EFFECT OF AMBIENT TEMPERATURE ON THE THERMODYNAMIC PERFORMANCE OF A COMBINED CYCLE

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الملخص

أصبحت محطات القدرة المركبة من التقنيات المسخدمة في توليد الكهرباء في ليبيا، حيث تم إنشاء بعض منها، وجاري التخطيط لبناء البعض الآخر. يعتمد الأداء الديناميكي الحراري لهذه المحطات على درجة حرارة المحيط الجوي، والذي يتغير بشكل كبير من فصل إلى آخر في ليبيا. تهدف هذه الورقة إلى دراسة تأثير التغير في درجة حرارة المحيط الجوي على الأداء الديناميكي الحرارية لهذه المحطات.

تم في هذه الدراسة استخدام غازات العادم من وحدتين تربينيتين غازيتين في توليد البخار فيما يسمى مولد بخار الحرارة المسترجعة لتشغيل محطات قدرة بخارية ثنائية الضغط، حيث استخدم برنامج هايسيس لنمذجة تأثير التغير في درجة حرارة المحيط الجوي على الأداء الديناميكي الحراري للدورة. تم استخدام بعض من البيانات الحقيقية مثل درجة حرارة المحيط الجوي، معدلات تدفق الهواء والوقود، ونسبة الضغط عند الحمل الكامل في هذا التحليل. تنخفض كثافة الهواء الجوي وينخفض معدل تدفق كتلة الهواء مع إرتفاع درجة حرارة المحيط الجوي، وعند الحفاظ على نسب ضغط ثابتة، تنخفض القدرة الكلية المتولدة وتنخفض كفاءة محطة القدرة الغازية. يمكن الإستفادة من غازات العادم في توليد البخار وتحسين الأداء بصفة عامة. على سبيل المثال، بيّن التحليل أنه عند استخدام الدورة المركبة وكانت درجة حرارة المحيط الجوي 15°C فإن كفاءة القانون الأول بلغت 42.8%، وكفاءة القانون الثاني بلغت 40.20%، وتحسنت القدرة الكلية بنسبة 53.46%. بينما بينت الدراسة ايضا أنه عند ارتفاع درجة حرارة المحيط الجوي إلى 40°C فإن كفاءة القانون الأول أنخفضت إلى 41.11% وكفاءة القانون الثاني إلى 38.60%، وارتفعت نسبة القدرة المكتسبة إلى 60.98%.

ABSTRACT

Combined cycle power plants are now becoming widely accepted for generating electricity in Libya. Some of these plants are being installed, and others are planned to be built in the near future. The thermodynamic performance of these plants depends on the ambient temperature which varies considerably from one season to another in Libya. The object of the current study is to investigate the effects of these variations on the performance of combined cycle power plants.

In the study, the hot effluent of two selected gas turbine power units is taken to be utilized to generate steam in a heat recovery steam generator and operate a proposed dual pressure steam power cycle. The influence of ambient temperature variations on gas, steam, and combined cycles performance is simulated using HYSYS software. A real time data including ambient temperature, air mass flow rate, pressure ratio and fuel flow rate, for the selected gas unit are obtained at full load operation. These data are extrapolated to find the thermodynamic performance at different ambient temperatures.

Both of the density and the mass flow rate of air at the compressor entrance decrease as the ambient temperature rises. Furthermore, when pressure ratio is kept constant, a drop in each of the net power and the efficiency of the gas turbine unit occurs. The exhaust gases can be utilized to operate a steam turbine power cycle to improve the overall performance. For instance, the results of the analysis show that for the combined cycle at an ambient temperature of 15^{o}C, the first and second law efficiencies rise to 42.80% and 40.20% respectively, and the percentage gain in power becomes 53.46%. At an ambient temperature of 40^{o}C the results show that the first and second law efficiencies drop to 41.11% and 38.60% respectively, and the percentage gain in power rises to 60.98%.

KEY WORDS: HYSYS software; Dual pressure combined cycle; Heat recovery steam generator; Exergy; Effectiveness.

INTRODUCTION

Recently, the gas/steam combined cycle based power plants have become popular, as they offer more effective utilization of the fossil fuel energy. They attain higher thermal efficiency as compared to the gas turbine or the steam turbine based plants alone. The performance of the gas/steam combined cycle power plant depends upon the performance of topping and bottoming cycle. Gas turbine offers high specific work output as the turbine inlet temperature is raised. This has been supported by the findings of Yadav and has shown that the increased inlet gas turbine temperature improves the performance of the heat recovery steam generator and consequently the steam turbine with subsequent improvement in combined cycle performance [1]. Modern heat recovery steam generators are designed to have multi-pressure levels to improve the plant performance. However, such a design makes the total system operation rather complicated [2].

