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Optimum Gas Turbine Configuration for Improving the performance of Combined Cycle Power Plant

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Abstract

The thermodynamic analysis of combined cycle gas turbine with effect different configuration for gas turbine are presented and discussed in this paper. The effects of ambient temperature and compression ratio have been proposed to select optimum configuration for gas turbine and its effect on CCGT performance. The analysis performance code has been performed used the MATLAB software. The simulating code for gas turbine configuration results show that the simple gas turbine configuration is more suitable with regards to power output, but the regenerative gas turbine configuration has higher efficiency with effect ambient temperature. The simple gas turbine configuration has higher power output with effect the compression ratio, while the regenerative gas turbine configuration has higher efficiency with effect lower compression ratio, therefore the variation of total power output is insignificance at lower compression ratio. The extensive modelling performed in this study reveals that, the ambient temperature and compression ratios are strongly influence on the performance of combined cycle, a higher overall efficiency can be achieved for combined cycle with add regenerative to topping cycle.

Keywords: Combined cycle; Gas turbine configuration; Ambient temperature; Compression ratio

1. Introduction

The gas turbine power plant is well-known to trait low capital cost, high reliability, high flexibility without complexity [1]. Gas turbines have come to play a significant role in distributed energy systems

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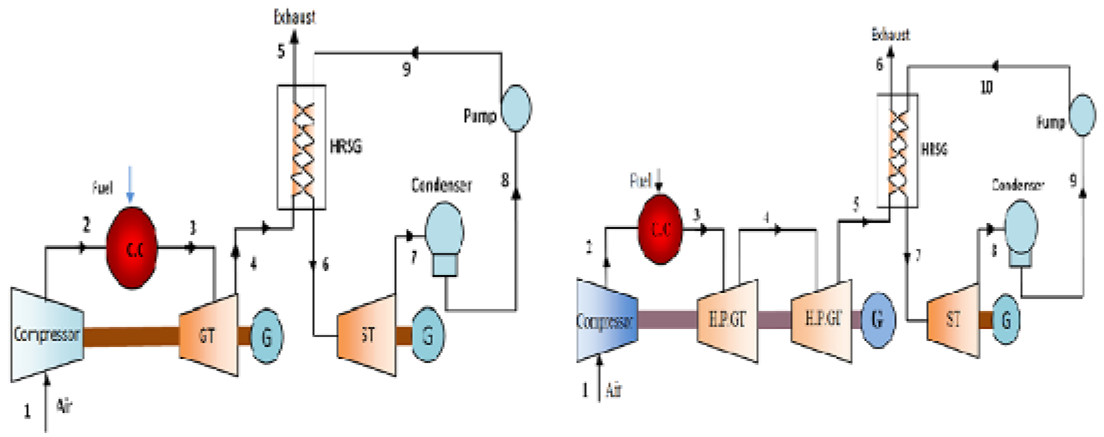
due to its multi-fuel capability, compact size and low environmental impact and reduced operational and maintenance cost. Nevertheless the low electrical efficiency, typically about 30% (LHV), is an important practical obstruction to the accomplishment of gas turbine competing to reciprocating internal combustion engine at equal power output [2]. The simple combined cycle gas turbine power plant continues to be one of the world's most efficient fossil fuel to electricity converters. The growths continue to boost gas turbine power plant performance and increase turbine inlet temperature and it has been recommended [3, 10].Combined Cycle gas turbine Power Plants (CCGT) and connected technologies have been mature sufficient attributable almost 40 years of experience and carrying out in power generation field [4]. The design of CCGT power plants is intrinsically complex due to the presence of two different power cycles which are joined through the HRSG. The performance of the whole system robustly depends on the optimal incorporation between the power units. As widespread carry out, gas and steam turbines are selected within a set of commercially obtainable ones, whereas the HRSG is the component of a CCGT cycle which can be made to order particularly for each gas turbine unit and for each specific power plant. Currently overall thermal efficiencies up to 60% are confirmed by the foremost manufacturers from the sector as state of the art (Bagla

n Energy plant in UK, operational since 2003 was the first with efficiency 60%), and special options have been proposed to improve the overall thermal efficiencies more than 60% [5]. The execution of CCGT with overall thermal efficiency of 60% is technically practicable for the power production manufacturers (for example GE H-technology) and additional improvements of the CCGT have been concentrated mostly on advanced gas turbine design lead to the increased turbine inlet temperature of the gas turbine and exhaust gas temperature [6].

