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COMPARATIVE ENERGY ANALYSIS ON A COMBINED POWER PLANT OF GAS TURBINE AND STIRLING ENGINE

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ABSTRACT
Thermodynamic performance of a gas turbine cycle integrated with a Stirling engine was investigated in this research. A part of gas turbine exhaust gases are used to providing the heat needed for the Stirling engine. The compression ratio, the air fuel ratio, the fuel flow rate, the turbine after pressure, and the exhaust temperature were selected as crucial guidelines in this study to investigate the combined power system effects, thermal efficiency and power outputs.. According to the obtained results, the electrical efficiency of the combined power plant is diminished with the increase of the compressor pressure ratio, exhaust temperature, and the air fuel ratio rate whereas the overall power output of the combined system decreases dramatically with the increase of the system pressure. Furthermore, increasing the compressor pressure ratio and the air fuel ratio decrease the Stirling engine cycle power output but the increasing in the fuel flow rate has a positive impact on the performance of the Stirling engine.

KEYWORDS: Stirling engine, Efficiency, Gas turbine, Compression ratio, Power plant.

Nomenclature

C_p	constant pressure specific heat(kJ/kg.k)
$\dot{Q}$	total heat supplied(kW)
LHV	low heating value(kJ/kg)
$\dot{m}$	mass flow rate(kg/s)
P	power(kW)
p	pressure(bar)
RV	piston compression ratio
T	temperature(K)
$\dot{W}$	work net(kW)
r_p	compressor compression ratio

Greek symbols

η	efficiency
γ	specific heat ratio
ϵ	effective of the heater
ξ	ratio of the minimum and the maximum temperature inside SE

Subscripts

a	air
C	compressor
CC	combustion chamber
f	fuel
g	flue gases
S	Stirling
T	turbine
TIT	turbine inlet temperature(K)

INTRODUCTION
Gas turbine is one of the important energy sources and it is characterized by its comparatively low capital cost to power ratio, short construction lead time, and fast starting–accelerating compared with the steam power plant [1]. A part of the mechanical energy produced by the gas turbine is used to run the

compressor and the rest of it is transported to the generator to produce electricity [2]. The investigators try to discover new techniques to enhance the overall efficiency of the gas turbines. One of technique to increase the gas turbine plant efficiency done by integrated the gas turbine with another heat engine such as the Stirling and Rankine cycles , which can significantly boost power output and increasing the overall efficiency to more than 50% [3], [4].

Many researchers interested in combination of power plant cycles in order to improve energy efficiency and increase productivity [5], [6], [7], [8], [9].Güven et al [10] were investigated three kind of Stirling engines for waste heat recovery on a heavy-duty diesel engine. Baghernejad et al [11] investigated the integrated model of solid oxide fuel cell and gas turbine hybrid system.Yue and Lior [12] has completed energy and exergy analyzes of gas turbine power combined with the solar systems. In another study, Nami and Akrami [13] developed a gas turbine hybrid system to enhance overall system efficiency and minimize the production cost.

In this research, an integrated hybrid Brayton cycle combined with a Stirling engine is developed for simultaneous power output and combined system performance. The performance of the system is analyzed in terms of significant variables of the system.

GENERAL SYSTEM DESCRIPTION

A schematic diagram of the combined GT-SE system has been shown in Figure 1. The suggested system consists of an air compressor, gas turbine, , combustion chamber, Stirling engine, and heat exchanger. In this model, the air enters the compressor where its compressed to a system operating pressure and then it's mixed with the fuel in combustion chamber. The chemical reactions occurs between fuel and air in the combustion chamber to produces hot exhaust gases with high thermal energy which expanded in the gas turbine and converted a large amount of thermal energy to generate work . Finally, the hot gases after exiting the gas turbine carry to the Stirling engine and give the heat that the engine needs to work. The Stirling engine generates additional power, thus increasing system efficiency and power output.The next assumptions are applied in modeling and simulating the combined power plant:

- All of the gases are assumed to behave as ideal gases.
- The process of the compressor and turbine is assumed to be adiabatic.
- The compressor inlet states are assumed to be equal to ambient conditions.
- The processes are considered to be steady state and reversible.
- The Stirling engine's operates with a constant speed.
- The compression and expansion processes of Stirling engine are adiabatic.

