Comparative study of RDE and conventional plant for moderate scale power generations

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Abstract. Electricity generation processes from coal burning at conventional plant and nuclear at Reaktor Daya Eksperimental (RDE) plant are compared using Cycle-Tempo. RDE is a conceptual demonstration nuclear plant with thermal capacity 10 MWth to generate steam and turbine to expand into condenser pressure and electricity generation. In reactor vessel, operating conditions are maintained on pressure drop 0.25 bars, inlet temperature 250 °C, and outlet temperature 700 °C. Environment conditions are set in pressure 1.013 bars and temperature 35 °C. Objective of present paper is to analyses performance of those plants on moderate scale power. In analysis, power plants are simplified into available components within code Cycle-Tempo, and approximated into steady-state flow. Mathematical formulation method is applied to calculate mass and energy balances on each component. Results show that RDE has values of generator power output 2863.8 kW, thermal efficiency 27.051 %, turbine efficiency 88.81 %, and back work ratio 0.87; conventional plant has values of generator power output 2863.8 kW, thermal efficiency 25.022 %, turbine efficiency 80.34 %, and back work ratio 0.869. It is concluded that RDE is properly used for utilizing nuclear heat source on moderate scale power plant.

1. Introduction

Electric power can be generated from burning of coal or nuclear where the steam cycles are widely in use. Reaktor Daya Eksperimental (RDE) is a conceptual demonstration pilot nuclear plant with moderate scale power [1-2]. RDE plant is projected to be installed in the Serpong field. There are a reactor core having thermal capacity 10 MWth to generate steam and turbine to expand low pressure steam and electricity generation. In steam generator cycle of RDE, helium in primary side has a high temperature source and discards heat at a high temperature that can easily be used by water in secondary side as a heat energy source. Conventional plant has simplified components including boiler, steam turbine, condenser, and pump [3, 4]. The coal is used as primary heat energy source within the boiler for producing steam and electricity [3]. In conventional plant, only a small portion of coal energy is converted into electricity and the remaining will be lost as waste heat [4-9].

A deficiency to the application of steam cycle is the limited temperature of the primary heat source. This gives a constraint on the maximum superheated temperature and the vaporization pressure of the generated steam. Then, this constraint will restrict the achievable thermal efficiency of the power cycle. Possible solution, based on the same technology, is the employ of nuclear fuel as primary heat source. This means that the RDE plant can be used to higher thermal efficiency of the power cycle. The water/steam circulation begins from the condenser chamber in which the feed water is pumped.
The water pump increases the thermodynamics pressure of the feed water to steam generator pressure (about 60 bars). The feed water is preheated within the steam generator up to its boiling point at the constant pressure. The generated steam is flowed into the steam turbine of RDE cycle. In turbine, the superheated steam is well expanded to condenser pressure.

The objective of this paper is to analyze and compare the performance of the RDE plant and a conventional plant for moderate scale electric power. Computer program Cycle-Tempo is used to simulate models of the 10 MW\textsubscript{th} RDE and simplified conventional plants. The Cycle-Tempo software package is a Fortran code of thermodynamic modelling for power generations \cite{10, 11}. In this simulation, input data are thermal power, temperature, pressure, etc., and output data are thermal efficiency, net generator power, and back work ratio. A methodology is applied to calculate with the component models the mass and energy equations (mass and energy balances) over the components of RDE and conventional plants are used to solve an unknown variable such as mass flow rate or enthalpy.

2. Recent Status of RDE
RDE plant has helium circulation and water/steam circulation within steam generator. RDE core can generate thermal power of 10 MW\textsubscript{th} up to temperature 700 °C \cite{1-2}. Table 1 presents thermophysical properties for helium gas. From Table 1, it can be seen that critical pressure and temperature of helium are lower than water. The operating pressure at inlet of core in RDE plant is lower than in case of a conventional steam cycle in a power plant. Turbine of RDE works with high temperature steam 520 °C \cite{2}, then thermal efficiency of RDE will increase although lower turbine pressure. Out of turbine the pressure will be expanded into condenser pressure. Meanwhile, hot helium flows via steam generator to reactor vessel. Work temperature of RDE is so far above of saturation line, hence helium must be circulated by high blower efficiency.

