Analysis of RPV strength in current RDE based on temperature

E. Saragi, S. Sudadiyo, T. Taryo
Centre for Nuclear Reactor Technology and Safety, National Nuclear Energy Agency of Indonesia (BATAN), Puspiptek Area, Building 80, Serpong,15310, Indonesia.

Email: frida@batan.go.id

Abstract. Analysis of the strength of the reactor pressure vessel (RPV) was conducted based on the mechanical strength of the pressure vessel of the Experimental Power Reactor (RDE) and the analysis refers to the design data from the HTR-10 high temperature reactor tank. The RPV design should be capable of ensuring the safety of RDE operation where the reactor pressure vessel will be located. Helium gas is used as a cooling medium for RDE core. The flow of helium gas in a pressure vessel was flowing through the gap between the spheres up to 700 °C and cold helium gas (250 °C) flowing from the outlet nozzle to the nozzle input which causes material degradation due to temperature differences. Analysis of material strength is based on the calculation of stress from the temperature load. Calculation of distribution temperature uses self-developed code based on finite element method and the specification of pressure vessel material was used ASME SA516-70. The results of the calculations are presented in the form of temperature distributions in the form of contours and stress distributions in tabular form. The evaluation of the strength of the material with the temperature difference occurring in the pressure vessel shows stress due to temperature still below the ASME SA516-70 tensile strength limit. However, the stress allowed under ASME Boiler and Pressure is 1/3 of the ASME SA516-70 tensile strength value. The stress calculation that meets the ASME SA516-70 criteria is 192 MPa at an inlet temperature close to 400 °C and an output temperature of 350 °C, respectively. This result can be used as a reference for the basic design of RDE pressure vessel.

1. Introduction
Experiment Power Reactor (RDE) is a small reactor, with thermal power of 10 MW, would be developed in Indonesia. The RDE reactor core is cooled by helium gas, moderated by graphite, and uses Uranium spherical fuel elements (TRISO) and the analysis refer to data of HTR-10 [1–5]. Maria Elizabeth Scari.et al had done transient thermal of a HTR simulation using the RELAP5-3D code with a point kinetics model. The results presented similar thermal behavior in comparison with the data from the IAEA reference document[6]. The pressure vessel is an important part of the RDE that prevents the helium from leaking from the reactor core. Especially the pressure vessel has a relative large diameter and small wall thickness [7]. J. Li et al has done three-dimensional finite element analysis of dissimilar metal welded joints connected the safe end to pipe nozzle of the reactor pressure vessel using software ABACUS [8]. Chaudhry. V et al has discussed the detailed thermo-mechanical stress analysis for reactor pressure vessel during various operating conditions of the reactor. The results have been used for structural integrity assessment of reactor pressure vessel [8]. Xiaohong Jia
et al, has done the 2D-axisymmetric finite element (FE) model of RPV sealing system and including the C-rings with the consideration of non linear material and contact problem and multiple coupled effects. With this model, RPV deformation is analyzed and the result shows a good agreement with the data from factory hydraulic test[9]. The hot gas pressure vessel is a coaxial gas line that serves to drain between the reactor pressure vessel and the steam generator [8-9]. Hot helium gas (700 °C) flows from the reactor to the steam generator in a pipelines and cold helium gas (250 °C) flows from the gas outlet nozzle of the steam generator to the input nozzle on the reactor vessel in the annulus between hot gas vessels and gas pipeline. This hot gas pressure vessel consists of seamless that is welded to the reactor pressure vessel and pressure vessel steam generator.

The mechanical design of the hot gas pressure vessel needs to be further investigated for determine the strength of the material due to the heat load experienced by the pressure vessel under the operating thermodynamic conditions. In RDE operating of 30 bar and the temperature around 700 °C, the hot gas vessel section should be designed able to withstand stress due to the resulting thermal and mechanical load. Pressure vessel (tank) design requires calculation involving a combination of thermal and mechanical loads with the propagation of stress in all directions, so it is difficult to do conventionally. The problem can be solved with finite element method (FEM) which can then be equipped with computer program. The required input data is an element type, load and geometry. The calculation is done to solve the matrix equation.

In this paper, the design and evaluation of high temperature reactor tank strength calculation has been performed using a self-developed code based on the finite element method [10-14]. The geometry, operating conditions, and parameter data used refer to SA516 Grade 70 carbon steel [7] as the design data of HTR-10 high temperature reactor tank. Calculation is done to get the result of temperature and stress distribution. The strength analysis is performed by calculating the maximum stress caused by the temperature load. The design results are compared with result of calculation according to the ASME design.

2. Theory
Stress due to temperature effect
Due to thermal loads, material strength will decrease and result in dimensional changes. The magnitude of the stress occurs as shown in the equation below [10], [13].

$$\sigma = D\varepsilon$$

where; \(\sigma\) is thermal stress, MPa
\(\varepsilon\) is strain
\(\varepsilon = (1 + \mu)\alpha\Delta T\)
\(\alpha\) is the coefficient of thermal expansion
\(\mu\) is Poisson ‘ratio
\(D\) is material property matrix
\(\Delta T\) is Temperature, °C

3. Working Procedure
The evaluation of the strength of the high temperature reactor pressure vessel due to the heat load experienced by the vessel under the operating process thermodynamic conditions needs to be further investigated. Evaluation is done by calculating the stress distribution due to thermal load that occurs in the tank with self-developed program based on finite element method. Then the calculation result is compared by the material strength data. The operating conditions are based on the description data of the HTR-10 reactor pressure vessel.