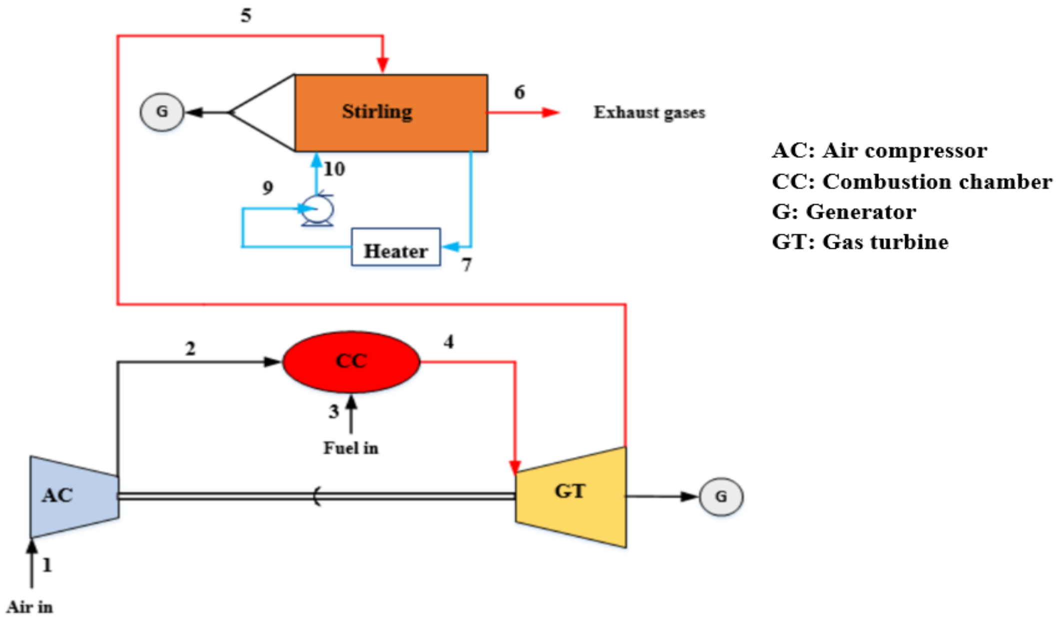

Figure 1: Schematic of gas turbine and Stirling engine combinedpower plant

COMPRESSOR

Applying the first law of thermodynamic and using the ambient condition at the of compressor, isentropic efficiency for compressor, and pressure ratio (r_p) , we can calculate the following parameter: The compressor compression ratio (r_p) can be calculated as[14]:

$$r_p = \left(\frac{p_2}{p_1}\right) \qquad \textbf{(1)}$$

where P1 and P2 are the pressures of air at the compressor inlet and outlet of compressor respectively. The isentropic efficiency for compressor and turbine in the range of 80-90% is calculates as [14]:

$$\eta_C = \frac{(T_{2s} - T_1)}{(T_2 - T_1)} \qquad \textbf{(2)}$$

where η_C is the isentropic efficiency of the compressor,T_{2s} is compressor isentropic outlet temperature, $T_1$and T_2 are the temperatures of air at the compressor inlet and outlet of compressor respectively. The temperature of the air or fuel leaving the compressor is calculated from this equation:

$$T_2 = T_1 + \frac{T_1}{\eta_C}\left[r_p^{\frac{\gamma-1}{\gamma}} - 1\right] \qquad \textbf{(3)}$$

Where γ is the ratio of the specific heat capacities of the gas? The power needed for adiabatic compression is:

$$P_C = \dot{m}_a C_{p,a} \frac{T_1}{\eta_C}\left[r_p^{\frac{\gamma-1}{\gamma}} - 1\right] \qquad \textbf{(4)}$$

Where $\dot{m}_a$ is the mass flow rate of air compressed, and $C_{p,a}$ is the constant pressure specific heat.

