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Research paper

Parametric investigation of combustion process optimization for Gas Turbines at SJ Putrajaya

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ABSTRACT

Gas Turbine (GT) power plants have been represented as essential assets of energy units because of their numerous advantages compared to conventional coal power plants. However, their low thermal efficiency may make the continuous baseload operations a lossmaking alternative and threaten to continue. This fact is raising the importance of performing thermodynamic investigation according to the current operations' conditions. This paper aims to conduct a thermodynamic investigation for two Siemens V94.2 gas turbine (GT) units based on current operations' conditions. The reason for selecting these units is because they are operating at a much lower thermal efficiency than the designed thermal efficiency, and due to the age factor, the GTs are not suitable for major retrofitting due to poor return on investments. A numerical model is designed to simulate the overall thermodynamic process in the gas turbine using MATLAB SIMULINK.

The obtained numerical results are validated by comparing them with the operational data collected from the stations. The thermal efficiency is increased by 30%, with a maximum output power equal to 140MW. The power output had decreased by 0.2% when the ambient temperature was increased by about 6.0 °C. A graphical optimization, where various conditions are plotted as graphs, is also carried out to achieve the maximum thermal efficiency and power output. Finally, a number of recommendations are made to address decreased thermal efficiency and output power.

1. Introduction

Gas Turbine (GT) power plants are the primary choice in power generation due to several factors, including fast starting and loading during peak power demand. In addition to the high reliability, GT is more efficient than the coal-fired power plants, especially at the full load operating condition (Gonzalez-Salazar et al., 2018). GTs are favourable when compared to other types of thermal plants as the readily available primary fuel. Natural gas is produced in the country, which reduces dependency on other countries. Furthermore, the GTs can provide "black start" operations, providing electricity supply when a national blackout is advantageous. GTs also relatively simpler to operate as "push start" operations enable fast-firing up the GT from turning gear to full load with minimal operator intervention. However, the output power capacity is limited at the base load operating conditions, and the thermal efficiency is lower at the GT than at the coal-fired power plants(Energy, 2016).

In a developing economy where the demand is ever-growing, GTs that can only produce less than 200 MWn per unit are not favourable as other thermal plants can produce more than 500 MWn per unit. Nevertheless, the existing plant at SJ Putrajaya is still relevant as it has a well-maintained infrastructure that is fully operational. However, it is not economically viable to consider major retrofitting of aged plants such as SJ Putrajaya as the returns on investment are not attractive and require huge capital investment. In the SJ Putrajaya GT power station in Malaysia, the increase of the natural gas price and the low thermal efficiency of this station are increasingly threatening the existence of this power plant. The current thermal efficiency, about 26%, is relatively low compared with the designed thermal efficiency. The low thermal efficiency is generally becoming a fast economic and environmental issue and a considerably significant factor for the GTs with the increased price of natural gas (Malaysia, 2016). In

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Nomenclature

T1	Inlet temperature to the compressor
T3	Turbine inlet temperature
T4	Turbine outlet temperature (exhaust gas)
r_p	Compression ratio
P_1	Compressor's inlet pressure
P_2	Compressor's exit pressure
AFR	Air–fuel ratio
$\dot{m}_a$	Mass flow rate of air
$\dot{m}_f$	Mass flow rate of the used fuel
ηth	GT thermal efficiency
ηc	Compressor efficiency
W_{net}	The net-work produced by the gas turbine
Q_{add}	Heat added to the system during the combustion
W_c	Compressor work
Cpa	Specific heat of air which is taken as constant 1.005 kJ/kg K
R_{PA}	Compression ratio of air
η_m	Is mechanical efficiency of both compressor and turbine
LHV	LHV is the lower heating value for natural gas
C_{pf}	Specific heat of fuel
C_{pg}	Specific heat of gas
f	The fuel–air ratio by mass
W_t	Shaft work
W_{net}	Net-work
P	Output power
SFC	Specific fuel consumption

addition, the strong competition on the unit price of energy from the coal-fired power plants has put extra pressure on the less efficient GT systems (Yusop and Dahlan, 2014). Consequently, the thermal efficiency of the GTs at SJ Putrajaya of TNB has become an issue and a challenge that needs to be addressed urgently. Effective optimization and control approaches using advanced control technology and techniques could be used to control such challenges (Kulor et al., 2021; Gul et al., 2020)

However, this research aims to enhance the performance of a GT by optimizing a number of key variables using a SIMULINK model designed to simulate the overall thermodynamic process that occurs in the gas turbine within Ambient temperature, taking into consideration the combustion process at a specified time air–fuel ratio. The novelty of this research is that since actual plant data is utilizing in validating the model, the research outcomes are reliable and could be applied in a real-life scenario at the actual GT plant, in this case, SJ Putrajaya. Ultimately, the approximately 26% thermal efficiency of the SJ Putrajaya GT power plant station is much lower than the designed efficiency. This deficiency is due to the high competition for energy and the increase in produced emissions. Therefore, lowering thermal efficiency has become an urgent issue.

This paper is a critical review discussing design and control challenges and recommends the most effective optimization and control approaches using advanced control technology and techniques. To this end, the study draws on existing works done by numerous researchers in the field and tactically reviews the current works to envisage the limitation in the current approach to suggest the way forward. The technique used for the review focused on technology, application, availability and environmental impact analysis, controllability and implementation challenges. The results clearly show that the available technology is limited to the design of the high-power plant and not made available for the medium level plant manufactures due to high implementation costs.

This paper is organized as follows: In Section 2, previous work on modelling and optimizing Gas Turbines is reviewed. Then, in Section 3, the methodology and thermodynamic modelling is presented. In Section 4, the obtained results from the validated proposed model are presented with discussion and analysis. Finally, conclusions about the paper are presented in Section 5.

2. Previous work on factors affecting GT performance

In this section, the three major factors affecting GT performance, which are ambient temperature, the effect of external factors and the determination of optimal compression ratio for GT, are introduced to discuss the contributions of previous works in GT performance.

