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RESEARCH ARTICLE

Performance analysis of 110 MW steam power plant with solar aided reheating system using GateCycle software

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ABSTRACT - Along with the world's rapid population growth, the demand for electrical energy is also increasing. Hence, it is necessary to take innovative and environmentally friendly steps toward existing power plants to overcome the issue. One is using a solar-aided reheating system implemented in a steam power plant to increase its performance. In this study, an analysis of the reheating system with a solar collector was carried out on a particular steam power plant for the same loadings. The conditions of the Direct Normal Irradiance (DNI) at the location where the steam power plant was established were also considered in this study. A mathematical analysis was carried out to calculate the increase in thermal oil temperature heated by the solar collector with several different conditions throughout the year. The results were in the form of thermal oil outlet temperatures, which were then used as input for the simulation of a steam power plant that was assumed to be integrated with the solar-aided reheating system using GateCycle software. It was found that the performance of the steam power plant worked better when using a solar-aided reheating system compared to those without the solar system. At 100%, 75%, and 50% loading, power increased by 4.51% to 5.86%, 6.18% to 8.18%, and 8.91% to 11.42%, respectively. The highest performance increase occurred in March, and the lowest occurred in January due to the level of DNI in both months.

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1.0 INTRODUCTION

Along with the rapid growth of the world's population, the need for electrical energy continues to increase [1]. In Indonesia, the per capita national electricity consumption in 2020 reached 1142 GWh, an increase of 5.08% from 2019 [2,3]. By 2030, the world's energy needs are predicted to increase by more than 60%. The world's power plants are currently dominated by fossil fuel thermal power plants. In fact, the availability of fossil fuels is very limited in nature[4,5]. Therefore, innovations are needed to improve the performance of the existing power plants to meet the increasing electrical energy needs. One of these is utilizing the free surrounding energies, one of which is solar energy [3].

The existence of solar energy is quite abundant in almost all locations in the world. There are two forms of utilizing solar energy into electricity according to the process used, the first is by converting photovoltaic (PV) energy into thermodynamic cycles, and the second is concentrated solar power (CSP) [6,7]. Several concentrating technologies can be used at this time. One of these is a parabolic trough collector, which is the oldest and most mature technology to be applied in actual circumstances, especially since it can heat the working fluid to 400 C with high thermal efficiency and low cost [8–12].

The use of renewable energy is emerging as a leading applicative solution in preventing climate change and global warming. In Riau, where the 110 MW coal-fired power plant was established, the level of air pollution or AQI in July could reach 104 US AQI based on real-time data in the field. It indicates that air pollution in Riau is no longer healthy [13-15]. In this condition, renewable energy is important in mitigating and adapting to climate change in countries vulnerable to climate change [16,17]. Analysis of the effect of increasing renewable energy capacity by 1% shows a reduction in carbon intensity in the range of 0.028% - 0.043%. On the other hand, the addition of non-renewable energy capacity can lead to an increase in carbon emissions up to 0.46% per capita in the long term [18,19].

There are several systems that can be used to improve the performance of the Rankine cycle, such as reheat and regenerative cycles, which are used to heat turbine extraction steam and feed water, respectively. Both are applied to improve the efficiency of the whole cycle [21–23]. Reheating in high-pressure turbines is one solution to increase the efficiency and capacity of power plants. The power generated increases up to 48.72% [24]. Therefore, the reheating

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method is used to improve the performance of steam power plants so that the power generated will also increase. It can be a solution to meet electrical energy needs.

The innovation of the solar reheating system is one of the solutions to improve the performance of steam power plants by utilizing solar energy. Solar radiation can produce useful heat to heat working fluid so that its temperature can increase, and it can be used for heating the working steam [25–27]. The use of a solar-aided reheating system by utilizing solar energy to heat the working fluid can increase the efficiency of exergy in power plants by 56.63% to 78% and can increase the power generated by 16.8 MW for gas and steam power plant with a capacity of 200 MW [28]. The use of solar collectors for reheating process is strongly influenced by DNI (Direct Normal Irradiance) conditions, so a specific region's climatic conditions will affect the solar collector's performance and will continue to affect the steam turbine's performance and efficiency [29,30]. Therefore, this study will show the effect of DNI on the performance and efficiency of a steam power plant in Indonesia, with a particular assumption in the form of an integrated solar-aided reheating system with certain specifications at the power plant.

