Estimation of Wasted Thermal Energy from Gas Turbine Units in Mosul Power Station

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Abstract

The present study involve a thermal analysis of a gas turbine unit like those which are used in Mosul gas turbine power station in order to estimate the amount of thermal energy is wasted in the exhaust gases. A computer program is developed to investigate the effect of ambient temperature on the performance of the gas turbine unit including the mass flow of air, power output, thermal efficiency, specific fuel consumption, exhaust gas temperature and the amount of wasted thermal energy (Q_{exh}).

Results indicate that mass flow of air decreases as the ambient temperature increase; this eventually affected the power out, thermal efficiency and specific fuel consumption. Results show that the power output decrease by 28.5% when the temperature increased from 15 ºC to 45 ºC. However, the temperature of exhaust gases increased by nearly 0.04% as the temperature approach 45 ºC and the thermal energy expelled with exhaust decreased nearly by 0.12%. It also found that the wasted thermal energy nearly twice the produced power output of gas turbine.

Keywords:- Gas turbine, Wasted thermal energy, Ambient temperature effect

تخمين الطاقة الحرارية المهدورة من الوحدات الغازية في محطة الموصل الغازية

الخلاصة

يتضمن البحث الحالي التحليل الحراري لوحدة غازية مشابهة للوحدات الغازية العاملة في محطة الموصل الغازية لغرض تقييم الطاقة الحرارية المهدورة في غازات العادم. تم بناء برنامج حاسوبي لملاحظة تأثير درجة حرارة الجو على أداء الوحدة الغازية ليشمل كل من كمية الهواء الداخلة والقدرة الناتجة والكفاءة الحرارية و الاستهلاك النوعي للوقود و درجة حرارة غازات العادم وأخيرا الطاقة الحرارية المهدورة .

بينت النتائج إن كمية الهواء الداخلة تنخفض بشكل واضح مع ارتفاع درجة حرارة الجو والتي بدورها تؤثر على القدرة المتولدة و الكفاءة الحرارية والاستهلاك النوعي للوقود. حيث لوحظ إن القدرة المتولدة تنخفض تقريبا 28.5% عندما تصل درجة حرارة الجو إلى 45 درجة مئوية، بينما لوحظ إن درجة حرارة غازات العادم تزداد بمقدار % 0.04 في حين وجد إن الطاقة الحرارية المهدورة مع غازات العادم تنخفض بنسبة 12% .كما بينت النتائج على انه هنالك طاقة حرارية كبيرة مفقودة مع غازات العادم والتي قدرت على انه تساوي ثلثي الطاقة الحرارية المجهزة للوحدة الغازية.

الكلمات الدالة: - محطات التوليد الغازية، الطاقة الحرارية المهدورة، تأثير درجة حرارة الجو

Nomenclature

C_a Axial velocity (m/s)
CP_a Air specific heat at constant pressure (kJ/kg.K)
CP_g Hot gases specific heat at constant pressure (kJ/kg.K)
CP_f Fuel specific heat at constant pressure (kJ/kg.K)
CVF Calorific value of fuel (kJ/kg)
m_a Air mass flow rate (kg/s)
m_g Hot gases mass flow rate (kg/s)
m_f Fuel mass flow rate (kg/s)
P Pressure (bar)
Q Heat (KW)
r_P Pressure ratio
SFC Specific fuel consumption
T Temperature (K)
W_c Compressor work (kW)
W_t Work produced by turbine (kW)
η_{th} Thermal efficiency
ΔH_o Enthalpy of combustion at 298 ˚K per unit mass of fuel
Number in the subscripts are used to denote state

Introduction

The gas turbine generators have become an important prime mover for conversion of natural gas into electricity. In the last decades significant improvement have been achieved in the efficiency of gas turbines through advances in materials and turbo machinery design. Recently most of the world countries, including Iraq, are turning to gas turbine generators for their needs because gas turbine generators provides the highest efficiency and lowest emissions of combustion technology available today[1]. Efficiencies have increased from around 25% in 1960 to almost 40% today [2].