2.1. Effect of ambient temperature on GT performance

Several researchers investigated the effect of the ambient temperature on GT performance, including but not limited to Shukla and Singh (2014), who reported that the output power of a GT could be strongly affected by the variation of the air temperature. When the ambient temperature is decreased by about 9 °C, the thermal efficiency is enhanced by approximately 0.3%. This improvement is based on the assumption that the intake pressure and humidity are kept constant. Gautam et al. (2018) have tested the thermal performance of the gas turbine under different values of the compression ratio and ambient temperature. Their results showed that the thermal efficiency has increased with the decrease of the ambient temperature at a wide range of the tested compression ratios. Igoma et al. (2016) examined a 25.0 MW GT power plant's thermal performance in an arid climate. The authors found that the power output had decreased by 0.2% when the ambient temperature was increased by about 6.0 °C. This finding was mainly attributed to the reduced air density at the inlet port of the compressor, lessening the amount of oxygen entering the combustion chamber (El-Shazly et al., 2016). Based on these findings, various cooling systems for improving the GT performance have been adopted by many researchers. GT cooling systems including evaporative cooler and absorption chiller were utilized to reduce the intake air temperature (El-Shazly et al., 2016). The achieved results of GT with cooling systems were compared with that of the baseline performance. The output power was improved by 25.47% and 5.56% when the absorption chiller and evaporative cooler were used, respectively, after considering additional auxiliary consumption by the chiller and cooler. Moreover, Marzouk et al. stated that the GT power plant is negatively influenced by ambient temperature rise (Marzouk and Hanafi, 2013). In Kim (2012), Kim considered that the cooling of the gas turbine blades plus the wet-compression gas turbine cycle could be the most efficient method of ensuring a high operating temperature while maintaining a high thermal efficiency and output power.

2.2. Effect of external factors on the overall performance of GTs

Enormous studies were carried out to demonstrate the effect of the environmental and operational parameters on the overall performance of the GT power plants (Haseli et al., 2008). Rahman et al. (2011a) studied and analyzed thermodynamically the most effective operational parameters that could optimize the performance of the GT power plants. The authors concluded that the compression ratio, ambient temperature, air to fuel ratio, and isentropic efficiency could highly affect the overall thermal efficiency of a GT power plant. The authors' results showed that the rise of the intake air temperature and the used air to fuel ratio could constantly decrease the thermal efficiency. Nevertheless, the heat release rate and the specific fuel consumption could increase.

On the other hand, the effect of varying the compression ratio and intake temperature on GT performance was investigated by Lebele-Alawa and Asuo (2013). Different strategies were used by Ibrahim and Rahman (2014), aiming to improve the thermal performance of the GT power plant. In that research, the increase in the compression ratio could significantly increase the output power and reduce the specific fuel consumption. As a result, the maximum thermal efficiency of 50.7% was achieved at a compression ratio of 12.4. Moreover, the lower specific fuel consumption of about 0.14 kg/kWh was attained too. These results were mainly attributed to the use of an intercooler, which permitted the gas turbines' compression to be increased without a noticeable decrement in the intake air density.

On the other hand, the results of sixty weeks of collected data by Lebele-Alawa and Asuo (2013) showed that the intake temperature could potentially affect the GT power plant performance. When the intake temperature decreased by about 45 °C, the GT thermal efficiency is slightly enhanced by about 0.12%, whereas the outpower is significantly increased by 2.24 MW. This finding was due to increased intake air density, increasing the ratio of oxygen to the same amount of injected fuel per cycle. This outcome might lead to complete combustion and a greater heat rate per power cycle to be released (Gautam et al., 2018).

2.3. Determination of optimal compression ratio for GTs

The performance of the GT by determining the optimal compression ratio has been analyzed by R.L.a.J. (2016). In their study, the optimum compression ratio for the maximum output power was obtained analytically. Meanwhile, the maximum system efficiency was obtained by using the iteration method. A thermodynamic analysis was performed by Verdan et al. on a GT operated in a combined heat and power system by using real-time parameters of air and burnt gases at previously designed testing conditions (Mrzljak Vedran et al., 2019). In the conducted analysis, the maximum heat and power losses during the combustion process were calculated. By considering most of the system losses, the studied GT overall efficiency was about 33%. A potential enhancement in an 11.5 MWe solar thermal GT power plant was obtained by adopting a 3.5 MWe Rankine combined cycle (Meliche et al., 2014). A thermodynamics analysis and prediction modelling were performed on the thermal performance of a concentration power plant in the south of Algeria. A TRNSYS16 software and its available library STEC.03 were used to run the numerical simulation and modelling. The exergetic and energetic analysis were the main focus of the conducted study to evaluate the effect of the real-time operating conditions on the overall performance of the GT plant station. Improvement in the thermal efficiencies (exergetic and energetic) and the output power was observed when the waste heat of the combustion process was utilized in the form of the heat recovery process.

The majority of the previous work focuses on improving the inlet air quality of the GT by the usage of various types of chillers that incur a considerable capital cost. Furthermore, some previous studies were conducted in hot, arid climates where the average temperatures hover around 45–500 °C. In some instances, complex software was utilized, which incurred capital cost and training cost of utilizing the soft.

This research work fills the gap of purely focusing on operational parameters which will not incur additional capital investment, whereas previous research has focused on major retrofitting, which is not viable in aged plants such as that in the present research. Furthermore, the climate of Malaysia is moderately warm with average temperatures of around 30–350 °C; thus, the previous work and optimizations are not applicable in the present study. Furthermore, a simplified model using MATLAB is cost-effective and may be immediately utilized by plant operators with minimal training.

3. Methodology and thermodynamic modelling

The main focus of the presented investigation is to demonstrate the ability of the SIMULINK package to model the processes of a 135 MW Siemens V94.2 ratio model. In developing the simulation model, a number of key parameters were identified and used for simulating the combustion process and obtaining a set of optimized results. Historically relevant data was obtained from the power unit, categorically arranged and used as input to the model. The integrity of the designed model and the results obtained are ensured by keeping the test running for a number of days while comparing the data being fed and the power obtained with the actual power output as per station data. The work execution steps is shown in Fig. 1.

Accurate identification of relevant key parameters is crucial for further investigation based on real-time data collected from the SJ Putrajaya power plant. Processing the captured data is divided into three parts: health data assessment, cleaning, and validation. Parameters' identification can provide a reliable data framework set for modelling and optimization. The processed actual data are used as inputs to the MATLAB Simulink model for further simulation investigations for any possible optimization in the system performance. A number of parameters that could strongly affect the combustion performance of the GT system are listed as follows:

3.1. Gas turbine operating temperatures (T_1) and (T_3)

The GT system's thermodynamic cycle is usually assumed to be an ideal cycle, and the compression and expansion processes are assumed to be polytropic processes (Pulkrabek, 1997), while the inlet temperature to the compressor (T_1) represents the ambient temperature. Any increase of T_1 could considerably affect the GT thermal performance due to decreased intake air density (Gautam et al., 2018). This, in effect, may reduce the mass flow to the turbine resulting in smaller output power due to the flawed combustion process. The turbine inlet temperature (T_3) is defined as the temperature of the working fluid entering the turbine after leaving the combustion chamber. However, it is worth mentioning that there is a maximum limit to the proper temperature, as the turbine blades can only withstand specific temperature values before the occurrence of any material degradation. Therefore, it is critical to ensure that T3 is below the maximum limit of the blades' operating temperature. Apart from this, the high turbine inlet temperature could provide greater thermal efficiency of the GT power plant.

