APPLICATION OF NEWTON – RAPHSON METHOD TO ANALYZE THERMAL EFFICIENCY OF GAS TURBINE BEFORE AND AFTER ENGINE REPLACEMENT

Damianus Mario Ricky Fernando[1*], Joko Waluyo[2], Nugroho Dewayanto[3]

[1]Master of System Engineering, Universitas Gadjah Mada
[2]Department of Mechanical and Industrial Engineering, Universitas Gadjah Mada
[3]Center for Energy Studies, Universitas Gadjah Mada
*Correspondence: damianus.mario.r@mail.ugm.ac.id[1]

Abstract

Gas turbine performance is one of the main concerns in the operating of industrial plants. Thermal efficiency is vital to analyze the performance of the gas turbine. This research purpose is to analyze the gas turbine's thermal efficiency after performed engine replacement in one of the gas industries in Kutai Kartanegara, East Kalimantan, Indonesia. The data was taken during the period from August 2017 to July 2018, while engine replacement was performed in February 2018. The data were processed to develop simulation models expressing the characteristics of the equipment.

The simulation models were then solved simultaneously using the Newton – Raphson Method. A beneficial advantage of Newton Raphson is that it enables to handle a massive number of data and provides faster iteration compare to other methods. Based on the simulation results, the thermal efficiency before performed engine replacement was 23.43% with a net power of 18.109 MW and fuel consumption of 1.640 Kg/s. Meanwhile, the development of thermal efficiency after performed engine replacement was 28.24% with a net power of 18.597 MW and fuel consumption of 1.397 Kg/s. This indicates that after performing engine replacement, the thermal efficiency increased by 4.81% and saved fuel by 0.243 Kg/s.

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1. Introduction

The gas production rate gradually decreases over time of gas production, indicated by reducing reservoir pressure. It is crucial to keep the pressure of the gas reservoir at the desired level. A gas turbine is widely employed to increase gas pressure and maintain it at a certain pressure (Musnal, 2014). For example, in one of the gas fields at the beginning of 2008, the reservoir pressure would decrease until low reach pressure. Therefore, the gas turbine was required to increase the gas reservoir's pressure to its' desired level. The gas turbine would also maximize the field deliverability during the initial sharp decline phase (Finaelf, 2002).

The other problem is pressure drops due to the length of the pipeline and bends of pipe. The higher gas flow rate can cause the pressure drop increase, and the pressure drop with a large bend angle in the pipe increases with increasing flow rate (Mahmuddin, 2017). Typically, the gas turbine works at high temperatures for an extended period. In that condition, the performance of the gas turbine will decline continuously. However, the gas turbine's reliability can be maintained by performing maintenance schedules such as preventive maintenance, predictive maintenance, and overhaul (Ramadhan, 2018). This maintenance will help to ensure the gas turbine always performs during its working period in optimal condition.

Regularly, the gas turbine engine is required to be replaced to maintain its good performance. In 2018, one of the gas industries in Kutai Kartanegara, East Kalimantan, performed engine replacement of gas turbine after reached more than 100,000 hours of running operation (Pamungkas, 2018). The gas turbine's performance gradually decreased; thus, engine replacement is required to be carried out. An analysis to determine the thermal efficiency of the gas turbine before and after perform engine replacement is essential to be conducted to evaluate the effect of engine replacement on gas turbine performance. Newton – Raphson can be used to analyze the performance of the gas turbine to calculate thermal efficiency. Newton – Raphson method can simulate many variables directly and more complex data (Stoecker, 1989).

Naryono and Budiono (2013) reported their study about gas turbine efficiency analysis with operation load in PLTGU Muara Tawar Blok I. Performance of gas turbine in PLTGU should be well maintained to provide optimal condition since the variation of operation load is usually happened in a power plant. With natural gas as fuel, gas turbines thermal efficiency decreased gradually a few months after the engine overhaul. The gas turbine's thermal efficiency was 36.2 % and 37.96% before and after engine overhaul, respectively. It was indicated that thermal efficiency increased by about 1.76% after an engine overhaul (Naryono and Budiono, 2013).