However, this implies that almost 60% of the input energy is contained within gas turbine exhaust gases. And because the widespread use of gas turbine for power production large energy saving can be obtained if this percentage can be reduced or better use or more use of these exhaust gases can be made compared to current practice.

In the present study an estimation of wasted thermal energy of exhaust gases of Mosul Power Station are involved taking in consideration the effect of ambient temperature on the over all performance of gas turbine unit. In addition, possible solution will be given to reduce wasting this thermal energy of exhaust gases.

Gas Turbine Unit

Gas turbines are steady flow heat engines consisting of three components, an axial flow compressor, a combustion chamber and an axial flow turbine. A schematic diagram for a simple gas turbine like those is used in Mosul power station is shown in figure (1). Air is drawn into the gas turbine by the compressor, which compresses it and delivers it to the combustion chamber. Within the combustion chamber the air is mixed with fuel and the mixture is ignited producing a rise in temperature and hence an expansion of gases. These gases are exhausted through the turbine, expand which produce work and finally discharge to atmosphere[3,4,5,6,7].

Thermodynamic Model

The thermal system to be simulated is a single shaft gas turbine for electricity production similar to that one installed at Mosul gas turbine power station as shown in figure (2). The reference thermodynamic cycle is an open Brayton- Joule cycle without regeneration.

The following assumption are considered in the present study :

1- the working fluid is air and treated as perfect gas

2- the specific heats at constant pressure of air and hot gases are temperature dependent
3- the compression processes and expansion processes are adiabatic and irreversible
4. There is no pressure loss in the inlet and exhaust ducting
5. The mass flow rate through the compressor and turbine are equal
6. The amount of heat loss from the combustion chamber is small and can be ignored

Figure (3) show the T-S diagram for the single gas turbine cycle, the ideal and actual processes are represented in dashed and full line respectively. In the axial compressor, air is drawn from atmosphere and compressed from point 1 to point2. The mass flow rate is calculated as follows[6]

$$m = \rho\, C_a\, A \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where
ρ: density of air at inlet of compressor
C_a : axial velocity
A: the annulus area

The density of air is calculated as follows

$$\rho = \frac{P_1}{R\,T_1} \quad \ldots\ldots\ldots\ldots\ldots (2)$$

The ideal compressor exit temperature may be obtained using the following formula

$$T_{2'} = T_1 (r_p)^{\frac{\gamma_a - 1}{\gamma_a}} \quad \ldots\ldots\ldots (3)$$

And by introducing the compressor isentropic efficiency, the actual compressor exit temperature can be obtained as

$$T_2 = \left[\frac{(T_{2'} - T_1)}{\eta_c} + T_1 \right] \quad \ldots\ldots\ldots (4)$$

The compressor isentropic efficiency (η_c) can be evaluated using the relations presented by Korakiaitis and Wilson[8] as,

$$\eta_c = 1 - \left(0.04 + \frac{r_P - 1}{150} \right) \quad \ldots\ldots\ldots (5)$$

Hence the compressor work can be determined as follows

$$W_C = m_a\, c_{P_a} (T_2 - T_1) \quad \ldots\ldots\ldots (6)$$

In the combustion chamber, the heat supplied is due to combustion of hydrocarbon fuel (Natural gas), which is considered as CH_4 of lower calorific value of 50000 kJ/kg in present study .

Obviously, since the combustion chamber inlet temperature, T_2 , is determined and the combustion chamber outlet temperature, T_3 , is specified. Therefore, the problem is to calculate the fuel-air ratio, f , required to transform unit mass of air at T_2 and f kg of fuel at the fuel temperature, t_f , to (1+ f) kg of the products at T_3.