COMBUSTION CHAMBER

By applying the energy balance for the combustion chamber [14]:

$$\dot{m}_a C_{p,a} T_1 + \dot{m}_f C_{p,f} T_f + \dot{m}_f LHV_f = \dot{m}_g C_{p,g} T_{TIT} \qquad \textbf{(5)}$$

where$\dot{m}_f$ is fuel mass flow rate, $C_{p,f}$ is specific heat of fuel, $T_f$is temperature of fuel , LHV is low heating value of fuel,$C_{p,g}$is specific heat of flue gas, T_{TIT} is the turbine inlet temperature, and $\dot{m}_g$ is the mass flow rate of combustion gases through the combustion chamber, and is calculated by:

$$\dot{m}_g = \dot{m}_a + \dot{m}_f \qquad \textbf{(6)}$$

GAS TURBINE

A turbine is a rotary engine that converts thermal power energy into mechanical power. The exhaust temperature of the gas turbine has a relation with the gas turbine pressure ratio as follow [14]:

$$\frac{T_{in}}{T_{out}} = \left(\frac{p_{in}}{p_{out}}\right)^{\frac{\gamma-1}{\gamma}} \qquad \textbf{(7)}$$

The mechanical power produced by the gas turbine can be obtained from the following equation:

$$P_T = \dot{m}_g \cdot C_{p,g} \cdot \eta_T \left[T_{in} - T_{out}\right] \qquad \textbf{(8)}$$

The net power of gas turbine can be found by using the following equation:

$$P_{out,GT} = P_T - P_C \qquad \textbf{(9)}$$

The total heat supplied to the system is calculated as:

$$\dot{Q}_{in} = \dot{m}_f LHV_f \qquad \textbf{(10)}$$

The gas turbine efficiency ($\eta_{th,GT}$) can be determined by the following equation:

$$\eta_{th} = \frac{P_{out,GT}}{\dot{Q}_{in}} \qquad \textbf{(11)}$$

The power output from the power plant can be calculated as:

$$\dot{W}_{net} = P_{out,GT} + P_{SE} \qquad \textbf{(12)}$$

The thermal efficiency of the combined power cycle is defined as the ratio between the net power output and the thermal energy input:

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} \qquad \textbf{(13)}$$

STIRLING ENGINE

The Stirling engine works based on the Stirling cycle, which involves four thermodynamic processes in one cycle: two isothermal processes, and two isochoric processes. In this research, the exhaust hot gases of gas turbine are considered as the heat source of the Stirling engine. Consequently, the heat source used in the analysis is the exhaust gases leaving the gas turbine, while water is utilized as the low-temperature sink. The power outputs for the Stirling engine are modeled as:

$$P_S = \eta_{pcy}\left(Q_{high} - Q_{loss}\right) \quad \textbf{(14)}$$

where Q_{high} is the heat rate which Stirling engine absorbs from the gas turbine exhaust gases, Q_{loss} is the rejected heat of the Stirling engine to the low-temperature sink. Polytropic efficiency η_{pcy} can be expressedfrom the following equation [6]:

$$\eta_{pcy} = \left[\frac{(1-RV^{1-\gamma})-\xi(RV^{1-\gamma}-1)}{(1-RV^{1-\gamma})+(1-\xi)(1-\epsilon_{st})}\right] \quad \textbf{(15)}$$

$$Q_{loss} = Q_{high}\left(1 - \eta_{mech,st}\right) \quad \textbf{(16)}$$

Where RV is piston compression ratio, and ϵ_{st} is efficiency of the heater inside the Stirling engine, γ is specific heat ratio, and ξ is the ratio of the minimum and the maximum temperature inside the Stirling cycle.It is defined as follows:

$$\xi = \left[\frac{T_{cooler,gas}+273.13}{T_{heater,gas}+273.13}\right] \quad \textbf{(17)}$$

$T_{heater,gas}$ and $T_{cooler,gas}$ can be calculated as:

$$T_{heater,gas} = T_{heater,wall} + \Delta T_{high} \quad \textbf{(18)}$$

$$T_{cooler,wall} = T_{water,in} + 0.6667\left(\Delta T_{high}\right) \quad \textbf{(19)}$$

$$T_{cooler,gas} = T_{cooler,wall} + \Delta T_{low} \quad \textbf{(20)}$$

where $T_{heater,wall}$ is the temperature of thehigh-temperature reservoir, and $T_{cooler,wall}$ is the temperature of the low-temperature sink inside the Stirling engine.

