Safety assessment of pressure vessel components for Reaktor Daya Eksperimental

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Abstract. The 10 MW Indonesia’s Reaktor Daya Eksperimental (RDE) which is to be constructed in Serpong Nuclear Zone, Puspiptek and was firstly developed in 2014 is expected to be operational in 2022/2023. The RDE is expected to be a landmark to Indonesia for a nuclear power technology provider in the imminent futurity. Till the end of 2018, the RDE is focused on the basic design including its reactor pressure vessel (RPV). This research paper presents mechanical stresses assessment on basic design of RPV structure components for RDE in ensuring the safety design targets of RDE which are no dangerous radioactive release to the workers, populations, and environments even in the worst accident. Results are presented from the structural stresses assessment under following conditions such as thermal loading, operating pressure, and mechanical loads. The geometric models and dimensions of pressure vessel components within the basic design calculations had been performed by using computer code RPV_RDE.exe in the previous work. These components were designed in accordance with ASME code specification for SA516-70 carbon steel plate. In this work, finite element analysis is applied to assess the occurred structure mechanical stresses upon those RPV components. This work recommends that the RPV components of RDE are safe in the basic design calculations by analysis approach as described in model simulations.

1. Introduction
The small modular reactor with passive safety features is one of the solutions to bear the Indonesia sustainable energy development as officially stated in the 2015-2019 national medium term development plant. The 10 MWn Indonesia’s Reaktor Daya Eksperimental (RDE) which is to be constructed in Serpong Nuclear Zone, Puspiptek, South Tangerang, Banten Province, was firstly developed in 2014 and expected to be operational in 2022/2023 [1-3]. High safety level shown by slight radioactive release to the environment on several probable accidents is the basic scientific consideration beside the economic [4]. The RDE is expected to be a landmark to Indonesia for a nuclear technology provider in the near future. Cooling by passive safety characteristics, the capability
of nuclear reactor to maintain its cooling performances only by natural mechanism with no external support [4-6], is very important feature to survive even in the worst condition.

Till end of 2018 and onwards, the RDE will be focused on basic and detailed designs. The international collaboration between BATAN and INET Tsing Hua University is expected to include the RPV simulation, and the result of the basic design can be verified. RDE refers to a high temperature gas-cooled reactor, in typical case similar with HTR-10 as reference power plant [3, 5-6]. Fortunately, the basic design of RDE was evaluated by the IAEA extraordinary team last October 2017. From the national point of view, the RDE design activities have been supported by the Ministry of Research, Technology and Higher Education since the beginning of 2018 through Program of the Insinas-Flagship RDE. The national stakeholders, such as, the related ministries and agencies, state and private universities have also actively participated since the 3rd quarter of 2017. It is also noted that the basic design of RDE has been proposed to National Nuclear Regulatory Body of Indonesia in the May 2018.

In basic design phase, reactor pressure vessel components of RDE are subjected to neutron irradiation of material during the operation of nuclear power plant. In order to avoid this material failure, simulations of finite element analysis will be conducted for determining the structure mechanical stresses of reactor pressure vessel components at RDE based on the American Society of Mechanical Engineers (ASME) code and standard [7]. The specification of material designation is SA516-70 carbon steel [3, 7]. This carbon steel is widely used for Reactor Pressure Vessel (RPV) [3, 7-15]. This material will undergo a failure from low energy brittle fractures at low temperature to high energy ductile fractures at the higher temperature.

The present study focuses on the design simulation of the pressure vessel components dimensions for RDE in the form of structure mechanical stresses that occur based on finite element analysis. The structure mechanical stresses include axial stress, hoop stress, radial stress, and von Mises. These stresses values are assessed to decide the safety analysis of RPV components.

2. RPV Structure

The safety analysis simulation of the neutronic and thermal hydraulic solver was performed somewhere using the computer software. The calculation results showed the cooling passive mechanism of RDE combining with the TRISO-based design of RDE were able to contain the radioactive isotopes provided fuel temperature underneath the limitation value of 1600 °C [8]. The cooling safety characteristic ensures the safety design target of RDE is no dangerous radioactive release to workers, populations, and environments even in worst accident. From view of neutronic point, RDE also proved that by taking into account the varieties of density and $^{235}$U fuel enrichment, RDE reactor core is totally safe in the event of air-ingress accident taking place during the RDE reactor operation. In addition, all estimated results show that reactivity changes of the RDE core taking into account some neutronic safety aspects previously mentioned are negative and hence RDE initial reactor core is totally safe. From RPV structure safety aspect of RDE, the work was performed to determine the geometric models and dimensions under material specification of SA516-70 carbon steel, according to ASME code and standard [3, 7]. Table 1 shows the material specification including chemical composition and mechanical properties requirement for carbon steel plates. The iterative calculations were performed by using Fortran code of RPV_RDE.exe [3]. It was estimated that the RPV structure was safe for SA516-70 carbon steel and the mechanical stresses values were computed for the minimum thickness on upper closure head, flange, cylindrical shell, and lower closure head of the RPV components [3]. Figure 1 depicts the basic design of the representative RPV for Indonesia’s RDE [3]. Table 2 indicates dimensions of reactor pressure vessel components [3]. Figure 2 describes some geometric models of pressure vessel components [3].
Table 1. Material specification for SA516-70 plate [7].