Since the combustion process is adiabatic with no work done, the energy equation is simply written as:

$$\sum (m_i\, h_i) - (h_a - f\, h_f) = 0 \quad \ldots\ldots (7)$$

Where
m_i : is the mass of product i per unit mass of air
h_i : is the specific enthalpy

Introducing the enthalpy of combustion at 25 °C , ΔH_o , the following equation can be used

$$(1+f)\, c_{p_g} (T_3 - 298) + f\, \Delta H_O + c_{p_a} (298 - T_{air}) + f\, c_{p_f} (298 - T_f) = 0 \quad \ldots\ldots\ldots\ldots (8)$$

However, such calculation can be carried in the computer program, but if dissociation is significant then ($f\,\Delta H_o$) term must be modified to allow for the incompletely burnt carbon and hydrogen arising from the dissociation of CO_2 and H_2O. Therefore, it is usually sufficient accurate to use tables or chart which have been compiled for typical fuel composition. Figure (4) shows the combustion temperature rise (T_3 - T_2) plotted against fuel-air ratio various values of inlet temperature T_2 and the data have been used for numerical calculation in present study after have been transformed to a mathematical equation

$$f = -0.0013084668 + 0.000258896\,(T_3 - T_2) + 0.0000002317\,T_2 + 0.000000001\,(T_3 - T_2) \quad \ldots\ldots\ldots\ldots (9)$$

Equation (9) represent the theoretical fuel-air ratio since the data which given in figure (4) based on the assumption that fuel is completely burnt. Hence the actual fuel-air ratio is simply calculated by introducing the combustion efficiency

$$f_{act} = \frac{f}{\eta_{comb}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (10)$$

However, the turbine inlet temperature (TIT) is limited to 1030 K due to metallurgical limit as given by the specialist who works at Mosul gas turbine unit. Hence the mass flow rate of fuel is calculated according to this temperature. Hot gases leave the combustion chamber and enter the axial flow turbine, expand to atmospheric pressure. Hence the isentropic turbine exit temperature is given as

$$T_{4'} = T_3 * \frac{1}{(r_p)^{\frac{\gamma_g - 1}{\gamma_g}}} \quad \ldots\ldots\ldots\ldots (11)$$

And the actual turbine exit temperature is obtained as

$$T_4 = T_3 - \eta_t\left(T_3 - T_{4'}\right) \quad \ldots\ldots (12)$$

Where η_t is the isentropic efficiency of the turbine estimated using the relation given by Korakiaitis and Wilson(8) as,

$$\eta_t = 1 - \left(0.03 + \frac{r_P - 1}{180}\right) \quad \ldots\ldots (13)$$

The turbine work is calculated as follows

$$W_t = m_g\ c_{P_g}\,(T_3 - T_4)\,(kW) \ldots\ldots (14)$$

The power output is obtained as follows

$$P_{ower} = W_t - W_c \quad (kW) \quad \ldots\ldots\ldots (15)$$

The thermal efficiency is found using the following equation

$$\eta_{th} = \frac{P_{ower}}{Q_{add}} = \frac{P_{ower}}{m_f * LCV} \quad \ldots\ldots (16)$$

And finally the specific fuel consumption is obtained as follows

$$SFC = \frac{m_f}{P_{ower}} * 3600 \quad \ldots\ldots\ldots\ldots (17)$$

Results and Discussions

For the given values of pressure ratio and turbine inlet temperature, the pressures and temperatures at different points in the cycles are evaluated. Thereafter the variation of gas turbine performance including power output, thermal efficiency, specific fuel consumption, temperature of exhaust gases and finally the amount of wasted thermal energy (Q_{exh}) were observed.

Figure (5) shows the relationship between the mass flow rate of air discharged by the compressor and the ambient temperature. It was found that there is nearly 10% reduction in the mass of air from the design value as the temperature reaches 45 ˚C. This is due to the decrease in density of the ambient air with the increase of its temperature which affect the mass flow rate of air delivered by the compressor.

As expected, the power output was found to decrease as ambient temperature increase, as shown in figure (6). This is due to the reduction in the mass flow rate of air with ambient temperature rise which affect the pressure ratio and the turbine work and ultimately the power output.

The reduction in power output was found to be 21% as the ambient temperature reaches 45 ºC. Figure (7) shows the relationship between the thermal efficiency and ambient temperature. Of interest is the relatively low decrease in the thermal efficiency with ambient temperature compared to the power output due to the decrease in the power output and the slight increase in specific fuel consumption. In this case the thermal efficiency was found to decrease by nearly 13% as the ambient temperature approaches 45 ˚C.