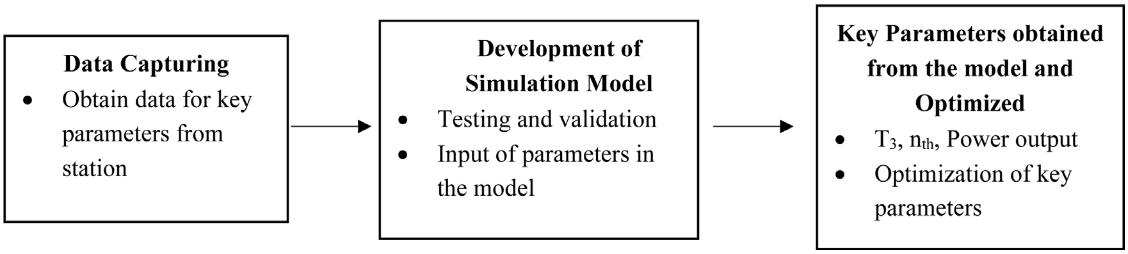

Fig. 1. Work execution steps.

3.2. Compression Ratio (r_p) and Air–Fuel Ratio (AFR)

Theoretically, the compression ratio (r_p) could strongly affect the thermal performance of the GTs. Practically, however, the higher r_p means a greater GT thermal efficiency, and hence a higher output power may be achieved (Bhargava et al., 2010). In this study, the compression ratio for the gas turbine is defined as the compressor's exit pressure (P_2) over the inlet pressure (P_1), as shown in Eq. (1). The compressor inlet pressure is assumed as the ambient pressure, and the pressure drop between the air filter house and compressor inlet was neglected. Furthermore, the air–fuel ratio (AFR), shown in Eq. (2), is defined as the mass flow rate of air ($\dot{m}_a$) entering the GT system over the mass flow rate of the used fuel ($\dot{m}_f$) injected inside the combustion chamber. Therefore, it is necessary to obtain the correct AFR to produce the maximum combustion efficiency during the combustion process. Furthermore, the closer the AF ratio to the stoichiometric limit, the greater the heat could be released during the combustion process, and the less harmful emissions could be produced (Heywood, 1988; Saif and Tariq, 2017). This could significantly reduce pollutant emissions and enhance the GT thermal efficiency. Besides, the AFR could directly influence the combustion process because if there is excess air presented during the combustion process, the GT thermal efficiency might decrease.

The GT thermal efficiency (η_{th}) is calculated based on Eq. (3) (Rahman et al., 2011a), where (W_{net}) and (Q_{add}) are respectively representing the net-work produced by the gas turbine and the heat added to the system during the combustion process inside the combustion chamber.

$$r_p = \frac{P_2}{P_1} \tag{1}$$

$$AFR = \frac{\dot{m}_a}{\dot{m}_f} \tag{2}$$

$$\eta_{th} = \frac{W_{net}}{Q_{add}} \tag{3}$$

The compressor work (W_c) (Rahman et al., 2011a), assuming that the following definition binds auxiliary cooling of turbine blade:

$$W_c = \frac{C_{pa} \times T_1 \times R_{PA}}{\eta_m} \tag{4}$$

Where T_1 is the compressor inlet temperature (ambient temperature), the specific heat of air (Cpa) and specific heat of flue gas (Cpg) are assumed constant at 1.005 kJ/kg K and 1.15 kJ/kg K for all the calculations (Rahman et al., 2011b), and ηm is the mechanical efficiency of both compressor and turbine.

The energy balance in the combustion chamber assuming energy generated by combustion is accomplished by a heat transfer source:

$$\dot{m}_a C_{pa} T_2 + \dot{m}_f C_{pf} T_f = (\dot{m}_a + \dot{m}_f)\, C_{pg} \times T_3 \tag{5}$$

where $\dot{m}_f$ is the fuel mass flow rate (in kg/s), $\dot{m}_a$ is the air mass flow rate (in kg/s), LHV is the lower heating value for natural gas equal to 20,300 Btu/lbm or 47,200 kJ/kg, T_3 is turbine inlet temperature, T_f is the fuel temperature, while C_{pf} and C_{pg} are specific heat of fuel and gas, respectively (Rahman et al., 2011a; Cengel, 2002).

Manipulating (Eq. (2)), the turbine inlet temperature (T3) can be expressed as:

$$T_3 = \frac{C_{pa} T_2 + f \times LHV}{C_{pg} + f \times C_{pg}} \tag{6}$$

where f is the fuel–air ratio by mass: $f = \frac{\dot{m}_f}{\dot{m}_a}$

The turbine outlet temperature (exhaust gas, T4) (Rahman et al., 2011a) is expressed as follows:

$$T_4 = T_3(1 - \eta_t \times R_{pg}) \tag{7}$$

where $R_{pg} = 1 - \frac{1}{r_p^{\frac{\gamma_g - 1}{\gamma_g}}}$ and $R_{pa} = \frac{r_p^{\frac{\gamma_a - 1}{\gamma_a}} - 1}{\eta_c}$ ($\gamma_a = 1.4$ and $\gamma_g = 1.33$)

The shaft work (Rahman et al., 2011a), W_t is defined as:

$$W_t = C_{pg} \times T_3 \times \eta_t \times \frac{R_{pg}}{\eta_m} \tag{8}$$

And the net-work (Rahman et al., 2011a), W_{net}:

$$W_{net} = W_t - W_c \tag{9}$$

The output power of the turbine (Rahman et al., 2011a) is defined as:

$$P = \dot{m}_a \times W_{net} \tag{10}$$

The specific fuel consumption (SFC) (Rahman et al., 2011a) is expressed as:

$$SFC = \frac{3600 \times f}{W_{net}} \tag{11}$$

The heat supplied (Q_{add}) (Rahman et al., 2011a) is defined as:

$$Q_{add} = C_{pg}[T_3 - T_1(1 + R_{pa})] \tag{12}$$

Ultimately, the GT efficiency (η_{th}) (Rahman et al., 2011a) is expressed as:

$$\eta_{th} = \frac{W_{net}}{Q_{add}} \tag{13}$$

4. Case study at SJ Putrajaya

SJ Putrajaya is a peaking plant that was initially commissioned as a baseload plant in 1993. The plant consist of two units of Siemens V94.2 GT units capable of producing 126 MWn each. The station is close to the federal capital of Malaysia, Putrajaya, which houses critical government agencies. Thus, the station's ability as a "Black Start" is vital as the station can restore supply to Putrajaya in less than an hour should there be a national blackout. Thus, despite the ageing infrastructure, the station has been well maintained and is fully operational on standby/peaking mode. In this context, "peaking" refers to producing load during "peak hours" when the other stations cannot cope with the generation demand at that time.

