ISSN: 2355-7524

THE CONDENSING STEAM TURBINE CASE STUDY FOR A 10 MW_{th} EXPERIMENTAL POWER REACTOR

Sri Sudadiyo, Syaiful Bakhri, Geni Rina Sunaryo
Center for Nuclear Reactor Technology and Safety, BATAN
Kawasan PUSPIPTEK Building 80, Serpong, Tangerang 15310
Telp/Fax: (021)7560012/(021)7560913, E-mail : sudadiyo@batan.go.id

ABSTRACT

THE CONDENSING STEAM TURBINE CASE STUDY FOR A 10 MW_{th} EXPERIMENTAL POWER REACTOR. A 10 MW_{th} Experimental Power Reactor (RDE) cooling system integrates helium blower cycle as primary circuit and steam turbine cycle as secondary circuit. This system can achieve higher thermal efficiency and mechanical power through proper utilization of energy by minimizing the energy loss towards a minimum. In this study, effect of the condensing steam turbine operational load such as steam pressure, condenser pressure, and turbine inlet temperature on power output and thermal efficiency of RDE is investigated. Outcome of this study can be utilized in order to simplify RDE's conceptual design with preferable values of efficiency and power. A Cycle-Tempo simulation has been carried out to study effects of the above mentioned parameters on steam turbine cycle. Various components of primary and secondary circuits are modeled including steam generator, blower, pump, condenser, turbine and generator. On this paper, turbine types of SST-60, SST-100, SST-111, SST-300, and SST-600 are used for simulation. Conservation method is proposed to solve equations of mass, momentum and energy for obtaining flow properties of helium in blower cycle and water/steam in turbine cycle. For a case of SST-100, simulation results offer values of turbine efficiency 92.26 %, optimum thermal efficiency 25.5 %, and mechanical power 3650.52 kW under blower speed 3255 rpm. Components characteristics of steam generator, condenser, and pump are also shown by presenting good results for attainable performance.

Keywords: 10 MW_{th} RDE, Rankine cycle, steam turbine, condenser, efficiency

ABSTRAK

STUDI KASUS TURBIN UAP KONDENSASI UNTUK REAKTOR DAYA EKSPERIMENTAL 10 MW_{th}. *Sistem pendingin Reaktor Daya Eksperimental (RDE) 10 MW_{th} mengintegrasikan siklus blower helium sebagai sirkuit primer dan siklus turbin uap sebagai sirkuit sekunder. Sistem ini dapat mencapai effisiensi termal dan tenaga mekanis yang lebih tinggi melalui pemanfaatan yang tepat dari energi dengan meminimalkan kehilangan energi menuju minimum. Dalam penelitian ini, pengaruh beban operasional turbin uap kondensasi seperti tekanan uap, tekanan kondensor, dan temperatur masuk turbin terhadap keluaran daya dan efisiensi termal RDE diinvestigasi. Hasil studi ini dapat dimanfaatkan untuk menyederhanakan desain konsep RDE dengan nilai efisiensi dan tenaga lebih sesuai. Simulasi Cycle-Tempo telah dilakukan untuk meneliti pengaruh parameter yang disebutkan di atas pada siklus turbin uap. Berbagai komponen dari sirkuit primer dan sekunder dimodelkan termasuk generator uap, blower, pompa, kondensor, turbin dan generator. Pada makalah ini, jenis turbin SST-60, SST-100, SST-111, SST-300, dan SST-600 digunakan untuk simulasi. Metode konservasi digunakan untuk menyelesaikan persamaan massa, momentum dan energi untuk memperoleh sifat aliran helium dalam siklus blower dan air/uap dalam siklus turbin. Untuk kasus SST-100, hasil simulasi memberikan nilai efisiensi turbin 92,26 %, efisiensi termal optimum 25,5 %, dan tenaga mekanis 3650,52 kW pada putaran blower 3255 rpm. Karakteristika komponen dari generator uap, kondensor, dan pompa juga ditunjukkan dengan menampilkan hasil yang baik untuk kinerja yang dicapai.*