The investigation of the developments of CCGT power plants in the last years shows the greater overall thermal efficiency increase practical along with the different energy systems and the efficiency increase has determined an increase of the size [7]. Higher efficiency level in CCGT (up to 64-65%) can be got due to many causes: enhancements in the gas turbine technology (i.e. higher compression ratio, turbine inlet temperature and ambient condition), HRSG optimization and improvement in HRSG design or the use of advanced thermodynamic plant configurations (i.e. two shaft gas turbine, combining intercooler cycle and regenerative cycle). The first kind of improvement is surely the most effective one in the perspective of efficiency increase. The focus of the analysis proposed in the present work is on the effect of ambient temperature, compression ratio and configuration of gas turbine, with the particular perspective of obtaining not only high efficiency CCGT power plants but also major operational flexibility.

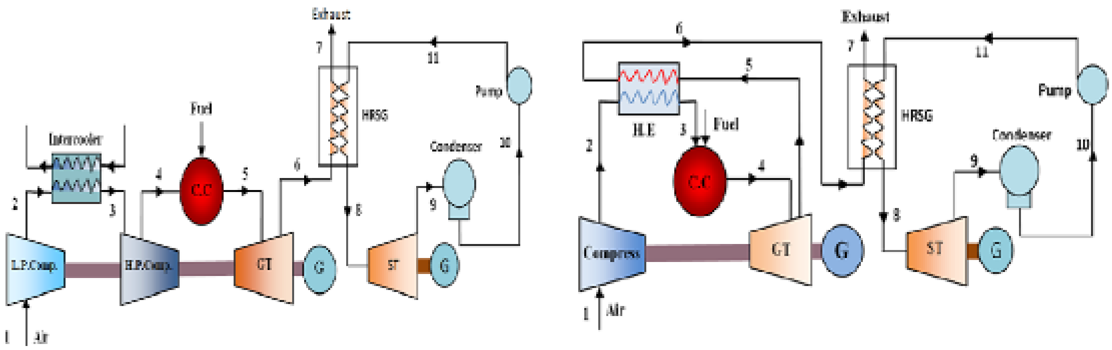
2. Modeling of Combined Cycle Gas Turbine

A simple CCGT power plants having Brayton cycle based topping cycle and Rankine cycle based bottoming cycle has been considered for the present study and analysis. Gas turbine power plants consist of four components, compressor, combustion chamber, turbine and generator. Air is drawn in by the compressor and delivered to the combustion chamber. Liquid or gaseous fuel is commonly used to increase the temperature of compressed air through a combustion process. Hot gases leaving the combustion chamber expands in the turbine which produces work and finally discharges to the atmosphere (state 1, 2, 3 in Figure 1(a)) [8]. The waste exhaust gas temperature from gas turbine decreases as it flows into the heat recovery steam generator (HRSG), which consists of superheater, evaporator and economizer. Then the HRSG supplies a steam for the steam turbine in producing electricity. In the latter, the waste condensate from the steam turbine will be flowed into a condenser, where cooling water transfers waste heat to the cooling tower. In the final stage, feed water is the output from a condenser, which is suctioned by the feed water pump and sent to the heat recovery steam generator and so on [9]. Figure 1(b) show the CCGT power plant with two shaft gas turbine as topping cycle (also named free power turbine), the first shaft use to drive the compressor and the second use to drive the generator. Figure 2(a) show the CCGT power plant with effect intercooler gas turbine. Figure 2(b) show the CCGT power plant with effect regenerative gas turbine.



(a) (b)

Fig.1. The schematic diagram: a) Simple combined cycle gas turbine power plant b) combined cycle two shaft gas turbine power plant.



(a) (b)

Fig. 2. The schematic diagram: a) Intercooler combined cycle gas turbine power plant b) Regenerative combined cycle gas turbine power plant.

2.1. Gas Turbine Model

It is assumed that the compressor efficiency and the turbine efficiency are represented η_c and η_t respectively. Using the first law of thermodynamic and knowing the air inlet temperature to compressor, compression ratio (r_p) and isentropic efficiency for compressor, we can determine the The net work of the gas turbine (W_{net}) is calculated from the equation:

$$W_{Gnet} = C_{pg} \times TIT \times \eta_t \left(1 - \frac{1}{r_p^{\frac{\gamma_g - 1}{\gamma_g}}}\right) - C_{pa} T_1 \left(\frac{r_p^{\frac{\gamma_a - 1}{\gamma_a}}}{\eta_c}\right) \quad (1)$$

where, C_{pa}: The specific heat of air which can be fitted by the following equation for the range of 200K<T<800K (R) and η_m is the mechanical efficiency of the compressor. The specific heat can be expressed as (5)

$$C_{pa} = 1.0189 \times 10^3 - 0.1378\, T_a + 1.9843 \times 10^{-4} T_a^2 + 4.2399 \times 10^{-7} T_a^3 - 3.7632 \times 10^{-10} T_a^4 \quad (2)$$

where, T_a in Kelvin.
The specific heat of flue gas is given by (6) [11].