4.1. Data collection

The real-time data is captured from a GT power plant at SJ Putrajaya and fed into the designed model for further simulation investigations. The data is captured from the power plant's monitoring system using the Plant Information (PI) add-in module, which is available in an Excel sheet. In order to extract the data, the desired time range of interest is selected, and the PI module extracts the data from the PI server. The data is then displayed on the excel spreadsheet. For this research work, data is collected explicitly from GT No.5. This gas turbine (i.e. GT No. 5) is a Siemens type V94.2 ratio model, and it is designed to produce an output power of 126 MW on baseload operating conditions, as per its nameplate. The captured data was recorded while GT No.5 operated during a baseline power generation of approximately 123–126 MW. Thus, the data is used to validate the model that is designed in our study. This has indeed ensured the integrity of the proposed model and the optimization study. Using real data represents a key advantage of this study: validating the proposed model using real-time captured data rather than simulated data.

4.2. SIMULINK model development

In order to perform and validate the simulation of the proposed model, all the relevant data and thermodynamic equations related to the GT power plant were carefully prepared and finalized. Simulation for the proposed model was carried out on MATLAB SIMULINK. The simulation results from the Turbine Inlet Temperature (T3) and the GT's network, alongside the power output and the overall thermal efficiency (η_{th}). The integrity of the optimized results of the proposed model was ensured by testing and validating them, while the optimization is carried out by varying key parameters such as ambient temperature (T_1), compression ratio (r_p), as well as Air–Fuel Ratio (AFR). After optimization, the results obtained were presented, discussed and analysed. The GT SIMULINK performance model used many of its library components to effectively express the adopted mathematical equations, as shown in Fig. 2. The required data was captured from the GT power plant station and used as inputs to the model workspace. The number of input(s) and output(s) on each block varied depending on the thermodynamic relations that were modelled. In particular, in complex equations, the output of a single component was used for two or three other blocks for calculations dependent on the previous block's output. Hence, this made it difficult to classify the model or subsystems. Once all the connections were established, critical parameters such as T3, power output and η_{th}, are obtained.

4.3. Validation of the simulated model

The operation data of thirty-five days were used as inputs to the designed model for validation to ensure that the obtained results are within a satisfactorily reliable range with 95% accuracy (Ibrahim and Rahman, 2016). The Lower Heaving Value (LHV) of natural gas was assumed to be constant throughout this study (Ibrahim et al., 2016b,a). The obtained output power from the designed model must match the actual output power station data. However, minor differences could be caused by many factors, such as the degree of accuracy of the collected data. The model was deemed valid when the model's power output occurred in the acceptable range compared with the reference station data. This was to ensure the integrity of the designed model and the proposed optimization.

5. Results analysis and discussion

This section presents the obtained results from the validated proposed model, discusses and fundamentally analyzes. Furthermore, the variations' effects of the compression ratio and ambient temperature on the gas turbine's thermal performance, including the thermal efficiency and output power, are also discussed and analysed. Fig. 3 shows the thermal efficiency (ηth) and compression ratio (rp). This figure shows that the thermal efficiency increases when T3 ranges from 1100 K to 1400 K (i.e. 725 °C to 1127 °C). However, at the intake temperature (T3) of 1000 K, the thermal efficiency increases when the compression ratio increases from 5 to about 15.

On the other hand, thermal efficiency decreases with the compression ratio from about 15 to 25, where the thermal efficiency strongly decreases. This performance could be mainly attributed to the rise of the compressor's exit temperature, which is similar to the inlet temperature of the combustion chamber of the gas turbine (Ibrahim and Rahman, 2014; Ibrahim et al., 2017). Moreover, increasing the compression ratio could play as a heat recovery system for the waste heat of the gas turbine (Dellenback, 2002; Ibrahim et al., 2019). This could considerably reduce the combusted fuel's heat losses, resulting in greater thermal efficiency of the GT power plant. Furthermore, increasing the generated power caused by the increased compression ratio could also maximize thermal efficiency. However, when the T3 is 1000 K, the thermal efficiency rapidly decreases from its peak value of 0.29 to 0.23. This is achieved when the compression ratios range from 14 to 25. Increasing the compression ratio leads to the work by the compressor to be increased, with the produced work by the turbine remains the same. Therefore, the thermal efficiency decreases while the compression ratio increases for the case of T3 at 1000 K. Considering the data of the SJ Putrajaya, the temperature (T3) is about 1000 K based on the current settings with compression ratios varying between 7 and 9. Consequently, the compression ratio could play as a heat recovery system for the waste heat of the gas turbine. This could considerably reduce the heat losses of the burned fuel resulting in greater thermal efficiency of the GT power plant.

With these results, it is evident that increasing the compression ratio and the T3 temperature increases the thermal efficiency of the used GT turbine at most of the tested operating conditions. For instance, when T3 increases from 1000 K to 1200 K at the compression ratio of 12, the thermal efficiency increases from 0.29 to 0.31. Fig. 4 presents the thermal efficiency compared to the compression ratio for different ambient temperatures (T1).

On the other hand, as shown in Fig. 4, the GT thermal efficiency increases with the rise of the adopted compression ratios and the reduction in ambient temperatures (T1). However, there is a sudden decrement in the attained thermal efficiencies for the four tested temperatures (T1) when the used compression ratios range from 19 to 21, which may be caused due to a minor anomaly. As the current ambient temperature in the GT unit of SJ Putrajaya is around 308 K, and for this temperature and a compression ratio of 12, the thermal efficiency is roughly 0.32. Meanwhile, an increase of 0.02 thermal efficiency is roughly obtained for a compression ratio of 12 and a temperature of 293 K. These desirable results could be attributed to the increased amount of oxygen entered the combustor for used fuel due to increased air density, while the ambient temperature has decreased. The thermal efficiency against compression ratio for different AFR ranges is illustrated in Fig. 5.

