PERFORMANCE ANALYSIS OF RANKINE CYCLE USING SUPERCRITICAL STEAM FOR ENERGY CONVERSION SYSTEM OF RDE

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ABSTRACT

PERFORMANCE ANALYSIS OF RANKINE CYCLE USING SUPERCRITICAL STEAM FOR ENERGY CONVERSION SYSTEM OF RDE. The energy conversion system in the experimental power reactor (RDE) is designed using a steam turbine or in a cogeneration configuration with a Rankine cycle. This energy conversion system also functions as a reactor coolant system that implements an indirect cycle. Between the primary cooling system and the secondary cooling system is mediated by a heat exchanger that acts as a steam generator (SG). The temperature of the reactor outlet is 700 ^{o}C and the temperature of the steam generator outlet is 530 ^{o}C with the pressure of 60 bar. One of the performance parameters for energy conversion systems is thermal efficiency. This research aims to study the possibility of increasing thermal efficiency by conditioning the supercritical vapor in the turbine inlet. The analysis and calculation of cooling thermodynamic parameters and coolant system performance parameters are performed using ChemCAD computer software. A simulation using ChemCAD for the RDE energy conversion system by conditioning the supercritical vapor at various pressure variations obtained that the highest thermal efficiency of 29.41 % occurred at supercritical vapor conditions with a pressure of 270 bar. This thermal efficiency is about 2.5 % higher than thermal efficiency at a pressure of 60 bar. Therefore a pressure of 270 bar can be considered as an operating parameter for the Rankine cycle on RDE.

Keywords: experimental power reactor, cooling system, ChemCAD, thermal efficiency

ABSTRAK

ANALISIS PERFORMA SIKLUS RANKINE MENGGUNAKAN UAP SUPERKRITIS UNTUK SISTEM KONVERSI ENERGI RDE. *Sistem konversi energi pada reaktor daya eksperimental (RDE) didesain menggunakan turbin uap atau dalam konfigurasi kogenerasi dengan siklus Rankine. Sistem konversi energi ini juga berfungsi sebagai sistem pendingin reaktor yang menerapkan siklus tak langsung. Antara sistem pendingin primer dan sistem pendingin sekunder diperantarai oleh penukar panas yang berfungsi sebagai pembangkit uap (steam Generator = SG). Temperatur outlet reaktor adalah 700 ^{o}C dan temperatur outlet pembangkit uap 530 ^{o}C dengan tekanan 60 bar. Salah satu parameter performa untuk sistem konversi energi adalah efisiensi termal. Penelitian ini bertujuan untuk mempelajari kemungkinan menaikkan efisiensi termal dengan mengkondisikan uap superkritis pada inlet turbin. Analisis dan perhitungan parameter termodinamika pendingin dan parameter performa sistem pendingin dilakukan dengan menggunakan perangkat lunak komputer ChemCad. Simulasi menggunakan ChemCad untuk sistem konversi energi RDE dengan mengkondisikan uap superkritis pada berbagai variasi tekanan diperoleh bahwa efisiensi termal tertinggi sebesar 29,41 % terjadi pada kondisi uap superkritis dengan tekanan 270 bar. Efisiensi termal ini lebih tinggi sekitar 2,5 % dibanding efisiensi termal pada tekanan 60 bar. Karena itu tekanan 270 bar dapat dipertimbangkan sebagai parameter operasi untuk siklus Rankine pada RDE.*

Kata kunci: *Reaktor Daya Eksperimental, sistem pendingin, ChemCAD, efisiensi termal*

INTRODUCTION

RDE (Reaktor Daya Eksperimental) is an experimental power reactor that is designed based on the high-temperature gas cooled reactor (HTGR) type with the thermal power of 10 MW. As a research reactor, RDE is being designed and planned to be built inside the Puspiptek area in Serpong [1]. This reactor is also designed to be capable of supplying electrical energy to the BATAN area in Serpong and supplying thermal energy for the experimental purpose. There are two cycles of energy conversion systems that are direct cycles which use gas turbines and indirect cycles which use steam turbines. An energy conversion system which uses a steam turbine is known as the Rankine cycle [2], and an energy conversion system which uses a gas turbine is known as the Brayton cycle [3]. The energy conversion systems of RDE is designed using a configuration of indirect cogeneration cycle or Rankine cycle.

One goal of the cogeneration concept is to differs the utilization and to improve the performance of energy conversion systems [4]. One of the performance parameters for energy conversion system is thermal efficiency. 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 [5–8]. The parameters that describe the performance of the cogeneration system are the total energy utilization factor (EUF) [9]. The total EUF is the sum of each EUF of installation unit utilizing thermal energy. 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 efficiency ranges according to the thermodynamic cycle used [10]. The Rankine cycle of HTGR system for small-scale nuclear power plants such as AVR Germany and HTR-10 has an efficiency of around 30 % [10], while for large-scale NPPs such as Peach Bottom 1 and Fort St. Vrain has an efficiency of 39 % [11]. The highest efficiency can be achieved through gas turbine direct coupling from HTGR.