RESULTS AND DISCUSSION

The parameter effect of compression ratio, air to fuel ratio, turbine after pressure, exhaust temperature, fuel flow rate, on the performance of the combined cycle gas turbine - Stirling engine power plants are presented in this section. The influence of this variable on the power output and thermal efficiency are obtained by the energy balance utilizing MATLAB software. The initial input parameters for the components of the combined power plant listed in Table 1.

Table 1. The combined power plant parameters

Parameter	**Value**
Compressor efficiency	**83%**
Combustion chamber efficiency	**99%**
Turbine efficiency	**85%**
Combustion chamber pressure drop	**5%**
Exhaust gases temperature	**410 K**
Temperature of fuel at inlet	**293 K**
Temperature of fuel at inlet	**298 K**
Input fuel flow	**3 kg/s**
Input air flow	**120 kg/s**
Fuel type	**CH_4**
Lower heating value of methane	**55 MJ/kg**
Specific ratio of helium	**1.667**
Mechanical efficiency of Stirling engine	**85%**
Heater effectiveness	**0.95**

Heater temperature difference	**125**℃
Cooler temperature difference	**60**℃

Figure 2, and **Figure 3** illustrate the effect of compressor pressure ratio on the total power output and overall thermal efficiency of combined cycle of GT-SE. When the system pressure increased from 4 to 14 bar, the total power output from the plant decreases as a result of the high reduction in the power produces from the Stirling engine due to the decrease in the temperature of the exhaust gasses after turbine. The temperature of the exhaust gasses after turbine is more affected by the system pressure, and it decreases as the compression ratio increases. Figure 3 showed that the thermal efficiency of the gas turbine decreased for an increase in the system pressure, after the value of system pressure reached 8 bar while the thermal efficiency decreased with an increase in the system pressure, for GT-.SE combined system due to the reduction in the power output from the SE. At a system pressure of 8 in the GT, the highest (best) thermal efficiency obtained was 38.7%.