Kata kunci: RDE 10 MW_{th}, siklus Rankine, turbin uap, kondensor, efisiensi

INTRODUCTION

The cooling technology of RDE utilizes helium in primary circuit and water/steam in secondary circuit as working fluids to achieve efficient, reliable, and economical power generation [1]. Primary circuit has a source of high temperature and discards heat at a high temperature that can easily be used by secondary circuit as a source of energy. Primary circuit employs blower so that it was also called by helium blower cycle and secondary circuit uses turbine so that it was named with steam turbine cycle. Helium blower cycle and steam turbine cycle are compatible with each other and can be combined in such a way as to attain a 10 MW_{th} RDE power plant [2, 3]. Blower is the cooling circulator device of RDE that works to raise pressure and be placed generally within steam generator chamber [3]. In blower, helium gas streamed under operation conditions of high temperature (about 250 °C) so that the occurred pressure difference is going to provide susceptible effects to steam turbine cycle. Secondary circuit or steam turbine cycle is a steam power plant that has key components of steam generator, feed pump, and condensing turbine [3, 4].

In the 10 MW_{th} RDE, nuclear fuel with pebble type is a major source of energy for making high temperature helium (700 °C) which can be used to produce steam to generate mechanical power in turbine cycle (steam power plant) [5, 6]. Efficiency enhancement of RDE to electric power generation is major issue of turbine cycle therefore implementation for energy conservation is very important. Energy conservation is mainly focused in energy efficiency [7, 8]. Efficiency is a property that enables to determine useful work for energy amount at specified circumstance. Usefulness of turbine cycle depends on each component conditions. Additionally, it had been known that optimum variables which are associated with steam turbine cycle may be highly affected by conditions of operating and performance of the condensing turbine. So, upon RDE, higher efficiency level can be achieved by incorporating enhancements in turbine cycle such as pressure and temperature of turbine, and vacuum pressure of condenser.

Steam turbine cycle consists of following four processes; isobaric heat addition within a steam generator, isentropic expansion in a turbine, isobaric heat rejection in a condenser, and isentropic compression in a pump. Specifically, the condensing turbine remains among one of key components of a secondary circuit that affect RDE performance. Main function of turbine is to expand into vacuum pressure at condenser entry so that specific power outturn of turbine could be increased. In this study, turbine types of SST-60, SST-100, SST-111, SST-300, and SST-600 were considered as representative of the condensing turbine technology [9]. Furthermore, computer program Cycle-Tempo is used to simulate model of this 10 MW_{th} RDE. Optimum operational conditions can be determined by calculating maximum power output by means of putting thermodynamic parameters on suitable input window of Cycle-Tempo and modeling components that affect performance significantly. The purpose of this case study is to analyze effect of the condensing turbine load on secondary circuit and to present a Cycle-Tempo simulation based on investigation of variations of power output and thermal efficiency on operating parameters such as steam pressure, condenser pressure, and turbine inlet temperature. A methodology is applied to solve the conservation equations of mass, momentum and energy.

THEORY

Figure 1 shows a RDE schematic diagram with primay circuit and secondary circuit, which reactor core could generate thermal power of 10 MW_{th} up to temperature 700 °C. In this figure, helium gas at 1 is circulated to a slightly higher pressure at 2 where helium enters reactor core, and is heated using pebble fuel, resulting in a hot helium at 3 [10]. Hot helium at 3 flows through steam generator, to blower at 1. Hot helium enters to steam generator to transfer heat to water/steam and exits at turbine inlet temperature at 4. Steam at turbine inlet expands to a lower pressure and temperature at 5. Steam at 5 with low pressure and low temperature will condensate in condenser to saturated water. Saturated water, out of condenser at 6 is pumped to a high pressure at steam generator. Then the condensing turbine supplies a power for an generator in producing electricity. Figure 2 shows a diagram of temperature versus enthalpy for turbine cycle at proposed RDE. Blower efficiency can be developed by considering isentropic process to pressure ratio. Ideal and actual processes of turbine expansion are also shown in Fig. 2. Key components of RDE are as follows :

- **Helium Blower Model :**

Compression ratio of blower is given as [11, 12]

$$r_P = P_2 / P_1 \quad (1)$$

where r_P is compression ratio, P_1 is initial pressure before compression, and P_2 is pressure after compression. Isentropic efficiency of blower (η_B) can be given as [11]

$$\eta_B = (T_2 - T_1) / (T_{2a} - T_1) \quad (2)$$

where T_1 is blower inlet temperature, T_2 is temperature at isentropic process, and T_{2a} is temperature at actual process. Blower work (W_B) can be calculated as [11]

$$W_B = (c_P\, T_1\, R) / \eta_m \quad (3)$$

where η_m is blade efficiency, R is blower characteristic constants, and c_P is specific heat.

