ANALYSIS OF THERMAL EFFICIENCY OF OPEN CYCLE GAS TURBINE POWER PLANT AT PUTRAJAYA (MALAYSIA)

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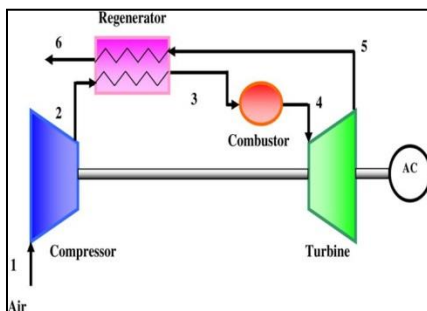
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Graphical abstract

Abstract

The purpose of this paper is to study the performance of an existing open cycle gas turbine power plant at Putrajaya power station. At compressor inlet temperature of 298.90K, thermal efficiency of 31 % was observed for the existing or current cycle whiles the modified configuration yielded thermal efficiency of 45 %, this result in 14 % increase in thermal efficiency. At pressure ratio of 3.67, thermal efficiency of about 31.06% and 44% was recorded for the current cycle and regenerative cycle respectively. The efficiency of both cycles increase considerably with increase in pressure ratio, but at pressure ratio of about 7, only a small increase in efficiency for both cycles was observed. The optimum value of the efficiencies for both cycles that correspond to pressure ratio of 7 is 43.06 and 56% for the current cycle and the regenerative cycle respectively.

Keywords: Power generation, gas power cycle, regenerative, thermal efficiency, thermodynamic analysis

1.0 INTRODUCTION

In recent times there is global concern on the increase in fossil energy consumption and their consequence increased in price and environmental challenges caused by the continuous dependence on these fuels. These challenges necessitate exploration of new ways to meet the global energy demand. The best ways to solve these problems is to design efficient and waste energy recovery utility systems that depend on fossil fuel for their operation. One of such systems is open cycle gas turbine cycle. After the oil crisis in the 1970s the efficiency of power plants became the top priority, and combined cycle plants become common power plant configurations [1]. Better performance of gas turbine can be reached with advanced cycles that take advantage of the energy contained in the turbine exhaust gases [2, 3]. In gas turbine power, the air leaving the compressor at high-pressure can be heated by transferring heat to it from the hot exhaust gases in a counter flow heat exchanger, which is

known as a regenerator [4]. More and more new configurations of power plants have been provided recently. For example Zhang, et al., [5] did analyze and optimize the performance of combined Brayton and inverse Brayton cycles with considerations of the pressure drop losses in the intake, low-pressure compression, high pressure compression, combustion, expansion and discharge processes. Sanjay, et al., [6] performed first and second law analysis of the Brayton-Diesel cycle based on exergy analysis. Ziviani, et al., [7] carried out extensive review of the use of Organic Rankine Cycle (ORC) to exploit low grade waste thermal energy. More recent studies can be found in the literatures [8, 9]. The performance analysis of an existing open-cycle gas-turbine power plant is performed in this paper. The inlet air cooling is one of primary method for increasing the performance of gas turbines. Sensitivity analysis was carried out to study the effect of compressor inlet temperature on the plant performance

2.0   BACKGROUND OF THE POWER PLANT UNDER STUDY

Putrajaya power station project started in 1993. This power station is constructed as a fast track project.

