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Energy and exergy study of Shatt Al-Basra gas turbine power plant

S H Faisal[1*], N K Naeem[2] and A A Jassim[3]
[1]Basra Technical College, Southern Technical University, Basra, Iraq.
[2,3]College of Engineering, University of Basra, Basra, Iraq.
[*]Corresponding author's email: s_hfaisal100@stu.edu.iq

Abstract. Energy and exergy analyses have been carried out on General Electric (GE) gas turbine unit in Shatt Al-Basra power plant located in Basra- Iraq. The analysis is based on both full-load and part-load actual operating data during the year 2017. An obvious drop off for plant performance characteristics is observed during the hot season. Energy and exergy analyses show that maximum thermal and exergy efficiencies were in February. Minimum exergy destruction in the unit is predicted in March. Improvement of the unit performance is recommended by installing intake air cooling as well as utilizing the discharged heat power that contains considerable work potential.

1. Introduction

Gas turbine power plants are one of the most widely used electricity power generating technologies at present. It is a type of heat engine, which converts the chemical energy of fuels into useful mechanical energy. This energy is used to drive the generator that produces electrical power. The gas turbine consists of three main parts compressor, combustion chamber, and turbine. The gas turbine power plants are characterized by low installation costs. Besides, it does not require a large space for the installation. Moreover, it has a high power production per unit size [1].

Studying the gas turbine and enlightening its performance is very important to explain the possible enhancement opportunities using modern available techniques. Although the analysis that based on conservation of energy is one of the fundamentals, the analysis according to the exergy principle has extended in recent times. That is due to its capability to discover the real losses that hinder access to the best possible performance situation [2].

As gas turbine technology is imperative, it has been studied and analyzed by several research projects. Faisal et al [3] performed an energy and exergy study of Rumaila Basra gas turbine power plant during the hot season. Results indicate that the combustion chamber has the largest exergy destruction among the plant components. Song et al [4] present a detailed performance study based on exergy analysis for a heavy-duty gas turbine model GE 7F working in part-load. Results have shown that the variable inlet guide vane (IGV) caused the increase of exergy destruction in the first stage of air compressor and thereby decreased the overall efficiency of the compressor. Ashley and Al Zubaidy [5] studied gas turbine performance at varying ambient temperatures. The empirical relationship developed in the study between the gas turbine's power and ambient temperature shows that for every 1 K rise in ambient temperature above ISO conditions, the gas turbine loses 0.1% in terms of thermal efficiency and 1.47 MW of its gross power output.

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2. Shatt Al-Basra gas turbine power plant

Shatt Al-Basra gas turbine power plant is located at Shatt Al Basra in the south of Basra, Iraq, About 39.7 km south of the city centre. The rate of power is 126.1*10 MW. Initially, the plant established in 2012 by METKA S.A. with a one-generation unit rating of 126.1 MW under ISO condition. The other nine units were commissioned in 2016. The plant may utilize natural gas, heavy fuel oil (HFO), or light fuel oil (LFO) in the combustion process for which the properties are given in Table 1 [6].

In the present study, unit six in Shatt Al-Basra gas turbine power plant is taken as a case study. This gas turbine unit is MS9001E (also referred to as Frame 9) of a single shaft arrangement. The 17-stages, axial compressor is supplied with IGV row that controls the air mass flow rate drawn by the unit at part-load operation. The combustion system is made of 14- separate combustion chamber, which is symmetrically distributed on the circumference of the gas turbine. The turbine is of impulse-reaction type consisting of three stages and running at 3000 r.p.m [7].

Table 1. Properties of fuel used in Shatt Al-Basra gas turbine power plant [6].

	Fuel gas[a], % by volume		**LFO, % by mass**		**HFO, % by mass**	
	CH_4	75.2	%C	85.5	%C	85.1
	C_2H_6	17.05	%H	11.5	%H	10.9
	CO_2	1.91	%S	3	%S	4
	N_2	1.1				
	C_3H_8	4.2				
	nC_4H_{10}	0.3				
	nC_5H_{12}	0.01				
	iC_4H_{10}	0.22				
	iC_5H_{12}	0.01				
Density, kg/m^3	0.86		0.93		0.97	
LHV, MJ/kg	46.256		40.6		39.57	
HHV, MJ/kg	53.5		43.02		41.83	

[a] Only 100% CH_4 is considered for ISO operating conditions.