In this figure, the thermal efficiency continuously increases as the AFR decreases, and the compression ratio increases. At the AFR of 45, the maximum thermal efficiency increment occurs at the compression ratio of 25, while the minimum increment

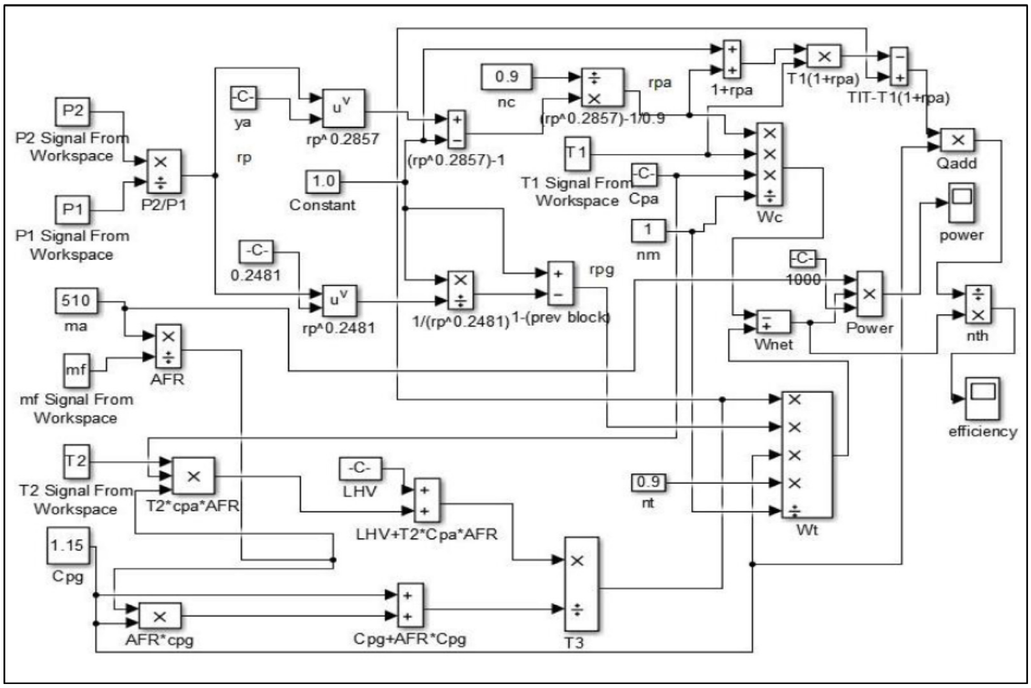

Fig. 2. GT SIMULINK performance model.

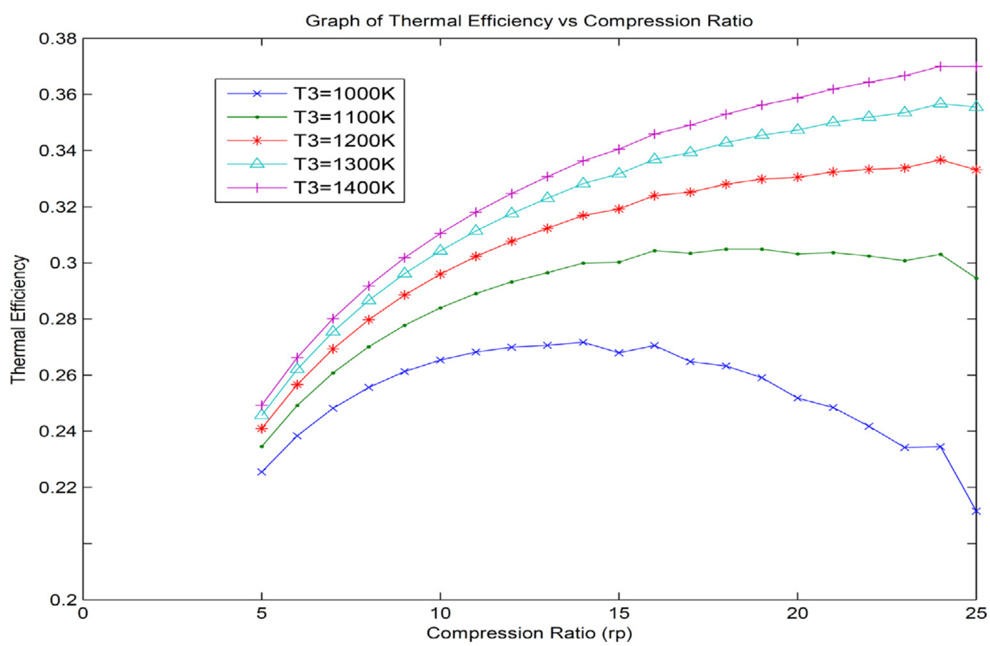

Fig. 3. Thermal efficiency vs. compression ratio for different Inlet Turbine Temperatures.

occurs at 5. On the other hand, when the AFR is set to 65, the thermal efficiency enhancement is much less significant than increasing the compression ratio from 5 to 25. This could mainly be attributed to excess air in the combustion chamber, causing an increase in the heat loss to the flue gases. In the case of SJ Putrajaya, the AFR is 60, and as per Fig. 3, it is evident that with a lower AFR, a higher thermal efficiency may be achieved, where a 2% increase in thermal efficiency is attained for a reduction of AFR from 60 to 50. Fig. 6 shows the compressor work is increasing as the compressor inlet temperature (T1) is rising for all adopted compression ratio values. For the case of SJ Putrajaya, and at a T1 temperature of 303 K, and a compression ratio of 12, the required compressor work is about 360 kJ/kg, while at 293 K (20 °C), and a compression ratio of 12, the required compressor work is about 350 kJ/kg, which would cause an increase in the network and hence, higher thermal efficiency. See Fig. 6. For the compressor work vs. compression ratio for different compressor inlet temperatures ranges.