Here were two suggestions were given by Naryono and Budiono to minimize decreasing in thermal efficiency: apply a new system for flushing the compressor filter inlet and install an air filter before the compressor filter inlet. Thermal efficiency analysis related to the gas turbine's overhaul was also reported by Sunarwo and Harijono (2016). The thermal efficiency of the gas turbine was determined based on the Brayton cycle in a gas turbine. It indicated the highest thermal efficiency increasing was 0.47% after overhaul at 225 MW load. This was influenced by the mass flow rate of fuel used for load after the overhaul was less than before the overhaul (Sunarwo and Harijono, 2016).

Another gas turbine thermal efficiency analysis was also reported for PLTG Balai – Pungut Duri. A simulation was performed based on the Brayton cycle for the combined process of PLTG and PLTU by utilizing exhaust gas from PLTG Balai-Pungut. Efficiency up to 52.41 and increasing of W_{nett} up to 63.842 MW was reported, and justify the conclusion that utilization of exhaust gas will improve the gas turbine's overall efficiency (Gusnita and Said, 2017). Brayton cycle-based analysis was also utilized to analyze the thermal efficiency of gas turbines in PT. Pupuk Kaltim. It was reported that the actual efficiency of the gas turbine increased about 0.93% from 20.11% to 21.04% after performing primary inspection, include replacement of gas turbine rotor to increase the pressure ratio and efficiency of the compressor. On the other hand, fuel consumption slightly decreased by about 0.02 Kg/s from 1.22 Kg/s to 1.2 Kg/s (Sulistiyo and Rangkuti, 2018).

Newton-Raphson method was employed to analyze the thermal efficiency of PLTGU Priok. Interestingly, this method demonstrated minimal differences between thermal efficiency calculated by simulation and their actual experimental data. Newton-Raphson method resulted in 42.664% and 42.623% thermal efficiency than experimental data about 42.665% and 42.644% at output power 311.5 MW and 310.7 MW, respectively (Chaterine, et al., 2010). Based on the result, this study aimed to analyze the gas turbine's thermal efficiency during the period of engine replacement by using the Newton-Raphson method and justify the insignificant difference between this simulation method and conventional test.

2. Methodology

This study was conducted in field X, owned by a private gas company located in Kutai Kartanegara, East Kalimantan, Indonesia. The main objective of this research is to analyze the thermal efficiency of the gas turbine before and after perform engine replacement then perform a simulation with the Newton – Raphson method to analyze the performance. The basic principle of a gas turbine is shown in Figure 1. The air enters the axial flow compressor and then compressed before entering the combustion chamber.

Then heat addition will happen in the combustion chamber before entering the gas turbine. The gas turbine's power will turn the shaft and produce net energy to being used by the load. Based on primary data retrieved before and after perform engine replacement, then proceed the data with the following steps:

1. Daily data collection of a gas turbine.
2. Develop equation to correlate parameters of axial flow compressors, such as air mass flow rate ($\dot{m}$) versus outlet pressure of axial flow compressor (P_2) and axial flow compressor power (W_C) for the outlet pressure of axial flow compressor (P_2)
3. Develop equation to correlate parameters of a gas turbine-like air mass flow rate ($\dot{m}$) vs. an inlet pressure of gas turbine (P_3) and gas turbine power (W_T) vs. an inlet pressure of gas turbine (P_3)
4. Determine nett power of the gas turbine (W_{nett}) using the Newton – Raphson simulation method based on those equations mentioned above.
5. Perform the iteration to achieve convergence results.
6. Analyze the thermal efficiency of the gas turbine.