In figure (8) the specific fuel consumption is plotted against the ambient temperature. It was found that the specific fuel consumption increases by approximately 15%. The relatively high increase is due to the reduction in the pressure ratio and compressor work, which made it necessary to increase the mass flow rate of fuel to keep the turbine inlet temperature constant at 1030 ˚K.

Figure (9) shows the relationship between the ambient temperature and exhaust gas temperature. It can be seen that exhaust gas temperature increase nearly by 20˚C as the ambient temperature approaches 45 ˚C. The thermal energy available in exhaust gases is plotted against the ambient temperature as given in figure (10).As expected the wasted thermal energy (Q_{exh}) represent a significant amount of energy nearly 66% of the total supplied energy which has been expelled to atmosphere with out being used in further thermal or energy process.

Finally, a clear picture can be made by examining figure (11) and figure (12) Examining figure (11) indicates that the power output from gas turbine units at Mosul power station decreases in summer time including June, July, August, September and October.

Figure (8) shows comparison between the power the power out and wasted thermal energy in the exhaust gases. It can be seen that the wasted thermal energy nearly twice the produced power output of gas turbine.

Clearly the suggested solutions for this energy problem can be put in the following

1. Replacing the old gas turbine units with new one which include regeneration system, so the wasted thermal energy would decrease.
2. Using a heat recovery steam generator to generate steam which to be used in steam turbine for further power production (combined power plant)
3. Applying inlet air cooling system (absorption unit) to obtain constant power output through the year.

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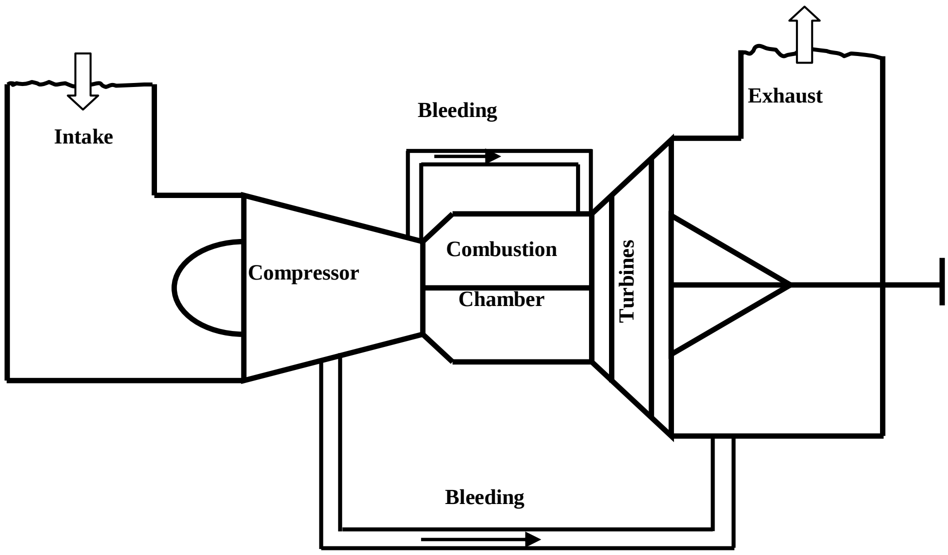

