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Influence of Steam Injection into Combustion Chamber on the Performance of the Combined Cycle

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ABSTRACT

Combined cycle power plants have a key role in power generation. In this paper, a thermodynamic analysis with different ambient temperatures has been employed for the combined gas and steam turbine power plant is located at Zawiya, Libya, with and without steam injection into the combustion chamber of the cycle. Two cases for the combined cycle have been examined in different ambient temperatures. The first case is the normal combined cycle, the second case is the combined cycle with steam injection, where it injects steam into the combustion chamber to compensate for the increase in the amount of fuel needed at a constant power output when increasing the ambient temperatures, or to enhance the cycle performance where it finds the power output decreases with increasing ambient temperatures. In this paper, also exergy destruction of each component of the combined cycle at different inlet temperatures was evaluated utilizing exergy analysis. The results show that improvement in the thermal performance of the combined cycle can be achieved by injecting steam into the combustion chamber, where power output is increased by 10 % and efficiency of the combined cycle is improved by about 10 %. Gas turbine combustion chamber has the greatest exergy destruction compared to other components and representing about 13 % increase in exergy losses when the steam injection has been used, the second major exergy loss is in the heat exchanger.

Keywords: Gas turbine, Steam turbine, Exergy analysis, Exergy destruction.

Nomenclature

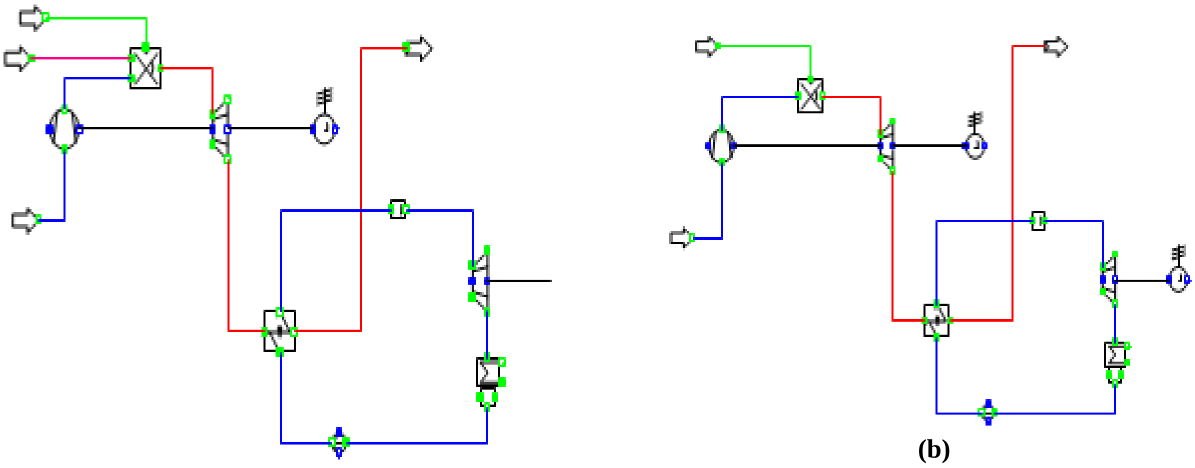
$dT_{1\text{-}2}$	Temperature different between 1 and 2	Q_{in}	Power input to the cycle
Cpa	Air specific heat at constant pressure	Ra	Air constant
Cpg	Gas specific heat at constant pressure	Rg	Gases constant
g	Air Specific heat ratio	S	Entropy
h	Specific enthalpy	s	Specific entropy
I	Irreversibility	S_{gen}	Entropy generation.
LHV	lower heating value	T_1	Compressor inlet temperature (K)
m_a	Air mass flow rate	T_2	Compressor outlet temperature (K)
m_f	Fuel mass flow rate	T_0	Environment temperature
m_g	Gases mass flow rate	β	fuel air ratio
m_{st}	Steam mass flow rate	$\Delta\varphi$	Exergy
P_1	Compressor inlet pressure	η_{cc}	Combined cycle efficiency
P_2	Compressor outlet pressure	η_c	Compressor isentropic efficiency
P_3	Combustion chamber outlet pressure	φT	Turbine exergy
P_g	Power of the gas turbine		
P_s	Power of the steam turbine cycle		