This project consists of two separate contracts namely open cycle gas turbine which is of John Brown type with power output of 110MW and Siemens AG 135MW.
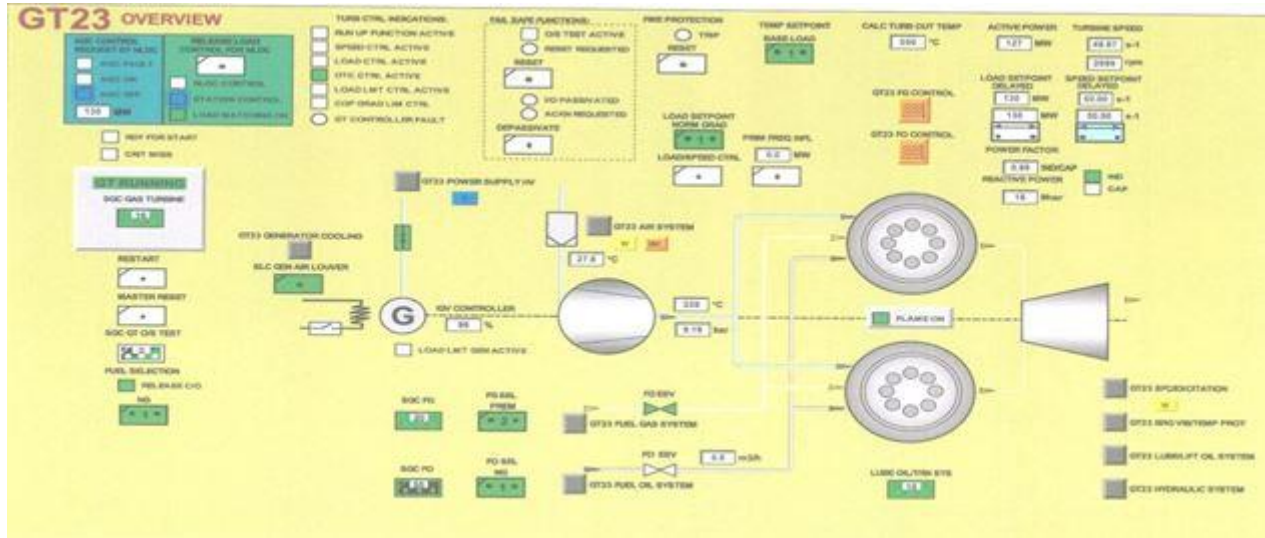

Figure 1 System layout

The Siemens AG 135MW was selected for the purpose of this study. The gas turbines are designed base on open cycle operation which means the exhaust gas from the turbine is directly release into the air through the exhaust stacks. The detail flow sheet of the cycle to be studied is shown in the Figure 1. The turbine use dual firing mode (see Figure 1) with natural gas as the main fuel which is supplied from Petronas gas and high grade distillate as standby fuel. This study is limited to the performance analysis of an open cycle power plant. The compressor is made of 17 stages and the turbine is made of 4 stages as shown in Figure 2.
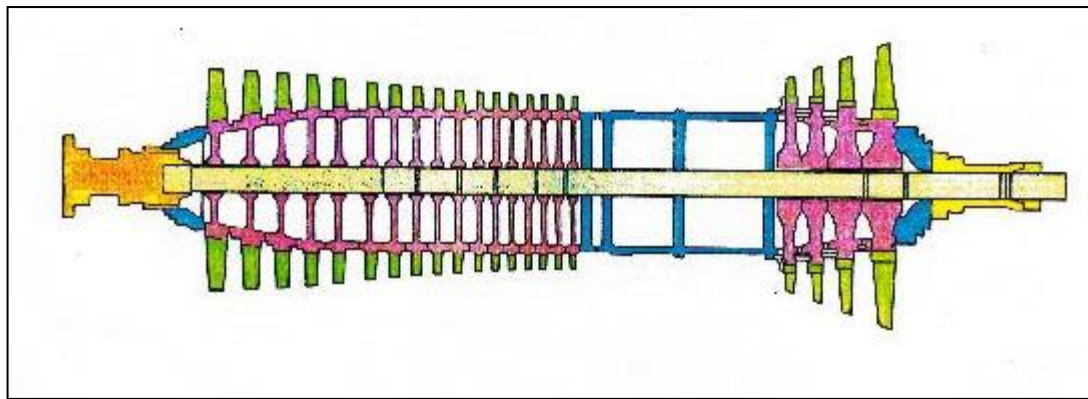

