Performance analysis of cogeneration energy conversion system design for RDE

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Abstract. An Experimental Power Reactor called RDE is a non-commercial power reactor with the thermal power of 10 MW. RDE is being designed based on the high-temperature gas-cooled reactor (HTGR). The purpose of the RDE designed is to supply thermal energy for experimental purposes and to generate electricity for supplying the electricity in Serpong research area. The energy conversion system of RDE is designed in cogeneration configuration with a Rankine cycle. The outlet reactor coolant temperature of RDE is 700 °C, and the steam temperature at the outlet of the steam generator is 530 °C. The performance analysis of the RDE energy conversion system is concentrated on two parameters are the thermal efficiency and the energy utilization factor (EUF). This research aims to calculate and analyse the optimal of the two parameters in the RDE energy conversion system. Calculation and analysis of the performance of the RDE energy conversion system are performed by simulation using computer code ChemCad. The simulation results show that the energy utilization factor of the cogeneration for the RDE energy conversion system can increase by more than 60%. It can be concluded that the energy conversion system in a cogeneration configuration can increase the EUF.

1. Introduction

As a research institute, the National Nuclear Energy Agency (BATAN) is going to develop a small experimental power reactor which is called Reaktor Daya Eksperimental (RDE). RDE which has a 10 MW thermal power design developed from the type of high-temperature gas-cooled reactor (HTGR). The HTGR type reactor was chosen because HTGR has inherent safety properties, high electricity generation efficiency, and has a variety of uses [1,2]. The high output temperature of the reactor provides an opportunity to construct an energy conversion system in a cogeneration configuration. With a cogeneration configuration, a nuclear reactor is not only used as a power plant but can also be used for supplying thermal energy for industrial purposes [3,4]. HTGR is also a type of Generation IV reactor that meets the criteria for securing nuclear material and the inherent safety criteria [5].

There are two types of HTGR viewed from the core design of the reactor, namely prismatic type of HGTR, and pebble-bed type of HTGR. In this case, the design for the reactor core of RDE refers to the pebble-bed type of HTGR. The RDE cooling system consists of 3 loops starting from taking heat from the reactor core to discharging residual heat through the cooling tower. The primary cooling system consists of helium gas as a cooling media serves to transfer heat generated from the reactor core to the
steam generator. The secondary cooling system consists of water as cooling media. Water circulated in the secondary loop is converted to steam in a steam generator to drive a steam turbine. In the design of the RDE cogeneration energy conversion system, the reactor outlet temperature is 700 °C with a helium gas pressure of 30 bar, while the temperature of steam at the steam generator outlet is 530 °C with a steam pressure of 60 bar [6]. For start-up and shut-down purposes, a flash tank is installed between the steam turbine and the steam generator to condition the coolant in the secondary loop.

Various research and development to complement the RDE design requirements have been carried out. Some RDE design parameters have been verified through simulations using various computer programs. Related to the performance of the steam generator in the RDE cogeneration system, Dibyo et al have examined by simulation the characteristics of the operating parameters at the outlet temperature and void fraction in the steam generator [7]. The simulation results show that at the outlet temperature of the steam generator between 275.5 °C - 600 °C, steam coming out of the steam generator is superheated. To support the application of the concept of cogeneration in the design of RDE, some research has also been carried out [8]. The results showed that the high-temperature steam at the outlet of the steam generator can also be used for the hydrogen production process with the steam methane reforming method. This result strengthens the cogeneration design in the RDE energy conversion system. Several studies to support the application of the concept of cogeneration in the RDE energy conversion systems have also been carried out, the results show that the RDE energy conversion system can be configured cogeneration [9]. In addition to secondary loops with water cooling media that are converted to steam, several studies related to primary loops have also been carried out, namely on the purification of helium [10]. The other researches that have also been carried out to support the detailed design of RDE are research on pressure vessels [11] and research on instrumentation systems.

This research is to analyse the performance of the RDE energy conversion system and calculate its optimal performance. The performance of the energy conversion system is expressed by two common parameters, namely artificial thermal efficiency (ATE) and energy utilization factors (EUF) [12,13]. Analysis and calculation of the performance of the RDE energy conversion system have been done by simulation using a Chemstations™ commercial process simulation software ChemCAD with variations in the mass flow rate of the energy conversion system. ChemCAD is a software that has been widely used for simulation, and calculation heat and mass balance of an energy conversion system [14,15].