The most effective and efficient method for analyzing power plants is to model the power generation process, and one is by using GateCycle software. The error obtained from the modelling process using GateCycle software in most parameters was obtained no more than 3%, which shows that the simulation results using GateCycle software are close to the actual data of the power plant being studied [4,31,32]. Since optimizing power plants is essential in solving the problem of increasing energy demand, modeling a steam power plant with an integrated reheating system using GateCycle software was accomplished in this research to help gain broad insights related to its performance. It can also be a reasonable consideration for related companies to implement in actual practice.

2.0 METHODS AND MATERIAL

2.1 Reference Steam Turbine Power Plant

The steam power plant in Riau, Indonesia, was selected as the case under study. Figure 1 shows a diagram of the working fluid closed loop power generation system, which is the focus of this research. Important data used in this study, including schematic diagrams, working fluid parameters, fuel, and cooling fluid, were obtained from the power plant datasheet belonging to the related company [33]. Apart from being used in the validation process, this data is also used in mathematical calculation and simulation using supporting software when performing model variations.

2.2 Proposed System

Integrating a solar collector system in an existing power plant does not require much modification. This integration process only changes the shape or arrangement of one pipeline to reheating through the heat exchange process. The solar collector system, which functions as a solar-aided reheating system, is used to collect heat coming from the sun and send to heat the working steam. The working steam reheated is the extraction of the high-pressure turbine (HPT) before entering the low-pressure turbine (LPT). Through this proposed new design, increased power generation and efficiency may be obtained. A study using analytical calculations and GateCycle simulations was carried out to determine the impact of adding solar-aided reheating to system efficiency in several variations of power plant loading and solar collector systems, where the loading of solar collectors is adjusted to fit power plant loading.

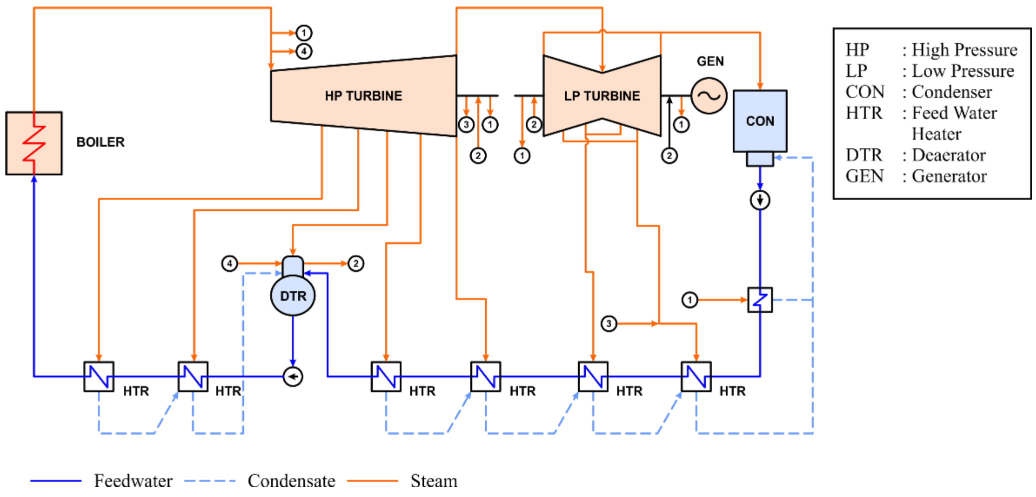

Figure 1. Schematic diagram of the referenced steam power plant

2.3 Mathematical Model of Reheating Analysis

The equations for parabolic trough solar collector (PTC) analysis have been derived with respect to several assumptions to simplify the calculation. The derivative of the basic governing equation gives the final result in the form of thermal oil temperature equation out of the solar collector absorber pipe. This outlet temperature will be used as input representing the power plant reheating system in the simulation. The equation can be written as follows [8]:

