Performance Analysis of RDE Energy Conversion System in Various Reactor Power Condition

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A B S T R A C T

Reaktor Daya Eksperimental (RDE) is an experimental power reactor based on High Temperature Gas-cooled Reactor (HTGR) technology with thermal power of 10 MW. As an experimental power reactor, RDE is designed for electricity generation and provides thermal energy for experimental purposes. RDE energy conversion system is designed with cogeneration configuration in the Rankine cycle. To ensure the effectiveness of its cogeneration, the outlet temperature of the RDE is set at $700°C$ and steam generator outlet temperature is around $530°C$. Analysis of the performance of the energy conversion system in various power levels is needed to determine the RDE operating conditions. This research is aimed to study the performance characteristics of RDE energy conversion systems in various reactor power conditions. The analysis was carried out by simulating thermodynamic parameter calculations on the RDE energy conversion system and the overall cooling system using the ChemCad program package. The simulation is carried out by increasing the reactor power from 0 MW to 10 MW at constant pressure and constant mass flow rate. The simulation results show that the steam fraction at the steam generator outlet increases starting from 3 MW reactor power and reaches saturated steam after the thermal power level of 7.5 MW. From the results, it can be concluded that with constant mass flow rate and operating pressure, optimal turbine power is obtained after the reactor thermal power reached 7.5 MW.

1. INTRODUCTION

Research and development of new and renewable energy in the world are focused on safe and sustainable energy. Related to the availability and sustainability of energy resources, nuclear energy could be an option in the future. This is because the availability and sustainability of conventional energy sources, namely fossil fuels, are uncertain in the long term. Some conventional energy sources are expected to be depleted in the next few decades. Related to this energy resources problem, the role of nuclear energy as a global energy supplier can be increased. For this purpose, research and development related to the utilization of nuclear energy must continue to be improved. The development of nuclear energy utilization technology can enhance the role of nuclear energy as a global energy supplier [1, 2]. The role of nuclear energy as a global energy supplier will increase research and development activities of nuclear energy technology, especially nuclear reactor technology. The latter leads to the concept of cogeneration systems [3, 4], where thermal energy generated from nuclear reactors is not only used for electricity generation but also provides heat for industrial purposes [4, 5]. The design of a

cogeneration system is intended to optimize the use of nuclear energy both to produce electricity and provides thermal energy to the industry [6].

BATAN as a nuclear technology research institute is currently developing an experimental power reactor design with a cogeneration configuration on its energy conversion system, called Reaktor Daya Eksperimental (RDE) or Reaktor Daya Non-Komersial (Non-Commercial Power Reactor/RDNK). RDE is designed based on high temperature gas-cooled reactor (HTGR) technology with thermal power of 10 MW and an outlet temperature of 700°C. The selection of the HTGR as the base of the RDE is due to its very high coolant output temperature, making it suitable for the application of the cogeneration concept. Various studies on the cogeneration system in HTGR have been widely developed in various countries. For example, as reported by Hiroyuki Sato [7], the GTHTR300C cogeneration system can be used as electricity generation, hydrogen production, and seawater desalination. Gustavo Alonso et al. [8] stated that the cogeneration system in the Pebble Bed Modular Reactor (PBMR) is capable of generating electricity and providing thermal energy to produce gasoline in oil refineries.

RDE design refers to the PBMR technology. It uses helium gas as its primary coolant and water as a secondary coolant which also functions as the medium in its energy conversion system. The conceptual design of RDE which includes the reactor core design, reactor coolant system, and energy conversion system has been compiled and determined based on user requirements [9]. The RDE is planned to be built within the Puspiptek area in Serpong. The selection of a 10 MW thermal power is estimated to be sufficient to supply electricity for several BATAN research centers.