3. Mathematical model

A schematic of a gas turbine power plant and its representation in the T-S diagram are shown in figure 1. The following assumptions are taken into consideration:

- Steady-state operating conditions.
- The processes are adiabatic in the compressor, combustion chamber, and turbine.
- The potential and kinetic energy and their accompanied exergy are all neglected.
- Air and combustion gases are modeled as ideal gases with variable thermodynamic properties.
- The reference conditions are taken as $\boldsymbol{P_o = 101.325\ kPa}$ with variable ambient reference $\boldsymbol{T_o}$ temperature.

3.1. Energy analysis

Based on the first law of thermodynamics, the energy conservation equation applied to an open system is [8]:

$$Q + \dot{m}_i h_i = \dot{m}_e h_e + \dot{W} \tag{1}$$

The mass flow rate at inlet and exit is restricted by the mass conservation equation:

$$\dot{m}_i = \dot{m}_e \tag{2}$$

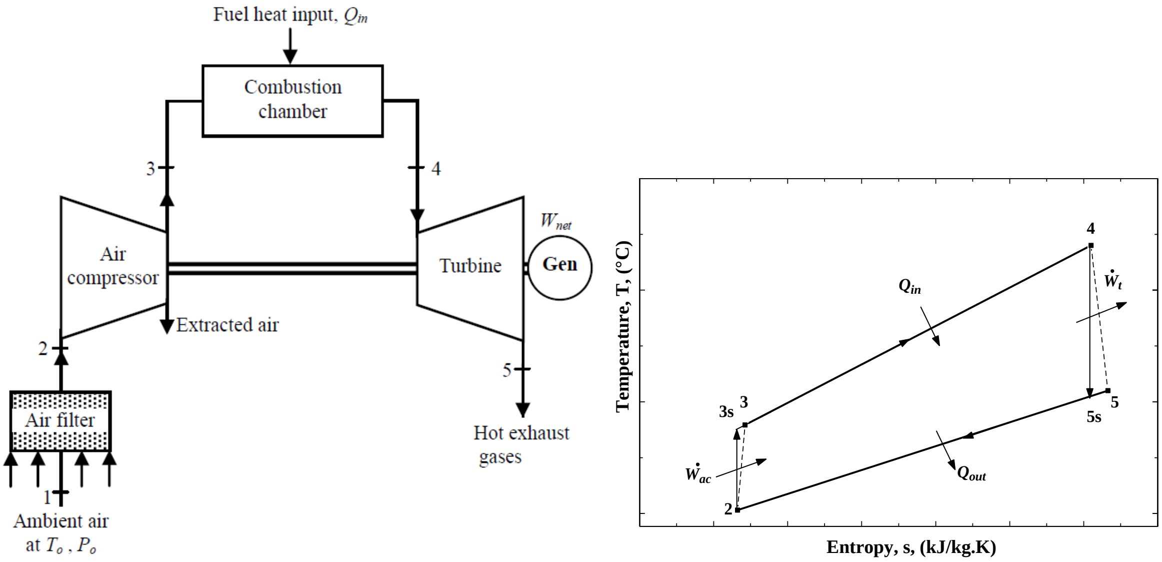

Figure 1. Sketch of gas turbine power plant and its representation on T-S diagram.

3.2. Exergy analysis

The exergy analysis is based on the second law of thermodynamics. The general exergy balance equation is [8,9]:

$$\Psi_{\mathrm{w}} = \sum_{k}\left(1-\frac{T_o}{T_k}\right)Q_k + \sum[(\dot{m}\psi)_i - (\dot{m}\psi)_e] - T_o S_{gen} \tag{3}$$

The flow stream exergy is [8,9]:

$$\psi = \dot{m}[(h-h_o) - T_o(s-s_o)] \tag{4}$$

The exergy destruction or so-called irreversibility (I) is:

$$I = T_o S_{gen} \tag{5}$$

Alternatively, the entropy balance equation can be used to identify the exergy destruction via determination the entropy generation term(S_{gen}) as follows [8,9]:

$$S_{gen} = \sum(\dot{m}\cdot s)_e - (\dot{m}\cdot s)_i - \sum\frac{\dot{Q}_k}{T_k} \tag{6}$$

The resultant needed equations for the three components are given in [3].

