Effect of Superheated Steam Pressure on the Performance of RDE Energy Conversion System

Ign. Djoko Irianto, Sriyono, R. Kusumastuti, K. Santoso, H. Subiyah, A. Citra, S. Dibyo, Zuhair, S. Bakhri, G. R. Sunaryo

Center for Nuclear Reactor Technology and Safety
National Nuclear Energy Agency of Indonesia
Puspiptek Area, Building 80, Serpong, Tangerang 15310, Indonesia

Email: igndjoko@batan.go.id

Abstract. An experimental power reactor (RDE) is designed based on the high-temperature gas cooled reactor (HTGR) type with the thermal power of 10 MW. The energy conversion system of RDE is designed in a cogeneration configuration with a Rankine cycle to generate electricity and to supply a thermal energy for experimental purposes. The temperature of the reactor outlet is 700 °C and the temperature of the steam generator outlet is 530 °C. One of the performance parameters for energy conversion systems is thermal efficiency. To achieve better performance parameters of the RDE, optimization of thermal efficiency need to be determined. This research aims to optimize the thermal efficiency by conditioning the pressure of superheated steam in the turbine inlet. The calculation and analysis of cooling thermodynamic parameters and coolant system performance parameters are performed by simulation using ChemCad. The result shows that at 90 bar steam pressure and 3.3 kg/s cooling mass flow rate, the highest thermal efficiency was 29.21%. This thermal efficiency is higher than thermal efficiency at a pressure of 60 bar and the cooling mass flow rate of 3.2 kg/s. Therefore, a pressure of 90 bar can be considered as an operating parameter for the energy conversion system of RDE.

Keywords: Superheated steam pressure, performance, RDE, energy conversion system

1. Introduction

The experimental power reactor called Reaktor Daya Eksperimental (RDE) was designed to be built in Serpong [1]. This reactor is also designed for both experimental purposes and electrical generation supplying the BATAN’s area in Serpong [2]. The reactor is designed based on the high-temperature gas cooled reactor (HTGR) type with the thermal power of 10 MW. To support the design of RDE, some researches have been done. Tjahjono [3] has investigated the change of thermal parameters of RDE in response to the long-term of a station blackout. The thermal parameter changes of RDE showed that in long-term of station blackout condition, the reactor is still safe with the maximum core temperature of 1140 °C. Other previous research investigated the system performance, such as the normal operation and the start-up condition [4]. The operating parameter at the outlet of RDE steam generator has been investigated [5], the result shows that the superheated steam outlet temperature (void fraction = 1.0) is obtained in the range of 275.5 °C – 600 °C. The study on system component
designs has also been done such as the feedwater pump to the RDE steam generator [6]. It shows that optimal values of the performance characteristics feedwater pump were obtained when flow capacity was 4.8 kg/s.

There are two cycle models that can be used as energy conversion systems for RDE designed, that are a direct cycle which uses gas turbine and indirect cycle which uses steam turbine [7]. The energy conversion system which uses a steam turbine is known as the Rankine cycle [8], and the energy conversion system which uses a gas turbine is known as the Brayton cycle [9]. The energy conversion system of RDE is designed in cogeneration configuration of the indirect cycle or Rankine cycle.

One goal of the cogeneration concept is to increase the reactor utilization and to improve the performance of energy conversion systems [10,11]. There are some performance parameters for the energy conversion system, such as thermal efficiency and energy utilization factor (EUF). The thermal efficiency of energy conversion systems in the cogeneration cycle includes thermal efficiency for electricity generation and thermal efficiency for the other utilization of thermal energy [12,13]. The parameters that describe the performance of the cogeneration system is the total EUF [14,15]. The total EUF is the sum of each EUF of installation unit utilizing thermal energy. In a Rankine cycle, the thermal efficiency and EUF are greatly influenced by the performance of the intermediate heat exchanger which also functions as a steam generator [16].