To support and complete the data on the basic design and detailed design of RDE, various researches and developments related to the design of reactor technology and reactor system technology are needed. The study of the steam generator of RDE has been carried out, Dibyo et al [10] have investigated the characteristics of the operating parameters of the outlet temperature and void fraction in the RDE steam generator. The investigation result shows that the superheated steam outlet temperature from the steam generator of RDE is obtained at a range of 275.5-600°C. Further studies on superheated steam in RDE show that the highest thermal efficiency is achieved at a steam temperature of 530.46°C [11]. The application of the cogeneration in the RDE design has also been carried out. Researches show that the RDE, in addition to producing electricity, can also

supply heat [12–14]. Other studies including research about pressure vessels [15], research on instrumentation systems [16], and research on helium purification systems [17] have also been carried out.

The purpose of this research is to analyze the performance of the RDE energy conversion system in various reactor thermal power levels, from 0 MW up to 10 MW. The analysis is performed by simulation calculation for various thermodynamic parameters using ChemCad program. ChemCad is a computer program widely used for various studies involving the analysis and design of the processing system. [18–20].

2. NUCLEAR STEAM SUPPLY SYSTEM

The primary system design for RDE refers to the HTR-PM design where the pressure vessel for the steam generator is placed lower than the pressure vessel for the reactor [21]. The primary system for RDE the which also functions as a supplier of steam in the energy conversion system is shown in Fig. 1, as detailed in the design document [22].
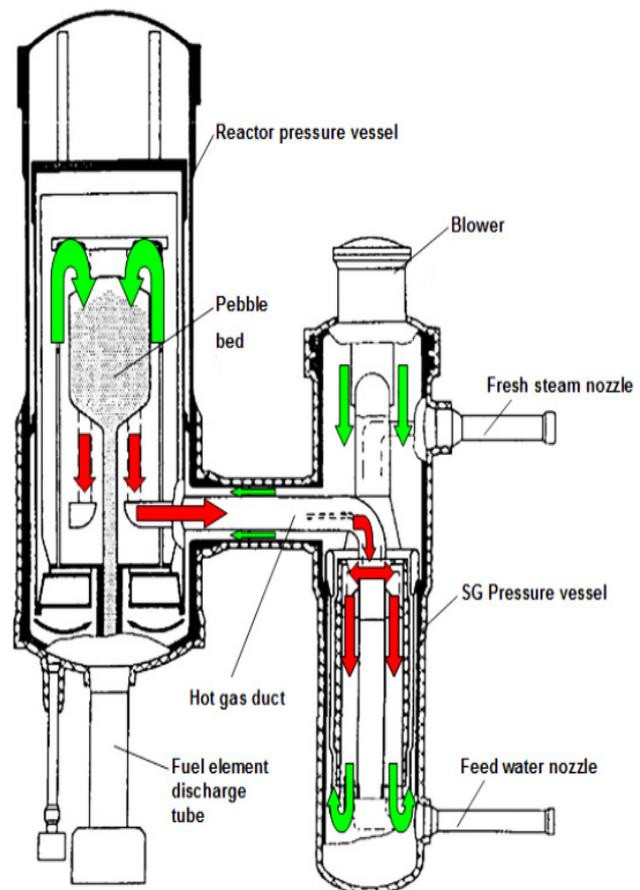

Fig. 1. Schematic diagram of the nuclear steam supply system [22]

Such pressure vessel configuration is intended to reduce the possibility of water intrusion into the reactor. The intrusion of water and also air from the steam generator into the reactor core can cause corrosion in the reactor structure which consists mainly of graphite [23, 24]. The blower or compressor used to circulate helium gas in the primary cooling system loop is installed at the top of the pressure vessel for the steam generator. Hot helium gas flows through the pipe inside of the steam generator. Meanwhile, steam from the steam generator to the steam turbine system flows through a fresh steam nozzle installed at the top of the steam generator. Feedwater to the steam generator flows through the bottom side of the steam generator.