1. INTRODUCTION

Under the Kyoto Protocol, the world's wealthier countries assumed binding commitments to reduce greenhouse gas emissions [2] and the energy supply to the demand limited day after day around the world. The growing demand of power has made power plants of scientific interest. However, most power plants are designed by the energetic performance criteria based on the first law of thermodynamics only. The real beneficial energy loss cannot be determined by the first law of thermodynamics, because the real plant inefficiencies are not related to energy loss but to exergy destruction. Exergy analysis and determining the exergy destruction of each component of the power plant is a useful concept in ecology and sustainability because it can be used as a common measure of research quality along with quantity, and to improve system efficiency [1]. In recent years, various methods have been used for improving the gas turbine performance. Several methods show success in improving and maintaining the performances of the gas turbine cycle with a high amount of steam injected at various points in the cycle [7]. For several years, the injection of steam into the combustion chamber has represented a common way to improve the performance of gas turbine power plants, increasing both the efficiency and the power output due to greater mass flowing through the turbine and reducing at the same time NOx emissions [3,4, 6]. Emissions such as NO, CO2, O2, and HC were reduced when the engine was run with steam injection [8]. In this paper, steam injected into the combustion chamber is used to improve the performance of the cycle with different ambient temperatures, and is used to compensate for the shortage of fuel mass when the combined cycle runs at full load. The comparison shows a good agreement. The optimization of the combustion chamber has a significant role in reducing the exergy loss of the total combined cycle.

2. MODEL DESCRIPTION

The combined cycle with and without steam injection is shown in figure 1 in which the air compressor compresses the inlet air (raises its pressure). Fuel is mixed with the high- pressure air in burners and burnt in special chambers called combustion chambers. The hot pressurized gas coming out of the combustors is at a very high temperature (up to 1100° C). The gas generator is matched to the power turbine by the fact that the mass flow leaving the gas generator must equal that at the entry to the power turbine. The gas passes through a gas turbine, giving the turbine energy to spin the compressor and energy to turn a generator to produce electricity. Because some of its heat and pressure energy has been transferred to the turbine, the gas is cooler and at a lower pressure when it leaves the power turbine. It is then either discharged to the atmosphere or is directed to a special type of heat exchanger, called a heat recovery steam generator to capture heat from the gas turbine exhaust. Steam produced in the heat recovery steam generator powers a steam turbine generator to produce additional electric power as shown in figure 1. The turbine entry temperature in a gas turbine cycle is considerably higher than the peak steam temperature. Depending on the compression ratio of the gas turbine, the turbine exhaust temperature may be high enough to permit efficient generation of steam using the waste heat from the gas turbine. A configuration, such as this is known as a gas and steam turbine- combined cycle.



(a)

(b)

Figure 1 Gas–Steam Turbine Combined Cycle with and without steam injection

The system shown in figure (b) represents the same cycle in figure (a) in addition to the injection of steam to enhance the performance of the cycle. The IPSEpro program has been used to model and examine the combined thermodynamic cycles to determine the optimum mode of operation and configuration [9]. This work examines the operation of the combined cycle. The heat input to the combined cycle is the same as that for the gas turbine, but the power output is higher than the power output of the Rankine cycle steam turbine [10]. This work examines the performance of the combined cycle, according to the first and the second law of thermodynamics using the energy and the exergy analysis in the operation of the combined cycle. The compressor discharge temperature at constant speed increases with increasing temperature. Thus, the amount of heat that can be added to the gas at a given maximum firing temperature is reduced. The net effect of higher ambient temperatures is an increase in heat rate and a reduction in the power output. The impact of ambient temperature is usually less pronounced for the heat rate than for the power output, because changes in the ambient temperature impact less the component efficiencies than the overall cycle output.

3. THERMODYNAMIC ANALYSIS

The present study introduces a comparative energy and exergy analysis for the gas and steam combined cycle with and without Steam injection. The analysis has investigated the effects of different ambient temperatures. The steam entering the combustor is in superheated condition, and it is assumed not to participate in the chemical reactions of the combustion. The pressure of the steam when injected must be somewhat higher than the pressure of air coming from the combustor. To keep a constant turbine inlet temperature, the amount of fuel supplied in the combustor is larger for a steam injected gas turbine compared to a common combined cycle. The increase of fuel power in a steam injected gas turbine will thus be smaller than the gain in net power output of the gas turbine, which gives that higher efficiency. By injecting steam in the combustion zone, the peaks in flame temperature are decreased. Usually, the maximum steam injection rate is about 15-20% of the air mass flow [11]. Combined effects of compression ratios and steam injection on performance, combustion and emission characteristics of a HCCI engine are numerically investigated and the results show that the performance of the HCCI engine is very low if the steam injection exceeds 20% [5]. The steam, which is injected into the combustion chamber of the gas turbine, is blended with the combustion gases, and will follow the gas to the stack.