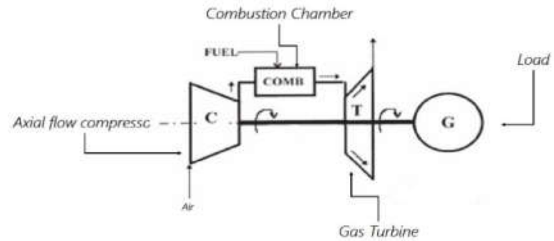


Figure 1. Schematic of the gas turbine

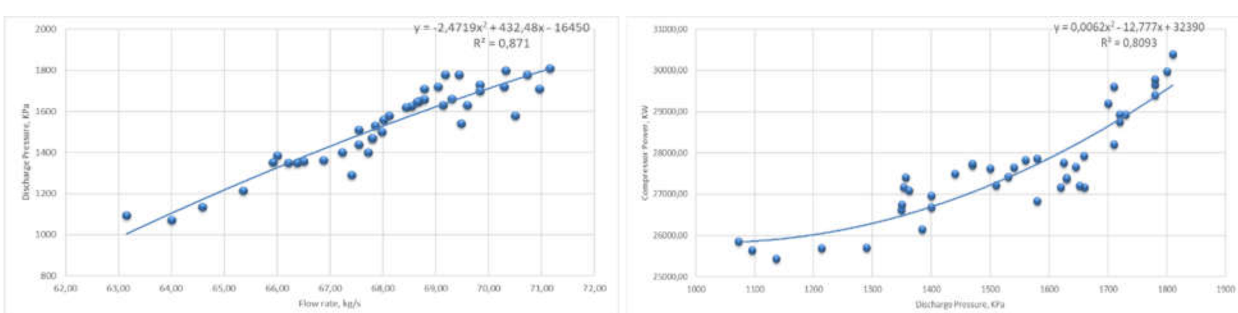
The basic equations are developed from the plots of gas turbine primary data retrieved from the daily reading of a gas turbine by the process operator. The basic equations were divided into two main categories, namely before and after engine replacement. Then from these equations, the Newton - Raphson method will be simulated using the basic equation shown in equation (1) (Chapra, et al., 2010).

$$X_{i+1} = X_i - \frac{f(X_i)}{f'(x_i)} \qquad (1)$$

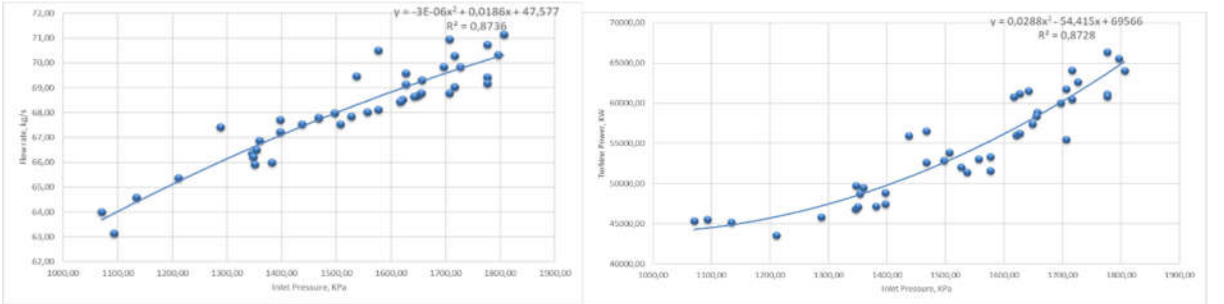
Based on equation (1), denote it as the iteration i. The iteration value will be continued until a certain amount is desired or reaches a convergent value.

3. Results & Discussion

The primary data before engine replacement was taken six months before engine replacement from August 2017 until January 2018, and the primary data after engine replacement was taken for six months from February until August 2018. The correlation between parameters of the gas turbine before engine replacement shows in Figure 2: (a) discharge pressure of axial flow compressor (P_2) and air mass flow rate ($\dot{m}$), (b) power of axial flow compressor (W_C) and discharge pressure of axial flow compressor (P_2), (c) air mass flow rate ($\dot{m}$) and the inlet pressure of gas turbine (P_3), and (d) power of gas turbine (W_T) and the inlet pressure of gas turbine (P_3) and the correlation between parameters of gas turbine after engine replacement shows in Figure 3: (a) P_2 and $\dot{m}$, (b) W_C and P_2, (c) $\dot{m}$ and P_3, and (d) W_T and P_3.