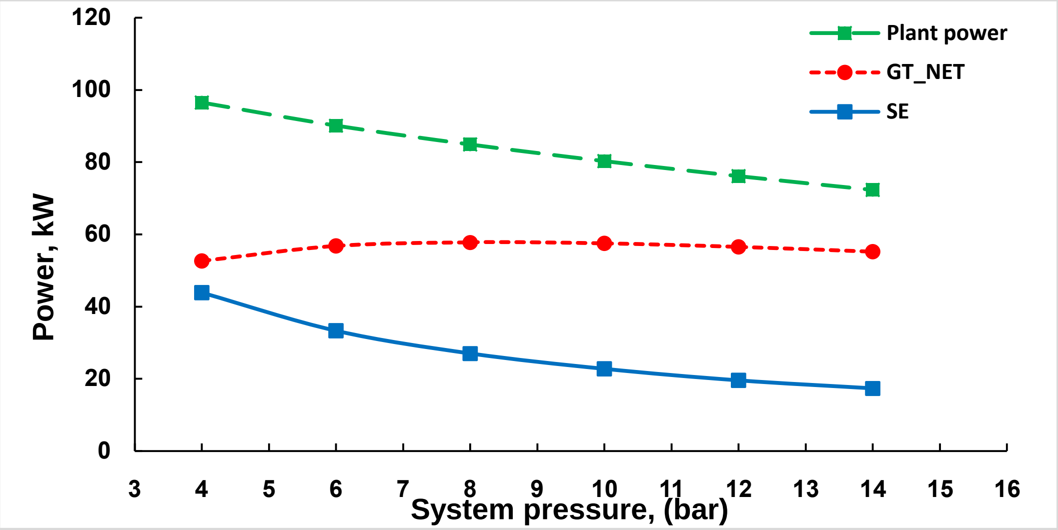

Figure 2: The effect of system pressure on the total power output

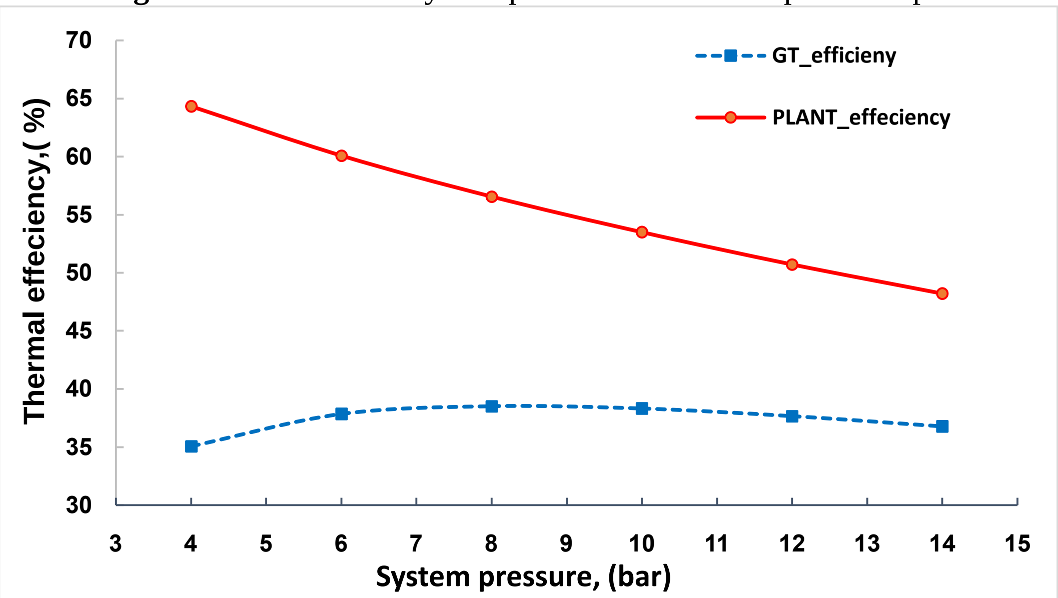

Figure 3: The effect of system pressure on the thermal efficiency

The variation in the effect of the fuel flow rate on power output for different components of the combined system is shown in Figure 4. It can also be seen that the power output increased with the increase of the fuel flow rate for both GT and SE and this lead to an increase in the total power output from the combined system.