$$C_{pg} = 1.8083 - 2.3127 \times 10^{-3} T + 4.045 \times 10^{-6} T^2 - 1.7363 \times 10^{-9} T^3 \quad (3)$$

where, $T_3 = TIT$ = turbine inlet temperature and LHV= fuel low heating value.
Also, the output power from the turbine (P) can be expressed as in (11):

$$\text{Power,} \quad P = \dot{m}_a \times W_{net} \quad (4)$$

The specific fuel consumption (SFC) can be determined by (12):

$$SFC = \frac{3600\, f}{W_{net}} \quad (5)$$

The heat supplied is also expressed as:

$$Q_{add} = f \times LHV \quad (6)$$

The gas turbine efficiency (η_{th}) is expressed as in (14):

$$\eta_{th} = \frac{W_{net}}{Q_{add}} \quad (7)$$

2.2. Two shaft gas turbine

In the two shaft gas turbine one shaft used to drive the compressor and the second turbine used to drive the generator, therefore the work done is:

$$W_{Gnet} = C_{pg} \eta_t \left(TIT - \frac{C_{pa} T_1 \left(\frac{r_p^{\frac{\gamma_a - 1}{\gamma_a}} - 1}{\eta_c}\right)}{C_{pg} \eta_m} \right) \left[1 - \frac{TIT - \frac{C_{pa} T_1 \left(\frac{r_p^{\frac{\gamma_a - 1}{\gamma_a}} - 1}{\eta_c}\right)}{C_{pg} \eta_m \eta_t}}{r_p^{\frac{\gamma_g - 1}{\gamma_g}}} \right] \quad (8)$$

2.3. Intercooler Gas Turbine

The work down for intercooler gas turbine is[7]:

$$W_{Gnet} = C_{pg} TIT.\left[\eta_t\left(1-\frac{1}{\left(r_p^2\right)^{\frac{\gamma_g-1}{\gamma_g}}}\right)\right] - C_{pa}T_1\left(\frac{r_p^{\frac{\gamma_a-1}{\gamma_a}}-1}{\eta_c}\right)\left[2+\left(1-x\right)\left(\frac{r_p^{\frac{\gamma_a-1}{\gamma_a}}-1}{\eta_c}\right)\right] \tag{9}$$

2.4. Regenerative Gas Turbine

In the regenerative gas turbine the exhaust gas from the turbine is used to heat air before it enters the combustion chamber, and therefore the fuel consumption is reduced in the combustion chamber. The net work done for this cycle is[12]:

$$W_{Gnet} = C_{pg} TIT.\eta_t\left(1-\frac{1}{r_p^{\frac{\gamma_g-1}{\gamma_g}}}\right) - C_{pg}T_1\left(\frac{r_p^{\frac{\gamma_g-1}{\gamma_g}}-1}{\eta_c}\right) \tag{10}$$

2.5. Steam Turbine Cycle Model

The efficiency for the steam turbine power plant is;

$$\eta_{st} = \frac{W_{snet}}{Q_{av}} \tag{11}$$

Where W_{snet} = net work for the steam turbine cycle and Q_{av}= heat available with exhaust gases from gas turbine

The overall thermal efficiency for the combined cycle gas turbine power plant is;

$$\eta_{all} = \frac{W_{Gnet} + W_{snet}}{Q_{add}} \tag{12}$$

The total heat rate is;