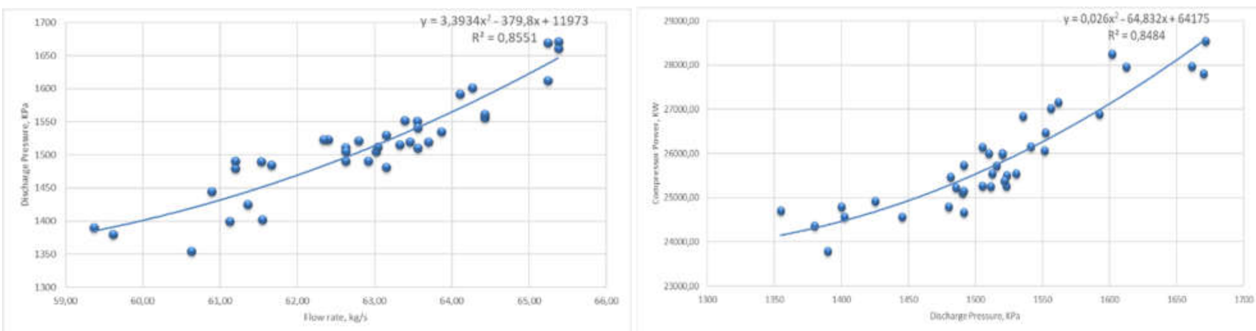


(a) (b)

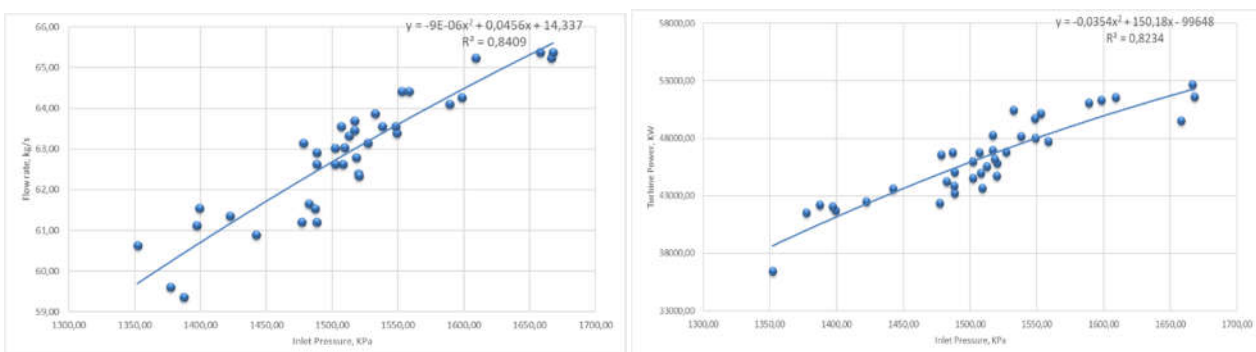


(c) (d)

Figure 2. Correlation between parameters of the gas turbine before engine replacement: (a) P_2 and ṁ, (b) W_C and P_2, (c) ṁ and P_3, and (d) W_T and P_3



(a) (b)



(c) (d)

Figure 3. Correlation between parameters of gas turbine after engine replacement: (a) P_2 and ṁ, (b) W_C and P_2, (c) ṁ and P_3, and (d) W_T and P_3