- **Reactor Core Model :**

Reactor core is fed with high pressure helium which is being heated at constant pressure before being passed through hot gas duct to steam generator [5, 10]. Core operation is based on energy balance [10, 11],

$$Q_R = m_{he}\, c_P\, (T_3 - T_2) \quad (4)$$

where Q_R is thermal energy of core, m_{he} is helium mass flow rate, and T_3 is core outlet temperature. Design parameters of RDE are listed in Table 1.

Table 1. Parameter design in current study [5, 10]

Item	Unit	Value
Thermal power	MW_{th}	10
Helium temperature at reactor inlet / outlet	°C / °C	250 / 700
Primary helium pressure	bar	30

- **Steam Generator Model :**

In this work, steam generator is considered by applying energy balance as follows [4]

$$m_s\, (h_4 - h_7) = m_{he}\, c_P\, (T_3 - T_1) \quad (5)$$

where m_s is steam mass flow rate of, h_4 is enthalpy at end of steam generator towards turbine, h_7 is water enthalpy at steam generator inlet.

- **Steam Turbine Model :**

The energy balance of steam turbine as represented in Fig. 2 gives [6, 13]

$$W_T = m_s\, (h_4 - h_5) \quad (6)$$

where W_T is turbine work, h_5 is enthalpy at end of isentropic process.

- **Condenser Model :**

The heat rejected (Q_C) in the condenser is given as [11, 14]

$$Q_C = m_W\, (h_5 - h_6) \quad (7)$$

where m_W is water mass flow rate, h_6 is enthalpy at end of condenser.

- **Pump Model :**

Pump work (W_P) can be determined as [11, 15]

$$W_P = m_W\, v_6\, (P_7 - P_6) \quad (8)$$

where v_6 is specific volume, P_6 is pump inlet pressure, and P_7 is steam generator pressure.

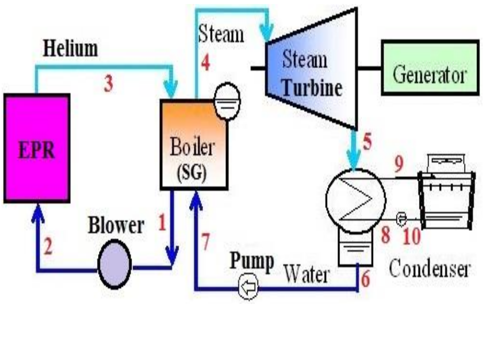

Fig.1. Simplification configuration of key components of RDE [11]

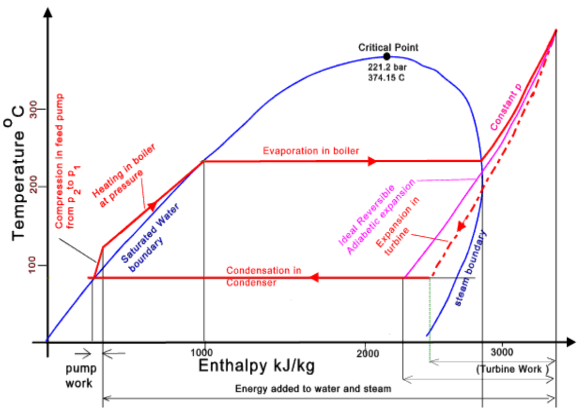

Fig. 2. *T-h* diagram for steam turbine at secondary circuit [11]

METHODOLOGY

An overview of model simulation is illustrated in Fig. 3. This work was carried out in accordance with the following steps, namely :

- Determination of components models for RDE. Thermal power was designed 10 MW_{th}.
- Thermal flow is plotted by using Cycle-Tempo software. The thermal scheme was drawn in two parts of primary and secondary circuits by using graphic editor.
- Data input of components (apparatus) can be given for core, blower, steam generator, turbine, power generation, condenser, pump, cooling tower, and sink.
- The ambient condition is considered on 1.013 bar and 25 °C, respectively.
- Several adjustments are conducted to arrange thermal flow according to thermodynamic conditions and by referring on the existing literatures [5, 10].
- The simulation by using the fluid properties database of Cycle-Tempo software is validated based on data of HTR-10 in China [5].
- Simulation of blower load is conducted by changing pressure and temperature according to rotational speed and helium mass flowrate.
- Simulation of RDE operational condition was varied on compression ratio of blower load values of pressure 35 bars and temperature 435 °C.
- Simulation is continued by using turbine load for types of the condensing turbine SST-60, SST-100, SST-111, SST-300, and SST-600, respectively [9].