3. METHODOLOGY

Performance analysis of the RDE energy conversion system in various power reactor conditions is carried out using computer code ChemCad. The Process Flow Diagram (PFD) of the RDE energy conversion system, which includes the main components of the steam generator, steam turbine, cooler, and two pumps, is modeled using ChemCad as presented in Fig. 2.
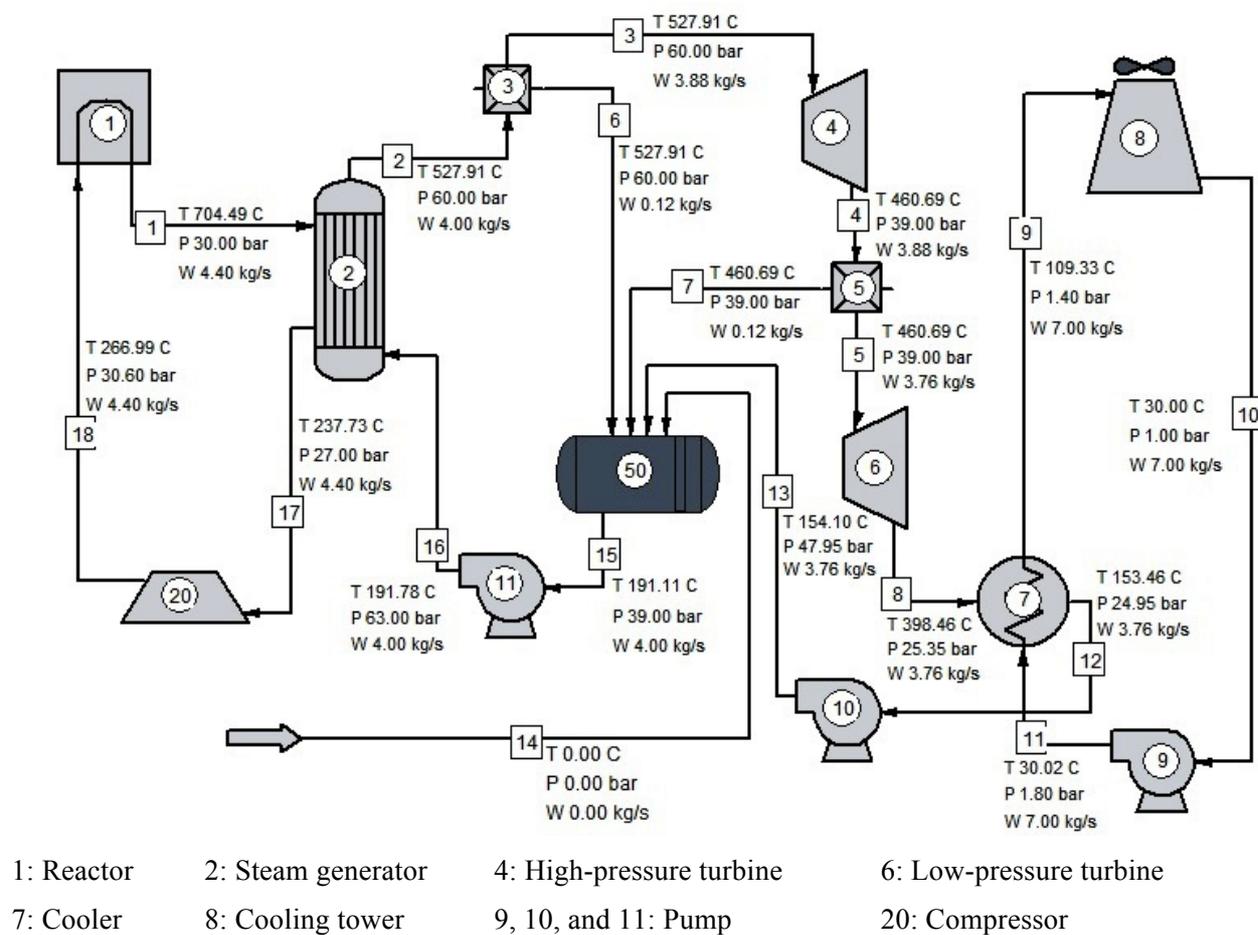

1: Reactor 2: Steam generator 4: High-pressure turbine 6: Low-pressure turbine
7: Cooler 8: Cooling tower 9, 10, and 11: Pump 20: Compressor