3.1. Description of Reactor Pressure Vessel
The design and evaluation of the strength of the pressure vessel is based on of geometric shape and operation parameters reactor vessel HTR-10 as shown in Figure 1 [7]. The nuclear fuel, moderator and
Coolant used in HTR-10 are UO$_2$, graphite and helium gas, respectively. Helium gas has good thermal stability and chemical stability; it can be compatible with the graphite material in the core and the metallic material in the primary system at high temperature condition. The average helium temperature at reactor inlet is 250 °C. After flows from the top of the pebble bed to the bottom, the helium is heated up to 700 °C [8-12]. To design and evaluate the strength of the tank is evaluated the stress and strain on the exterior temperature of the tank. Tank outer temperature design for 350 °C [7-8] and inner temperature is 400 °C, 500 °C and 700 °C and pressure vessel material using SA516-70[7]. External temperature conditions can be designed by calculating the size of the tank cooling system determined by the concrete wall cooling system.

![Figure 1. Schematic of the RDE-based nuclear steam supply system [15]](figure)

Calculations with self-developed programs based on finite elements [13-14]. The calculation steps are as follows:

- **Idealization problem.** Type of analysis performed steady state. The material is SA 516-70 with the following material data as Young modulus of 2E11 N/m$^2$, Poisson ratio is 0.3 and Thermal expansion coefficient of 12.0 µm/m$^2$-C, thermal conductivity of materials of 52 W/m K.
- **Geometry.** 2-dimensional geometry design by simplifying the vessel geometry by taking only a quarter of the portion, since the tank is symmetrical without including the nozzle and does not count the connection to the vessel. The inside diameter is 4.1 m and vessel thickness of 0.08 m [7].
- **Boundary condition.** The boundary conditions are taken as the load in the form of interior wall temperature and the outer side temperature of the tank wall with steady state conditions.

4. **Results and Discussions**

The HTR-10 vessel design shows inner diameter wall thickness are 4.2 m and 0.08 m, respectively. In addition, while the design temperature is 350 °C, the shell material uses SA516-70. Modeling was developed by simplifying the geometry of the pressure vessel by taking the 1/4 part of vessel cylinder without taking into account the nozzles and the connections. An axisymmetric finite element model with 300 elements and 176 nodes was used for these structural and thermal as shown in Figure 2.
This analysis considers helium gas flowing through the gap between the sphere and the temperature reaching 700 °C and cold helium gas (250 °C) flowing from the outlet nozzle to the input nozzle in the reactor vessel which causes the heat difference to flow into the vessel wall. Due to the difference of temperature in this tank material at each point (node), thermal stress takes place. Temperature distributions due to the heat propagation of the tank inner wall at the temperature of 400 °C, 500 °C and 700 °C are respectively shown in Figures 3, 4 and 5. From the temperature distribution results, the temperature decreases gradually at the radial direction.

**Figure 3.a.** Contour temperature distribution with inner wall temperature of 400 °C using self-developed program based on finite element method.
Figure 3.b. Graphic distribution temperature with inner wall temperature of 400 °C vs vessel thickness

Figure 4. Graphic distribution temperature with inner wall temperature of 500 °C vs vessel thickness

Figure 5. Graphic distribution temperature with inner wall temperature of 700 °C vs vessel thickness

The temperature distribution results are the used as input data for the determination of stress distribution. The stress calculation caused by the temperature load. Stress that occurs in the vessel wall decreases the strength of the material. By using Equation (1), the stress distribution results are respectively shown in Tables 1, 2 and 3. From all of those Tables show as the temperature increase, stress decreases and increased stress causes a decrease in material strength. Based on the results of stress known limit of material strength able to withstand load due to thermal load. The tensile strength of ASME SA516-70 is 620 MPa. The permissible stress of the material is noted to be 1/3 of the tensile strength of the material [16]. From the analytical calculations and based on temperature formulation due to temperature, while the allowable stress is about 208 MPa at the inner wall temperature of about 433 °C and the outer surface wall temperature of 350 °C [8]. Therefore, the cooling of the vessel wall should be stable by maintaining coolant flow both inside the vessel and in the outer wall of the vessel.
Table 1. Stress Distribution due to temperature load at Tinlet of 250 °C

| \( \Delta T \) (°C) | Strain (\( \varepsilon \)) | Stress (MPa) |
|---------------------|--------------------------|--------------|
| 350                 | 5.46E-03                 | 1.68E+02     |
| 338.9               | 5.29E-03                 | 1.63E+02     |
| 327.8               | 5.11E-03                 | 1.57E+02     |
| 316.7               | 4.94E-03                 | 1.52E+02     |
| 305.6               | 4.77E-03                 | 1.47E+02     |
| 294.4               | 4.59E-03                 | 1.41E+02     |
| 283.3               | 4.42E-03                 | 1.36E+02     |
| 272.2               | 4.25E-03                 | 1.31E+02     |
| 261.1               | 4.07E-03                 | 1.25E+02     |
| 250                 | 3.90E-03                 | 1.20E+02     |