$$HR_t = \frac{3600}{\eta_{all}} \tag{13}$$

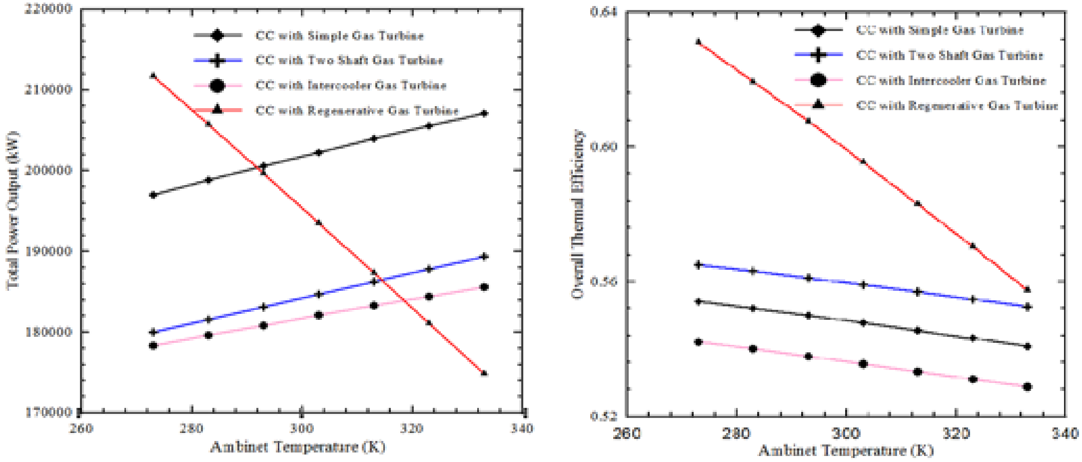
3. RESULTS AND DISCUSSION

The parameter influence in terms of ambient temperature and compression ratio on the performance of the combined cycle gas turbine cycle power plant is presented in this section. The effects of these parameters on the total power output and overall thermal efficiency are obtained by the energy-balance utilizing MATLAB10 software. Fig. 3(a) shows the variation of ambient temperature on the total power output of the combined cycle for different gas turbine configuration. It can be seen that the total power output increases with the increase the ambient temperature for all configuration except regenerative gas turbine. The power output of combined cycled regenerative gas turbine decreases with increase of ambient temperature. When the ambient temperature increase from 273K to 333K, the total power output increase about 7% for all configurations except the regenerative gas turbine. It is because of the steam cycle power output increases with increases the mass flow rate for exhaust gases. This leads to increases the steam flow rate in the steam cycle with increases the ambient temperature. However, the total power output of combined cycle regenerative gas turbine decreases about 19%. It is because of reduces the exhaust gases temperature. Therefore, the total power output for the most combined cycle configuration increases with increase of the ambient temperature, it is because of the increases in the steam turbine cycle more than the gas turbine power output, also the total power output increase with increases the ambient temperature.

Fig. 3(b) shows the effect of ambient temperature on overall thermal efficiency of the combined cycle for different configuration of gas turbine. The overall thermal efficiency decreases with increases the ambient temperature. It is because of the decrease the thermal efficiency for gas turbine compared with thermal efficiency of the steam turbine cycle. The overall thermal efficiency also decreases due to increases the losses of the exhaust gases. It can be seen that the overall thermal efficiency of the combined cycle obtained maximum value with regenerative gas turbine configuration about 62.8% at ambient temperature 273K and the minimum value of the overall thermal efficiency was about 53% for intercooler gas turbine configuration at ambient temperature 333K. As the ambient temperature increases, the compressors specific work increases, thus reducing overall thermal efficiency for the combined cycle with all gas turbine configurations. The compressor of a gas turbine is designed to operate with a constant volume of air. While the ambient temperature increases, its specific mass is reduced. In order to ensure the same air volumetric flow, the mass flow is reduced, as a result causing the power output of the gas turbine and the amount of heat generated in the HRSG to fall. Also the temperature at the inlet of the combustion chamber increases, this lead to reduced the burning fuel and decreases the turbine inlet temperature, then decreases the gas turbine efficiency and decreases the overall thermal efficiency of combined cycle.

