Chain and Sprocket Analysis of Control Rod Drive Mechanism of HTGR Experimental Power Reactor

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Abstract. High Temperature Gas Cooled Reactor (HTGR) is being developed through a national program called Non-Commercial Experimental Reactor (Reaktor Daya Eksperimental; RDE). One of most important system in controlling the reactor is Control Rod Drive Mechanism (CRDM). CRDM has ten control rods that working for controlling reactivity which is driven by a mechanism that uses chain and sprocket transmission. To assure that the chain and sprocket components will work properly for the designed life time, a stress analysis is importantly required. Therefore, this study has been conducted to determine the strength and stress of chain and sprocket made by Inconel 625 at operational temperature of 150-750°C using finite element method. The analysis results show that the chain and sprocket could hold up the maximum stress up to 409.51 MPa and 398.94 MPa, respectively. These stresses are still below the maximum allowable stresses Inconel 625, 517 MPa. Accordingly, the chain-sprocket using Inconel 625 alloy in the RDE design is safe to be applied up to temperature of 750°C.

Keywords: control rod drive mechanism, RDE, HTGR, stress analysis, finite element.

1. Preliminary
The design of the Non-Commercial Experimental Reactor (RDE) refers to the HTGR-type pebble bed design that controls its power in normal operation by using a Control Rod Drive Mechanism (CRDM). The control rod is also used to shut down the reactor. If this system fails, the Small Absorber Ball System (SAS) is enabled and the reactor must be ascertained. The CRDM and SAS include the internal parts of the Reactor Pressure Vessel (RPV). Therefore, the CRDM; control rods and its driver mechanisms, must use a material that is resistant to high temperature and high radiation on its workload for a long time.

RDE selects chain transmission for the CRDM because the control rod channel is quite long, 2700 mm and during its insertion into the channel, the chain should be in straight line. Chain transmission also could move faster up and down to run to control the neutron bombardment. Due to the length of control rod, the total mass that system should hold is heavy. Therefore, the stresses that occurred in chain and sprocket must be analyzed.
Recent research and evaluation for stress intensity metal in the control rod drive mechanism led to the use of Inconel 625 to replace Incoloy 800H \cite{1}. The evaluation compares the endurance of mechanical properties at various temperatures for the application of control rod system between the Incoloy 800H used at HTR-10 and Inconel 625 at the HTR-PM. Based on that, the material analysis needs to be extended to study maximum stress that occurred at CRDM, especially in the chain and sprocket components, including the prediction of safety factor.

2. Theory

2.1. Non-Commercial Experimental Reactor (RDE)

The National Nuclear Energy Agency of Indonesia (BATAN) as a nuclear energy research and development institute has planned the development of Non-commercial Experimental Reactor (Reaktor Daya Eksperimental, RDE). The chosen type of reactor is Pebble Bed Reactor (PBR) because it is considered very safe, could be coupled with turbine for cogeneration, fuel flexibility, the technology has been proven, competitive cost, multipurpose usage, and it is suitable for Indonesia’s condition, to meet the needs of electricity. From the point of view of safety, the passive safety system of the PBR design ensures a very minimum radiation release to the environment under any conditions including severe conditions such as those occurred in Fukushima accidents. The PBR design has an inherent safety system that relies only on natural mechanisms so that the reactor core system becomes very simple when compared to today's commercial nuclear reactor systems. The general scheme of RDE system is shown in Figure 1.

![General Scheme of Non-Commercial Experimental Reactor (RDE)](image)

In Figure 1, RDE has two main parts: first one is the heat generating section and the second one is the power plant. The heat generating section consists of Reactor Pressure Vessel, Control Road Drive Mechanism, Hot Gas Duct, Steam Generator, and Cooling System, while the power plant consists of Turbine and Generator.
2.2. Control Rod Drive Mechanism (CRDM)
The control rod drive mechanism of RDE is a system to control reactivity on the reactor core and for the shutdown process of the reactor. The RDE design refers to a Chinese HTR-10 design that utilize each of ten independent control rods using one drive system as shown in Figure 2. The control rod system consists of two parts, namely: driver and reactivity control parts. Looking at more detail component, driver parts consist of: stepper motor, magnetic damper, gear box, chain transmission system using sprocket (chain-sprocket), worm gear reducer and rod control positioning instrument. In the reactivity control section the control rod device consists of a five-segment pellet array of sintered boron carbide (B$_4$C) absorber neutrons. Each neutron absorber segment is placed inside a closed stainless steel annulus tube. Each annulus tube is parallel connected with another tube by a mechanical connection. At the bottom of this device is installed spring impact dampening factor that serves as a damper when the component goes down by gravity. This control rod device and the drive system are connected by a chain of chain-sprocket components. The design of this control rod system requires chain is able to work at high temperatures and radiation. The chain is exposed at low temperatures when the chain is in the control rod drive system unit and when it is exposed inside the core or inside the side reflector, the chain is subjected to high temperatures. Therefore, it is very important to select a proper material for the chain and sprocket to resist in such extreme conditions and to have a long life span. A preliminary literature study has been carried out to select the material for this study. Among of several references, the material considered suitable for chains and sprocket materials is Inconel 625 [3]. Inconel 625 has better mechanical properties compared to Incoloy 800H (HTR-10).

2.3. Mechanical Properties of Inconel 625
Inconel 625 material has been used in HTR-PM and modern industry because of its very high strength, strong to fatigue load, high temperature resistance, oxidation resistance and carbonizing in changing
environment, corrosion resistance of chlorine, and has good welding\cite{1}\cite{6}. Modulus of elasticity of Inconel 625 at high temperature can be seen in Table 1.