Zawiya power plant input data and some assumptions.

Methane (CH4) gas enters a steady-flow adiabatic combustion chamber at 20°C and 20 bars.

Table 1. The sample unit design parameters

Design Parameters	
Mass of air (kg/s)	488.203
Inlet temperature (^{o}C)	15
Inlet pressure (bar)	1.013
Steam mass flow (Kg/s)	60
Fuel mass flow (Kg/s)	9.06049
The input data for compressor	
Compressor isentropic efficiency (%)	0.99
Turbine isentropic efficiency (%)	0.9
The characteristics of heat exchanger are	
Pressure drop of the hot temperature side (bar)	0.1
Pressure drop of the low temperature side (bar)	0.1

The temperature increase of the air during the compression is:

$$\left(\frac{dT_{1-2}}{T_1}\right)_{actual} = \left(\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right) / \eta_s \qquad (1)$$

The pressure ratio P_3 / P_2 can be obtained directly from the combustion chamber pressure loss

$$\frac{P_3}{P_2} = 1 - \left[\Delta P / P_2\right] \qquad (2)$$

The overall efficiency of the combined cycle (η_{CC}) is calculated using the following equation.

$$\eta_{CC} = \frac{P_G + P_S}{Q_{in}} \qquad (3)$$

The steam injected is not taking active part in the combustion process, but will be heated to the same temperature as the rest of the gas, i.e. to the turbine inlet temperature. Since the steam is not reacting in the combustion process, the gas and steam flows can be treated separately. The heat balance, thus becomes:

$$m_a.h_{2,a} + m_f.LHV + m_{St}.h_{St,in} = \left(m_{3,a} + m_f\right).h_{3,g} + m_{St}.h_{St,ex} \quad (4)$$

$$\beta = \frac{m_f}{m_{air}} \qquad (5)$$

$$\beta = \frac{h_{3,g} - h_{2,a} + \frac{m_{St}}{m_{air}}\left(h_{St,ex} - h_{St,in}\right)}{LHV - h_{3,g}} \qquad (6)$$

4. EXERGYDESTRUCTION IN DIFFERENT COMPONENTS OF COMBINED CYCLE

The complex thermodynamic analysis of combined cycle has been based on the second law of thermodynamics. Because the conventional first law analysis of any thermodynamic system has the capability to determine the energy distribution across the system boundaries but does not explain the means of energy degradation that cause decreases in the power output of the system. The exergy analyses for combined cycle components has been conducted to determine the energy loss caused by irreversible processes. Exergy analysis usually predicts the thermodynamic performance of an energy system and the efficiency of the system components by quantifying the entropy generation of the components. This analysis provides a tool for the optimal design and operation of complex thermal systems. The exergy and irreversibility equations for each component are written as follows [10],

Compressor: The exergy and irreversibility in compressor is given by

$$\Delta\varphi = m_a(h_1 - h_2) - T_o m_a(s_1 - s_2) \qquad (7)$$

$$I_c = m_a T_0 \left(S_2 - S_1\right) \qquad (8)$$

Where

$$s_2 - s_1 = c_{p_a} ln\frac{T_2}{T_1} - R_a ln\frac{P_2}{p_1} \quad and \quad R_a = C_{p_a}\frac{(\gamma - 1)}{6}$$

Combustion Chamber: As an approximation, the virtual power is used to calculate the exergy of the combustor component. The exergy balance of this component and exergy loss due to irreversibility in the combustion chamber is given by

$$\varphi_{c.c} = Q_{in} + T_o S_{gen} \qquad (9)$$

$$I_{c \cdot c} = T_0 S_{gen} \qquad (10)$$

Where

$$S_{gen} = \left(\dot{m}_a + \dot{m}_f\right)\left(c_{pg} ln\frac{T_3}{T_2}\right) - \frac{Q_{in}}{T_{av}} \quad (11)$$

And T_{av}= average (T_3, T_2)