3. Theory
Conventional power plant is commercially operated in the moderate power in Indonesia. This technology has been proven and successfully applied for several decades in coal fired power plants. Characteristics of conventional plant can be evaluated by using the simulation software Cycle-Tempo. Table 1 presents also thermophysical properties for water/steam \cite{12}. Conventional plant employs type of water/steam circulation within the boiler \cite{13}. The water/steam circulation begins from the feed water pump. This pump raises the pressure of the feed water up to boiler pressure (170 bars). Water absorbs heat and some of water is converted into saturated steam. Figure 1 shows a diagram of temperature versus entropy for water \cite{14}. Water friction yields in pressure drop in boiler, condenser, and pipeline between components. Heat energy losses to surrounding occur as water/steam flows through components. Friction and losses will contribute to a decrease in thermal efficiency of conventional power plant.

### Table 1. Thermophysical properties of water and helium \cite{12}.

| Scientific Name | Chemical Formula | $P_c$ [bar] | $T_c$ [K] | $v_c$ [m$^3$/kg] | Molecular Weight [g/mol] |
|----------------|------------------|-------------|-----------|------------------|--------------------------|
| Water          | H$_2$O           | 220.6       | 647.1     | 0.0031           | 18                       |
| Helium         | He               | 2.27        | 5.2       | 0.0143           | 4                        |
In this paper, it can be presented the calculation results for net generator power \( W_{\text{gen, net}} \) in kW, thermal efficiency \( \eta_{th} \) in %, and back work ratio \( \text{BWR} \) in dimensionless.

- The net generator power output is given by \( W_{\text{gen, net}} = W_{\text{gen, bruto}} - \sum W_{\text{pump}} \) \( (1) \), where \( W_{\text{gen, bruto}} \) is gross (brutto) generator power (in kW) and \( W_{\text{pump}} \) is pump power (in kW).

- The thermal efficiency is obtained by \( \eta_{th} = \frac{W_{\text{gen, net}}}{Q_{\text{in}}} \) \( (2) \), where \( Q_{\text{in}} \) is input thermal power of heat source (in kW).

- The back work ratio can be calculated by \( \text{BWR} = \frac{W_{\text{gen, net}}}{W_{\text{turbine}}} \) \( (3) \), where \( W_{\text{turbine}} \) is turbine power (in kW).

4. Methodology

The simulation methodology of moderate scale power plants will be separately modeled for each component. Table 2 shows the available components within computer program Cycle-Tempo, and approximated (or assumed) into steady-state flow \( [11] \). Then, all of component models are integrated into a overall cycle which representing the power plants. The environment conditions are set in pressure 1.013 bars and temperature 35 °C, respectively. Figure 2 depicts the flowchart of algorithm.
for Cycle-Tempo simulation. The values of net generator power, thermal efficiency, and heat rate are computed by applying the Equations (1) to (3).

Table 2. Available components of plants in Cycle-Tempo [11].

| Component Name | Schematic View | Input Data                                           |
|----------------|----------------|------------------------------------------------------|
| Boiler         |                | Lower heating value of the coal, combustion efficiency, pressure drop |
| Reactor vessel |                | Thermal power, inlet temperature, outlet temperature, pressure drop |
| Turbine        |                | Type code of turbine                                  |
| Condenser      |                | Condenser pressure, pressure drop, saturation code    |
| Pump           |                | Discharge pressure, pump efficiency                   |
| Circulator     |                | Discharge pressure, circulator efficiency             |
| Steam generator|                | Outlet temperature, pressure drop                     |
| Cooling tower  |                | Outlet temperature, outlet pressure, pressure drop    |
| Electric generator |            | Generator efficiency                                |

Figure 2. Computational algorithm for simulation of power plants.
5. Results and Discussion

From the Table 1 it follows that the critical temperature, therefore, the operating temperature at the inlet of turbine in steam cycle is usually superheated to avoid moisture formation in end turbine stage. This moisture can affect the performance and durability of the steam turbine. Table 3 shows output data of computer program Cycle-Tempo for a RDE and a conventional plant with coal fired boiler. It can be seen on the Figure 1 that water (wet fluid) has slope with saturation curve appropriate for a steam cycle process. The characteristics of water or helium can be evaluated by considering some of thermophysical properties (on the Table 1) for those fluids under the simulation software package Cycle-Tempo. The thermophysical properties of these working fluids have an affect the design and complexity of the components such as turbine and condenser.