Fig. 2. The RDE energy conversion system model using ChemCad

RDE energy conversion system consists of 3 loops, namely the primary loop, secondary loop, and tertiary loop. The primary loop, which uses helium as a heat-carrying medium, consists of 3 main components, namely reactor (unit no 1), steam generator (unit no 2), and compressor (unit no 20). Helium is circulated by a compressor which is mounted at the inlet of the reactor. The secondary loop, which uses water as the heat carrier, consists of a steam generator (unit no 2), steam turbines (unit no 4 and 6), cooler (unit no 7), and two pumps (unit no 10 and 11). In this secondary loop, the water is converted into steam in the steam generator and flows to the turbine coupled with an electric generator. The steam generator that also functions as a heat exchanger is modeled as a shell and tube type heat exchanger mounted between the primary and secondary loops. Tertiary loops that function to remove the residual heat from the secondary loop through the turbine outlet consists of a cooling tower (unit no 8), pump (unit no 9), and cooler (unit no 7).

The simulation began by establishing the main component parameter data of the RDE energy conversion system. The reactor data as shown in Table 1 and the steam generator data as shown in Table 2 refer to the BATAN conceptual design data based on the user requirements document [22, 25] and used for the input simulation. Reactor thermal power is increased from 0 MW to 10 MW with a 0.5 MW interval. Meanwhile, constant pressure is maintained both on the primary and secondary loops of 30 bar and 60 bar, respectively, as well as the mass flow rate at primary and secondary loops at 4.0 kg/s and 4.4 kg/s, respectively. All parameters of the main components of the energy conversion system which include steam generator, steam turbine, cooler, and pump are determined according to the user requirements document. During the increase of reactor power, the changes in temperature, steam fraction, compressor power, and turbine power that occur in the RDE energy conversion system are recorded for analysis.

Table 1. The Reactor Data [22]

Parameter	value	unit
Power of reactor	10	MW
The density of mean power	2	MW/m^3
The pressure of the primary system	30	bar
The temperature of the inlet reactor	250	^{o}C
The temperature at outlet reactor	700	^{o}C

Table 2. The Steam Generator Data [22]

Parameter	value	unit
Thermal power of SG	10.0	MW
Primary coolant mass flowrate	4.4	kg/s
The primary inlet temperature	700	^{o}C
Primary outlet temperature	245	^{o}C
Primary inlet pressure	30	bar
The steam temperature at outlet SG	530	^{o}C
Steam pressure at outlet SG	60	bar
Feedwater temperature of SG	160	^{o}C
Secondary coolant mass flowrate	4.0	kg/s
Tubes number of SG	93	
Outside of diameter tube (OD)	23	mm
Heat transfer area for SG	70	m^2