$$T_{\text{out}} = T_{in} + \frac{K_3}{\dot{m}C_p} Q_s - \frac{K_4}{\dot{m}C_p} \left(T_{in}^4 - T_{am}^4\right) \tag{1}$$

where K_3, K_4, and the other parameters can be obtained through the following equation:

$$K_4 = \frac{K_1 K_2}{K_2 + 4\, T_{in}^3\, K_1} \tag{2}$$

$$K_3 = \frac{\eta_{opt}\, K_2}{K_2 + 4\, T_{in}^3\, K_1} \tag{3}$$

$$K_2 = \left(\frac{1}{A_{ri} h} + \frac{1}{2\dot{m}C_p}\right)^{-1} \tag{4}$$

$$K_1 = A_{ro}\, \varepsilon_r^*\, \sigma \times \left[1 + \frac{A_{ro}}{A_{co}} \times \frac{4\, T_{am}^3\, \varepsilon_r^*\, \sigma}{\varepsilon_c\, \sigma\, 4\, T_{am}^3 + h_{out}}\right]^{-1} \tag{5}$$

$$\varepsilon_r^* = \left(\frac{1}{\varepsilon_r} + \frac{1 - \varepsilon_c}{\varepsilon_c} \times \frac{A_{ro}}{A_{ci}}\right)^{-1} \tag{6}$$

$$Q_s = DNI \times A_a \tag{7}$$

2.4 GateCycle Modeling

In this study, GateCycle software was used to model and simulate a typical steam power plant system with a load of 100%, 75%, and 50%. Modelling was carried out based on the schematic diagram and also data related to the steam power plant given by the owner of the referenced power plant [33]. Modelling is done well, where each component in the turbine and boiler section can be modelled completely and precisely according to the actual conditions.

2.5 Validation

This study performed the validation test by comparing the data from the modelling simulation on the GateCycle software with the data in the performance test report [33]. Meanwhile, reheating process validation is carried out by calculating different conditions from several journals and comparing the results.

Table 1. Validation results of 100% loading power plant model

Parameter Items	Unit	Performance test data	Simulation Result	Error (%)
Generated electrical Power	KW	110289	110524.7	0.214
HPH1 - Extraction	t/h	17.116	17.19	0.432
Daerator - Inlet Pressure	MPa	0.602	0.602	0.000
Daerator – Inlet Temp	°C	260.7	260.4	0.115
Fuel Flow	t/h	79	79.4	0.506

The results of model validation at 100% loading can be seen in table 1 above. Based on the tabel, the referenced steam power plant model simulated using GateCycle software obtained a very small average error value. Likewise, the 75% and 50% loading show the simulation results with also a very small error value. Based on these simulations, at 100% loading, the largest error value was obtained, namely 0.506% in the fuel flow. At 75% loading, the largest error was obtained, namely 0.456% in the HPH2-temperature, and at 50% loading, the largest error was obtained, worth 1.68% in the section of generated electrical power. In other words, thoroughly, the error value obtained was enough to prove that the simulations were valid because all the error values obtained were small enough.

And from the mathematical analysis of reheating process, based on figure 2 above, it can be seen that the results of the analysis compared with some literature showed suitable values with the largest error was 1.774%, so the equations derived and used in this study were declared feasible for use.

2.6 Validation

The solar collector system is designed whose parameters can be seen in table 2 to meet the heat requirements needed in the reheating process. The type of solar collector used is the Eurotrough ET-150 type, where the solar collector is used to heat thermal oil Therminol VP-1 [38]. The parameters of the solar collector ET-150 used in this research can be seen in table 2, which contains the detailed dimensions of the ET-150 solar collector. While the thermal oil used works at a pressure and temperature about 20 bar and 227 °C, respectively.