Enhancing the performance of a combined cycle has been the topic of many investigations; the majority of which have been focused on the improvement of gas or steam cycle efficiency. Kim et al have investigated effect of inlet-air cooling, compression ratio optimization, and elevated gas turbine's inlet temperature on the gas cycle's efficiency [3]. Naradasu et al have demonstrated the use of optimal utilization of the flue gas recovery heat with single and dual pressures heat recovery steam generator configurations [4]. Victor et al have pursued the maximization of the exergy transfer to the water/steam circuit using an original and fast method of exergy optimization of the heat recovery steam generator [5].

The thermodynamic analysis of the simple gas/steam combined cycle power plants has been carried out for a cycle operating while employing different types of gas turbine cooling [1]. Mitre et al have used HYSYS software to evaluate effect of operating conditions on emission levels of pollutants, and waste-heat and waste-water rejections of a combined-cycle gas/steam power plant [6]. The net power output of a gas turbine drops as a result of an increase in the ambient air temperature because of the reduction in air mass flow rate. Jaber et al have reported that a drop of about 25% of the rated power capacity of the gas turbine from that at ISO conditions when the ambient temperature reached 40°C [7]. Deng-Chern Sue and Chia-Chin Chuang have also reported, in a study dealing with an engineering design and exergy analysis of gas turbine power generation system, that the power output decreases by 18% as the inlet air temperature increases from 15 to 30^{o}C [8]. However, the output of the gas turbine can be maintained almost constant by controlling the inlet air for combustion at a specific condition. Deng-Chern Sue and Chia-Chin Chuang have concluded that, by installing inlet air-cooling system, it was possible to provide maximum electrical power during hot summer days, when the demand on the Taiwan power grid is at its highest level [8].

Modeling and optimization of the triple-pressure reheat combined cycle as well as irreversibility reduction of its HRSG have been considered by Bassily [9]. He has, also, investigated effects of varying the gas turbine inlet temperature on the performance of all cycles.

Somkiat and Pichai have studied the combined cycle power plant consisting of two gas turbine units and one steam turbine unit from exergetic point of view [10]. The plant, which is in Samutprakran-Thailand, has a total capacity of 322.45 MW, an air compppressor pressure ratio of 12, and burns natural gas at air to fuel ratio of 44. They have found that the exergy efficiency of the steam turbine, the gas turbine, heat recovery steam generator (HRSG) and the combined cycle power plant were 82.8, 20.7, 56.5 and 31 % respectively.

The change of the ambient air temperature induces a change in the specific weight of the suction air. At constant-speed compressor, this means a decrease in air mass flow rate as the ambient air temperature increases. Kam and Priddy have found that the air mass flow rate in most gas turbines drops by about 12% as the ambient air temperature increases from -18^{o}C to 15^{o}C[11]. Al-Tobil Is'haq has performed an analysis simulating the performance enhancement of gas turbines by inlet air cooling [12]. The simulation results obtained using the vapor compression refrigeration system shows a 27% increase in output power for the single shaft engine and about 20% increase in power for the two shafts engine at an ambient temperature of 40^{o}C. The corresponding values for these two engines when vapor absorption refrigeration is used are 31.8% and 26.7% respectively.

Veszely has explored the variances of reasonable solutions and systems that integrate the conventional combined cycle and the nuclear power plant into a common cycle in the light of relevance and feasibility [13]. A 3.2-5.5 times increase in electricity output has been obtained, and the gross efficiency has fallen between 46.8-52% and above, depending on the applied solution. Mahmoudi et al has performed an energy and exergy analysis of simple and regenerative gas turbine with inlet air cooling using lithium bromide-water absorption refrigeration cycle[14]. The results of analysis has shown that for each 10^{o}C drop in inlet air temperature, the net output power increases by about 6-12% and the first and second law efficiencies increase by about 2-7%.

The ambient temperature in Libya may reach as high as 40°C or higher in summer. The peak demand occurs during this season due to increasing electricity consumption of air conditioning and refrigeration equipments. For this purpose it is aimed in the present paper to investigate effects of ambient temperature changes on the thermodynamic performance of a proposed combined power unit by utilizing the HYSYS software.

