Modelling of load variation effect on the steam power plant heat rate and performance using Gatecycle

Nurdin Hasananto*, Djarot B Darmadi, Lilis Yuliati
Mechanical Engineering Department, Brawijaya University
MT Haryono 167, Malang 65145, Indonesia
*Email: nurdinhasananto@student.ub.ac.id

Abstract. One of the notable problems faced by power plant sector is the continuous increasing of policy urging air pollutant reductions such as NOX, SOX, and CO2. Therefore, there is a substantial necessity for power plant to conduct the most efficient scheme. One of the viable solutions is examining the present condition, evaluating as well as changing into better result. The present paper deals with the study of the powerplant performance running on fuels. In particular turbine maximum continuous rate (TMCR) were compared with other values. The outcomes show that heat rate, efficiency and fuel flow of the boiler increased respectively as a caused from the increasing load. In equipment level, heat transfer conducted by boiler is the biggest compared to another installed equipment. The result analysis highlighted that the design is able to be a replacement or insight for future operational data.

Keywords: power plant, heat rate, fuel consumption, heat transfer

1. Introduction
Nowadays, the number of regulations for reducing of fossil fuel usage has been continuously increased since the massive usage of coal and oil which are considered harmful for environmental condition. Many scientist in powerplant sector are rallying with time to find the better scheme to preserve our environment condition. The existence of renewable energy sources (RES) is also changing the selected management and power production approach [1]. The undeniable condition about fluctuating of energy production supplied into the system crucially affects the thermal power plants outputs. Responding quickly either high and low operational load is the underpinning for updating the new energy map in the worldwide [2].

During the last decades, numerous modelling of steady thermodynamics have been developed covering from boiler, condenser, and heat exchanger until entire power plant. Madejski [3] Studied about modelling a boiler specifically front wall combustion process including the char combustion, devolatilization, and particle heating. Similarly observing about boiler combustion Zhang et al. [4] investigated in circulating fluidized bed boiler. The selected variables are bed pressure drop and air flow in primary and secondary showing that the largest losses came from exhaust flue gas.

In the different power plant sector. Kwak et al. [5] studied the difference between part load and rated load condition considering the thermal resistance ratio. The result show about the optimum value is changing when the part load condition was calculated. Similarly, performance of condensers heat transfer observed by applying several air-side improvement using computational
The result found that by reducing fin spacing of the conventional, smooth fins caused in the largest growth in cycle efficiency. Ensuring the conversion from steam energy uninterruptedly into work, there are few research focusing turbine performance improvement by additionally integrating units [7], applying new formulation [8], as well as using process integration [9].

Moreover, after ensuring all the components work well, observing fuel consumption is also fundamental in power plant management. Experiment from [10] showing that SCCR (Standard Coal Consumption Rate) of power plant will increase when load-up process and will decrease when load down. In addition to fuel consumption, increased heat rate is giving signal about the marginal cost and cost production ratio. This is because the relevant one of the relevant measurements of power generation efficiency is heat rate. Recent examination about the relationship about heat rate and Green House Gas (GHG) emissions. The experiment results show that the increasement of heat rate is affecting the level of GHG emission [11,12].

Gatecycle is a program that has been selected for modelling and performance engineering analysis for this study since the validity was already checked in previous studies: simple-cycle GTCC study [13], cogeneration system in food industry optimization [14], integrated plant assessment [15] and absorption chiller coolant for turbine [16]. This paper deals with the comparison between multiple TMCR using Gatecycle software versions SP 1. This paper is unique in analyzing the output value such as fuel consumption, heat rate, and heat transfer duty not only for single condition load but also three others load. In line with fuel consumption, the heat rate value is also observed respectively. All important components which are hugely impactful for the powerplant operations that combining the first and the second law of thermodynamics. We hope that this study will provide valuable information regarding the possibility of optimization from the experimental result in the next step.