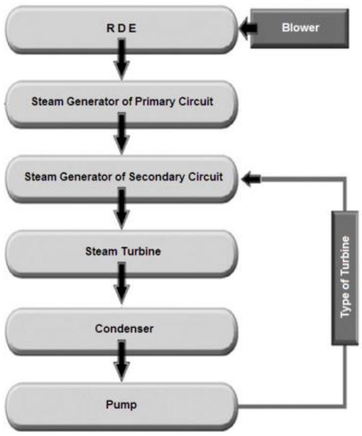

Fig. 3. Algorithm diagram used in this study

DESCRIPTION OF THE CONDENSING STEAM TURBINE

Model simulation is carried out on base of technical data of SST-060, SST-100, SST-111, SST-300, and SST-600, respectively [9]. These steam turbines are the condensing type turbine and were manufactured by Company Siemens AG [9], as shown Table 2.

Table 2. Features overview for the condensing turbine [9]

Type	Feature
SST-060	- Package unit design, oil unit integrated in base frame, and quick-start without preheating - Suitable for saturated steam service, organic Rankine cycle and gas expansion
SST-100	- A single-casing multi-stage steam turbine, compact design, radial exhaust, and short start-up - Oil system integrated in base frame, separation of oil and steam piping, and rapid load changes - Suitable for electric generator, mechanical drive, cogeneration, and industrial power
SST-111	- Compact design, multistage turbine, and oil unit integrated in base frame - Suitable for saturated steam operation and decentralized energy supply system
SST-300	- Compact design, single casing turbine, operational flexibility, and rapid load changes - Suitable for diverse application such as waste-to-energy, chemical industry, and cement
SST-600	- Fast load changes and compact design for simplified transportation - Suitable for many possible applications such as pulp and paper mills, and desalination plants

RESULTS AND DISCUSSIONS

Model validation is done in order to validate current work, and a comparison is done with the existing literatures [5, 7, 10]. An algorithm has been developed to at isentropic efficiency contours, as shown in the Fig. 2, for different pressures values at primary circuit and secondary circuit, while steam generator pressure was remained contant. An isentropic efficiency contour is a curve on which points having same efficiency lie. These curves have been generated for ideal conditions assuming perfect heating process, no pressure drop in reactor core and steam generator and isentropic efficiency equal to 100 % for rotating equipments such as turbine, pumps, and blower. At model validation of Cycle-Tempo, design parameters of RDE is compared with field data of HTR-10 in China [5], as shown in Table 3.

 ISSN: 2355-7524

On Cycle-Tempo simulation, first step is to make apparatus models and to entry form of properties on all apparatus and working fluid. Next step is validate all thermodynamics parameters including mass flow rates of helium and steam or turbine power of heat balance. Relative deviation in this validation process is acceptable if it was not more than 5 % [8].

Table 3. Rankine cycle validation for RDE and HTR-10

Item	Unit	RDE	HTR-10 [5]	Deviation [%]
Reactor thermal power	MW_{th}	10	10	0
Inlet / outlet temperatures of core	°C / °C	252.2 / 700	250 / 700	0.88 / 0
Mass flow rate of helium / steam	kg/s / kg/s	4.3 / 3.47	4.31 / 3.47	0.23 / 0
Inlet / outlet temperature of turbine	°C / °C	343 / 41.51	345 / 41	0.58 / 1.24

Effect of operating conditions such as pressure ratio, temperature and pressure on power and thermal efficiency of turbine cycle had been considered in this work. Computer code Cycle-Tempo is utilized to investigate effect of operating conditions on power output and efficiency are obtained from energy balance. Figure 4 shows simulation of turbine cycle on helium flow rate 4.3 kg/s and blower speed 3255 rpm. Pressure and temperature changed by helium blower are calculated depending on blower rotational speed, helium flow rate, blower characteristic constant, pressure ratio, and isentropic efficiency.