Table 3. Steam cycle comparison for RDE and conventional plants.

| Parameter                                      | Unit       | RDE [1, 2] | Conventional Plant |
|------------------------------------------------|------------|------------|--------------------|
| Thermal power of reactor vessel / boiler       | MW<sub>th</sub> | 10         | 10.9               |
| Inlet / outlet temperatures of reactor vessel / boiler | °C / °C     | 250 / 700  | 43.4 / 350.2       |
| Mass flow rates of helium / steam              | kg/s / kg/s | 4.27 / 3.57| - / 4.368          |
| Inlet / outlet pressures of turbine             | bar / bar  | 61.67 / 0.08| 165 / 0.08         |
| Inlet / outlet temperatures of turbine          | °C / °C     | 520 / 41.51| 350.2 / 41.51      |

Figure 3 represents the corresponding thermodynamic cycle of RDE components. Figure 4 shows a reactor vessel model of RDE with the input data into Cycle-Tempo code. A steam generator is often employed to reach a higher thermal efficiency of this cycle. Out of reactor vessel, helium flows in steam generator for heating water into steam. After expansion process within turbine, the steam remains superheated with quality greater than 89 % on the condensation temperature 41.51 °C (which corresponds to the environment temperature 35 °C). In this case, the rejected condensation heat should be brought to the temperature level of a specific environment in cooling tower. In the Figure 3, it is clearly seen the electric power output 3041.67 kW for the thermal power of a reactor core of 10 MW<sub>th</sub>. The net generator power output (W<sub>gen,net</sub>) of RDE plant is 2872.56 kW from the Equation (1). The thermal efficiency (ƞ<sub>th</sub>) of RDE plant is 28.73 % from the Equation (2). The back work ratio (BWR) of RDE plant is 0.87 from the Equation (3). The other results of Cycle-Tempo simulation are circulator (blower) efficiency of 92.53 %, turbine efficiency of 87.47 %, condensate pump efficiency of 85.68 %, and cooling pump efficiency of 86 %.

Figure 3. Cycle-Tempo simulation for a simplified RDE plant.
Figure 4. Reactor vessel with input data into Cycle-Tempo for a RDE plant.

At Figure 5, cycle diagram of conventional plant is reproduced with Cycle-Tempo simulation. This simplified conventional plant is chosen as reference cycle in the present comparison with RDE plant. Although this diagram appears similar to the steam cycle of RDE, but is one significant difference. A steam cycle of conventional plant commonly operates with the superheated steam. Turbine that can execute saturated steam typically has very low efficiency. The inlet and outlet conditions of turbine are correlated by way of the turbine efficiency value. As a consequence, to achieve a desired pressure at the turbine outlet, the conformity between vaporization pressure and minimum superheating temperature should be taken into calculation. From the simulation of computer program Cycle-Tempo, it is obtained turbine efficiency of 80.34 % with steam quality of 68.25 % at outlet condition, condensate pump efficiency of 92.95 %, and cooling pump efficiency of 85.53 %. By using the Equations (1) to (3), it is computed the net generator power output ($W_{gen,net}$) of 2863.74 kW, the thermal efficiency ($\eta_{th}$) of 25.02 %, and the back work ratio (BWR) of 0.869.

Figure 5. Cycle-Tempo simulation for a simplified conventional plant.
In Figure 6, influence of a steam generator on the thermal efficiency of steam cycles is made obvious for the specific case of working fluid, implementing the parameters listed in Table 4. The parameters of steam cycles in the case, apply to the performance that is evaluated by assuming stable conditions of all components. To enable the comparison between steam cycles based on RDE and conventional plant, the optimal cycle is simulated by the predefined set of pressure levels of the condenser. In the present study, it has been assumed that the heat source is at a constant temperature on inlet turbine. Consequently, only steam cycles with identical turbine type and condenser are compared. In Figure 6, it is plot the achieved thermal efficiency as a function of the condenser pressure for all considered plants. It needs to be noted that for the condenser pressure above circa 0.05 bars it is possible for the considered steam cycle to reach the same values of cycle thermal efficiencies (circa 28.6 %). Based on these values of Figure 5, it can be stated that RDE steam cycle displays a superior performance compared to the one of conventional plant.

**Table 4.** Steam cycle parameters used in the cases of RDE and conventional plants.

| Parameter                              | Unit | Value       |
|----------------------------------------|------|-------------|
| Condenser pressure                     | bar  | 0.03 / 0.05 / 0.07 / 0.09 / 0.11 |
| Pressure drop within reactor vessel    | bar  | 0.25        |
| Pressure drop within steam generator or boiler | bar  | 5           |
| Saturation code                        | -    | 0           |
| Steam quality                          | %    | 100         |
| Turbine type                           | -    | 1           |