2. Experimental method

2.1 Basic assumption

The selected assumption was performed by considering the actual condition such as the ambient condition as partly presented in Table 1. Four stages closed feed water heater were modelled using ‘accept incoming steam’ where the terminal temperature difference (TTD) is calculated and there is no demand from hot inlet steam flow. Single open feed water heater ‘Constant Pressure: Demand Pegging Steam Flow’ method for maintaining the operating pressure as well as to deaerate the feed water. For deaerator vent line, 0.0082 fraction steam is inputted. In order to increase temperature of working fluids, there are two pumps, located after deaerator and condenser. These pumps were modelled using specified efficiency as equal as 0.85.

| Table 1 Power plant ambient condition |
|---------------------------------------|
| Ambient temperature                   | 30°C                    |
| Ambient pressure                      | 101,320 Pa              |
| Ambient relative humidity             | 0.77                    |

In turbine section, the model is developed as close as the actual condition. The number of steam extraction is based on operational data. The rotational per minute of the turbines is inputted 3600. The efficiency of generator is assumed 0.985. In a condenser cooling water is used to cool steam or a steam/water mixture down to saturated liquid conditions. In this study, the condenser calculation is modelled with ‘desired pressure method’. Tube thickness, tube gauge and material of the condenser are 0.065, 16, stainless steel type 304 respectively. Condenser pressure
drop in this case is considerably neglected. Checking error is also conducted by ensuring the difference between commissioning data and results is below 2%.

2.2 Thermodynamics analysis

![Figure 1. Modelled power plant scheme](image)

The mathematical model of power plant was made taking into account a real parameter from the monthly performance sheet. Heat balance of each component is formulated based on the number of streams either input or output. This research uses ASME (American Society of Mechanical Engineers) 1993 as the selected steam properties calculation standard. Heat mass balance of boiler, steam turbine, feed water heater and condenser will be presented. Condenser is modelled with 2 output streams and 3 input streams. Heat balance of the condenser is:

\[ \dot{m}_{39} h_{39} + \dot{m}_7 h_7 = \dot{m}_{38} h_{38} + \dot{m}_5 h_5 + \dot{m}_{20} h_{20} \] (1)

1st LPH (Low Pressure Heater)

\[ \dot{m}_8 h_8 + \dot{m}_{14} h_{14} + \dot{m}_{36} h_{36} = \dot{m}_{20} h_{20} + \dot{m}_{35} h_{35} \] (2)

2nd LPH

\[ \dot{m}_{10} h_{10} + \dot{m}_{35} h_{35} = \dot{m}_9 h_9 + \dot{m}_{36} h_{36} \] (3)

As we can see from Figure 1, the presented picture gives us information about turbine bleeding streams. For the shaft power of the n-th turbine (n= 1, 2, 3, 4 and 5) is computed as [17]:

\[ W_{ti} = \eta \left[ \dot{m}_{in} h_{in} - \sum_{j=1}^{n} \dot{m}_{sej} h_{sej} - \dot{m}_{out} h_{out} \right] \] (4)

1st HPH (High Pressure Heater)

\[ \dot{m}_{22} h_{22} + \dot{m}_{13} h_{13} + \dot{m}_{12} h_{12} = \dot{m}_{17} h_{17} + \dot{m}_{43} h_{43} \] (5)

2nd HPH

\[ \dot{m}_{16} h_{16} + \dot{m}_{43} h_{43} = \dot{m}_{22} h_{22} + \dot{m}_6 h_0 \] (6)

Boiler

\[ \eta_b \dot{m}_{fuel} LHV + \dot{m}_1 h_1 = \dot{m}_3 h_3 \] (7)
Where the number of steam extraction in this study are \( n_{se} = 5 \) for combining the low and high pressures turbine. In addition, turbine efficiency is ratio between actual work of turbine and ideal work of turbine. This ratio defines how well the maximization of steam usage that entered the steam turbine and formulated such this formula:

\[
\eta_{\text{Turbine}} = \left( \frac{W_a}{W_i} \right) \times 100\%
\]  \( (8) \)

As in [11], heat rate formula is expressed:

\[
HR = \frac{\text{Total energy of fuel consumed}}{\text{Net electricity Generation}}
\]  \( (9) \)

By using Gatecycle software and equation 1 to 9, the parameter that we want to observe are how significance the load variation is affecting the fuel consumption, heat rate, power plant efficiency and heat transfer duty.