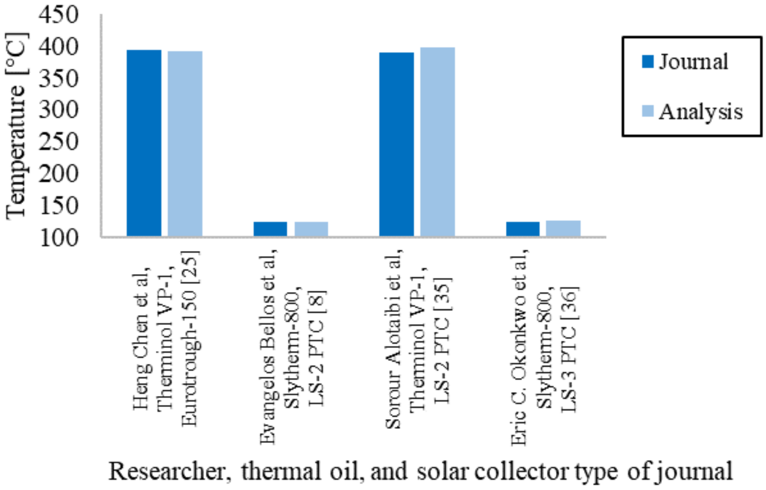

Figure 2. Reheating process validation with some literature

The DNI data is the average data taken from 2007 to 2016, and the data were taken based on laboratory results in that area [34]. The mass flow rate properties can be seen on Table 3.

Table 2. Validation results of 100% loading power plant model

Parameters	Solar Collector (ET-150)
Peak Optical Efficiency [7]	75%
Receiver Outer/Inner Diameter [7]	0.07/0.065 m
Cover Outter/Inner Diameter [7]	0.12/0.115 m
Receiver Outer/Inner Surface	32.97/30.615 m^2
Cover Outer/Inner Surface	56.52/54.165 m^2
Reciever/Cover Emmitance [8]	0.2/0.9
Reflective apparature area collector [7]	817.4 m^2
Number of Solar Collector	70
Total Apparature area Collector	57218 m^2
Heat Transfer Coefficient Cover-Ambient [8]	10 W/m^2. K
Ambient Temperature [8]	300 K
Solar Irradiance	According to World Bank Group [36]

The mass flow rate resulting from pump works of solar collector system was adjusted to the power plant loadings. In other words, the work of the pump on the solar system was adjusted to the electricity generated from the power generation.

Table 3. Thermal oil mass flow rate property for three types of loading

Parameters	100% Loading	75% Loading	50% Loading
Mass Flow Rate (kg/s)	112	84	59.52

3.0 RESULTS AND DISCUSSION

Analysis of solar collectors, reheating processes, and power increases of the power plant were carried out under different conditions of both power plant and solar collector system loading, as well as direct normal intensity or DNI. A detailed explanation is discussed as follows:

3.1 Analysis of Solar Collectors

Solar collector analysis aims to calculate the temperature increase of thermal oil heated using solar thermal energy through an installed solar collector system. The thermal oil used in this study is Therminol VP-1 because it is a good thermal oil in the heat transfer process and is also commonly used in various industrial needs [39]. The solar collector analysis calculation results can be seen in figure 3 with 100%, 75%, and 50% loading conditions in different months.