For Nuclear Power Plant (NPP) which is only used for electricity generation, the total EUF is equal to the thermal efficiency of the NPP. The thermal efficiency of a nuclear power plant is defined exactly as with any other thermal generator where the heat thermodynamic cycle generated by the fuel is converted to steam through the steam generator. HTGR has different thermal efficiency ranges according to the thermodynamic cycle used. The Rankine cycle of HTGR system for small-scale nuclear power plants such as AVR Germany and HTR-10 has a thermal efficiency of around 30% [17], while for large-scale of NPP such as Peach Bottom 1 and Fort St. Vrain has a thermal efficiency of 39% [18]. The higher thermal efficiency can be achieved through gas turbine direct coupling from HTGR.

The thermal efficiency and EUF of all system are a measure that shows the performance of a power plant. Targets for high thermal efficiency in some modern power plants are regulated not only because of the economics but also to improve the performance of the power plant. To achieve the target of high thermal efficiency, there are several ways in the design of an energy conversion system of the power plant. The reactor's thermal efficiency can be increased by increasing the output temperature of the reactor [17] so that high exhaust heat can be utilized as cogeneration. This cogeneration concept in addition to producing electricity can also be used for industrial or other heat processes [19]. There are some ways to improve the thermal efficiency of the power plant. Some of them are reducing the condenser pressure, increasing pressure on the boiler and making supercritical vapor with high temperature [20,21]. Therefore, based on the fluid conditions in the RDE energy conversion system, the performance of the RDE energy conversion system applying the Rankine cycle still has the opportunity to be improved.

This research was conducted to find the optimal pressure of RDE energy conversion system using superheated vapor as working fluid in the secondary cooling system. This study becomes very important because there is no research on superheated vapor as a working fluid in the secondary cooling system of RDE. The study was conducted by a simulation using ChemCad 6.1.4 computer program package by varying the cooling system thermodynamic parameters including temperature, pressure, and mass flow rate. ChemCad software has been widely used in the modeling and simulation of energy conversion system [22,23].

2. Theory
The Rankine cycle is a steam power cycle that is ideally used to convert thermal energy into mechanical energy through a phase change process of working fluid. One of the main components in the Rankine cycle is the steam turbine. This system is often used in both steam power systems and nuclear power plants. In the Rankine cycle, the working fluid undergoes heating, evaporation,
expansion, cooling and compression processes. In the steam turbine cycle, there is a T-S diagram illustrating the relationship between temperature (T) and entropy (S) fluid under certain pressure, enthalpy, phase and density conditions. In the T-S diagram, there is a dome-shaped curved line called a steam dome, where the vertex of the steam vault is a critical point of the fluid. Since the liquid temperature reaches its critical temperature, the fluid change from the liquid phase to the gas (vapor) without evaporation.

As shown in Figure 1, there are three type T-S diagrams for three type of Rankine Cycles. Figure 1a shows the T-S diagram of simple Rankine cycle, Figure 1b shows the T-S diagram of the simple Rankine cycle with superheat, and Figure 1c shows the T-S diagram of the supercritical Rankine cycle [24].

![T-S Diagrams](image)

**Figure 1. T-S Diagram of Rankine Cycle [24]**

The thermal efficiency (\(\eta\)) of an energy conversion system can be shown by the ratio of working capacity divided by the heat entered into the system (\(Q_{in}\)). In the simple Rankine cycle, the work of system is the work of the turbine. Thus, the thermal efficiency of the Rankine cycle can be written as follows [24]:

\[
\eta = \frac{W_{turb}}{Q_{in}}
\]

where \(\eta\) is the thermal efficiency of the system, \(W_{turb}\) is the work of the turbine, and \(Q_{in}\) is the heat put into the system. In terms of enthalpy (h), as shown in Figure 1, the efficiency for the Rankine cycle with and without superheating can be defined by the following equations respectively:

\[
\eta_{simple} = \frac{h_3 - h_1 - h_4 + h_5}{h_3 - h_1}
\]

\[
\eta_{superheat} = \frac{h_4 - h_1 - h_5 + h_6}{h_4 - h_1}
\]