3. Result and analysis

![Figure 2. Heat rate and efficiency of steam power plant at load variation](image1)

![Figure 3. Fuel consumption at load variation](image2)
The main characteristics of thermal power plant operation at four observed loads as they were extracted from commissioning data. We also obtained the convergent steam power plant Gatecycle from modelling. The observed steam generation is selected from actual parametric values that used daily in power plant report. As mentioned in the previous chapter, the selected parametric will give the reader in a 25 MW power generation plant.

3.1 Heat rate and power plant efficiency
Since the efficiency and heat rate have inverse relation one to another, so we combined that two power plant into one graphic as be seen in the Figure 2. This picture illustrates the value of heat rate and efficiency of the power plant on four selected TMCR (50, 75, 100, and 110). The figure indicates that heat rate (orange line) increase with the decreasing of power plant load, while the efficiency (blue line) of power plant decline. The gained values of heat rate from Gatecycle simulation for TMCR 50, TMCR 75, TMCR 100, and TMCR 110 are 3618 kcal kW-hr⁻¹, 3439.37 kcal kW-hr⁻¹, 3358.91 kcal kW-hr⁻¹, 3284 kcal kW-hr⁻¹ respectively. The TMCR 50 has the highest heat rate while the TMCR 110 has the lowest heat rate. Efficiency of each load variations are 13 for TMCR 50, 18.53 for TMCR 75, 25.34 for TMCR 100 and 27 for the last TMCR.

The rise in heat rate and fall in efficiency is affected by one of them being the change in mass flow of the working fluid and the heat transfer process that happens in the components of the power plant, specifically the boiler, steam turbine, condenser, feed water heater and deaerator. Fluctuations in the performance of each component of the power plant will be discussed in another section of this article. This graphic also can predict about the reduction of emission rates and particular unit cost as in line with recent studies by [18]. As we can see from equation [9] we can achieve the lower heat rate by increasing the power production or decreasing the fuel consumption. Since the fuel consumption will be presented later. In terms of power generation, a significance rise can be achieved by such actions: Evaluating pipe and stream installation about the fouling or slagging condition, redesign about the geometry of the crucial part if it is possible, and altering the fuel type into the bigger calorie value.

3.2 Fuel flow
In terms of saving fuel expenditure, the lower power generation heat rate indicates the bigger of money saved and vice versa. This will result in lesser electricity prices per kWh, where the cost of purchasing materials is a fairly dominant component in the cost of producing electricity. Figure 3 depict the fuel consumption for electric generation for steam power plant. Theoretically, the fuel flow is depended on the type of the coal or fuel. At the similar amount of energy needed, the higher calorie value will quickly sufficient that necessity compared to the lower one. In general, range of fuel consumption on four conditions is 52-104.54 Mega Joule per second during the load ramping up process of water boiling, the fuel flow curve changes, as shown in Figure 3.

The underpinning reason why TMCR 110 illustrated as the highest is because the feed water flow. Even though the enthalpy, pressure and temperature are identical, the increasing of mass flow will increase the amount of energy required for steam generation. In line with the previous statement, the TMCR 50 has the lowest fuel consumption among the other. This is in line with [19] results, stating 50% maximum continuous rating has lower fuel consumption compared to 100% maximum continuous rating. However in this research, the 110 TMCR fuel consumption is 5% higher than 100 TMCR. Since fuel consumption depends on the quality of the steam however the rise is acceptable as the power shaft rising outweigh that value.
3.3 Heat transfer

Figure 4 exemplify the distribution of heat transfer duty of installed equipment. The selected power plant equipment are boiler, condenser and four stages of closed feed water heater. The deaerator is assumed to be not selected since the energy of heat transfer is not be taking into account in this subchapter but later in the next research. From the picture, the keen reader will notice that boiler and condenser are two equipment that transferring heat bigger than the other equipment. Those equipment heat transfer have also increased as the load variation considerably increased.