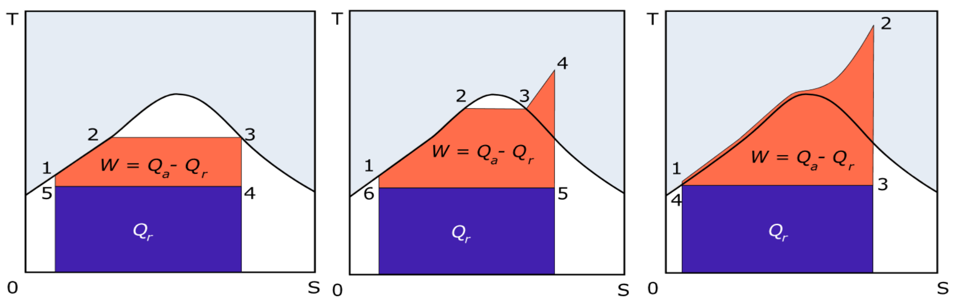
The thermal efficiency and EUF of all system is a measure that shows the performance of a plant. Targets for high efficiency in some modern power plants are regulated not only because of the economics but also to improve the performance of the plant. To achieve the target of high efficiency, there are several ways in the design of energy conversion system of the power plant. The reactor's thermal efficiency can be increased by increasing the output temperature of the reactor 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 [12]. Then the second way is the improvement of heat loss that occurs in the heating system generator. Meanwhile, to increase the thermal efficiency of the power plant there are various ways such as reducing condenser pressure, increasing pressure on the boiler and making supercritical vapor with high temperature [13, 14].

The thermal efficiency of RDE that implements steam turbine systems still has an opportunity to improve. This research is conducted in an effort to increase the thermal efficiency of RDE reactor using a simulation of the supercritical fluid condition. This research becomes very interesting due to the absence of studies on the supercritical condition of RDE. The simulation is done by using ChemCAD 6.1.4 computer program package which is widely used in system process simulations for optimization [15–17].

THEORY

The Rankine cycle is a steam power cycle used to or steam engine working process on the working fluid. Rankine cycle systems are most commonly used in steam power plants and nuclear power plants. Working fluids undergo 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) of fluid under certain pressure, enthalpy, phase and density conditions. In the T-S diagram, there is a dome shaped curved line called the steam dome, where the vertex of this vapor dome is a critical point of the fluid. As the temperature of the fluid reaches its critical temperature, the fluid changes from the liquid phase to the gas (vapor) without evaporation.

As shown in Figure 1, there is three type T-S diagram 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. [18]



T-S Diagram in Simple Rankine Cycle

T-S Diagram in Simple Rankine Cycle with Superheat

T-S Diagram in Supercritical Rankine Cycle

Figure 1. T-S Diagram of Rankine Cycle [18]

Steam turbine cycles can be improved its thermal efficiency by changing the steam conditions into supercritical. 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 is between the gas and liquid phases.

NUCLEAR STEAM SUPPLY SYSTEM

The Experimental Power Reactor (RDE) is a reactor designed of TRISO-fueled HTGR type and helium-gas refrigerated. RDE is thermally powered at 10 MW and generates about 3 MW of electricity. The helium gas enters the reactor at 250 °C, and then exits from the reactor at 700 °C and 30 bar with a coolant mass flow rate of 4.4 kg/s as shown in Table 1 [19, 20]. The schematic of flow coolant 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 [20]. Water from the secondary cooling system enters the steam generator and exits a saturated vapor with a temperature of 530 °C at 60 bar pressure with a flow rate of 4.0 kg/s. The saturated steam from the steam gene-rator leads to a turbine that is coupled to the generator to generate electricity. Steam turbine process results in condenser condensed so that the phase changes from steam to water. Water with a temperature of 160 °C will be fed back to the steam generator as presented in Table 2.