3.3. Overall plant performance

The net output power from the plant $\dot{W}_{net}$ is calculated as:

$$\dot{W}_{net} = \eta_{gen}\left(\dot{W}_t - \dot{W}_{ac}\right) \tag{7}$$

The exhaust heat rejected by the gas turbineQ_{out} is defined as:

$$Q_{out} = Q_{in} - \dot{W}_{net} \tag{8}$$

The thermal efficiency or first law efficiency $\eta_{I,gt}$ of the unit is the ratio of net output power to the input heat, i.e.:

$$\eta_{I,gt} = \frac{\dot{W}_{net}}{Q_{in}} \tag{9}$$

The exergy efficiency or second law efficiency $\eta_{II,gt}$ for the plant can be written as:

$$\eta_{II,gt} = \frac{\dot{W}_{net}}{\dot{m}_f EX_f} = 1 - \frac{I_{tot}}{\dot{m}_f EX_f} \tag{10}$$

The input fuel exergy EX_f is formed of two parts. The first part is the physical exergy, which is associated with the fuel flow stream. The second part, which is essential in exergy analysis, is the chemical exergy EX_f^{ch}associated with its chemical energy. The fuel exergy, in this case, will be [9]:

$$EX_f = (\psi_f - \psi_{f@15^{\circ}\mathrm{C}}) + EX_f^{ch} \tag{11}$$

A detailed method to calculate the chemical exergy for liquid and gaseous fuel is given in [9]. The total irreversibility in the plant components is:

$$I_{tot} = I_{ac} + I_{cc} + I_t \tag{12}$$

The lost exergy due to exhaust gases is:

$$EX_{lost} = \dot{m}_f EX_f - \dot{W}_{net} - I_{tot} \tag{13}$$

4. Results and discussion

The mathematical model is set in computer code using Engineering Equation Solver (EES). In the operating data, there are no direct measurements for the air mass flow rate and firing temperature. Fortunately, other useful data are measured. Subsequently, two main iterations loops are made in the solution algorithm. In the first loop, the net power output is used to estimate the air mass flow rate. The second loop has to approximate the firing temperature using the measured exhaust temperature. All the reference data and assumptions required are given in Table 2 [7,10]. The data of the plant are recorded 12 times per day. The collected data per month are averaged from January to November. The unit enters the schedule maintenance in December and it works a few days.

Table 2. Reference data and assumptions [7,10].

ISO conditions	15 ℃, 101.325 kPa
Fuel conditions	25 ℃, 2500kPa
$\eta_{ac,m} = \eta_{t,m} = \eta_{gen}$	0.95
$\eta_{ac,is}$	0.87
$\eta_{t,is}$	0.92
η_{cc}	0.98
$\Delta P_{ac}=\Delta P_t = \Delta P_{cc}$	0.01%
Compressor air extraction	12.5%

4.1. Model verification

The standard ISO specifications are adopted to verify the mathematical model. The standard ISO specifications and their predicted values are given in table 3. All the results show fine agreement except the thermal efficiency. It has a maximum error of 7.7%. However, this absolute error percentage can be considered as acceptable since the fuel mass flow rate is too low compared with the air mass flow rate. This is a well known since air to fuel ratio of gas turbine engines is of order 50:1 [1].

Table 3. Gas turbine model specification GE MS9001E model (standard and predicted).

	Standard Value [7]	**Predicted value**	**Absolute Error, %**	**Remarks**
Net power output, MW	126.1	126.2	0.1	-
Compression ratio	12.6	12.6	-	As input
Air mass flow rate, kg/s	407	397.5	2.3	-
Fuel mass flow rate, kg/s	No Record	6.944	-	-
Exhaust gas temperature,℃	543	541.3	0.31	-
Firing temperature,℃	1124	1129	0.45	-
Thermal efficiency,%	33.8	36.4	7.7	-