Figure 2 Compressor 17 stages, turbine 4 stages

3.0 INTEGRATION OF REGENERATION TO THE PUTRAJAYA POWER PLANT

Regenerated gas turbines can increase efficiency 5-6% and are even more effective in improved part load applications [10]. For the Brayton cycle, a heat exchanger can be placed between the hot gases leaving the turbine and the cooler gases leaving the compressor (see Figure 3).
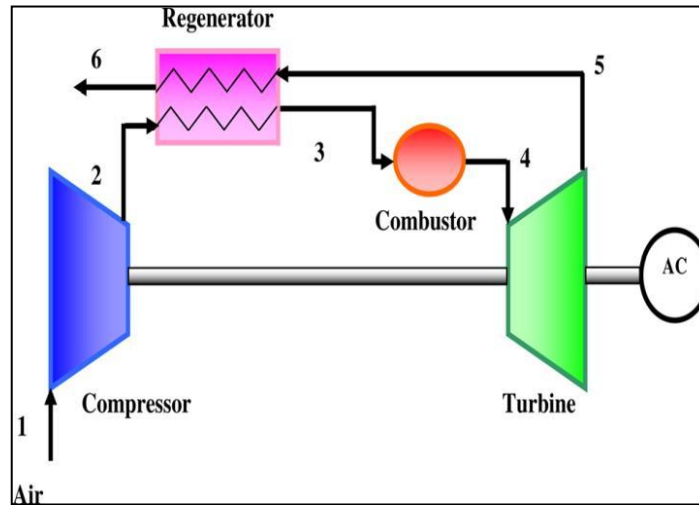
Figure3 Schematic diagram of regenerative Brayton cycle [8]

4.0 THERMAL EFFICIENCY OF THE BRAYTON CYCLE IS DEFINED as $\eta_{th, Brayton}$

Applying the first law of thermodynamics for the Brayton cycle, the thermal efficiecy of the cycle can be expressed as [11]:

$$\eta_{th, Brayton} = \frac{Wnet}{Qin} = 1 - \frac{Qout}{Qin} \tag{1}$$

Upon derivation $\eta_{th, Brayton} = 1 - \frac{1}{rp^{\frac{(k-1)}{k}}}$ (2)

Where the pressure ratio is $r_p = \frac{P_2}{P_1}$ (3)

As part of the aim to improve the performance of the power plant under study, an alternative model with a heat exchanger (regenerator) was studied. For ideal gases using the cold-air-standard assumption with constant specific heats, the regenerator effectiveness ε_{regen} becomes [11]:

$$\varepsilon \cong \frac{T_5 - T_2}{T_4 - T_2} \tag{4}$$

Upon derivation the thermal efficiency becomes

$$\eta_{th, regen} = 1 - \left(\frac{T_1}{T_2}\right)(r_p)^{(k-1)/k} \tag{5}$$

The work developed by turbine after installing regenerator is [11]:

$$W_t = C_{pg} T_4 \eta_T \left[1 - \frac{1}{rp\left(\frac{kg-1}{kg}\right)}\right] \tag{6}$$

$$W_{net} = C_{pg} T_4 \eta_T \left[1 - \frac{1}{rp\left(\frac{kg-1}{kg}\right)}\right] - C_{pa} T_1 \left[\frac{rp\left(\frac{ka-1}{ka}\right)}{\eta C}\right] \tag{7}$$

The Power Output is, $\therefore$ Power = $\dot{m}$ x W_{net} (8)

Properties used in calculations.
C_{pa} = 1.005 kJ/kg.K (specific heat for air)
C_{pg} = 1.15 kJ/kg.K (specific heat for gas)
K_{air} = 1.4, K_{gas} = 1.33 (specific heat ratio)

5.0 RESULTS AND DISCUSSION

This paper focuses on a real open cycle gas power plant at Putrajaya. Raw data such as compressor inlet temperature were carefully taken and recorded for the purpose of evaluating the thermodynamic models. Table 1 shows some of the data and the results of numerical calculations.