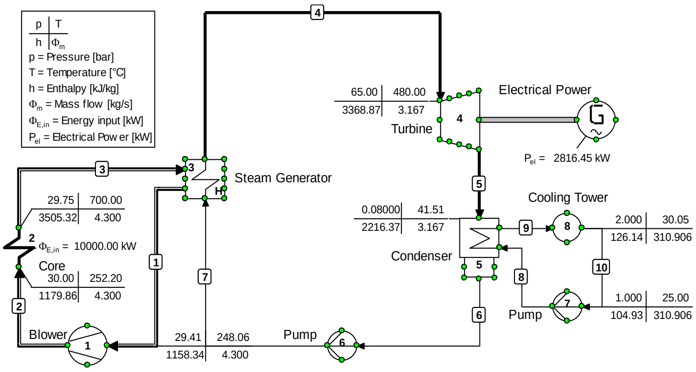

Fig. 4. The Cycle-Tempo simulation for a 10 MW_{th} RDE with turbine type of SST-100

Figure 5 presents relation between thermal efficiency and compression ratio for inlet temperature and pressure of turbine. It can be seen that thermal efficiency increases with compression ratio at higher temperature and pressure. Deviation of thermal efficiency at higher compression ratio is not significant, but variation at lower compression ratio is vital for thermal efficiency of RDE. Temperature and pressure of turbine are crucial for compression ratio. Thermal efficiency at lower compression ratio increases from 22.4 % to 24.4 % with an increase of Turbine Inlet Temperature (TIT) of SST-100 from 435 °C to 480 °C. Thermal efficiency also increases with enhance in compression ratio. However, variation in thermal efficiency is insignificant at higher compression ratio. Thermal efficiency decreases from 25.5 % to 23.3 % when mass flow rate of steam increases from 3.167 kg/s to 3.215 kg/s. Figure 5 illustrates also simulation result which be done by maintaining value of helium flow rate (4.3 kg/s) at reactor core. Primary circuit with helium blower has a high source temperature (700 °C) and rejects heat at a temperature that is conveniently used as energy source for secondary circuit with steam turbine cycle.

Steam energy is converted into mechanical power by expansion process via turbine. Expansion process takes place thru a series of fixed blades and moving blades. Each row of fixed blades and moving blades is called a stage. Moving blades rotate on rotor and the fixed blades are concentrically arranged within circular turbine casing which is constructed to withstand steam pressure. Martensitic stainless steel materials is applied only on high temperature stages [16], where its higher yield, endurance, creep, and rupture strengths are needed. The A-286 material is a nickel-based super alloy that is generally used in hot steam expanders with stage temperatures between 480 °C and 625 °C [17]. Another blade material is titanium with high strength, low density, and good erosion resistance made it a good candidate for high rotational speed or long last stage blade [16]. Turbine cycle is fed with steam under temperature 480 °C, pressure 65 bars, and the enthalpy value 3368.87 kJ/kg, as shown in Table 4. Expanding within turbine, steam produces power 3650.52 kW and goes into condenser under conditions with pressure 0.08 bars and the enthalpy value 2216.37

kJ/kg. The efficiency value of turbine SST-100 is 92.26 %. Hence its reject heat 6.47 MW_{th} to cooling water and the resulted condensate with lower enthalpy value than turbine inlet enthalpy, but with same temperature and pressure comes to feed water pump, as shown in Fig. 6. At expense of pump power 32.2 kW, pressure and enthalpy of the feed water rise to pressure 65 bars and enthalpy 182.57 kJ/kg with which feed water enters steam generator where it is heated and evaporated due to heat added.