Table 1. Data of reactor[20]

Parameter	value	unit
Reactor power (thermal)	10	MW
Mean power density	2	MW/m^3
Core diameter	1.8	m
Mean core height	2.0	m
Primary system pressure	30	bar
Primary coolant temperature (inlet/outlet)	250/700	^oC

Table 2. Data of steam generator [20]

Parameter	value	unit
Primary coolant mass flow	4.4	kg/s
Primary coolant inlet temperature	700	^oC
Primary coolant outlet temperature	245	^oC
Primary coolant inlet pressure	~ 30	bar
Mass flow rate of steam	4.0	kg/s
Main steam temperature	530	^oC
Feed water temperature	160	^oC
Main steam pressure at SG outlet	60	bar
Number of tubes	93	
Tube outside diameter (OD)	23	mm
Heat transfer area	70	m^2

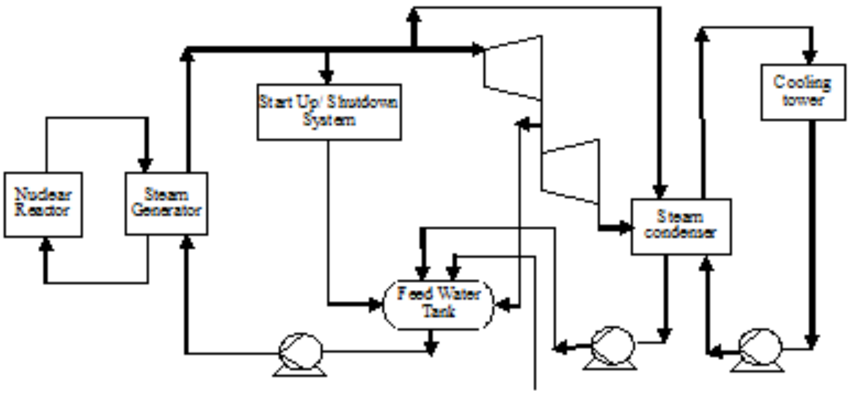


Figure 2. Schematic of RDE Cooling System [20]

METHODOLOGY

Performance analysis of the supercritical Rankine cycle is performed by simulating the RDE cooling system using the ChemCAD. The cooling system of RDE as shown in Figure 2 was be modeled using ChemCAD to become the model as in Figure 3. The input parameter of each component for the simulation is shown in Table 3.

However, in the simulation used in this study plus deaerator as hot water preheater before entering the steam generator so that the temperature of the water produced reached 160 °C. The simulation result showed that the value of mass flow rate, turbine work, and thermal efficiency can be calculated. In addition, it is possible to know the parameters of pressure, temperature, enthalpy and mass flow rate coming out of each component as described in the description in Figure 3.

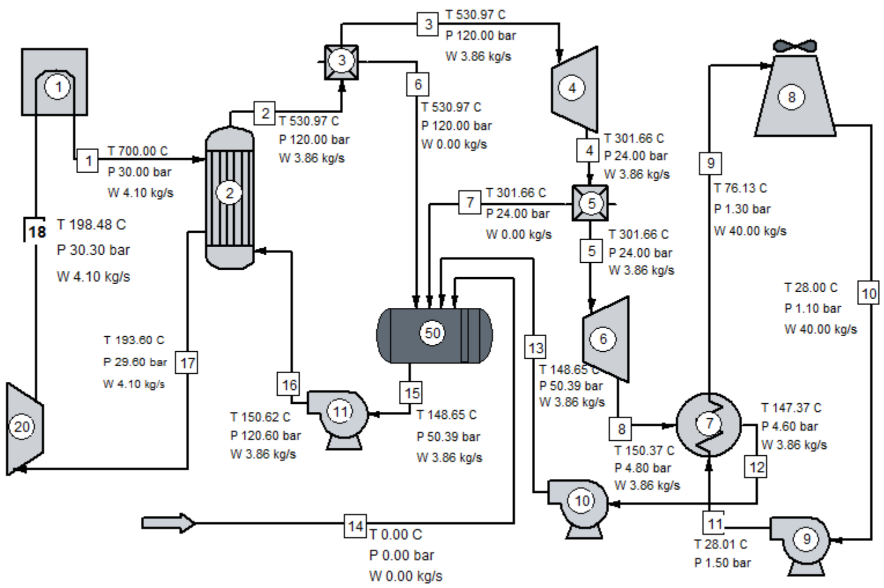


Figure 3. Model of RDE Cooling System Using ChemCAD

Table 3. Input Parameter For Simulation

No	Component	Input Parameter	Value
1.	Reactor	Reactor Power (Q)	10 MW_{th}
		Outlet Pressure (P_{out})	40 bar
2.	Blower	Irreversible Efficiency (h_i)	90 %
		Outlet Temperature (T_{out})	245 ^oC
3.	Steam Generator	Primary Inlet Temperature ($T_{in\ He}$)	700 ^oC
		Secondary Inlet Temperature ($T_{in\ water}$)	160 ^oC
		Secondary Outlet Temperature ($T_{out\ steam}$)	530 ^oC
4.	Turbine	Irreversible Efficiency (h_i)	90 %
5.	Condenser	Secondary Outlet Temperature (T_{out})	35 ^oC
6.	Pump	Irreversible Efficiency (h_i)	90 %
7.	Deaerator	Delta pressure	2 bar

Then to improve the thermal efficiency of the RDE operating conditions simulations were performed using the supercritical steam power steam pressure parameters at the same temperature of 530 °C as a comparison to the RDE component. In the simulation, the base pressure of RDE operation is 60 bar up to the supercritical steam power plant of 271 bar. While for the observation given the pressure is greater than the supercritical is 415 bar.