The thermal efficiency of the Rankine cycle which uses a steam turbine can be greatly improved by operating in the supercritical region of the coolant. As the temperature and vapor pressure are increased beyond the critical point, the thermodynamic properties will change very drastically, this is called the condition of the supercritical fluid. A supercritical fluid is not in the gas or liquid phase but it is between the gas and liquid phases. The supercritical Rankine steam cycle is shown in the equation below:

\[
\eta_{supercritical} = \frac{h_2 - h_1 - h_3 + h_4}{h_2 - h_1}
\]

### 3. Nuclear Steam Supply System

The Experimental Power Reactor (RDE) is a nuclear reactor designed of TRISO-fueled HTGR type and cooled by helium-gas. As an experimental power reactor, this reactor is designed could be used in cogeneration configuration to generate electricity and to supply thermal energy for industrial process
experiments. The nominal thermal power of this nuclear reactor is 10 MW. There are two steam turbines mounted serially in the secondary cooling cycle as components of the energy conversion system [25]. The hot vapor duct for the cogeneration cycle can be taken before the first turbine or between the two turbines.

The helium gas as reactor coolant flows out of the reactor at a temperature of 700 °C, the pressure of 30 bar, and with a mass flow rate of 4.4 kg/s [5]. The thermal energy of helium gas is transferred through the steam generator to convert water into superheated steam. Superheated steam is circulated in a secondary cooling system through two steam turbines to drive an electric generator to generate electricity. From the steam turbines, steam flows to the condenser and undergoes phase changes from steam to water. Water with a temperature range of 110 °C to 160 °C will be fed back to the steam generator [5]. In the secondary pump inlet, a feed water tank is installed that also serves as a water separator with vapor. Water from the secondary cooling system enters the steam generator and exits from the steam generator as a superheated steam at a temperature of 530 °C at 60 bar pressure with a flow rate of 4.0 kg/s.

The reactor and steam generator data in this analysis are shown in Table 1 and Table 2 [26]. The flow diagram of the reactor coolant system from the reactor vessel to the nuclear steam supply system that also serves as a coolant of the reactor of RDE is shown in Figure 2 [26].

![Figure 2. Schematic of RDE Cooling System [26]](image)

| Parameter                          | value | unit |
|------------------------------------|-------|------|
| Reactor power (thermal)            | 10    | MW   |
| Mean power density                 | 2     | MW/m³|
| Core diameter                      | 1.8   | m    |
| Mean core height                   | 2.0   | m    |
| Primary system pressure            | 30    | bar  |
| Reactor outlet temperature         | 700   | °C   |

Table 1. The Data of Reactor [27]
Table 2. Data of Steam Generator [26]

| Parameter                                      | value | unit |
|------------------------------------------------|-------|------|
| Primary coolant mass flow                      | 4.4   | kg/s |
| Primary coolant inlet temperature              | 700   | °C   |
| Primary coolant outlet temperature             | 245   | °C   |
| Primary coolant inlet pressure                 | ~30   | bar  |
| The mass flow rate of steam                    | ~4.0  | kg/s |
| Main steam temperature                         | 530   | °C   |
| Feed water temperature                         | 160   | °C   |
| The main steam pressure at SG outlet           | 60    | bar  |
| Number of tubes                                | 93    |      |
| Tube outside diameter (OD)                     | 23    | mm   |
| Heat transfer area                              | 70    | m²   |

4. Methodology

Performance analysis of RDE energy conversion system is performed by simulation using the computer code ChemCad 6.1.4. The first step of simulation is configuring the model of RDE energy conversion system as shown in Figure 2 using ChemCad 6.1.4. The model of RDE energy conversion system that has been configured with ChemCad 6.1.4 is shown in Figure 3. Each component parameter of RDE energy conversion system which is used as an input parameter in the simulation is shown in Table 3. In this simulation, deaerator is installed at the inlet of the steam generator as hot water preheater so that the water temperature before entering the steam generator reached 160 °C.