4.2. ISO full-load operating condition

The energy and exergy distribution among Shatt Al-Basra GE unit equipment are shown in Table 4. The fuel consumption represents the main source of energy and exergy input to the unit. The output power accounts for 36.77% from the input energy and 31.99% from input exergy. These two percentages are exactly the meaning of thermal efficiency and exergy efficiency. The unit discharges 63.23% of the fuel input energy to the atmosphere. This waste heat has a remarkable work potential that accounts for 21.48% from the input fuel exergy due to the elevated exhaust temperature of 543°C. Concerning exergy destruction, the combustion chamber has the highest exergy destruction among the types of equipment, which accounts for 42.51% from the input fuel exergy. This high irreversibility in this component is attributed to the high-temperature difference that accompanied by no work interaction with the environment. The exergy destruction in the air compressor and turbine are both too small comparing to that in the combustion chamber due to the work interaction found in these two components.

Table 4. Energy and exergy balance under ISO operating conditions (All in MW).

Total input heat energy	343.2	Total input exergy	394.5
Compressor work	140.12	Compressor irreversibility	8.597
Combustion chamber heat	343.2	Combustion chamber irreversibility	167.7
Turbine work	266.32	Turbine irreversibility	7.26
Lost heat in a stack	217	Lost exergy	84.72
Net-work output	126.2	Recovered exergy	126.2

4.3. Actual part-load operating conditions

The variation of actual power output from the unit during the year 2017 is illustrated in figure 2. The maximum power output was recorded in February that accounts 91.36 MW. The minimum power was recorded in November that accounts 69.11 MW. The variation in power output from the unit is attributed to two main reasons. The first one is the change in ambient temperature indicated in figure 3. Low ambient temperature was observed in January 14.7 °C and February 15 °C. The highest ambient temperature was reached in July 42.7 °C and August 42 °C. The low ambient temperature will result in higher air density. This will certainly improve the air mass flow rate passing through the compressor thereby the unit produces top power. The second reason is the effect of IGV. These vans are mounted on the compressor inlet to control the air mass flow rate drawn by the unit and thereby controlling the load applied on the engine. Operators usually choose the cold season to carry out periodic maintenance of the unit, preparing it for the stressful service during the harsh summer. The months after the summer season, the unit suffers many problems that lead the operators to reduce the load. That is why October and November have a low power output. Both of the two parameters, ambient temperature, and IGV are affecting the compressor pressure ratio. This factor is very critical in the performance of gas turbine performance.

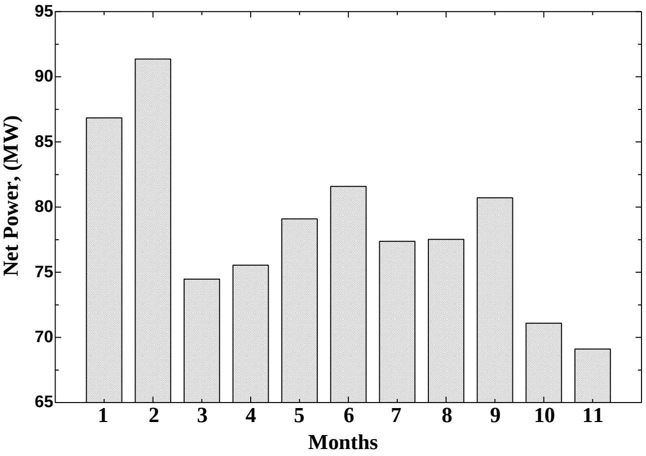

Figure 2. Net power output (MW).

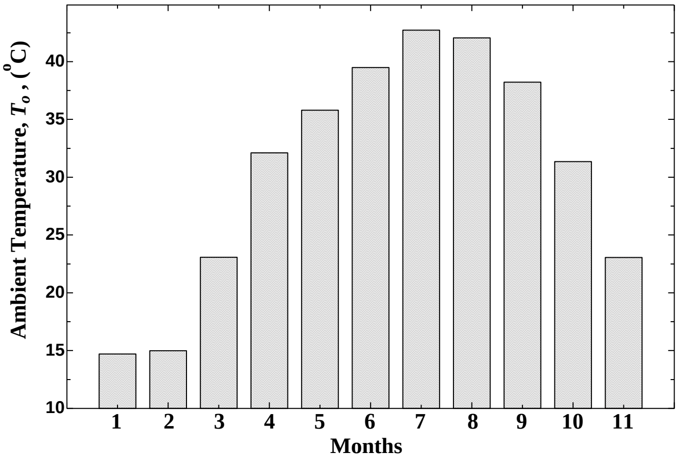

Figure 3. The variation of ambient temperature.