Turbine: The exergy loss due to irreversibility in gas turbine is given by

$$\varphi_T = m_g(h_3 - h_4) - T_o m_g(s_3 - s_4) \quad (12)$$

$$I_{GT} = m_g T_o(s_4 - s_3) \qquad (13)$$

Where

$$(s_4 - s_3) = C_{pg} ln\frac{T_4}{T_3} - R_g ln\frac{P_4}{P_3} \qquad (14)$$

And

$$R_g = C_{Pg}\frac{(\gamma-1)}{\gamma} \qquad (15)$$

Heat Exchanger: The exergy loss due to irreversibility in heat exchanger is given by

$$\Delta s_{cold} = s_{cold-ex} - s_{cold-in} \qquad (16)$$

$$\Delta s_{hot} = s_{hot-ex} - s_{hot-in} \qquad 17)$$

$$\varphi_{cold} = \left(h_{cold-ex} - h_{cold-in}\right) - T_o\left(s_{cold-ex} - s_{cold-in}\right) \quad (18)$$

$$\varphi_{hot} = \left(h_{hot-in} - h_{hot-ex}\right) - T_o\left(s_{hot-in} - s_{hot-ex}\right) \quad (19)$$

$$I_{EX} = T_o\Delta\dot{S}_o = T_o\left[m_{hot}(s_4 - s_6) - \dot{}m_{cold}(s_{ex} - s_{in})\right] \quad (20)$$

Where

$$s_6 - s_4 = C_{pg} ln\frac{T_6}{T_4} - R_g ln\frac{P_6}{P_4} \qquad (21)$$

5. SIMULATION AND RESULTS

Combined cycle represents an attractive option for power units, especially in the modern world. The generated power and efficiency of gas turbine plants depend on the temperature of the inlet air. Based upon the methodology developed and the thermodynamic equations shown, the effect of ambient temperature on the performance and on the exergy destruction due to irreversibility in the various components of the gas turbine and steam turbine, with and without steam injection is displayed graphically.

The following figures show the changes in the performance of the gas and steam combined cycle with the changing in the ambient temperatures. Exergy destruction is obtained from the exergy (second law) analysis. The power output and efficiency have been affected by ambient temperatures as shown in figure 2 and figure 3 and clearly show that the cycle performance decreases as ambient temperature increases. These figures show a significant increase in the performance with the use of steam injection. If the combined cycle with steam injection runs at design condition, more fuel consumption is needed when steam injection is used. If we fixed the mass of fuel by the value of 9.06049 kg/s in the two cases of the combined cycle (with and without steam injection), the power output and cycle efficiency in the second case when the combustion chamber was injected with steam mass equal to 12 % of the air mass flow are improved. Figure 2 shows enhancement in the cycle efficiency by about 10 % when steam (60 Kg/s) is injected into the combustion chamber. However, efficiency slightly decreases because of increasing ambient temperature.

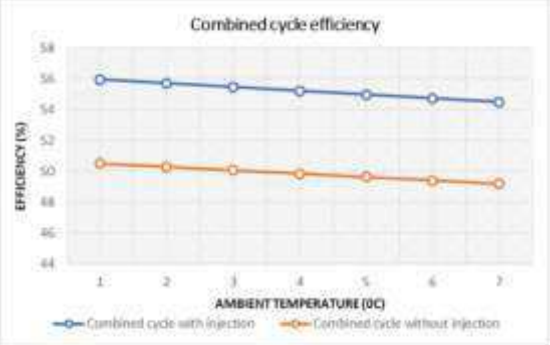


Figure 2. Combined-cycle efficiency variation with ambient temperature

Figures 3 shows the improvement in the power output of up to 10% more than the cycle without steam injection.

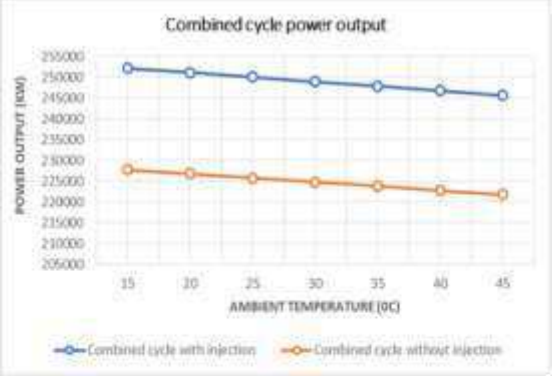


Figure 3. Combined-cycle power output variation with ambient temperature

Figure 4 shows the turbine inlet temperature increases because of increasing ambient temperature at constant fuel mass flow.