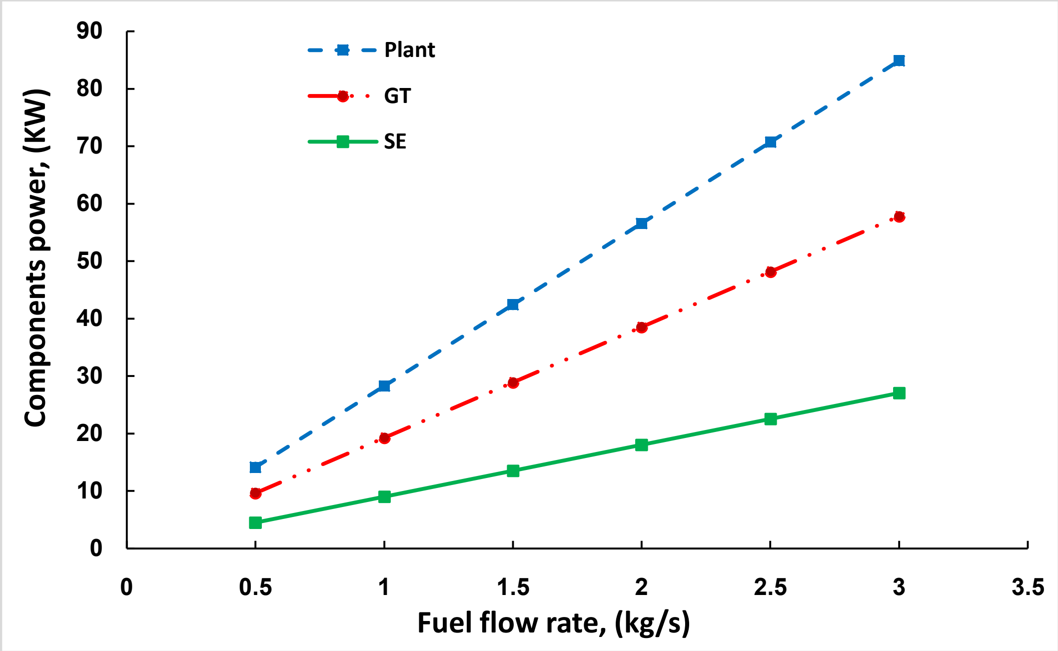

Figure 4: The effect of fuel flow rate on the component power

Figure 5, and **Figure 6** present the influence of air fuel ratio on the performance of the combined cycle of GT-SE. It can be seen that by increasing the air fuel ratio the output power of both GT and SE cycles decrease, as well as the total power of combined-cycle of GT-SE is decreased. At high mass flow rate of air, the power consumed by air compressor is increased which lead to a decrease in the net power output from the gas turbine, and the temperature after turbine is decreased which mean a reduction in the power output from SE at high mass flow rate of air. The decreasing in the power output from the Stirling engine reaches to 70%. The thermal efficiency of the combined-cycle is decreased with the increase of the air fuel ratio as a result of thee more reduction in the power produces from the cycle. The efficiency of the GT-SE system decreases from 63.32 to 30.9% when the air fuel ratio increases from 38 to 50.