Based on the data as plotted in Figure 2, the correlation between parameters before engine replacement can be expressed by the following equations:

$$P_2 + 2.4719\dot{m}^2 - 432.48\dot{m} + 16450 = 0 \quad (2)$$
$$W_C - 0.0062P_2^2 + 12.777P_2 - 32390 = 0 \quad (3)$$
$$\dot{m} + 3\,x\,10^{-6}P_3^2 - 0.0186P_3 - 47.577 = 0 \quad (4)$$
$$W_T - 0.0288P_3^2 + 54.415P_3 - 69566 = 0 \quad (5)$$

Furthermore, simulations on those equations were conducted using the Newton – Raphson method to determine the nett power by using equation (6) as the gas turbine's basic equation nett power.

$$W_{nett} = W_T - W_C \quad (6)$$

Based on these five equations, iteration is performing using the Newton – Raphson method. The corrected value of iteration is iteratively searched until the convergence value was achieved (Chapra and Canale, 2010). Newton – Raphson method can be used to find a solution, and it can achieve convergence quickly if the initial value of the iteration close to the actual solution (Bakari, et al., 2016). Table 1 shows the initial cost that had been chosen for the iteration.

Table 1. The initial value of the iteration before engine replacement

Unknown Variable	Initial Value
P_2 (KPa)	1000
ṁ (Kg/s)	50
Wc (KW)	20000
P_3 (KPa)	900
Wt (KW)	36000
Wnett (KW)	16000

Those initial values were employed as the starting value for the Newton – Raphson Method. Table 2 shows the iteration result of the Newton – Raphson method. Based on the Table, the convergence result was achieved at the fourth iteration, and W_{nett} before performs engine replacement was determined as about 18.109 MW.

Table 2. W_{nett} iteration before engine replacement

Iteration	Wc (KW)	Wt (KW)	Wnett (KW)
1	25573.292	42452.779	16879.487
2	25790.688	43781.556	17990.868
3	25815.724	43923.995	18108.271
4	25815.897	43924.970	18109.073
5	25815.897	43924.970	18109.073
6	25815.897	43924.970	18109.073
7	25815.897	43924.970	18109.073
8	25815.897	43924.970	18109.073
9	25815.897	43924.970	18109.073

Thermal efficiency is the ratio of net power to heat energy that was added in the combustion chamber; therefore, it is being expressed as the following (Oyedepo, 2014):

$$\eta_{th} = \frac{W_{net}}{\dot{m}_{fuel}\ x\ LHV} \qquad (7)$$

Figure 4 shows the fuel rate before engine replacement. The data was starting from August 2017 until January 2018. Based on the data, the average fuel mass flow rate ($\dot{m}_{fuel}$) that has been used was 1.640 Kg/s for six months.

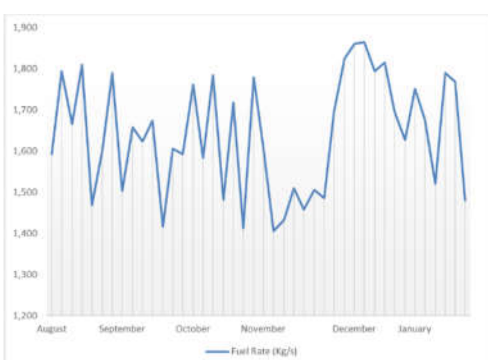


Figure 4. Fuel mass flow rate before engine replacement

A lower heating value is the value of the combustion product if H_2O is gas combustion. The fuel system of the gas turbine uses natural gas, which means the LHV of the fuel system is 47.141 MJ/Kg (ESSOM CO, 2008). The thermal efficiency is calculated based on equation (7). The result of thermal efficiency before engine replacement is 23.43%.