**Table 1. Modulus of Elasticity of Inconel 625 at Various Temperature\cite{4}\cite{5}**

| Temperature \( ^\circ\text{C} \) | Tension Modulus of Elasticity, GPa | Shear Modulus of Elasticity, GPa |
|-----------------|---------------------------------|---------------------------------|
|                 | Anneal | Solution-Treated | Anneal | Solution-Treated |
| 21              | 207.5  | 204.8            | 81.4   | 78.0             |
| 93              | 204.1  | 200.6            | 80.0   | 76.5             |
| 204             | 197.9  | 193.7            | 76.5   | 74.5             |
| 316             | 191.7  | 187.5            | 74.5   | 71.7             |
| 427             | 185.5  | 180.6            | 71.7   | 68.9             |
| 538             | 178.6  | 173.1            | 68.3   | 66.2             |
| 649             | 170.3  | 165.5            | 64.8   | 63.4             |
| 760             | 160.6  | 157.2            | 60.0   | 60.7             |
| 871             | 147.5  | 148.2            | 55.2   | 57.2             |

**Table 2. Room Temperature Mechanical Properties\cite{5}**

| Form And Condition | Tensile Strength ksi | Yield Strength ksi (0.2% Offset) | Elongation % | Reduction Of Area % | Hardness, Brinell |
|--------------------|----------------------|----------------------------------|--------------|---------------------|-------------------|
| ROD, BAR, PLATE    | 120-160              | 827-1103                         | 60-110       | 414-758             | 60-40 175-240     |
| As-Rolled          | 120-150              | 827-1034                         | 60-95        | 414-655             | 60-40 145-220     |
| Annealed           | 105-130              | 724-986                          | 42-60        | 290-414             | 65-40 90-60 116-194 |
| Solution-Treated   | 100-120              | 689-827                          | 40-75        | 267-517             | 55-30 145-240     |
| SHEET and STRIP    | 120-150              | 827-1034                         | 60-90        | 414-602             | - 145-240         |
| Annealed           | 120-140              | 827-965                          | 60-75        | 414-517             | - 55-30           |
| TUBE and PIPE, COLD-DRAWN | 100-120 | 689-827 | 40-75 | 276-517 | 60-40 |
| Annealed           | 120-140              | 827-965                          | 60-75        | 414-517             | - 55-30           |
| Solution-Treated   | 120-140              | 827-965                          | 60-75        | 414-517             | - 55-30           |

3. Methodology
The chain-sprocket analysis of the control rod drive mechanism in Non-Commercial Experimental Reactor type of HTGR uses the following methodology. It was started with literature study of HTR-10, HTR-PM, RSG Gas Siwabessy and other reactor types. Continued with 2D and 3D image
modeling of chain-sprockets using solid work software. Afterwards, stress analysis was performed on chain-sprocket using finite element software with double load to compensate impact load. The fixed support structure was set as a given constraint, so that the loading on chain and sprocket become maximum. The stress analysis is performed at various temperatures to simulate the real condition of control rod in the vessel reactor. Furthermore, the calculation of safety factor was also carried out to see whether the selected material could withstand with the determined loading or not. The working temperature is ranging between 150-750°C, indicates at 150°C, the control rod is in the idle position and 750°C is the approximate temperature inside the reactor core.

4. Results and Discussion

The 2D modelling with meshing of a single chain using hexa dominants is shown in Figure 3.

The effect of temperature to the stress of chain and sprocket with the loading 1200 N is shown in Figure 4. It indicates that the increase of operational temperature will increase the equivalent Von-Misses Stress linearly. At the predicted maximum temperature, 750°C, the equivalent Von-Misses stress in the chain and sprocket is around 409.51 and 398.94 MPa, respectively, below the maximum allowable stress of yield stress of Inconel 625, 517 MPa.

The calculation of safety factor was employed by using this formula;
The result of safety factor analysis on the temperature increment is indicated in Figure 5. At the low temperature, 150°C, the safety factor is about 6.5, which is considered very safe. However, as the temperature increases, the safety factor decreases significantly, and reach value of 1 at the maximum working temperature, 750°C. This value has minimum security level with static load.

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\text{Safety Factor} = \frac{\text{Yield Strength of a Material}}{\text{Applied Stress}}
\]  

(1)

The stress analysis on the chain and sprocket also gave the precise location of the maximum stress (von-mises stress) as shown in Figure 6 and 7, respectively. In the Figure 6, the maximum stress was located at the bending point of a single chain, while in Figure 7; the maximum stress was at mechanical lock of the sprocket. Those points require more attention so that the early failure of components can be hindered.
5. Conclusion
The results of the strength and stress analysis of the control rod drive mechanism on the chain and sprocket is listed below:
The stresses occurring in the chain and sprocket increased as the temperature rise. The maximum value of equivalent Von-Misses stress in the chain and sprocket at 750°C is 409.51 and 398.94 MPa, respectively. This value is considered to be in safe condition as it is below the yield strength of Inconel 625; 517 MPa.
The safety factor decreased significantly as the operational temperature of reactor increased. At the highest temperature, the safety factor was 1, which is suggested as the minimum value for reactor safety.
The recommendation of this study that Inconel 625 is safe for the application of chain and sprocket as the parts of control rod drive mechanism of HGTR RDE.

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