| Parameter                  | Unit | Value  |
|----------------------------|------|--------|
| Carbon                     | %    | ≤ 0.22 |
| Manganese                  | %    | 0.77-1.0 |
| Silicon                    | %    | 0.13-0.45 |
| Nickel                     | %    | ≤ 0.43 |
| Chromium                   | %    | ≤ 0.34 |
| Sulfur                     | %    | ≤ 0.018 |
| Phosphorus                 | %    | ≤ 0.015 |
| Copper                     | %    | ≤ 0.12 |
| Vanadium                   | %    | ≤ 0.06 |
| Yield strength at 371 °C   | MPa  | 260    |
| Ultimate tensile strength at 371 °C | MPa | 485 |

Figure 1. Representative RPV for RDE [3].

Table 2. Dimensions for reactor pressure vessel components [3].

| Components                   | Height [mm] | Diameter [mm] | Thickness [mm] |
|-------------------------------|-------------|---------------|----------------|
| Upper closure head            | 1050        | 4200          | 60             |
| Upper flange                  | 1221        | 4200          | 238            |
| Shell flange                  | 1222        | 4200          | 238            |
| Upper cylindrical shell       | 2929        | 4200          | 60             |
| Lower cylindrical shell       | 3394        | 4200          | 100            |
| Lower closure head            | 1864        | 4200          | 60             |
3. Methodology
In this research work, computational procedures have been developed for the basic design of RPV components used in RDE applications based on geometric models and dimensions, and ASME code material specifications, Section III, Division 5. In addition, this procedure is assessed with numerical methods using the finite element analysis so that basic design validation can be attempted in the case of various conditions for pressure and temperature. Simulations for finite element analysis of reactor pressure vessel components are conducted by using computer code SolidWorks. The study focuses on the basic design calculations of structural stresses analyses on the RPV components for the RDE. The components of this reactor pressure vessel comprise upper closure head, upper flange, shell flange, upper cylindrical shell, lower cylindrical shell, and lower closure head.

The detailed procedure of safety assessment carried out is shown in the Figure 3 in the form of flowchart. An important step in the basic design calculations of RPV components for RDE is the knowledge of stresses distributions and strain displacement throughout the wall thickness on the specific temperature for a given set of operating conditions. In the previous work, a numerical computation had also been developed by the first author to assist in the analysis and basic design of the RPV components for the RDE [3]. This computation predicted the three-dimensional (3-D) geometric models and dimensions of RPV components for the RDE.
4. Result and Discussions
In this study, the investigated reactor pressure vessel for RDE is presumably made of SA516-70 carbon steel, which has been increasingly applied to the design and manufacture of boiler and pressure vessel [7]. A material SA516-70 has mechanical properties as shown on the Table 1 above. The carbon steel is commonly assumed to be linear elastic isotropic when loaded below yield point for finite element elastic analysis and to be elastic isotropic perfectly plastic when loaded beyond the yield strength for finite element plastic analysis.

3-D solid geometric model is used for all pressure vessel components considered in which the various dimensions are as indicated in Table 2. A full curvature based mesh element of the RPV components is created by using the computer code SolidWorks. This type of element is picked as it contributes both elasticity and plasticity and in consequence it is suitable for this simulation. The model is simulated by using the operating pressure of 3 MPa and temperature of 371 °C. This pressure leads to expansion on the pressure vessel surface. The finite element meshing for geometric models of RPV components are displayed in Figure 4. Table 3 indicates the solid meshed properties used for the SolidWorks simulation. After meshing the pressure vessel components two different support constraints are applied on the solid geometric models. The first one is free support mounted on the edge of the component model which is supposed to be symmetrical and the other one is fixed support used for the outer ring of the RPV components for RDE. The design pressure is applied on the entire inner wall of the reactor pressure vessel and these RPV components models are then solved.