Table 1 Actual plant data and calculation results from Putrajaya Power Plant

Inlet Temperature, T_1 (K)	Thermal efficiency, Brayton (%)	Pressure Ratio, r_p	Turbine Inlet temperature T_3 (K)	Effectiveness/ Thermal Ratio (ε)	Thermal Efficiency, Regen (%)
300.90	30.7	3.6	789.44	0.59	45.0
305.30	30.7	3.6	791.51	0.59	44.0
303.70	30.9	3.64	782.19	0.58	44.0
298.90	31.0	3.67	786.17	0.59	45.0
301.90	31.2	3.7	780.70	0.58	44.0
306.80	31.3	3.72	782.48	0.58	43.0
302.80	31.6	3.77	778.99	0.58	43.0

After modification of the current cycle at Putrajaya Power Plant with regeneration, the efficiency of regenerative was observed to be higher. At compressor inlet temperature of 298.90K, thermal efficiency of 31 % was observed for the existing or current cycle while the modified configuration yielded thermal efficiency of 45 %, which is a 14 % increase in thermal efficiency. Taking the average values of the results in Table 2, the following observations were made:

Inlet Temperature, T_1 = 303K
Thermal efficiency for Current cycle, $\eta_{th,Brayton}$
= 31.06 %
Pressure Ratio, r_p = 3.67, T_2 = 439K, where T_{2s} = 343K , T_3 = 784.50 K

Effectiveness/ Thermal Ratio, ε = 0.58, Thermal Efficiency, $\eta_{th, regen}$ = 44.0 %
So, the average value of the efficiency with regenerative cycle is 44.0 %

5.1   Effect of Compressor Inlet Temperature on Thermal Efficiency of Regenerative Cycle

Sensitivity analysis was carried out to study the effect of compressor inlet temperature on the system output. Figure 4 and 5 shown that when the inlet temperature decreased, the thermal efficiency increased while the regenerative effectiveness increased. It is observed that the thermal efficiency is higher for regenerative cycle.
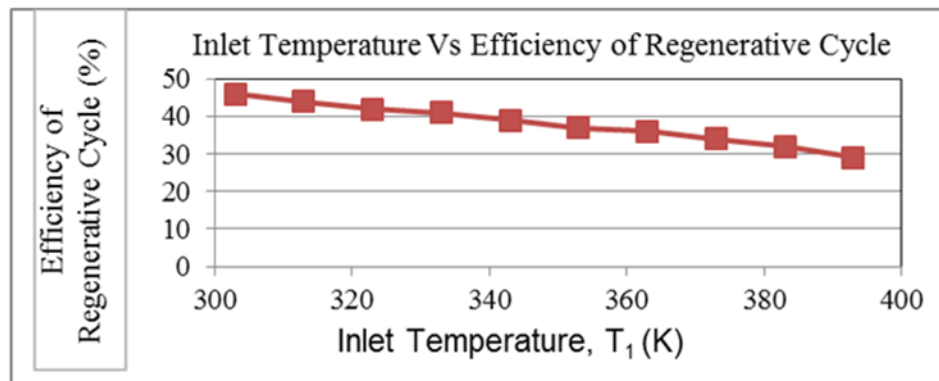