It is shown in Figure 3, the characteristic of the gas turbine after engine replacement was performed. After fitting, data are obtained as the following:

$$P2 - 3.3934\dot{m}^2 + 379.8\dot{m} - 11973 = 0 \qquad (8)$$
$$W_C - 0.026P_2^2 + 64.832P_2 - 64175 = 0 \qquad (9)$$
$$\dot{m} + 9\,x\,10^{-6}P_3^2 - 0.0456P_3 - 14.337 = 0 \qquad (10)$$
$$W_T + 0.0354P_3^2 - 150.18P_3 + 99648 = 0 \qquad (11)$$

The following equations performed the simulation with the Newton – Raphson method to determine the gas turbine's next power after performed engine replacement. The initial value for these equations uses the same amount before engine replacement shows in Table 1. The initial value is selected based on a value that is close to daily reading data.

The initial value is based on data from February 2018 until July 2018, then starts to perform a simulation with the Newton – Raphson method. Table 3 shows the iteration result of the gas turbine after performed engine replacement. Based on the table, convergence result was achieved at the fifth iteration with W_{nett} is 18.597 MW

Table 3. W_{nett} iteration after engine replacement

Iteration	Wc (KW)	Wt (KW)	Wnett (KW)
1	22835,871	32171,938	9336,068
2	23377,054	40210,416	16833,363
3	24548,824	42982,089	18433,265
4	24794,488	43390,197	18595,709
5	24801,151	43398,699	18597,548
6	24801,154	43398,702	18597,548
7	24801,154	43398,702	18597,548
8	24801,154	43398,702	18597,548
9	24801,154	43398,702	18597,548

Thermal efficiency after performed engine replacement will be calculated with equation (7). Based on data W_{nett} is 18.597 MW, LHV of the fuel system is 47.141 MJ/Kg, and the fuel rate after performed engine replacement is shown in Figure 5. The average fuel mass flow rate ($\dot{m}_{fuel}$) after engine replacement is 1.397 Kg/s in February 2018 until July 2018.

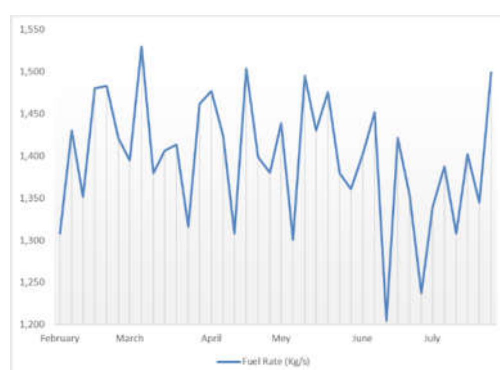


Figure 5. Fuel mass flow rate after engine replacement

The result of thermal efficiency after performed engine replacement is 28.24%. There is an increase in the thermal efficiency of 4.81%.

4. Conclusion

This paper concludes that after performing engine replacement, the gas turbine has increased thermal efficiency by 4.81%; before performed engine replacement, the thermal efficiency approximately 23.43% with a net power of 18.109 MW and an average fuel mass flow rate of 1.640 Kg/s. Then, after an engine replacement, the thermal efficiency has increased and reached 28.24% with a net power of 18.597 MW and an average fuel mass flow rate of 1.397 Kg/s. Engine replacement has a positive effect on gas turbine performance.

The nett power is an increase of about 0.488 MW and saves more fuel consumption around 0.243 Kg/s. Maintaining the gas turbine's performance is the main thing that must be done in the gas industry to maintain the deliverability of the production process. Process the data with the Newton – Raphson method can help to simulate extensive data and various equations with faster iteration. This can help stimulate the gas turbine's thermal efficiency over a certain period or long-term condition.

Nomenclature

LHV	Lower Heating Value (Kj/Kg)
$\dot{m}$	Air mass flow rate (Kg/s)
$\dot{m}_{fuel}$	Fuel mass flow rate (Kg/s)
P_2	Axial flow compressor outlet pressure (Kpa)
P_3	Gas Turbine inlet pressure (Kpa)
W_C	The energy was used in the axial flow compressor (KW)
W_{nett}	The nett energy was generated by the turbine (KW)
W_T	The energy was produced by the gas turbine (KW)
η_{th}	Thermal efficiency (%)

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