Finite element analysis of the reactor pressure vessel components for RDE is exhibited from Figure 5 up to Figure 10. Contour of axial stresses set up within the reactor pressure vessel components can be classified under the conditions of the longitudinal stress generated by internal pressure, the uniform compressive stress produced by the sum of the weights assumed to act along the component axis, and the bending stress provided by the horizontal loads and by the resultant weight in case eccentric to the
component axis. From Figures 5 to 10, it can be observed that the values for the highest axial stresses of RPV components are smaller than the ultimate stress strength of $SA516-70$ carbon steel.

![Meshed geometric models for reactor pressure vessel components.](image)

**Figure 4.** Meshed geometric models for reactor pressure vessel components.

| Components            | Weight [N] | Total Nodes | Total Elements |
|-----------------------|------------|-------------|----------------|
| Upper closure head    | 116257     | 18492       | 9032           |
| Upper flange          | 128151     | 42895       | 23788          |
| Shell flange          | 175194     | 32222       | 18330          |
| Upper cylindrical shell | 277502   | 14669       | 7135           |
| Lower cylindrical shell | 402937   | 15962       | 7738           |
| Lower closure head    | 204755     | 16519       | 8254           |

**Table 3.** Solid mesh properties of reactor pressure vessel.

On the Table 3, weight of RPV components is determined by its minimum wall thickness. This thickness is obtained by running computer code $RPV_RDE.exe$ in the previous work [3]. The distribution of the Hoop stress on the RPV components as shown on Figures 5 to 10 are performed under the internal pressure of 3 MPa. It is evident from those figures that the values of Hoop stresses are lower than the yield strength of $SA516-70$ carbon steel. The value of the Hoop stress on the lower cylindrical shell of the RPV is around 237.26 MPa as seen on Table 4.
It can be noted that when the internal pressure is applied to RPV, the diameter of the cylindrical shell is uniformly developed in the radial direction. Radial stress distribution has various stresses from pressure on the inner surface to the outer surface. This implies that the pressure has compressive stress value which equal to the internal pressure on the inner surface. The radial stress value is circa 48.89 MPa on the lower cylindrical shell as shown in Table 4. Figures 5 to 10 illustrate also the results of finite element analysis for von Mises stress that occurs in the reactor pressure vessel component walls on RDE. From Table 4, the highest value of von Mises stress is about 229.84 MPa on the pressure vessel component of lower cylindrical shell. Fully plastic state will be attained when the von Mises stress approaches to material yield strength.

Table 4. Highest structure mechanical stresses [in MPa] for reactor pressure vessel.

| Components            | Axial   | Hoop    | Radial  | von Mises |
|-----------------------|---------|---------|---------|-----------|
| Upper closure head    | 54.24 MPa | 149.84 MPa | 25.76 MPa | 139.07 MPa |
| at node 1447          | at node 18120 | at node 3318 | at node 65 |
| Upper flange          | 25.45 MPa | 67.81 MPa | 19.94 MPa | 45.36 MPa  |
| at node 20732         | at node 20732 | at node 20732 | at node 20732 |
| Shell flange          | 15.46 MPa | 54.72 MPa | 10.86 MPa | 51.63 MPa  |
| at node 20669         | at node 2195 | at node 445 | at node 2195 |
| Upper cylindrical shell| 52.59 MPa | 135.25 MPa | 46.85 MPa | 86.29 MPa  |
| at node 4558          | at node 4517 | at node 14577 | at node 4517 |
| Lower cylindrical shell| 70.87 MPa | **237.26 MPa** | 48.89 MPa | **229.84 MPa** |
| at node 1582          | at node 15881 | at node 3800 | at node 15881 |
| Lower closure head    | 32.52 MPa | 60.21 MPa | 17.37 MPa | 60.72 MPa  |
| at node 1641          | at node 9248 | at node 183 | at node 16394 |

Figure 5. Finite element analysis of stresses simulations for upper closure head.
Figure 6. Finite element analysis of stresses simulations for upper flange.

Figure 7. Finite element analysis of stresses simulations for shell flange.
Figure 8. Finite element analysis of stresses simulations for upper cylindrical shell.

Figure 9. Finite element analysis of stresses simulations for lower cylindrical shell.
5. Conclusion
The research conducted shows the results obtained by finite element analysis allowing the design simulations of geometric models to approve for RPV component dimensions. The highest value of structure mechanical stress in the form of Hoop stress is found in the lower cylindrical shell (237.26 MPa). Thus, the RPV components of RDE are considered to be safe in the design calculations.

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