2. Methodology
Conceptually, the RDE cooling system which also functions as an energy conversion system is shown in Figure 1. The heat energy generated from the reactor core is transferred to the secondary loop by a steam generator. Saturated steam that comes out of the steam generator is flowed into the steam turbine to be converted into mechanical energy which is then used to rotate the electricity generator to produce electricity.

![Figure 1. Flow diagram of RDE cooling system.](image-url)
In addition to safety system factors, the energy conversion system of HTGR can be ordered to be
cogeneration configuration [9]. In a cogeneration system, the efficiency of an energy conversion system
is not only calculated based on the ability of electricity generation, but also the ability to provide thermal
energy for other industrial uses. Thus, the performance of a cogeneration system could be expressed by
ATE and EUF [12].

The total thermal efficiency value is the result of the division between thermal energy for electricity
generation reduced by thermal energy to drive all components of the energy conversion system with
the thermal energy generated from the reactor. If all thermal energy is only used for electricity generation,
the value of total thermal efficiency can be expressed using equation (1) as follows [16]:

\[ \eta_t = \frac{\sum W_T - \sum W_C - \sum W_S}{Q_{in}} \times 100\% \]  

(1)

Where \( \eta_t \) is the value of thermal in the energy conversion system; \( \sum W_T \) is the output work of all turbine,
MW; \( \sum W_C \) is the consumption work of all compressor or pumps, MW; \( \sum W_S \) is the consumption work
of all system, MW; and \( Q_{in} \) is the heat absorbed in the reactor, MW.

In a cogeneration system, thermal efficiency is expressed ATE. ATE takes into account the quality
of heat and electricity, the value of ATE can be expressed using equation (2) as follows [12]:

\[ ATE = \frac{P_{net}}{Q_f - Q_h/\eta_{b,ref}} \times 100\% \]  

(2)

Where \( ATE \) is the artificial thermal efficiency; \( P_{net} \) is the net power output of the unit, MW; \( Q_f \) is the
total energy of the reactor, MW; \( Q_h \) is the net heat output of the unit, MW; \( \eta_{b,ref} \) is the efficiency of the
reference boiler, which chosen as 0.83.

The EUF value of an energy conversion system can be expressed using equation (3) as follows [17]:

\[ EUF = \frac{P_{net} + Q_h}{Q_f} \times 100\% \]  

(3)

Where \( EUF \) is the value of energy utilization factor; \( P_{net} \) is the net power output of the unit, MW; \( Q_h \) is the
net heat output of the unit, MW; \( Q_f \) is the total energy of the reactor, MW.

Simulation for analysing the performance of the RDE energy conversion system is carried out using
the ChemCAD computer program. The first step in the simulation process is to develop an RDE energy
conversion system model that also functions as an RDE cooling system as shown in Figure 1 based on
ChemCAD as shown in Figure 2. After the model is formed, the next step is to set the operating
parameters for the reactor and energy conversion system and all its main components.

Figure 2. The ChemCad-based RDE cogeneration energy conversion system model.
The main components that have the most influence on the performance of the energy conversion system are the reactor as a heat source and a steam generator that transfers heat from the primary cooling system to the secondary cooling system. The nominal data for the RDE reactor core is shown in Table 1, the data of the steam generator in Table 2, and other component data in Table 3. All of the parameter data refers to the BATAN document regarding the conceptual design of the RDE [6].

Table 1. The nominal data of reactor core [6].

| Parameter                          | Value | Unit   |
|------------------------------------|-------|--------|
| The thermal power of reactor power | 10    | MW     |
| Mean power density                 | 2     | MW/m³  |
| Reactor Core diameter              | 1.8   | m      |
| Mean core height                   | 2.0   | m      |
| Primary system pressure            | 30    | bar    |
| The primary coolant inlet temperature | 250 | °C    |
| The primary coolant outlet temperature | 700 | °C    |

Table 2. The data of steam generator [6].

| Parameter                              | Value | Unit |
|----------------------------------------|-------|------|
| A mass flow rate of the primary coolant | 4.4   | kg/s |
| The inlet temperature of the primary coolant | 700   | °C   |
| The outlet temperature of the primary coolant | 245   | °C   |
| Inlet pressure of the primary coolant   | ~30   | bar  |
| The mass flow rate of the steam        | ~4.0  | kg/s |
| The main steam temperature at SG outlet | 530   | °C   |
| Feed water temperature to SG           | 160   | °C   |
| The main steam pressure at SG outlet    | 60    | bar  |
| Tubes number in the SG                 | 93    |      |
| The outside diameter of the tube (OD)  | 23    | mm   |
| The area of heat transfer               | 70    | m²   |

Table 3. The other data of component for energy conversion system.