The predicted values of thermal and exergy efficiencies of the unit during the year 2017 are given in Figure 4. Maximum thermal efficiency is found to be in February 33.16 % while minimum thermal efficiency was in October 29.99%. The behaviour of this parameter is directly related to the power output and fuel mass flow rate. As power output decreases, then the fuel mass flow rate will also decrease. The behaviour of exergy efficiency is the same as thermal efficiency. That is mainly due to the difference in energy and exergy content of the fuel. The exergy content of the fuel is higher than the energy content. As exergy recovered is the only power output of the unit, then the exergy efficiency will be lower than the thermal efficiency.

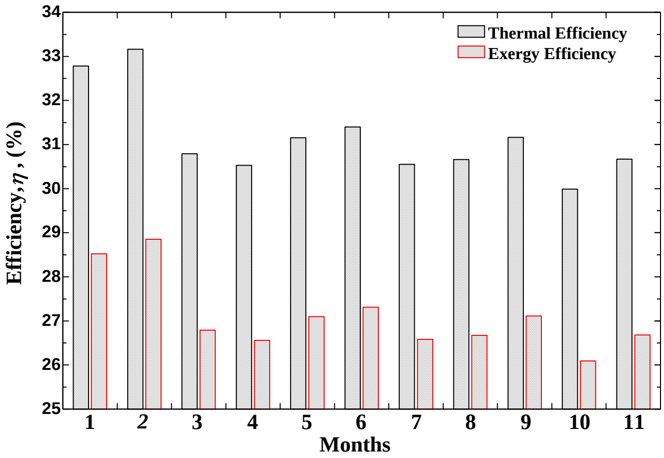

Figure 4. Prediction the thermal and exergy efficiencies.

The variation of lost heat to the atmosphere is shown in Figure 5. Unfortunately, a huge amount of heat accompanied by a promising work potential is wasted and not utilizing yet. The maximum heat power discharged is predicted in February 183.5 MW. The minimum one is observed to be in October 165.6 MW.

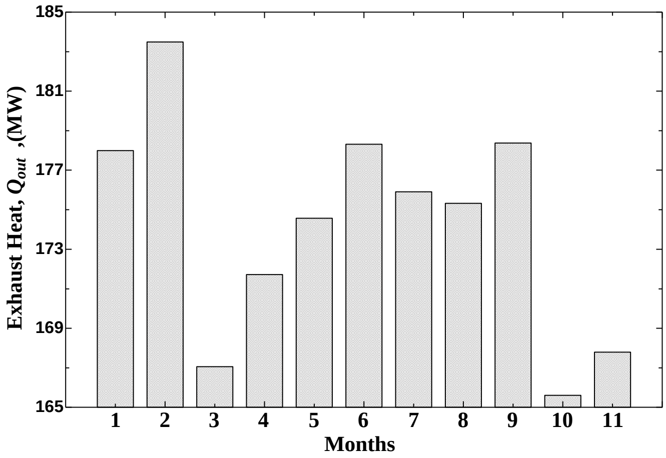

Figure 5. Variation of lost heat.

The variations of total exergy destruction in Shatt Al-Basra GE unit, as well as lost exergy due to exhaust gases, are shown in Figure 6. Both of these items are affected by ambient temperature and load requirements. The irreversibility of each component is directly proportional to ambient temperature and air mass flow rate. The lost exergy from the unit is accompanied by exhaust gases, which is a strong function of exhaust temperature. Higher lost exergy is recognized in the winter season. The minimum total exergy destruction is observed in March 149 MW. Generally, the unit discharges a huge amount of hot exhaust gases with a remarkable high temperature in the excess of 500 °C. This will make the exergy lost to the environment is higher.