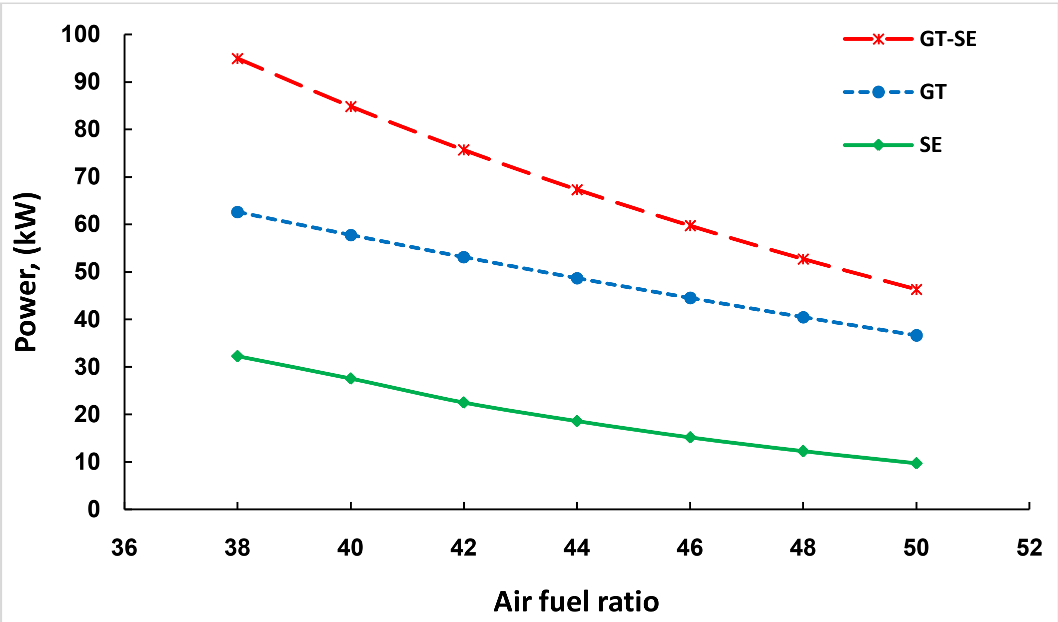

Figure 5: The effect of air fuel ratio on the total power output

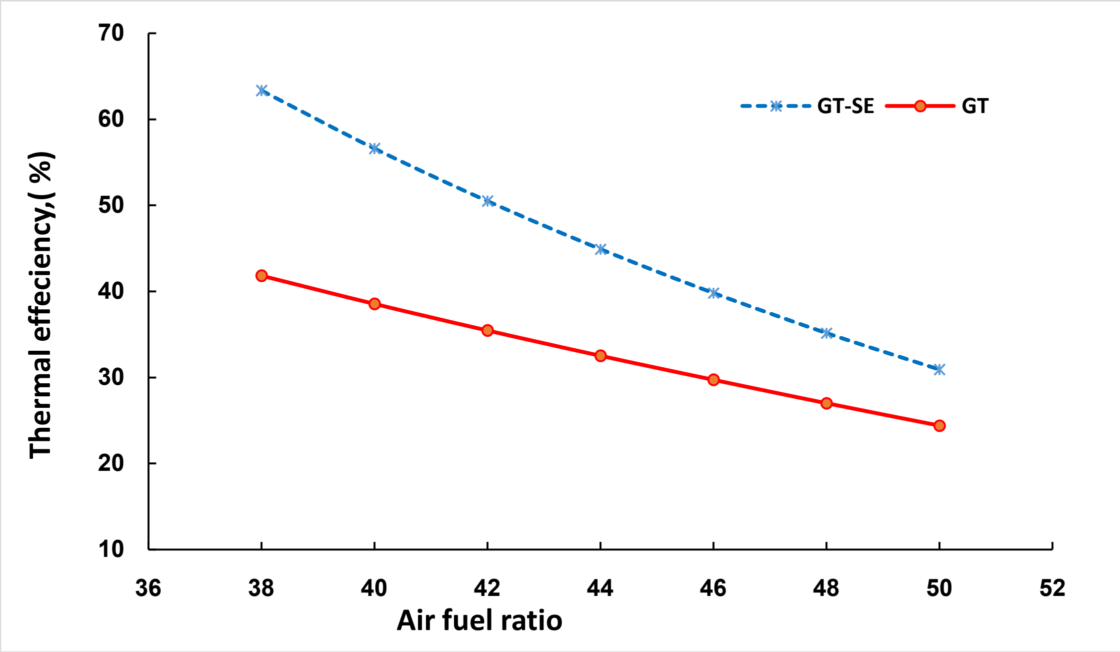

Figure 6: The effect of air fuel ratio on the thermal efficiency

Figure 7, and **Figure 8** illustrate the influence of turbine after pressure on the performance of the combined cycle of GT-SE. It is presented from this figures that by increasing this parameter the gas turbine power will decrease as well as the overall power output from the combined cycle. The efficiency of the combined-cycle and gas turbine diminish with the increment of the turbine after pressure.