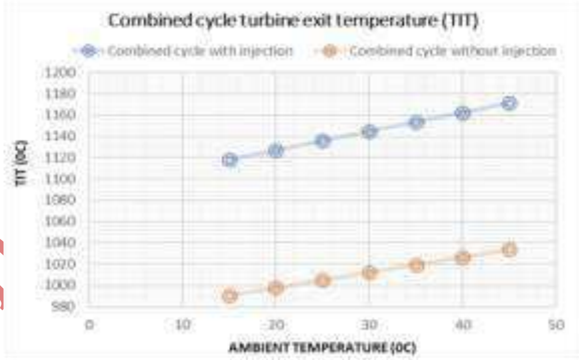


Figure 4. Combined-cycle turbine exit temperature variation with ambient temperature

Figures 5-7 represent how the performance and turbine inlet temperature vary with the ambient temperature and with different steam mass flow at a constant fuel consumption.

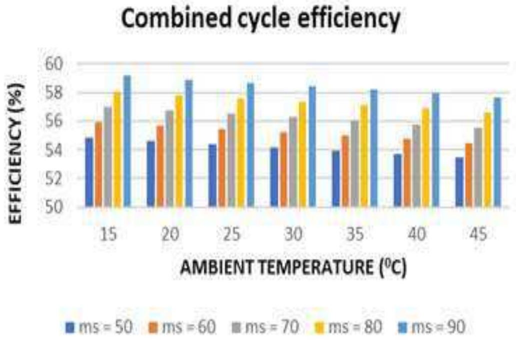


Figure 5. Combined-cycle efficiency variation with ambient temperature and different steam mass flow

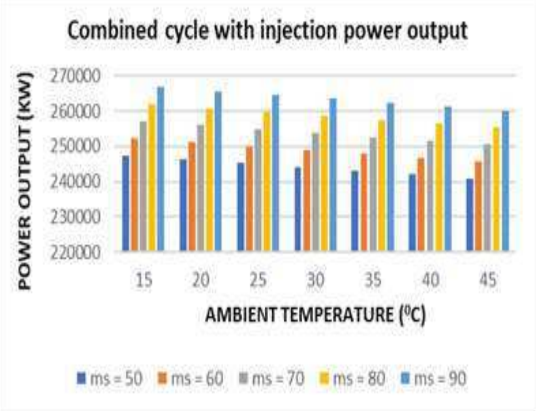


Figure 6. Combined-cycle steam mass flow variation with ambient temperature and different steam mass flow

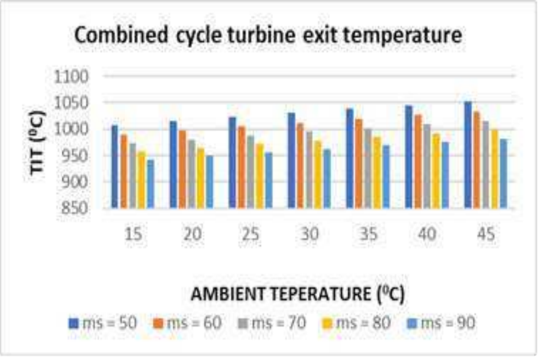


Figure 7. Turbine inlet temperature (TIT) in a gas turbine variation with ambient temperature and different steam mass flow

We compensate the increase in the fuel consumption that is needed in the elevated temperature (hot days) by taking advantage of the steam injection when the cycle runs at full load constant gas turbine power output and fixed fuel mass flow. Figure 8 shows the steam mass flow variation at different ambient temperature.

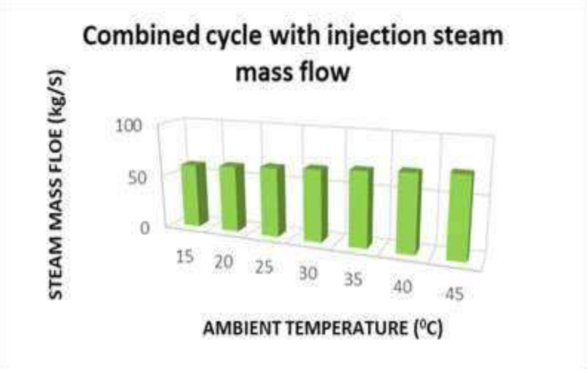


Figure 8. Steam mass flow at a full load condition variation with ambient temperature

Figure 9 demonstrates the effect of the exergy destruction with a different steam mass flow. The steam injection rate can vary from 0 to 20 % of air mass flow, which means that the amount of process steam can also be varied. However, the amount of steam that can be injected is highly dependent on the gas turbine type, whether it is a one shaft or double shafts gas turbine and on the pressure and temperature in the combustion chamber. As it shown in figure 9, when the steam mass flow increases, the risk of exergy destruction also increases. At the same time, significant improvement in power output can be obtained when high amount of steam mass is injected into the gas turbine as shown in figure 6.