RESULTS AND DISCUSSION

Simulation result of the RDE cooling system using the ChemCAD 6.1.4 computer package program to the analysis of the performance of the supercritical Rankine cycle is shown in Table 4. Then the opportunity to increase the thermal efficiency of RDE, the varying parameters in the simulation is the pressure in the condition of supercritical vapors. Since the steam generator pressure out of the steam generator on RDE is 60 bar, the pressure conditions in the simulation using ChemCAD 6.1.4 on the pressure range 60 (as the base of HTGR -10MWth), 120, 180 and 271 (the base of supercritical conditions based on the reference plant [21]), 335, 415 bar with the same temperature.

The application of RDE operating conditions of the steam turbine cycle after simulation obtained a thermal efficiency value of 26.91 % with turbine work of 2869.666 kW as the base of RDE 530.810 ° C. In this study there is more pressure than the supercritical fluid pressure of the power plant for the observation point, which has a steam operating condition of 560 °C and a pressure of 271 bar with an efficiency of 29.41 %.

From Figure 4, it can be seen that the increase in pressure at the base pressure of RDE to the observation pressure (supercritical condition at a pressure of 271 bar) is followed by an increase in generator efficiency. Then the addition of pressure from 335 to 415 bar shows a clining efficiency trend. In this study it can be seen that the highest efficiency can be achieved is 29.41 % at 271 bar pressure, which is increased by 2.50 % of the base efficiency.

Table 4. The result of simulation in the condition supercritical steam

Pressure (bar)	**60**	**120**	**180**	**271**	**335**	**415**
Temperature (^oC)	530.810	530,97	530,62	530,59	530,17	531,69
Mass Flowrate (kg/s)	3.450	3,86	4,19	4,38	4,54	4,74
Enthalpy (kJ/kg)	-43.124	-48,447	-52,873	-55,71	-58,178	-61,23
Turbine Work 1 (kW)	-1664.827	-1779,47	-1836,7314	-1763,0696	-1699,4377	-1599,8839
Turbine Work 2 (kW)	-1204.839	-1302,8	-1369,391	-1361,3534	-1359,0962	-1367,6334
Pump Work (kW)	6,3663	21,3854	18,3773	35,9597	37,2639	56,3859
Power Reactor (kW)	10,6628	10,6829	10,9711	10,6239	10,5897	10,6244
Efficiency (%)	26,91%	28,85%	29,22%	29,41%	28,88%	27,93%

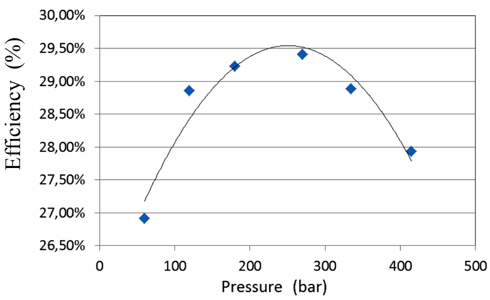


Figure 4. Graph of efficiency as a function of pressure

The phenomenon of pressure relation with efficiency can be explained that the higher steam pressure of turbine entering the thermal efficiency will increase as shown in Table 4. The increase of vapor pressure entering the turbine will result in the increase of the vapor enthalpy value. Under conditions of constant condenser pressure, the increase in vapor enthalpy results in an increase in turbine power. So that the overall increase in steam pressure in the turbine will result in increased efficiency of the plant.

The efficiency of the generator at a pressure of 335 bar observations indicates a decrease from previous observational pressure. This decrease is due to power consumption for pump and blower to turbine power is higher than the base condition. So the efficiency of the observation point at 335 bar pressure is lower than the observation point pressure of 271 bar.

Although supercritical steam applications have been performed on the energy conversion system of RDE, the optimum efficiency improvement in RDE is 29.41 %. Efforts to increase the efficiency of these plants cost more, considering the components (pumps and turbines) and materials designed specifically to work well at high temperatures and pressures.

CONCLUSION

From this study, it can be concluded that the application of a supercritical steam on RDE provides an effect of increasing overall generator efficiency from its base. Then the optimum operating conditions which provide the highest efficiency (29.41 %) is at a pressure of 271 bar with a temperature of 530.59 °C.

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