4. RESULTS AND DISCUSSION

The simulation results are displayed in graphical form in Fig 3, Fig 4, Fig 5, and Fig 6. Fig 3 is shown the rising temperature in the inlet and outlet of the reactor when the reactor power is increased. The increase is found not only at the reactor outlet but also at the reactor inlet. It can be explained that the heat generated by the reactor is not fully transferred and used to produce steam at the steam generator, some of which returns to the reactor in the primary cooling system cycle so that the temperature at the reactor inlet was increased. These results also show that the increase in the reactor power only affects the change in reactor temperature, because the pressure and mass flow rate are kept constant. This matter has been discussed in the previous studies that changes in the mass flow rate of the coolant can affect the reactor outlet temperature [26].
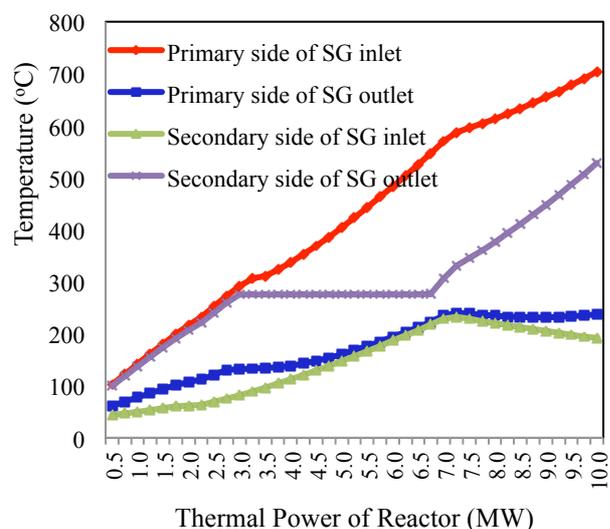
In Fig 3, there are two different points in the gradation of temperature rise, namely the reactor power of 3 MW and the reactor power of 7.5 MW. From the reactor power of 0 MW to 3 MW, thermal power generated from the reactor is only used to raise the temperature of the water on the secondary side of the steam generator. At 3 MW power, boiling started to occur at the steam generator, so that the fluid flowing out of the steam generator starting to become a mixture of steam and water. At the 7.5 MW power, the saturated steam condition is reached at the steam generator outlet.
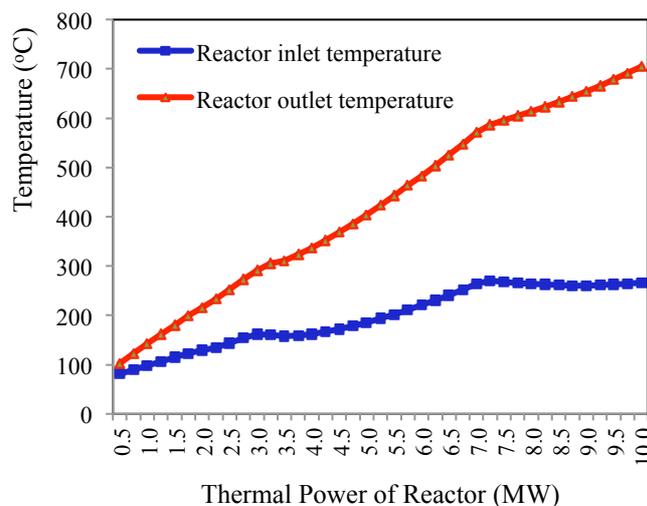
Fig. 3. The temperature at the inlet and outlet reactor as a function of reactor power.

Fig. 4. The temperature of inlet and outlet steam generator on the primary and secondary side as a function of reactor power

Temperature characteristics at the reactor and at the inlet and outlet of the steam generator are shown in Fig 4. It can be seen that the steam generator outlet temperature on the secondary side is constant at the increase in reactor power between 3 MW to 7.5 MW. This condition can be explained that at the reactor power below 3 MW, thermal energy from the reactor is insufficient to evaporate water on the secondary side of the steam generator. All thermal energy from the reactor is used to increase the temperature of the water in the steam generator. At the power between 3 MW to 7.5 MW, no increase of temperature is observed at the secondary side of the steam generator. This is because the thermal energy from the primary side is used to evaporate water in the secondary side of the steam generator at latent heat. In this condition, the liquid that flows out from the steam generator is a mixture of steam and water with increasing steam quality.

Saturated condition of the steam in the steam generator is achieved at the reactor thermal power larger than 7.5 MW. After the saturated condition is achieved, the steam temperature in the steam generator will continue to rise. In the saturated vapor condition, the steam turbine can work optimally. Thus, at a pressure of 60 bar and a mass flow rate of 4.4 kg/s, the optimum performance of a steam turbine can be achieved with the lowest reactor power of 7.5 MW.

The graph in Fig 5 shows the characteristics of the steam generator outlet temperature and the vapor fraction. In these figures, it appears that the vapor fraction is still zero at the reactor thermal power of less than 3 MW. At this power rate, the fluid flowing out of the steam generator is still water and not containing steam. From the steam fraction graph, it can be seen that at the outlet of the steam generator, a phase change occurs from completely water to saturated steam. At the reactor power of 0 MW to 3 MW, the fluid that flows out of the steam generator is fully water.