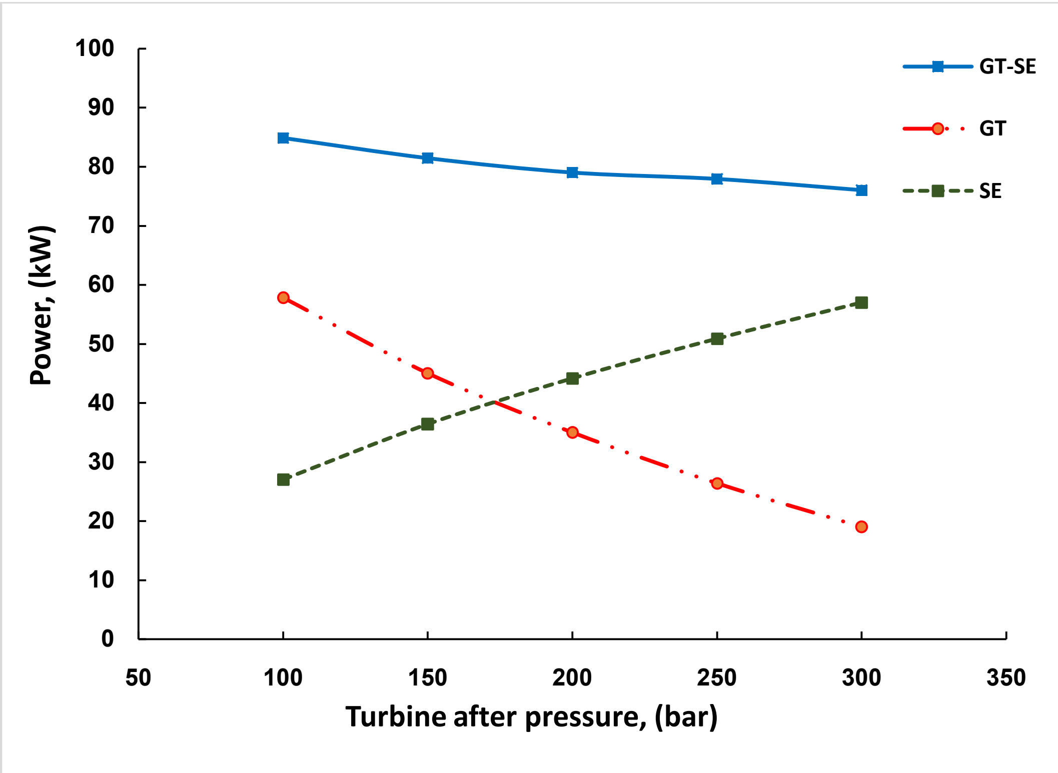

Figure 7: The effect of turbine after pressure on the total power output

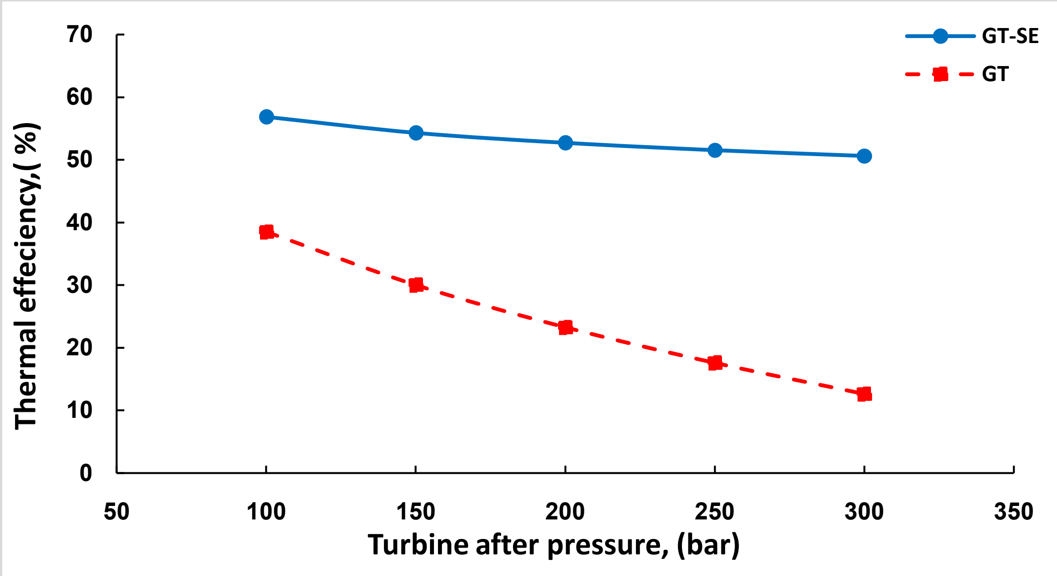

Figure 8: The effect of turbine on the thermal efficiency

CONCLUSIONS

An integrated hybrid Brayton cycle combined with a Stirling engine is have been used in this study to investigated the performance of the system in terms of significant variables. The simulated modeling results are as follows:

- The thermal efficiency of the gas turbine decreased for an increase in the system pressure, after the value of system pressure reached 8 bar while the thermal efficiency for GT-.SE combined system decreased with any increase in the system pressure.
- The power output increased with the increase of the fuel flow rate for both GT and SE and this lead to an increase in the total power output from the combined system.
- The thermal efficiency of the combined-cycle is decreased with the increase of the air fuel ratio as a result of thee more reduction in the power produces from the cycle.
- The efficiency of the combined-cycle and gas turbine diminish with the increment of the turbine after pressure.

Influence of operational parameters including the compression ratio, turbine inlet temperature and ambient temperature significantly influence on the performance of gas turbine power plant. The results were summarized as follows.

i) The thermal efficiency decreases and specific fuel consumption increases with the increasing in the ambient temperature.

ii) Increasing the turbine inlet temperature increases the output power and thermal efficiency as a result of increasing the turbine work.

iii) The peak efficiency, power and specific fuel consumption occur at when compression ratio increased in the gas turbine power plant.

iv) Maximum power for the turbine inlet temperatures are selected a compression ratio 6.4 for a turbine inlet temperature of 1000K result in a higher thermal efficiency.

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