The simulation is done through several stages. The first stage, simulated with a secondary pressure variation from 30 bar to 370 bar with 20 bar pressure increase. The secondary mass flow rate is set to maintain the steam generator outlet temperature of about 530 °C. The second stage simulation was performed with variations in secondary mass flow rate from 3 kg/s to 5 kg/s for 3 secondary system pressure conditions i.e. 60 bar, 90 bar, and 120 bar. The thermal efficiency value of the energy...
conversion system is calculated for each condition of the simulation. The performance of the energy conversion system can be demonstrated by the value of thermal efficiency.

Table 3. Input Parameter For Simulation

| Component       | Input Parameter            | value      |
|-----------------|-----------------------------|------------|
| Reactor         | Reactor Power (Q)           | 10 MW<sub>th</sub> |
|                 | Outlet Pressure (P<sub>out</sub>) | 30 bar   |
| Blower          | Irreversible Efficiency (η<sub>i</sub>) | 90 %      |
|                 | Outlet Temperature (T<sub>out</sub>) | 245 °C    |
| Steam Generator | Primary Inlet Temperature (T<sub>in He</sub>) | 700 °C    |
|                 | Secondary Inlet Temperature (T<sub>in water</sub>) | 160 °C    |
|                 | Secondary Outlet Temperature (T<sub>out steam</sub>) | 530 °C    |
| Turbine         | Irreversible Efficiency (η<sub>i</sub>) | 90 %      |
| Condenser       | Secondary Outlet Temperature (T<sub>out</sub>) | 35 °C      |
| Pump            | Irreversible Efficiency (η<sub>i</sub>) | 90 %      |
| Deaerator       | Delta pressure              | 2 bar      |

5. Results And Discussion

One of the goals of this performance analysis is to know the optimal conditions of the energy conversion system using a Rankine cycle. The performance analysis of the RDE energy conversion system has been done by simulation using ChemCad 6.1.4 computer program. Simulation has been done by varying the secondary pressure to get the optimal pressure and then varying the mass flow rate of the coolant in the secondary cooling system from 3 kg/s to 5 kg/s for 3 secondary system pressure conditions i.e. 60 bar, 90 bar, and 120 bar. The simulation results are shown in graphical form as shown in Figure 4, Figure 5, and Figure 6.

![Figure 4. The thermal efficiency of the RDE energy conversion system as a function of pressure](image1)

![Figure 5. Thermal efficiency as a function of the coolant mass flow rate at various pressure conditions](image2)
The thermal efficiency of the energy conversion system as described in equation (1) is the result of the division between the turbine work and the thermal energy generated by the energy source that is the reactor. Referring to Figure 1, the work of the turbine can be improved by regulating the steam conditions entering the turbine. The work of the turbine will increase by regulating superheated steam conditions or even supercritical steam. The steam conditions could be determined by temperature and pressure of the steam. This property of steam opens up the opportunity to increase the thermal efficiency of the RDE by regulating the steam temperature and pressure entering the turbine.

The simulation results shown in Figure 4 show a graph of thermal efficiency as a function of secondary coolant pressure. Simulation of RDE energy conversion system was performed by varying the steam pressure entering the turbine from a pressure of 30 bar to 370 bar with increasing pressure 20 bar at an outlet temperature of the steam generator is $530.46^\circ C$. Simulation results showed that at 30 bar secondary cooling pressure, the thermal efficiency of RDE generated by the energy conversion system was 26.66%.