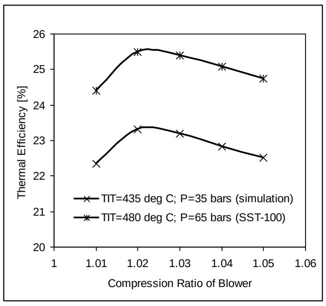

Fig. 5. Diagram of efficiency versus compression ratio

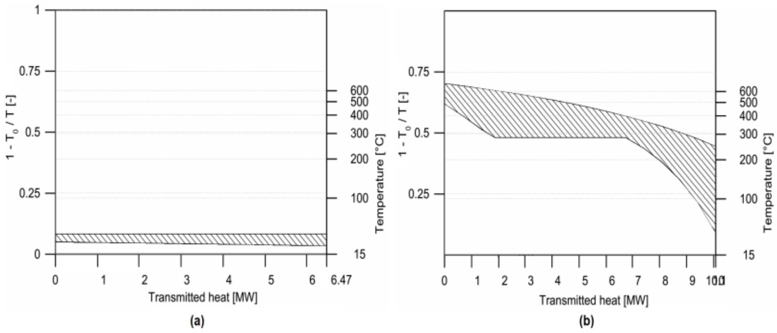

Fig. 6. Transmitted heat diagram for (a) condenser and (b) steam generator

Table 4. Solution of thermodynamic properties for a SST-100 upon RDE

Pipe No.	Pressure [bar]	Temperature [°C]	Mass Flow [kg/s]	Enthalpy [kJ/kg]	Entropy [kJ/kg/K]	Work Medium
1	29.54	248.06	4.3	1158.34	27.3843	Helium
2	30	252.2	4.3	1179.86	27.3934	Helium
3	29.75	700	4.3	3505.32	30.6121	Helium
4	65	480	3.167	3368.87	6.7765	Steam
5	0.08	41.51	3.167	2216.37	7.0837	Steam
6	0.08	41.51	3.167	173.85	0.5925	Water
7	65	42.23	3.167	182.57	0.5994	Water
8	4	25.03	310.906	105.33	0.3676	Water
9	3	30.03	310.906	126.14	0.4371	Water
10	1	25	310.906	104.93	0.3672	Water

Figure 6 shows a diagram of transmitted heat against temperature for condenser, illustrating condensation process is affected by ambient temperature. Turbine outlet temperature is not affected by changes in ambient temperature, however for steam with a lower pressure or a larger curvature of condensation temperature profile. It is possible that a low ambient temperature necessitates a higher condensation pressure. For case of turbine outlet pressure 0.08 bars, it is possible to reduce the cooling water mass flow rate, thereby allowing the cooling water outlet temperature to increase without violating condenser operation. These results in a lower power consumption of the cooling water pump of 131.65 kW, with a positive effect on performance for turbine cycle of a 10 MW_{th} RDE. Figure 6 shows also a plot of net heat duty as a function of temperature at steam generator work. This plot is produced for helium (hot side) and water/steam (cold side). Heat power of 10.1 MW_{th} is found when temperature profile allows two pinch point locations. Pinch points are at bubble point for cold stream of water and at inlet to steam generator for hot stream of helium gas. If steam generator pressure was fixed, temperature does not affect steam generator inlet or outlet conditions on working fluid side, but only pinch point location, since the working fluid condition at steam generator outlet is fixed, and conditions of both streams are determined by pressure independently of temperature. In conceptual design, steam generator could be divided into three parts corresponding to three zones, defined for cold stream of water as preheating, evaporation, and superheating.

Figure 7 displays clearly condenser outlet pressure after every stage of iteration. It can be seen that pressure takes place at first iteration. Saturated liquid flows through pump which increases its pressure to steam generator pressure, where water is first heated to saturation temperature, boiled and superheated to steam at temperature 480 °C and pressure 65 bars. As it can be seen in Table 4, water mass flow rate is about 3.167 kg/s for pumping power 32.2 kW or about 0.322 % of RDE's thermal power. In average, coolant temperature is rising to about 42.23 °C. This shows that pump power is on the order of 0.88 % of turbine power SST-100, and that most of heat addition occurs in two-phase flow region. Thermal efficiency of a 10 MW_{th} RDE is found to be essentially linearly dependent upon

 ISSN: 2355-7524

turbine efficiency, but barely affected by pump efficiency. For this work, thermal efficiency value was 25.5 % for electricity of about 2.817 MW_e. Sub cooling would increase heat input in the steam generator, and on the other hand, inclusion of steam into pump would cause poor performance, as shown in Fig. 7 at iteration stages 3 and 4.