Fig. 7 shows that the turbine thermal efficiency significantly increases as the compressor efficiency increases for compression ratios within the range 5 to 19 and 22 to 25. There is an incline at the compression ratio values of 19 to 21, which is unimportant as this dip exists in all five curves. For the GT case under study (SJ Putrajaya), the efficiency of the compressor is 0.80, and at this efficiency and compression ratio of 12, the thermal efficiency is 0.28. Thus, a 4% increase in the thermal efficiency is obtained

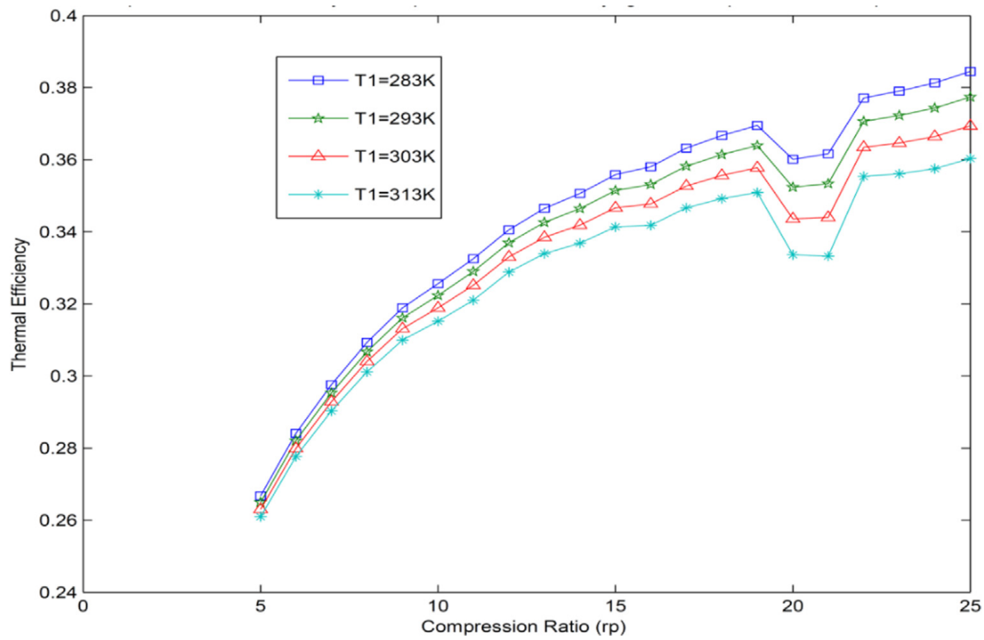

Fig. 4. Thermal efficiency vs. compression ratio for different ambient temperatures.

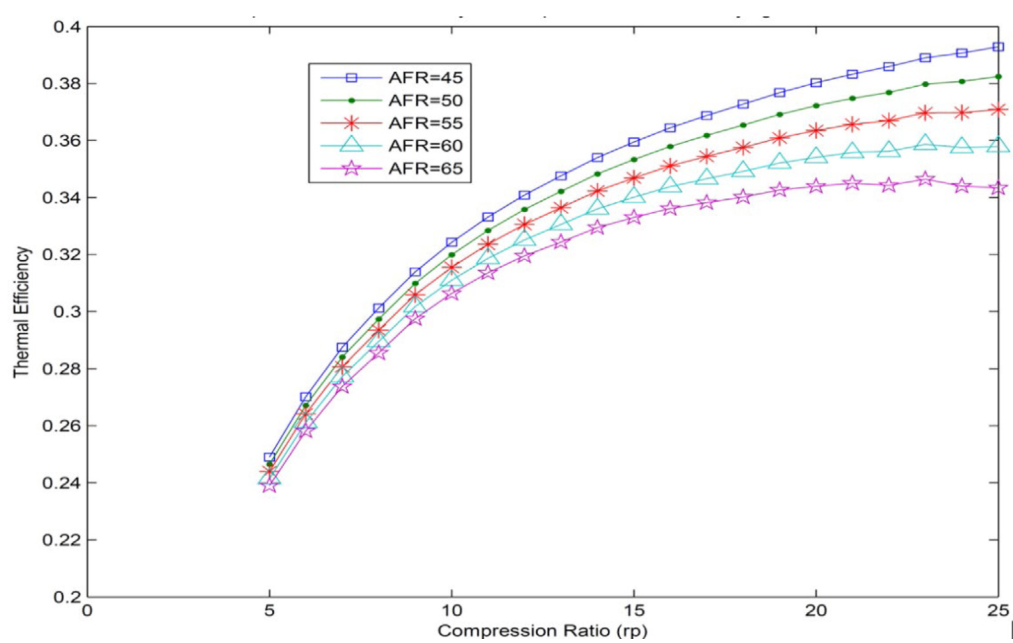

Fig. 5. Thermal efficiency vs. compression ratio for different AFR ranges.

with a compressor efficiency of 0.85 and a compression ratio of 12 (i.e., the thermal efficiency is 0.32). Hence, the compressor efficiency must be increased by adhering to a routine preventive maintenance schedule (Gul et al., 2020). As illustrated in Fig. 8, the turbine efficiency increases for compression ratios between 5 to 19 and 22 to 25. The slight dip present in the five curves, and considered insignificant, also appears in this figure between the compression ratios of 19 to 22. At this stage, the turbine efficiency is 0.90, and a compression ratio of 12, the thermal efficiency is about 0.32, while at a turbine efficiency of 0.95 and compression ratio of 12, the thermal efficiency is 0.37, which denotes a substantial increase of about 5% in the thermal efficiency.

Fig. 9 presents the thermal efficiency compared to compressor inlet temperature for different AFR ranges. The effect of the AFR ranging from 45 to 65 at different intake air temperatures to the compressor (T1) is presented. It can be seen that the thermal efficiency of the adopted gas turbine decreases as the AFR increases for all the used compressor inlet temperatures (T1). Though the thermal efficiency curve has a decreasing gradient trend, two irregular positive spikes can be noticed at 294 K and 318 K. At the presented operating AFR of 60 and compressor inlet temperature of 303 K (30 °C), the thermal efficiency of the cycle is approximately 0.30. Meanwhile, if the air–fuel ratio is reduced to 55 °C for the same temperature of 303 K, the thermal efficiency considerably increases by 0.5%.

Fig. 10 shows that GT's power is reduced as the air–fuel ratios increase for all the compressor inlet temperatures. The shape of all five lines exhibits an almost steadily linear with no anomaly behaviour.Between air–fuel ratios of 45, 50 and 55, the gaps between the lines are of noticeable importance as they signify the