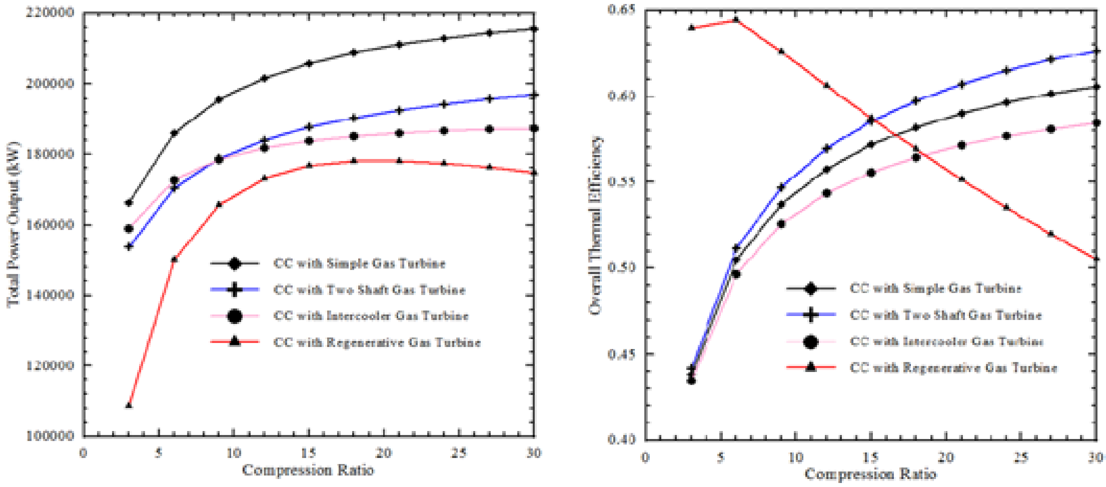
The simulation varies the gas turbine compression ratio from 3 to 30. This simulation is intended to show the effect compression ratio has on the performance of the combined cycle for different gas turbine configuration. Fig. 4(a) shows the variation of compression ratio on total power output of combined cycle for different gas turbine configuration. The compression ratio is affected by many factors such as work of compressor and power output of a gas turbine. The work of compressor is a function of inlet air temperature at the compressor air intake. The power output of a gas turbine is a function of turbine inlet temperature. As the compression ratio increases, the air exiting the compressors is hotter, therefore less fuel is required (lowering the air fuel ratio) to reach the desired turbine inlet temperature, for a fixed gas flow to the gas turbine. The work required in the compressor and the power output of the gas turbine, steadily increases with compression ratio, then cause decreases in the exhaust gases temperature. This lower gas temperature causes less steam to be produced in the HRSG, therefore lowering the outputs of the steam cycle. It is noticed that the total power output increases with compression ratio. However the variation of total power output is minor at lower compression ratio while it is significant at higher compression ratio for all gas turbine configurations. The higher total power output obtained with simple gas turbine configuration and lower value obtained with regenerative gas turbine configuration. It is because The power output of the gas turbine increases with compression ratio up to a certain value and then decreases for regenerative and intercooler gas turbine configuration. The combined cycle power output also has a similar trend to the gas turbine but the maximum value is reached at pressure ratio between 15 and 25. While the power output of combined cycle for simple and two shafts configuration increases constantly with increases the compression ratio.

Fig. 4(b) illustrates the variation of effect of compression ratio on overall thermal efficiency of combined cycle for different configuration of gas turbine. The overall thermal efficiency for regenerative gas turbine configuration is very significance with lower compression ratio it reaches to 64.6% at compression ratio 6.4. But when the compression ratio increases the overall thermal efficiency of combined cycle with regenerative gas turbine configuration decreases, because, when compression ratio increases, temperature of the exhaust gases from the turbine decrease and temperature of air in outlet of compressor increases, so, the recovered thermal energy in regenerative heat exchanger falls until zero



(a) (b)

Figure 3: Effect of ambient temperature on combined cycle for different configuration of gas turbine: a) Total power output b) Overall thermal efficiency.



(a) (b)

Figure 4: Effect of compression ratio on combined cycle for different configuration of gas turbine: a) Total power output b) Overall thermal efficiency.

corresponding to the compression ratio that at this point efficiency of simple gas turbine configuration and regenerative gas turbine configuration equals. For higher values of compression ratio the heat exchanger in regenerative gas turbine configuration would cool the air leaving the compressor and as a result reduce the efficiency. Also the overall thermal efficiency for other gas turbine configurations is not significance at lower compression ratio. The overall thermal efficiency of combined cycle for different gas turbine configurations are very significance with higher compression ratio.

4. CONCLUSION

In this study several cycles are examined: the combined cycle with topping cycle: simple gas turbine, two shaft gas turbine, intercooler gas turbine and regenerative gas turbine. The simulated modeling results show that the influence of the ambient temperature and compression ratio are significantly effect on performance of combined cycle gas turbine power plant for different gas turbine configuration. The results are summarized as follows:

1. The ambient temperature and compression ratios are strongly influence on the overall thermal efficiency of the combined cycle gas turbine power plant for different gas turbine configuration.
2. Higher overall thermal efficiency for combined cycle gas turbine with regenerative gas turbine configuration. Efficiency quoted range about 64.5% with low compression ratio.
3. The overall thermal efficiency of combined cycle decreases and total power output increases linearly with increase of ambient temperature for all gas turbine configurations except the regenerative gas turbine the total power output decreases.

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