As shown in the graph in Figure 4, the value of the thermal efficiency can be increased by increasing the steam pressure of the secondary cooling system. At a 90 bar secondary cooling pressure, the thermal efficiency value reached the highest of 29.21% with a secondary coolant mass flow rate of 3.3 kg/s. If the secondary coolant pressure continues to be increased, the RDE's thermal efficiency will decrease. It can be understood that by increasing the steam pressure entering the turbine while the steam temperature outlet of the steam generator is kept constant, the steam state turns into wet steam (condense). With steam conditions getting wet the turbine speed and turbine power will decrease.

The phenomenon of the relationship between steam pressure and thermal efficiency of the energy conversion system can be explained by changes in steam conditions. An increase in steam pressure entering the turbine will result in an increase in the value of the steam enthalpy. Under conditions of constant condenser pressure, the increase in steam enthalpy causes an increase in turbine power. So overall the increase in steam pressure on turbines will result in improved efficiency of the whole energy conversion system. According to the phenomenon, the thermal efficiency of RDE has an opportunity to increase by varying the steam pressure parameters or theoretically will continue to increase in supercritical steam conditions. For steam conditions that are getting dry or in supercritical conditions, turbine performance or turbine efficiency will increase. In addition, with dry steam or supercritical vapor coming into the turbine, will cause the turbine to be more durable.
The simulation results shown in Figure 5 show the value of thermal efficiency as a function of the secondary coolant mass flow rate. The simulation was done by variation of secondary coolant mass flow rate for three steam pressure condition i.e. 60 bar, 90 bar, and 120 bar. The simulation results show that in addition to steam pressure, thermal efficiency is also influenced by the secondary coolant mass flow rate. At low secondary coolant mass flow rate, the thermal efficiency is also low. Thermal efficiency will increase if the secondary coolant mass flow rate is increased. At a certain secondary coolant mass flow rate, the maximum thermal efficiency value is obtained, then thermal efficiency decreases if the mass flow rate is increased. As shown in Figure 5, the highest thermal efficiency value is 29.21% at a steam pressure of 90 bar and at 3.3 kg/s secondary coolant mass flow rate. At the steam pressure of 60 bar, the maximum thermal efficiency is 29.01% at a secondary coolant mass flow rate of 3.2 kg/s, and the vapor pressure of 120 bar, the maximum thermal efficiency is 29.19% at a secondary coolant mass rate of 3.5 kg/s. From the simulation results, as shown in Figure 5, it is seen that there is a certain value pair of steam pressure and cooling mass flow rate to obtain the highest thermal efficiency value. Figure 4 shows that the 90 bar pressure is the optimal vapor pressure to produce the highest thermal efficiency. If the steam pressure is 90 bar, then the optimum coolant mass flow rate is 3.3 kg/s as shown in the simulation model in Figure 7.

![Figure 7. Simulation model at the pressure 90 bar.](image)

As an experimental power reactor, RDE is built not only as a power station but also for supplying thermal energy for experimental purposes. Therefore, the thermal energy supplied after the exhaust from the turbine should be sufficient for industrial processes. The simulation results shown in Figure 6 are carried out in 3 pressure conditions, namely 60 bar, 90 bar, and 120 bar. The simulation results show that at the secondary cooling mass flow rate is low, the outlet temperature of the steam generator for the three pressure conditions is almost the same, and begins to show a difference if the secondary cooling mass flow rate is increased. From the results of this simulation it is shown that at a low secondary cooling mass flow rate, the pressure does not affect the steam temperature output from the steam generator.

6. Conclusion
From this research, it can be concluded that the application of superheated steam on the RDE energy conversion system enhances the thermal efficiency of the whole system by adjusting the vapor pressure and cooling mass flow rate. The simulation results showed that the steam pressure of 3.3 kg/s cooling mass flow rate and temperature of 530.46°C, the highest thermal efficiency are obtained at 90
bar. The highest thermal efficiency is 29.21%, which is higher than at 60 bar pressure and mass flow rate of 3.2 kg/s.

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