At this stage, all of the heat transferred from the reactor which is then transferred to the secondary side of the steam generator is used to raise the temperature of the water on the secondary side of the steam generator. While in the reactor power range between 3 MW to 7.5 MW, a mixture of water and steam in the outlet of steam generator occurs. It means that all the thermal energy from the reactor is used for the process of evaporation of water in at latent heat conditions, forming a mixture of water and steam on the secondary side of the steam generator. Therefore, at this stage, there is no increase in temperature. Furthermore, the reactor power above 7.5 MW, fluid flowing out of the steam generator is in saturated steam. This condition is ideal for obtaining the optimal steam turbine performance.
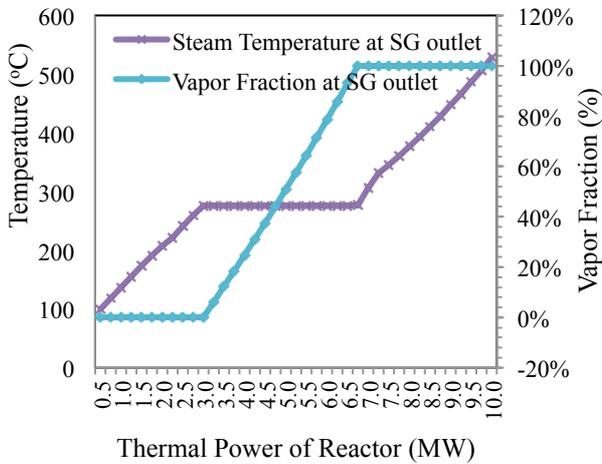
Fig. 5. Steam temperature and vapor fraction at the outlet of SG as a function of reactor power

In addition to the thermodynamic parameters in the secondary loop, which are affected by the increase of reactor power, the thermodynamic parameters in the primary loop are similarly affected by changes in reactor power. In Fig 6, it is shown that the power of the compressor or blower used to circulate helium gas in the primary cooling system is affected by changes in reactor power as well. The compressor power increase is linear with the increase in reactor power, meaning that the compression power is also increases. When the steam flowing out of the steam generator reaches saturated steam, the energy required is relatively constant, so the compressor power is also relatively constant.
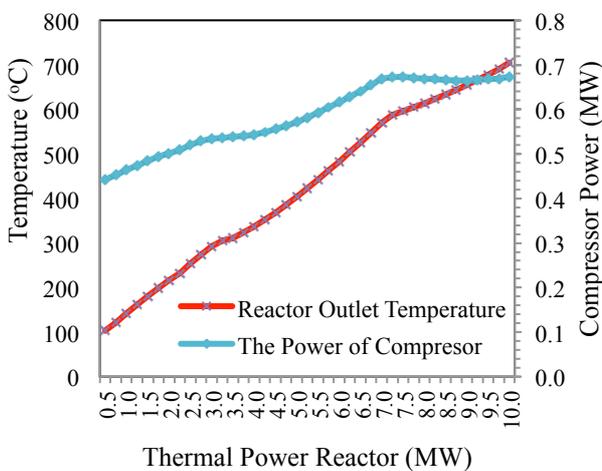

Fig. 6. Reactor outlet temperature and compressor power as a function of reactor power

5. CONCLUSION

Analysis of the performance of the RDE energy conversion system in various power levels using ChemCad has been carried out. The simulation is done by increasing the thermal power of the rectifier from 0 MW to 10 MW while maintaining the mass flow rate and pressure constant.

Simulation results show that changes in reactor power cause changes in vapor temperature and the quality of steam flowing out of the steam generator. There are 2 levels of reactor power that need to be considered during the increase in reactor thermal power from 0 MW to 10 MW, namely 3 MW power and 7.5 MW power. If the pressure and mass flow rate are maintained in normal operation, at power below 3 MW, the fluid flowing out of the steam generator remains as water, so that the steam turbine power stays zero. At thermal power between 3 MW to 7.5 MW, fluid flowing out of the steam generator is in the form of a mixture of steam and water, or often referred to as wet steam. Lastly, at reactor power above 7.5 MW, the fluid flowing out of the steam generator is 100% steam or dry steam. The optimal performance of the turbine is obtained with dry steam.

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