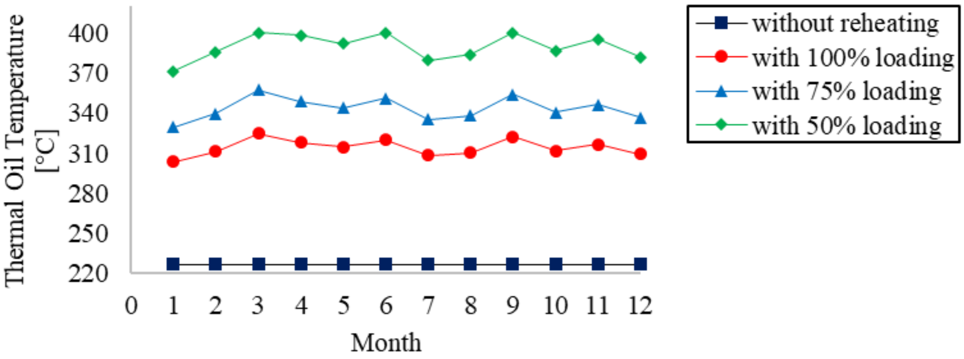

Figure 3. Comparison chart of thermal oil temperature

The graphic showed that in each of the loadings, thermal oil temperatures were highest and lowest in March and January, respectively. This difference is caused by different DNI values each month. At 100%, 75%, and 50% loading, the highest and the lowest increase in temperature of thermal oil occurred with an increase of 97.65 °C and 76.84 °C, 130.2 °C and 102.45 °C, and 173 °C and 144.36 °C, respectively. The greater increase in thermal oil temperature at low loading is caused by a longer contact time interval between the working fluid and the solar collector absorber pipe due to its low mass flow rate (low loading). As a result, the heat received by the fluid will be more, and the temperature of the fluid will be higher when it comes out of the solar collector pipe.

3.2 Analysis of Power Plant Simulation with GateCycle

Power plant simulation was carried out using GateCycle software to find out the increase in performance of the steam power plant after the addition of the reheating system. The resulting performance comparison is shown in Figure 4.

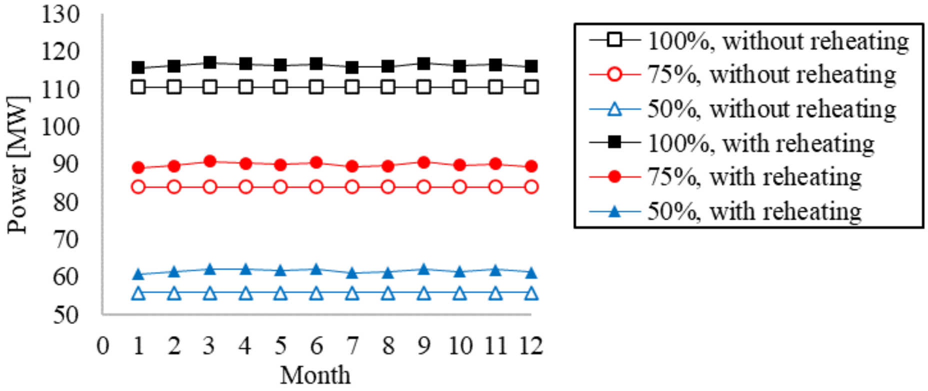

Figure 4. Gatecycle simulation comparison chart before and after reheat

Based on the results, it can be seen that in each loading, the highest increase in power occurs in March and the lowest increase in January, caused by intensity differences of solar radiation in different months. The highest and the lowest increase in power was 5.86% and 4.51%, 8.18% and 6.18%, and 8.9% and 11.42%, respectively.

The simulation results are close to the previous studies. Heng Chen et al. carried out a simulation using EBSILON professional to analyze a power plant modeling with a solar-aided reheating system that can increase the output power, which was originally 10.31 MW to 13.38% [25]. In addition, Gholamreza Ahmadi et al. carried out full repowering using solar reheating of a steam-gas turbine power plant (SGT) with a capacity of 400MW. They obtained a capacity increase of up to 10% [28]. However, it should be noted that the current simulation uses the outlet temperature of thermal oil resulted from a simplified mathematical analysis. Contact thermal losses are ignored because their value is considered remarkably small. Such an approach may lead to significant errors for larger-scale solar reheating systems. Therefore, this simplification of the equation can be reconsidered in future research, especially for large-scale solar reheating systems.

4.0 CONFLICT OF INTEREST

The authors declare that there is no any conflict of interest with respect to this publication. There is no monetary interest, personal interest or any course of professional relations both in the content, findings, and conclusions. All work has been done in a fair and unbiased manner and there were no third parties which compromised to this publication.

5.0 AUTHORS CONTRIBUTION

E. Yohana (Supervision; Conceptualisation; Methodology)

M.S.K.T.S Utomo (Resources; Project administration; Writing - review & editing)

K.A. Azis (Writing - original draft; Validation; Formal analysis; Data curation; Investigation)

A. Afinadi (Writing - review & editing; Data curation; Visualisation)

M.F.H. Dwinanda (Writing - review & editing; Funding acquisition)

M.E. Yulianto (Software; Writing - review & editing)

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