Figure (1): Simple Industrial Gas Turbine Schematic

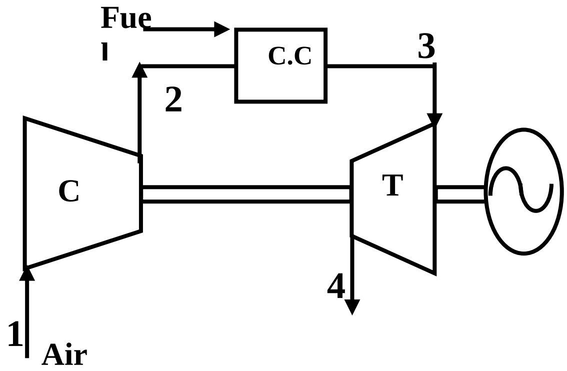

Figure (2): Simple single shaft gas turbine

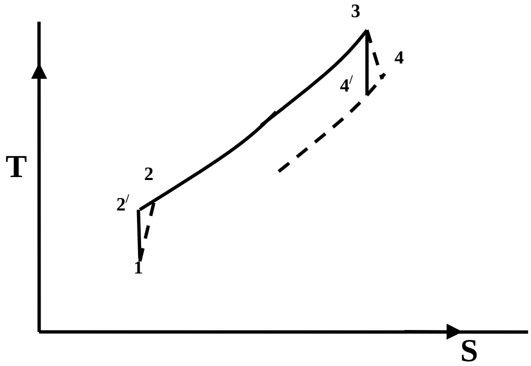

Figure (3): T-S diagram for simple gas turbine unit

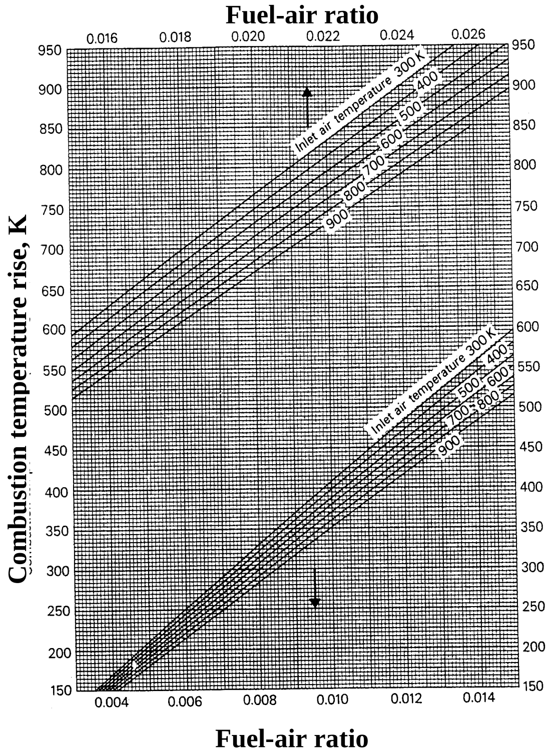

Figure (4): Combustion temperature rise versus fuel-air ratio(4)