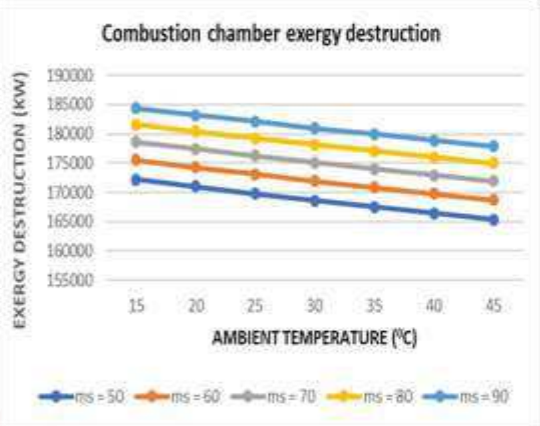


Figure 9. Combined cycle with steam injection combustion chamber exergy destruction variation with ambient temperature and different steam mass flow

Figures 10 shows exergy destruction in each individual component in the combined cycle. These results are obtained when using the fixed fuel mass flow of 9.06049 kg/s and pressure ratio of 13.8. The main source of exergy destruction in the combined cycle unit is the combustion chamber. These results clearly show that the combustor of topping cycle has the highest exergy destruction and shows the major site of thermodynamic inefficiency because of the large irreversibilities arising from the chemical reaction and heat transfer that occurs in the combustion process. Steam injection will also increase the exergy destruction due to mixing in the combustor. When the steam mass flow (60 kg/s = 12 % of air flow rate) is injected into the combustion chamber, there is an 13 % increase of exergy destruction in the combustion chamber. For this reason, the amount of steam mass flow should be limited.

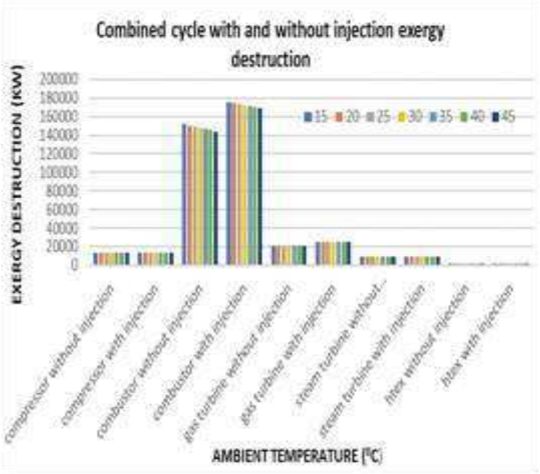


Figure 10. Combined cycle with and without steam injection components exergy destruction variation with ambient temperature

7. CONCLUSION

The simulation program IPSEpro has been applied successfully to the gas turbine cycle. Thermodynamic analysis based on the thermal efficiency and exergy have been analyzed. Steam injection into the combustion chamber is well-proven technology that can effectively improve power output and power generation efficiency for a combined gas and steam cycle. The production of electricity and efficiency are highest at cooler times of the day and the reverse at the hottest time of the day when they are needed most, unless when the combined cycle runs at constant gas turbine power output and constant fuel mass flow. Steam is injected into the combustion chamber of the gas turbine, increasing the flow rate through the turbine causing an increase in the power output of a gas turbine and the electrical efficiency, thus that the power output of the gas turbine with steam injection will be higher than the common combined cycle. A steam-injected gas turbine increases the power output by 10 % and can reach an electrical efficiency up to 55%, whereas the efficiency of the same cycle without steam injection can reach up to 50 %. When the same amount of fuel mass flow is used in the two cases of the combined cycle (with and without steam injection) the performance of the cycle with steam injected into combustion chamber can be improved by 10 % in the design condition. There are limitations of the amount of steam that can be injected, based on the above analysis, the following conclusions are made by varying the ambient temperature,

- The exergy analysis gives a real picture about the losses which occurred in the different cycle components.

- More exergy losses occur in the combustion chamber due to combustion irreversibility and this must be reduced with modern and advanced technology

- There are clear effects in the exergy losses when changing the amount of steam mass flow. At higher amounts of steam, exergy losses in the combustion chamber are higher, this leads to limitations in the amount of steam that can be injected.

- The optimum turbine inlet temperature and pressure ratio should be the next focus of study for minimizing the total exergy losses in all the components.

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