**Figure 6.** Thermal efficiency as a function of condenser pressure with parameters as in Table 4.
In this paper, efficiency value of turbine is expected to be well-designed in a range between 75 % and 90 %. Simulation result of Cycle-Tempo modelling shows that the obtained turbine efficiency of RDE plant equal to 87.47 % is good enough value. In addition, this efficiency has preferable value than the turbine efficiency of conventional plant on the moderate scale power 2863.74 kW (≈ 3 MW). In reality, the temperatures of a steam generator and a boiler do not remain at a constant level, but have a given temperature profile because the heat is transmitted gradually. This profile defines the thermal power $Q_{th}$ available between inlet and outlet temperatures, and is dependent on mass flow rate. The closer the heating process curves (preheating, evaporation, and superheating) within steam generator or boiler compatible this temperature profile, the more efficient the heat source will be transformed by the steam cycle. In this paper, it is also evaluated the simulations for a variable temperature profile of the heat source. Table 5 presents the simulation results for the gross and net generator powers ($W_{gen,brutto}$ and $W_{gen,net}$) and the cycle thermal efficiencies ($\eta_{th}$) under the pressure drop condition 0.25 bars in the reactor vessel, using the Equations (1) and (2). Figure 7 displays the corresponding heating profiles for the case that RDE plant is reproduced in the simulation with turbine efficiency of 87.47 %.

| Case            | $\eta_{turbine}$ [\%] | $P_{sat}$ [bar] | $T_{sat}$ [°C] | $W_{gen,brutto}$ [kW] | $W_{gen,net}$ [kW] | $\eta_{th,brutto}$ [\%] | $\eta_{th,net}$ [\%] |
|-----------------|------------------------|-----------------|---------------|-----------------------|-------------------|--------------------------|------------------------|
| RDE 1           | 87.54                  | 60              | 274.2         | 3036.24               | 2867.12           | 30.36                    | 28.67                  |
| RDE 2           | 87.32                  | 65              | 279.5         | 3051.99               | 2882.9            | 30.52                    | 28.83                  |
| RDE 3           | 87.13                  | 70              | 250.3         | 3067.08               | 2895.69           | 30.67                    | 28.96                  |
| Conventional plant 1 | 76.81               | 80              | 284.4         | 1638.39               | 1587.08           | 23.65                    | 22.91                  |
| Conventional plant 2 | 80.41               | 90              | 303.3         | 2251.21               | 2180.74           | 25.08                    | 24.3                   |
| Conventional plant 3 | 82.73               | 100             | 311           | 2863.94               | 2772.81           | 26.09                    | 25.26                  |

Figure 7. Heating profile for a case of RDE plant at the turbine efficiency of 87.47 %.
On the Table 5 for some selected cases, it can be seen the calculation results for the values of net generator power ($W_{\text{gen,net}}$). Depending on saturation pressure ($P_{\text{sat}}$) and saturation temperature ($T_{\text{sat}}$), the $W_{\text{gen,net}}$ value of conventional plant is higher than the one of RDE, but the thermal efficiency value of RDE is higher than for conventional plant. For steam cycle of the conventional plant, the selected evaporation pressure or the superheating temperature are the constraining variables. Because the evaporation heat is much higher for water, a higher evaporation temperature can be needed and over thermal energy on a higher level is required in steam cycle. On Figure 7, calculation and design of steam generator to recover the heat is not in scope of the present study. As a start, the effectiveness of steam generator is taken into account by defining a pinch line with minimum offset of 16.24 °C temperature difference to profile of heat source. The achievable superheating temperature for steam cycle of RDE plant are functions of saturation pressure, pressure drop of reactor vessel, thermal power, condenser temperature, turbine efficiency, and are limited to this pinch line. These simulations result in higher cycle efficiency (13 to 20 %) and in higher electric power generation for the RDE. Figure 8 shows diagram of moderate electric power generation for simulations of RDE and conventional plants with parameters as indicated on the Table 5. These obtained power values are based on the turbine power minus the pump power as supporting the plant in accordance with Equation (1). Output data are resulted from simulation of computer code Cycle-Tempo by maintaining pressure drop value at reactor vessel 0.25 bars.

![Power diagram based on Cycle-Tempo simulations with parameters as shown in Table 5.](image)

6. Conclusion
The performance analyses are performed for moderate scale power generations including evaluation of thermal efficiency, generator power output, and back work ratio. Results obtained for a 10 MW$_{\text{in}}$ RDE plant are the generator power output 3041.67 kW, the thermal efficiency 28.73 %, turbine efficiency 87.47 %, back work ratio 0.87; and for the conventional plant is the generator power output 2863.74 kW, the thermal efficiency 25.02 %, turbine efficiency 80.34 %, back work ratio 0.869. In some cases, the thermal efficiency and electric power of RDE are higher than that of conventional plant. Thus, RDE plant can be used for a closer fit to temperature profile of a heat source on moderate scale power.

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