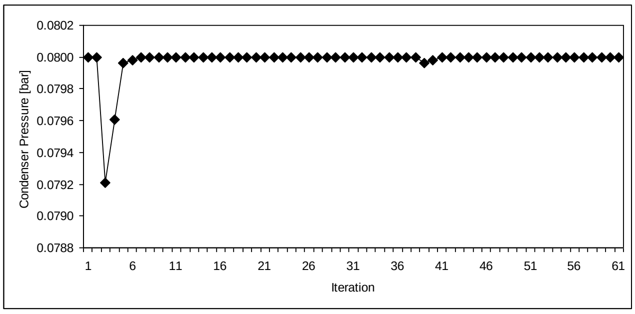

Fig. 7. Plot of pressure behaviour along condenser outlet for SST-100

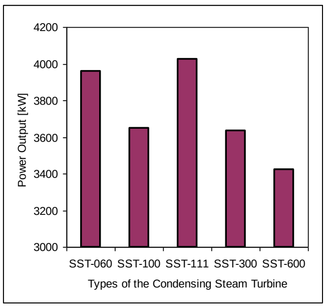

Fig. 8. Comparison for types of the condensing turbine

Table 5 shows technical data and typical dimensions for many of the condensing turbine including SST-60, SST-100, SST-111, SST-300, and SST-600 [9]. Five technologies of the condensing turbine were assessed with respect to power output and thermal efficiencies by using computer program cycle-tempo. From Table 5, it can be seen that thermal efficiency values for output range from 23.2 % to 28.2 %. Mass flow rates of the condensing turbine are 3.129 kg/s (SST-060), 3.167 kg/s (SST-100), 3.107 kg/s (SST-111), 3.24 kg/s (SST-300), and 3.325 kg/s (SST-600), respectively. Steam turbine division of the Siemens Group has focused on design development of turbine to cover range of applications in power output up to 4025.68 kW, as shown in Table 5 and Fig. 8. Final selection of the condensing turbine for RDE was important and is based on a feature overview (as shown on Table 2) and a standard technical data technology (as in Table 5). For a case study SST-100, turbine inlet pressure (65 bars) was more satisfy to steam turbine cycle (secondary circuit) of RDE.

Table 5. Technical data and dimension for many of the condensing steam turbine [9]

Item	**Unit**	**Turbine Type**				
		SST-060	**SST-100**	**SST-111**	**SST-300**	**SST-600**
TIT	°C	530	480	530	520	565
Turbine inlet pressure	bar	131	65	131	120	165
Condenser pressure	bar	0.08	0.08	0.06	0.25	1
Rotational speed	rpm	-	7500	-	12000	18000
Steam mass flowrate*)	kg/s	3.129	3.167	3.107	3.24	3.325
Steam quality*)	%	82.31	85.02	81.58	85.68	89.87
Power output*)	kW	3961.24	3650.52	4025.68	3634.42	3422.77
Electric power*)	kW	3056.17	2816.45	3105.89	2804.03	2640.74
Thermal efficiency*)	%	27.7	25.5	28.2	25.1	23.2
Length/width/height	m/m/m	1.5/2.5/2.5	8/3.7/3.4	8/4/4	12/4/5	19/6/5

*) Calculated by using computer code Cycle-Tempo

CONCLUSION

Results which have been obtained for a 10 MW_{th} RDE shows that operational load of the condensing steam turbine had a significant effect on secondary circuit. Application of turbine has provided to analysis results in thermal energy efficiency and power output. Thermal efficiency values were obtained for output range from 23.2 % to 28.2 %. For case of SST-100, optimum thermal efficiency of about 25.5 % is achievable if heat for steam turbine cycle was efficiently used. Analysis of work output in RDE shows that power of turbine SST-100 was valuable 3650.52 kW mainly dominated to operational load of blower 3255 rpm. Efficiency of turbine SST-100 was 92.26 %. Computer program Cycle-Tempo can be used to assess thermodynamic performance of this RDE as indicated in model validation and results at Table 5. Estimated values of characteristics of components such as steam generator, condenser, and pump can be also calculated with very accurate values of performance of steam turbine cycle itself. Furthermore, accuracy of Graphs as mentioned above will be sufficient for analysis and investigation of present RDE.

ACKNOWLEDGMENT

For this work, author wishes to acknowledge financial support of PTKRN, BATAN of Indonesia with project code of SPDIPA080.01.1.450310/2017.

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