Table 2. Stress Distribution due to temperature load at Tinlet of 500 °C

| \( \Delta T \) (°C) | Strain (\( \varepsilon \)) | Stress (MPa) |
|---------------------|--------------------------|--------------|
| 500                 | 7.80E-03                 | 2.40E+02     |
| 483.3               | 7.54E-03                 | 2.32E+02     |
| 466.7               | 7.28E-03                 | 2.24E+02     |
| 450                 | 7.02E-03                 | 2.16E+02     |
| 433.3               | 6.76E-03                 | 2.08E+02     |
| 416.7               | 6.50E-03                 | 2.00E+02     |
| 400                 | 6.24E-03                 | 1.92E+02     |
| 383.3               | 5.98E-03                 | 1.84E+02     |
| 366.7               | 5.72E-03                 | 1.76E+02     |
| 350                 | 5.46E-03                 | 1.68E+02     |

Table 3. Stress Distribution due to temperature load at Tinlet of 700 °C

| \( \Delta T \) (°C) | Strain (\( \varepsilon \)) | Stress (MPa) |
|---------------------|--------------------------|--------------|
| 700                 | 1.09E-02                 | 3.36E+02     |
| 672.2               | 1.05E-02                 | 3.23E+02     |
| 644.4               | 1.01E-02                 | 3.09E+02     |
| 616.7               | 9.62E-03                 | 2.96E+02     |
| 588.9               | 9.19E-03                 | 2.83E+02     |
| 561.1               | 8.75E-03                 | 2.69E+02     |
| 533.3               | 8.32E-03                 | 2.56E+02     |
| 505.6               | 7.89E-03                 | 2.43E+02     |
| 477.8               | 7.45E-03                 | 2.29E+02     |
| 450                 | 7.02E-03                 | 2.16E+02     |
5. Conclusion
From all calculations carried out, it is concluded that the temperature difference between the inner wall of the ship and the outer walls of the vessel increased stress. The increased temperature causes stress and hence decreasing material strength. The calculation results show that the thermal stress at inlet wall temperature is 700 °C and the outer wall temperature is 450 °C, which are both still below the tensile strength value of ASME SA517-70 material. The permissible stress of the material is 1/3 of the tensile strength of the material. However, as the ASME SA517-70 permissible criterion is 192 MPa, the inlet temperature close to 400 °C and the outer wall temperature is 350 °C. Indeed, the result can be applied as a reference for the basic design of RDE pressure vessel.

Acknowledgments
The research has been funded by BATAN DIPA 2018 and partly by INSINAS Flagship Kemenristekdikti FY 2018. Thanks to Dr. Syaiful Bakhri who has provided managerial assistance related to this work.

6. References
[1] Gou F, Chen F and Dong Y 2017 Energy Procedia 127 pp 247–254
[2] Zhang Zuoji, Dong Y, Li F, Zhang Z, Wang H and Huang X 2016 An Engineering and Technological Innovation 2 no 1 pp 112–118
[3] Fang C, Bao X, Yang C, Yang Y, and Cao J 2016 Nucl. Eng. Des 306 pp 192–197
[4] Sabharwall P, Bragg-sitton S M, and Stoots C 2013 Energy Convers. Manag 74 pp 574–581
[5] Inaba Y, Nishihara T 2017 Ann. Nucl. Energy 101 pp 383–389
[6] Scari M E, Costa A L, Pereira C, Velasquez C E and Fortini Veloso M A 2016 J. Hydrogen Energy 41 no 17 pp 7192–7196
[7] Li J, Cui P, Zhang G D, Xue F and Zhou C Y 2015 Procedia Engineering 130 pp 1535–1543
[8] Chaudhry V, Kumar A, Ingole S M, Balasubramanian A K, and Muktibodh U C 2014 Procedia Eng 86 pp 809–817
[9] Jia X, Chen H, Li X, Wang Y and Wang Y 2014 Nucl. Eng. Des 278 pp 64–70
[10] Giunta G, De Petro G, Nasser H, Belouettar S, Carrera E and Petrolo M 2016 Composite Part B: Engineering 95 no 17 pp 7192–7196
[11] Yan W 2014 Prog. Nucl. Energy 77 pp 344–351
[12] Zhao H, Chen X, Zheng Y, Ma T, and Dong Y 2018 Ann. Nucl. Energy 114 pp 551–560
[13] Saragi E and Setiadji M 2013 AIP Conference Proceedings 1554 p 166
[14] Saragi E 2012 AIP Conference Proceedings 1448 p 270
[15] PTKRN 2016 Dokumen Program Manajemen Penuaan Reaktor Daya Eksperimental (RDE) BATAN.
[16] ASME 2013 Boiler and Pressure Vessel Code, New York