In the boiler, feed water previously has 159 kcal kg\(^{-1}\) and transformed into 799 kcal kg\(^{-1}\). Moreover, this enthalpy will be calculated later with amount of fluctuating flows of working fluids. Condenser also transforming steam energy from 531 kcal kg\(^{-1}\) into 42.67 kcal kg\(^{-1}\). This amount of work is done by heat transferring with surrounding sea water as assumed in table 1. Since four stages of feed water heater are installed as cogeneration plant in this experiment, the rise of working fluid when still in the water form is 114.1 Celsius. However this significance of temperature rising is just 7 percent of the total heat transfer conducted in the selected equipment.

This is also similar with the reason of fuel consumption trend, the mass flow rate is a detrimental factor for heat transfer process [1]. Even though feed water heaters are injected of steam from the turbine but the energy of the multiplication between mass flow rate and the steam enthalpy is still lower than boiler and condenser has. Also, from the figure 4, it shows that recalculating the steam bleeding is future necessity since the portion from cogeneration plant. It appears there is probability of increasing steam power plant efficiency from increasing the steam bleeding. The other attempt that is viable by adding the other feed water heater especially the closed type either in the after or before the deaerator. By increasing the efficiency, the heat rate value will be decreased which is favourable for decreasing the fuel expenditure and fuel consumption of the power plant.

4. Conclusion

This study investigated the effect of load variation into power plant heat rate, fuel consumption and heat transfer duty. The combustion experiments were conducted using Gatecycle software. Our results show that this program are capable of calculating heat-rate, coal consumption and
thermal duty distribution comparing one output to another. Then, we also have several principal findings are as follows:

- Heat rate and efficiency are increased periodically as the load variations calculated. This was considered to be due to the increasing of the power is bigger than the increasing of fuel consumption.
- Fuel consumption increased because the amount of water also ramped up as the TMCR 100 has double amount of flow than TMCR 50.
- Boiler is the most crucial part in terms of heat transfer, the second one is condenser. This was because the amount of enthalpy change in huge amount of flow also conducted in those equipment.
- This type of study can predict about dynamic simulation without disturbing the power plant daily operation. This is favourable since this flexibility can help improve accurately the equipment.

Further experimental tests are needed to encompass fuel consumption, heat rate and heat transfer during other load variation to give clear validation. Also from the efficiency graphic, we can depict about how big of possibilities to enhance the equipment performance into more than 50 percent as the support of climate conservation.

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6. References
[1] I. Avagianos et al., “Predictive method for low load off-design operation of a lignite fired power plant,” Fuel, vol. 209, no. August, pp. 685–693, 2017, doi: 10.1016/j.fuel.2017.08.042.
[2] P. Eser, A. Singh, N. Chokani, and R. S. Abhari, “Effect of increased renewables generation on operation of thermal power plants,” Appl. Energy, vol. 164, no. 2016, pp. 723–732, 2016, doi: 10.1016/j.apenergy.2015.12.017.
[3] P. Madejski, “Numerical study of a large-scale pulverized coal-fired boiler operation using CFD modeling based on the probability density function method,” Appl. Therm. Eng., vol. 145, pp. 352–363, 2018, doi: 10.1016/j.applthermaleng.2018.09.004.
[4] G. Qi, S. Zhang, X. Liu, J. Guan, Y. Chang, and Z. Wang, “Combustion adjustment test of circulating fluidized bed boiler,” Appl. Therm. Eng., vol. 124, pp. 1505–1511, 2017, doi: 10.1016/j.applthermaleng.2017.07.005.
[5] Y. Kwak, S. Hwang, and J. H. Jeong, “Effect of part load operating conditions of an air conditioner on the number of refrigerant paths and heat transfer performance of a condenser,” Energy Convers. Manag., vol. 203, no. July 2019, p. 112257, 2020, doi: 10.1016/j.enconman.2019.112257.
[6] J. Lin, A. J. Mahvi, T. S. Kunke, and S. Garimella, “Improving air-side heat transfer performance in air-cooled power plant condensers,” Appl. Therm. Eng., vol. 170, no. December 2019, p. 114913, 2020, doi: 10.1016/j.applthermaleng.2020.114913.
[7] R. Carapellucci and L. Giordano, “Upgrading existing gas-steam combined cycle power plants through steam injection and methane steam reforming,” Energy, vol. 173, pp. 229–243, 2019, doi: 10.1016/j.energy.2019.02.046.
[8] R. Bontempo and M. Manna, “Work and efficiency optimization of advanced gas turbine cycles,” Energy Convers. Manag., vol. 195, no. January, pp. 1255–1279, 2019, doi: 10.1016/j.enconman.2019.03.087.
[9] S. S. Chauhan and S. Khanam, “Enhancement of efficiency for steam cycle of thermal power
plants using process integration,” *Energy*, vol. 173, pp. 364–373, 2019, doi: 10.1016/j.energy.2019.02.084.