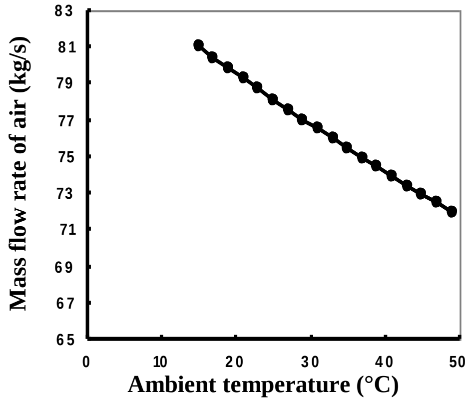

Figure (5):- Effect of ambient temperature on the mass flow rate of air

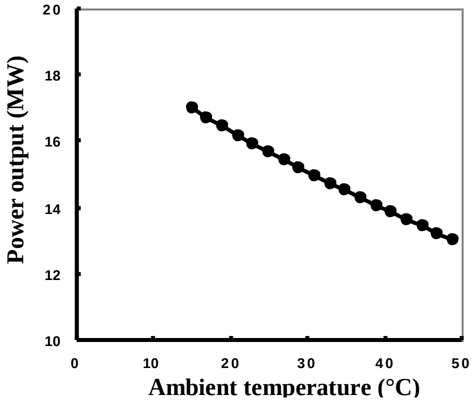

Figure (6):- Effect of ambient temperature on the power output

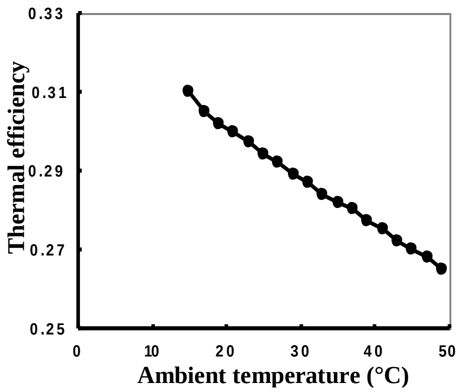

Figure (7):- Effect of ambient temperature on thermal efficiency

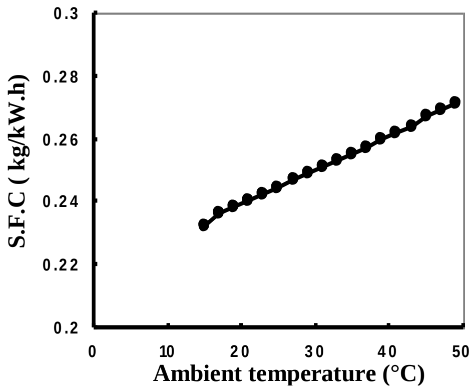

Figure (8):- Effect of ambient temperature on the specific fuel consumption

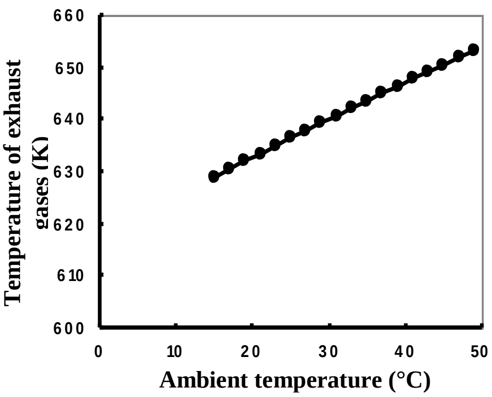

Figure (9):- Effect of ambient temperature on the exhaust gases temperature

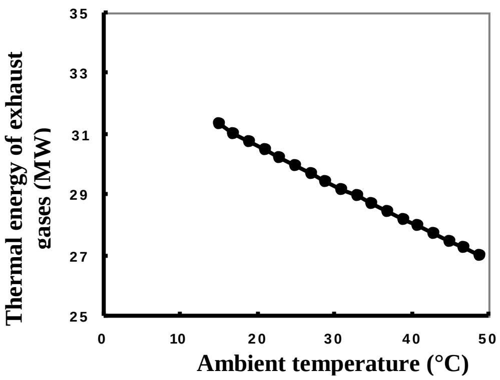

Figure (10):- Effect of ambient temperature on thermal energy of exhaust gases

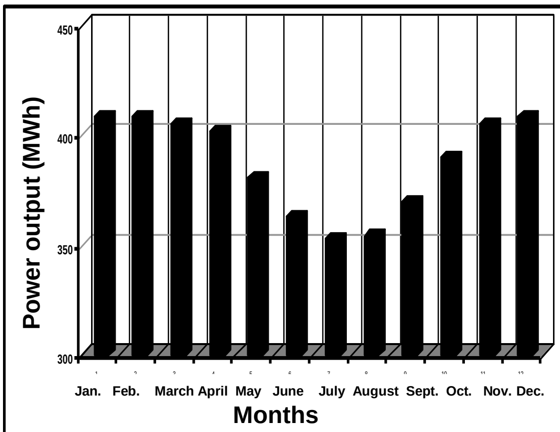

Figure (11): Daily power output for each month of Mosul gas turbine, unit 12.

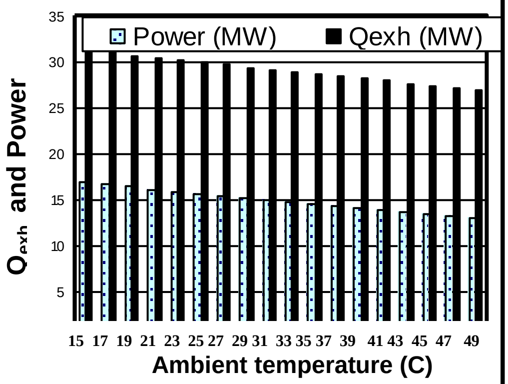

Figure (12): Variation of thermal energy of exhaust gases and power output with ambient temperature