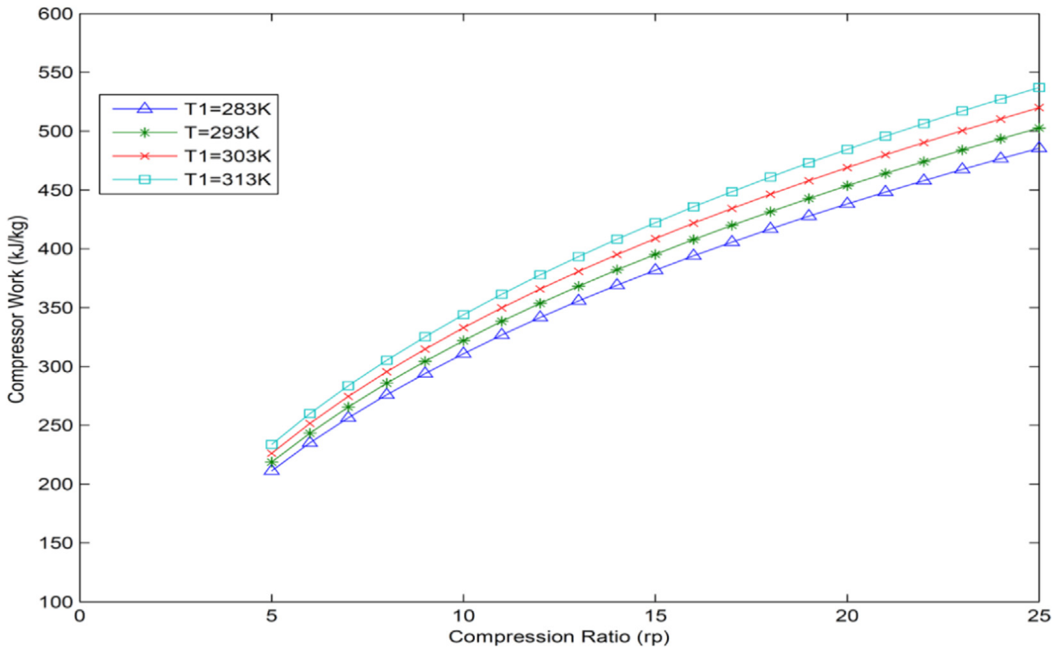

Fig. 6. Compressor work vs. compression ratio for different compressor inlet temperatures ranges.

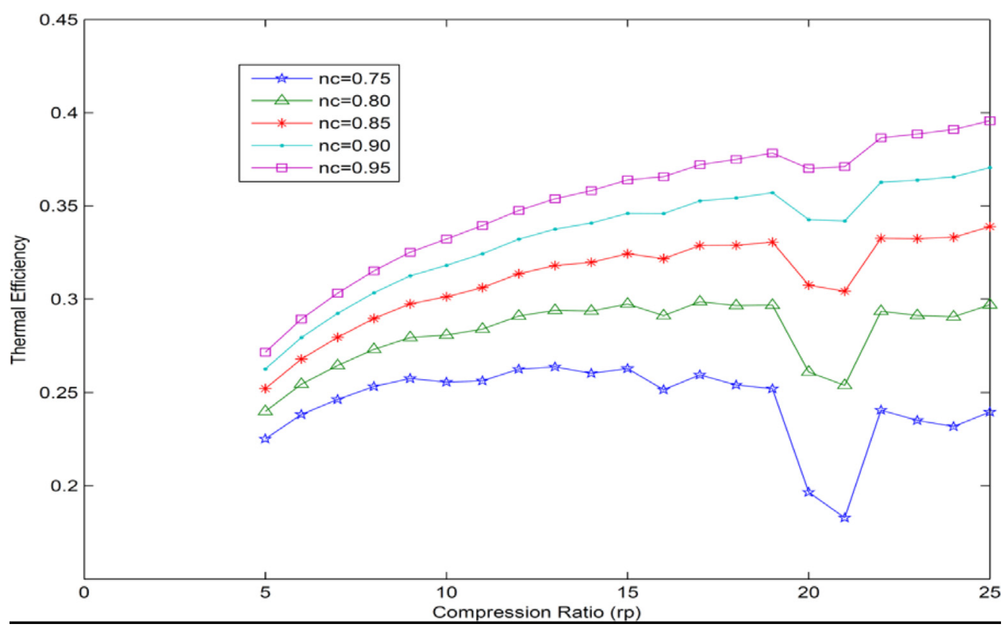

Fig. 7. Thermal efficiency vs. compression ratio for different compressor efficiencies.

power differences. A power of about 127 MW is produced when the air–fuel ratio of 60 and the compressor inlet temperature is 303 K (30 °C). However, the power produced is almost 140 MW for an AFR of 55. This was achieved at the compressor inlet temperature of 303 K, with an increase of nearly 13 MW. See Fig. 10 for the Power output vs. compressor inlet temperature for different Air–Fuel rations

6. Conclusions and future work

This study deals with how to increase the performance of old Gas Turbine (GT) power plants. The thermal efficiency of such power plants was degraded due to ageing, which made them practically of low economic value. Maintenance was also no longer of benefit in increasing the low thermal efficiency. However, the theory linked with the increasing performance power output of such power plants offered several ways by which this performance may be increased. In this paper, the targeted GT power plant was two aged GTs at SJ Putrajaya, for which a study has decided that it is not economically viable to retrofit those aged GTs. The main conclusion points can be summarized as follows:

- A strong influence on the thermal efficiency and power output is related to compressor inlet temperature and compression ratio.
- Decreasing the compressor inlet temperature and increasing the compression ratio were causing an apparent increase in the thermal efficiency.

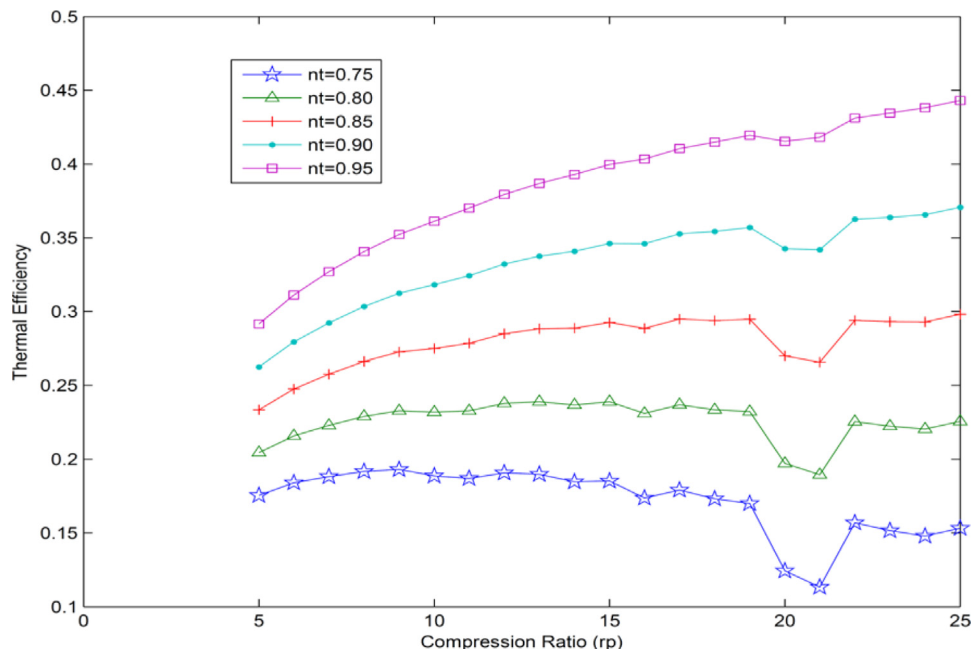

Fig. 8. Thermal efficiency vs. compression ratio for different turbine efficiencies.