[10] C. Wang, M. Liu, B. Li, Y. Liu, and J. Yan, “Thermodynamic analysis on the transient cycling of coal-fired power plants: Simulation study of a 660 MW supercritical unit,” *Energy*, vol. 122, pp. 505–527, 2017, doi: 10.1016/j.energy.2017.01.123.

[11] J. W. Burnett and L. L. Kiesling, “Power plant heat-rate efficiency as a regulatory mechanism: Implications for emission rates and levels,” *Energy Policy*, vol. 134, no. October 2017, p. 110980, 2019, doi: 10.1016/j.enpol.2019.110980.

[12] D. Grant, K. Running, K. Bergstrand, and R. York, “A sustainable ‘building block’?: The paradoxical effects of thermal efficiency on U.S. power plants’ CO2 emissions,” *Energy Policy*, vol. 75, pp. 398–402, 2014, doi: 10.1016/j.enpol.2014.10.007.

[13] H. M. Kwon, S. W. Moon, T. S. Kim, and D. W. Kang, *Performance enhancement of the gas turbine combined cycle by simultaneous reheating, recuperation, and coolant inter-cooling*, vol. 207. Elsevier Ltd, 2020.

[14] M. Vellini, M. Gambini, and T. Stilo, “High-efficiency cogeneration systems for the food industry,” *J. Clean. Prod.*, vol. 260, p. 121133, 2020, doi: 10.1016/j.jclepro.2020.121133.

[15] S. Briola, R. Gabbrrielli, and A. Delgado, “Energy and economic performance assessment of the novel integration of an advanced configuration of liquid air energy storage plant with an existing large-scale natural gas combined cycle,” *Energy Convers. Manag.*, vol. 205, no. November 2019, p. 112434, 2020, doi: 10.1016/j.enconman.2019.112434.

[16] H. M. Kwon, T. S. Kim, J. L. Sohn, and D. W. Kang, *Performance improvement of gas turbine combined cycle power plant by dual cooling of the inlet air and turbine coolant using an absorption chiller*, vol. 163. Elsevier B.V., 2018.

[17] L. Malinowski, M. Lewandowska, and F. Giannetti, “Analysis of the secondary circuit of the DEMO fusion power plant using GateCycle,” *Fusion Eng. Des.*, vol. 124, pp. 1237–1240, 2017, doi: 10.1016/j.fusengdes.2017.03.026.

[18] J. W. Burnett and L. L. Kiesling, “Power plant heat-rate efficiency as a regulatory mechanism: Implications for emission rates and levels,” *Energy Policy*, vol. 134, no. October 2017, p. 110980, 2019, doi: 10.1016/j.enpol.2019.110980.

[19] D. Neshumayev, L. Rummel, A. Konist, A. Ots, and T. Parve, “Power plant fuel consumption rate during load cycling,” vol. 224, no. February 2018, pp. 124–135, 2020, doi: 10.1016/j.apenergy.2018.04.063.