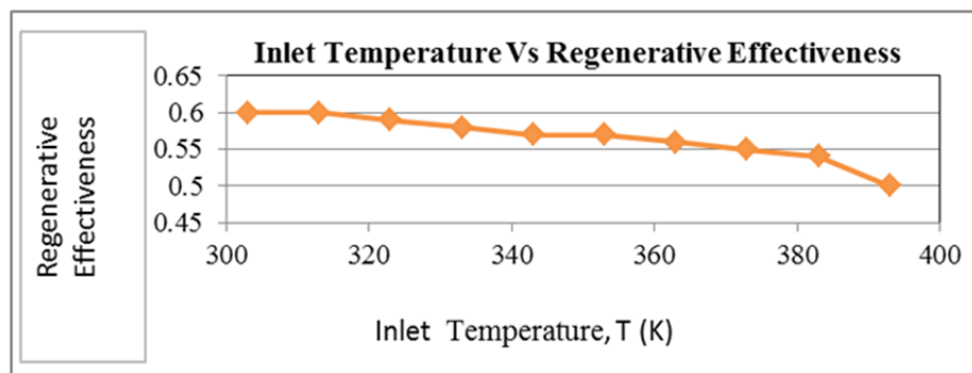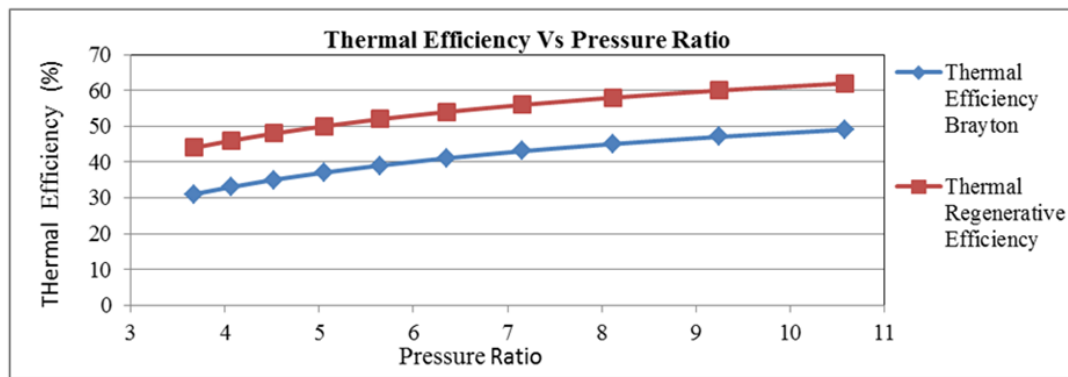**Figure 4** Inlet Temperature Vs Efficiency of Regenerative Cycle

Figure 5 Inlet Temperature Vs Regenerative Effectiveness

Table 2 shows the result after calculation of the thermal efficiency and pressure ratio. It shows that both parameters increase considerably. Figure 6 shows the range of pressure ratio over which the cycle can operate and also the optimized value of efficiency. At pressure ratio of 3.67, thermal efficiency of about 31.06% and 44% was recorded for the current cycle and regenerative cycle respectively. The efficiency of both cycles increase considerably with increase in pressure ratio, but at pressure ratio of about 7, only a small increase in efficiency for both cycles was observed. The optimum value of the efficiencies for both cycles that correspond to

pressure ratio of 7 is 43.06 and 56% for the current cycle and the regenerative cycle respectively.

Table 2 Actual plant data and calculation results from Putrajaya Power Plant

Thermal efficiency, Current cycle Brayton (%)	Pressure Ratio, r_p	Thermal efficiency, Regen (%)
31.06	3.67	44
33.06	4.07	46
35.06	4.52	48
37.06	5.05	50
39.06	5.65	52
41.06	6.35	54
43.06	7.16	56
45.06	8.12	58
47.06	9.24	60
49.06	10.58	62

Figure 6 Thermal Efficiency Vs Pressure Ratio

6.0 CONCLUSION

In this study the estimation of thermal efficiency of the regenerative cycle shows a considerable improvement over the existing cycle, this is due to the heat exchanger used to recover waste heat from the turbine exhaust. For this analysis it is therefore recommended that Putrajaya Power Station should modify to include generative equipment As a consequence, we hope that the results of the study will be helpful for the performance analysis by Putrajaya Power Station.

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