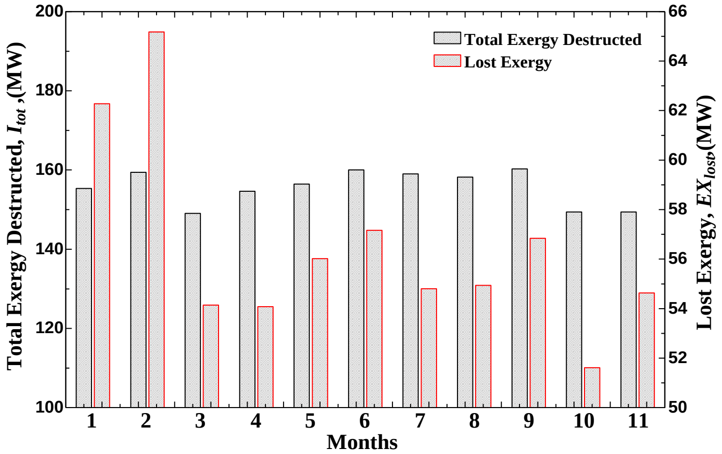

Figure 6. Variation of total exergy destruction and lost exergy.

5. Conclusions

The present study reveals the energy and exergy aspects of the GE unit six found in Shatt AL-Basra gas turbine power plant under Basra conditions during the year 2017. The following conclusions are reached:

- Studying Shatt Al-Basra GE unit shows that a huge amount of heat power is discharged that could be utilized in a variety of ways and the combined cycle may be the best. The maximum exergy lost is recognized in the winter season.
- Among the gas turbine equipment, the combustion chamber has higher exergy destruction. Besides, the maximum total exergy destruction in the unit is recognized in June.
- The ambient temperature has a significant effect on the performance of the unit. All the performance specifications are found to be declined with the rise of ambient temperature. the installation of an intake air cooling system is strongly recommended.
- The best performance of the unit in terms of first and second laws efficiencies are found in January and February.

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References

[1] Cohen H, Rogers G F C and Saravanamuttoo H I H 1972 *Gas Turbine Theory* (London: Longman Group).
[2] Dincer I and Rosen M A 2013 *Exergy, Energy, Environment and Sustainable Development* (UK: Elsevier Ltd).

[3] Faisal S H, Al.Mudhaffar M A and Khetar A D, 2017 *Basra J. Eng. Sci.* **17** pp 26-34.
[4] Song T W, Sohn J L, Kim J H, Kim T S and Ro S T, 2002 *Exery an Int. J.* Elsevier Ltd, **2** pp.105–12
[5] Ashley D S and Al Zubaidy S, 2011 *Appl. Therm. Eng.* Elsevier Ltd, **31** pp.2735–39.
[6] Personal communication, Shatt Al-Basra gas turbine power plant, Basra, Iraq.
[7] Technical manuals for Shatt Al-Basra gas turbine power plant 2012 (USA: GE Power Systems).
[8] Cengel Y A and Boles M A 2015 *Thermodynamics, An Engineering Approach* (New York: McGraw Hill).
[9] Kotas T J 1985 *The Exergy Method of Thermal Plant Analysis* (UK: Butterworth).
[10] Faisal S H 2002 *Utilization of Non-traditional Gaseous Fuels in Gas Turbine Based Power Plants* (M.Sc. Thesis, Basra University, Basra, Iraq).

Nomenclature

English symbols	
EX	Exergy term.
h	Specific enthalpy.
I	Irreversibility.
$\dot{m}$	Mass flow rate.
P	Pressure.
Q	Heat power.
s	Specific entropy.
S_{gen}	Entropy generation.
T	Temperature.
$\dot{W}$	Work power.

Greek symbols	
η	Efficiency.
Δ	Difference.
ψ	Flow physical exergy.
Ψ_w	Exergy due to work.

Abbreviations	
EES	Engineering equation solver.
GE	General Electric Co.
IGV	Inlet guide vans.
ISO	International standards organization.
HFO	Heavy fuel oil.
LFO	Light fuel oil.
HHV	Higher heating value.
LHV	Lower heating value.

Subscripts	
ac	Air compressor.
cc	Combustion chamber.
f	Fuel
gen	Generator.
gt	Gas turbine.
I	First law.
II	Second law.
in	Input.
i, e	Inlet and exit.
is	Isentropic
$lost$	Lost.
m	Mechanical.
net	Net value.
o	Denotes to the dead state.
out	Out.
t	Turbine.
tot	Total.

Superscripts	
ch	Chemical