. Fixture parameter in model](image)

2.2.3. **Meshing**

A solid mesh type have been made. The mesh using Curvature-based mesh with 20-100 mm element size. Different parameter are given to the bottom layer of the Ceramic Internals. The bottom layer using meshing control with 30 mm in element size. Meshing control is used to make fine meshing to some parts in the model. Figure 8 show the meshing model and the meshing control. The aspect ratio in the meshing model that is less than 3 is 92.2%. It means the mesh parameter is well made. The quality of meshing will be good if the aspect ratio less than 3 is more than 50%. Table 3 show meshing parameter of the simplified models.
Figure 8. Meshed model

Table 3. The meshing criteria

| Mesh Criteria                        | Value  |
|-------------------------------------|--------|
| No. of Nodes                        | 716937 |
| No. of Elements                     | 463621 |
| Meshing Aspect Ratio < 3 (%)        | 92.2   |
| Meshing with Aspect Ratio > 10 (%)  | 0.0934 |

3. Result and discussion

The load by the mass of layered graphite is about 73950 N. First principal stress distribution and third principal stress distribution is shown in figure 9 and figure 10. First principal stress is used to determine the distribution of tensile stress that is normal to the plane in which shear value is 0. This principal help to understand the maximum tensile induced in the parts due to the loading given. The stress distribution are almost the same along the plane. The significant difference of stress distribution happen on the dowel side. It may be caused by the dowel function. The maximum tensile stress with first principal locate in the dowel bottom plane. Different from first principal, the third principal stress help to understand the maximum compressive stress induced in the parts. The maximum compressive stress locate in the exit tunnel hot gas. It may be caused by the small area section in the tunnel to endure the upper load.
The lowest factor of safety value of Ceramic Internals is 93 as shown in figure 11. It locate in the bottom plane. These results indicate the stress is still below the maximum compressive strength, maximum tensile strength and also below the combination of compressive and tensile strength based on Mohr-Coloumb Criterion. From these results also we can assume that the model is able to maintain the structure integrity without causing significant failure. As shown on figure 11 (b), the side edge of the dowel have factor of safety minimum value, it means the dowel have local stress concentration. This local stress concentration is mostly due to endure the graphite movement. The stress concentration also occur in the dowel area that show on figure 11 (b). The stress concentration in the dowel occurs on the outside the dowel which indicates there is outward movement of graphite layer away from the reactor core. To prevent the failure of the dowel and the structure integrity of ceramic internals, adding a stopper pin in the side of graphite or add more dowel should be an important issues.

Figure 9. Stress distribution in P3 principal (a); Tunnel view P1 principal (b)

Figure 10. Stress distribution in P1 principal (a); Bottom view P3 principal (b)
4. Conclusion

The structure integrity assessment of ceramic internal have been performed using static structural in Solidworks. The minimum factor of safety of the models is 93. These result indicate the structural integrity of the model is safe and able to maintain the stress. The bottom side of the ceramic internals receives more load and giving an increasing in stress concentration. The stress concentration have maximum value at the dowel. These design of Ceramic Internals can be applied to RDE ceramic internals due the result of structure integrity and stability. The next research about ceramics internal must be perform to develop the simulation with another parameters such as pebbles load, temperature effect and radiation effect. The arrangement of each graphite layer also must be configured and detailed to obtain the full design of RDE.

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