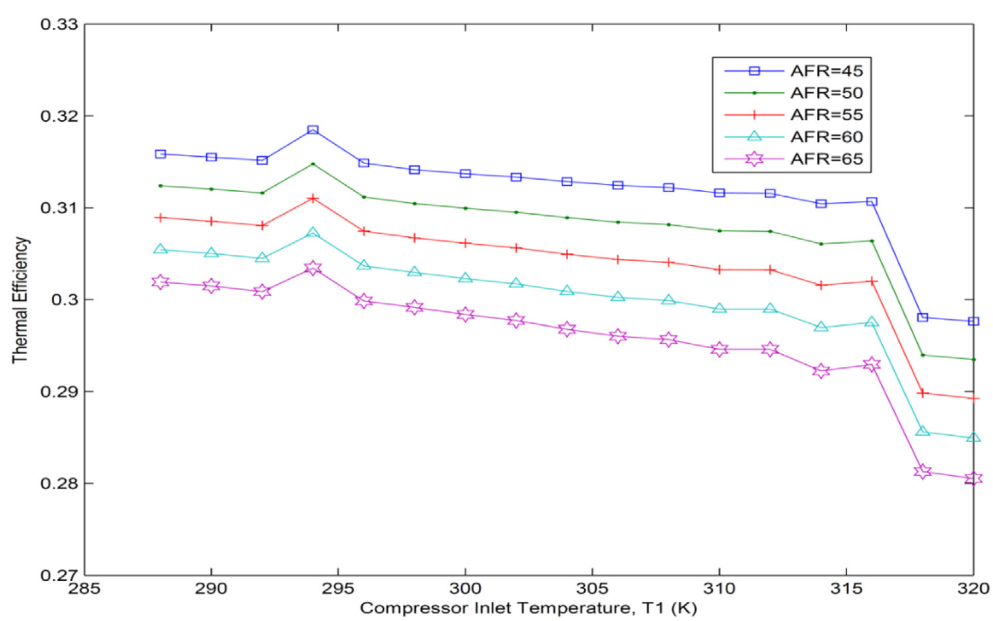

Fig. 9. Thermal efficiency vs. compressor inlet temperature for different Air–Fuel rations.

- Compared with the actual data obtained from the GT power plants, the compression ratio was increased to a maximum value of 12, while the present real value is approximately 8.
- It has also been found that the maximum thermal efficiency that may be achieved is about 30%, and the maximum output power is around 140 MW. This achievement could be attributed to modifying relevant parameters within a reasonable range.
- The error percentage is within the acceptable range, which is less than 2%.

Future works are desirable if an economic analysis is conducted alongside the thermodynamic analysis, which can effectively illustrate the monetary impact of efficiency deviations. The advantage of monetary impact is that the management will focus and emphasize essential losses; thus, the operations personnel can better manage those areas. Furthermore, the primary fuel, natural gas, should also be focused on in future works as the GT performance may be adversely affected by the lower quality of natural gas beyond the operator's control. It is also possible to reduce the compressor inlet temperature by adopting a cooling system at the air inlet unit, although a study with more details is needed to assure the cooling system's economic viability. The

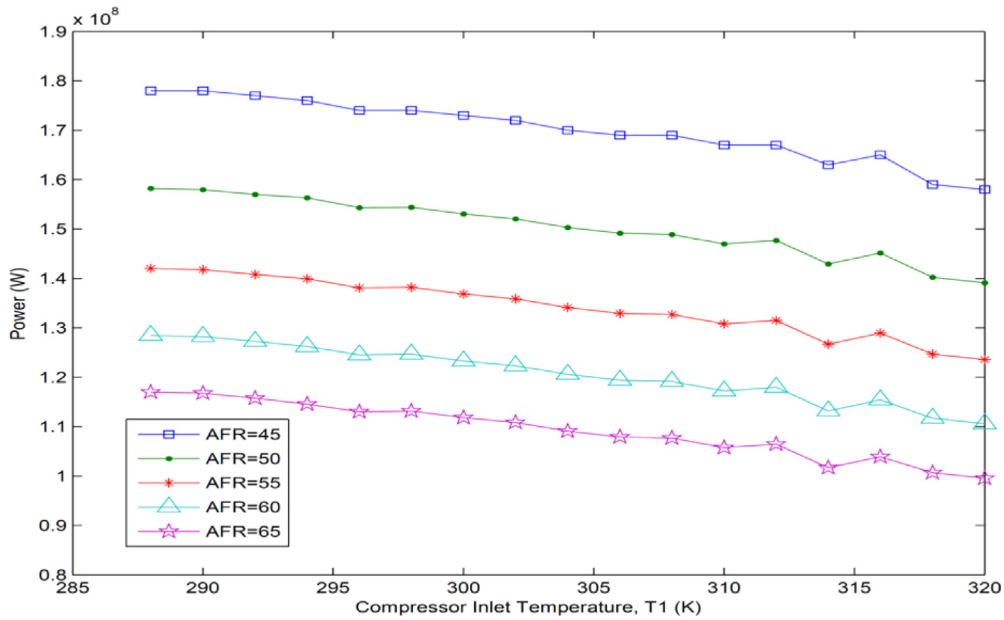

Fig. 10. Power output vs. compressor inlet temperature for different Air–Fuel rations.

thermal performance based on exergy analysis could also be a further extension of this work.

CRediT authorship contribution statement

Firas Basim Ismail Alnaimi: Conception and design of study, Analysis and/or interpretation of data, Writing - original draft, Writing - review & editing. **Manmit Singh Jasbeer Singh:** Conception and design of study, Acquisition of data, Analysis and/or interpretation of data, Writing - original draft,. **Ammar Al-Bazi:** Analysis and/or interpretation of data, Writing - original draft, Writing - review & editing. **Nizar F.O. Al-Muhsen:** Writing - original draft. **Thabit Sultan Mohammed:** Writing - original draft. **Rami Hikmat Al-Hadeethi:** Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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