| Component | Input Parameter | Parameter value |
|-----------|-----------------|-----------------|
| Blower    | Irreversible Efficiency (η₁) | 90 % |
|           | Outlet Temperature (T<sub>out</sub>) | 245 °C |
| Turbine   | Irreversible Efficiency (ηᵢ) | 90 % |
| Condenser | Secondary Outlet Temperature (T<sub>out</sub>) | 35 °C |
| Pump      | Irreversible Efficiency (ηᵢ) | 90 % |
| Deaerator | Delta pressure | 2 bar |

The performance parameters are calculated based on thermodynamic data and the results of the simulation. ATE of the energy conversion systems is calculated using equation (2) while the EUF is calculated using equation (3).

3. Results and discussion
Simulation to analyse the performance of the RDE cogeneration energy conversion system is done by maintaining constant pressure on both the primary and secondary loops of 30 bar and 60 bar respectively.
The primary cooling system that contains helium gas as a cooling media serves to cool the reactor core or take heat from the reactor core to be transferred to the secondary cooling system which is then converted to mechanical energy in a steam turbine. In this simulation, the primary coolant mass flow rate is set according to its conceptual design is 4.4 kg/s [6]. All parameters of the main components of the RDE cogeneration system which include steam generators, steam turbines, coolers, and pumps are determined according to its conceptual design or user requirements documents of the RDE design.

The simulation using ChemCAD is done by varying the secondary coolant mass flow rate from 3.0 kg/s to 6.0 kg/s to find the optimal mass flow rate. Simulation results consist of thermodynamic and thermohydraulic parameters of the energy conversion system. By using equation (1), the thermal efficiency of the energy conversion system if it does not apply the cogeneration system can be calculated. The calculation result of the thermal efficiency for the energy conversion system is shown in Figure 3. The value of thermal efficiency is not only influenced by temperature and pressure but also is influenced by the mass flow rate of steam circulating through the turbine. As shown in Figure 3, the thermal efficiency increases when the steam mass flow rate is increased from 3.0 kg/s to 3.2 kg/s. At the steam mass flow rate of 3.2 kg/s, the highest thermal efficiency value is reached by 29%, then the thermal efficiency value continues to decrease if the steam mass flow rate continues to be increased.

![Figure 3](image-url)

**Figure 3.** Thermal efficiency as a function of the mass flow rate of the steam

The second simulation is carried out by maintaining the pressure and mass flow rate of the steam in the secondary cooling system while the fluid mass flow rate for supplying heat to the cogeneration system is made varied. For all simulations processes, the thermal-hydraulic parameter conditions in the primary cooling system are set to the same conditions. The thermal efficiency value is calculated based on simulation results using equation (2), this thermal efficiency value is often referred to as ATE. Besides ATE, the value of EUF is calculated using equation (3). The calculation results of the ATE and EUF values are shown as a graph in Figure 4. In the graph in Figure 4, it appears that the ATE value decreases while the EUF value increases when the rate of fluid mass flow in the cogeneration system increases. As shown in Figure 4, changes in ATE values and EUF values occur at fluid mass flow rates in the cogeneration system of less than 2.0 kg/s. At fluid, the mass flow rate in the cogeneration system above 2 kg/s, the ATE and EUF values remain relatively unchanged.
The value of thermal efficiency in Figure 3 compared to the ATE value in the cogeneration energy conversion system in Figure 4 shows that there is a significant difference in value. This is understandable because the thermal efficiency value is calculated for the energy conversion system without cogeneration, while the ATE value is calculated in the cogeneration energy conversion system cycle. The thermal efficiency value and the ATE value are also influenced by the efficiency of the steam generation in the steam generator and the remaining heat energy from the steam turbine which is then discharged through the cooler.

As shown in the graph in Figure 4, the EUF value increases from 40.0% to 66.0% if the fluid mass flow rate in the cogeneration system is increased. The EUF value illustrates the amount of heat energy generated from the reactor that can be utilized both for electricity generation and other uses. The EUF value of the 66.0% RDE cogeneration energy conversion system means that 66.0% of the thermal energy generated from the reactor can be effectively utilized. In other words, only 34.0% of the thermal energy generated from the reactor is wasted.

4. Conclusion

Simulations to analyse the performance of the RDE cogeneration energy conversion system have been carried out. The simulation is based on the design of the RDE cogeneration energy conversion system and predetermined design parameters. Simulation and calculation results show that by configuring cogeneration can increase the value of energy utilization factor up to 66.0%. The cogeneration system can increase energy utilization and save fuel because only 34.0% of thermal energy is discharged.

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