MODELING THE SELECTED GAS TURBINE POWER UNIT

Two gas turbine units GT14 of South Tripoli gas turbine power plant are selected for the present investigation. The power plant was constructed by ABB a German-Swiss company in 1994. The plant has a design total capacity of 500 MW distributed evenly among five units. Each gas turbine unit, which is taken as the top cycle for the present study, consists mainly of three components; combustion chamber, compressor, and turbine, as shown in Figure (1). Initially, air is compressed almost adiabatically in the compressor, the compressed air enters the combustion chamber where fuel is injected and burned at essentially constant pressure. The products of combustion are expanded in a turbine until they reach the ambient pressure.

Air enters the compressor with the volumetric composition as: $O_2 = 21\%, N_2 = 79\%$. The fuel is approximated by light diesel n-Dodecane ($C_{12}H_{26}$) with lower heating value of 44423.18 kJ/kg.

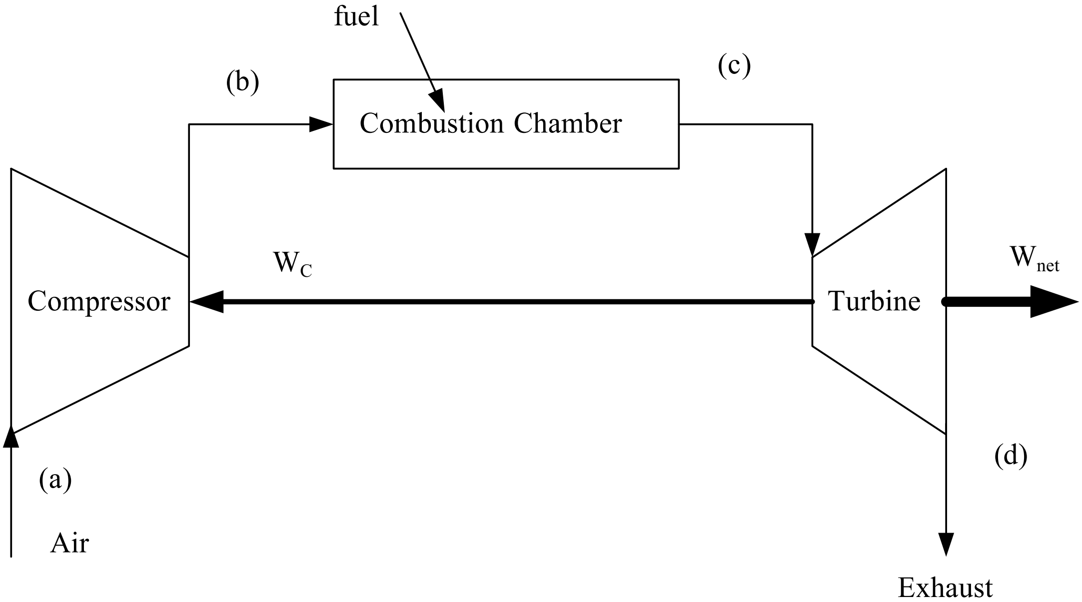

Figure 1: Schematic of the selected gas turbine power unit

From economical point of view, two gas turbine units are needed to operate one single steam power cycle. The following real time data are given for one gas turbine unit:

- Power 88 MW (100% load).
- Ambient temperature: 25°C.
- Fuel flow rate $(\dot{m}_f)$: 6.349 kg/s.
- Air flow rate $(\dot{m}_{air})$: 394.48 kg/s.
- Pressure ratio (r_P): 11

The following values are adopted for the analysis:

- C_P (average air+exhaust) = 1.21 kJ/kg.K
- k (air) = 1.4
- k (exhaust gas) = 1.31

The ideal gas equation is applied to calculate the density (ρ) of the incoming air, and hence the volume flow rate $(\dot{V})$:

$$\rho = \frac{P}{RT} \tag{1}$$

Where: $P = 100\text{kPa}$, $R = 0.287\frac{\text{kJ}}{\text{kg.K}}$, $T = 298.15\text{K}$, and therefore:

$\rho = 1.168647 \frac{kg}{m^3}$, and $\dot{V} = 337.5528 \frac{m^3}{s}$.

The pressure ratio is defined as:

$$r_P = \frac{P_b}{P_a} = \frac{P_c}{P_d} = \left(\frac{T_{bs}}{T_a}\right)^{\frac{k}{k-1}} = \left(\frac{T_c}{T_{ds}}\right)^{\frac{k}{k-1}} \quad (2)$$

The compressor isentropic efficiency is defined as:

$$\eta_c = \frac{w_{isentropic}}{w_{actual}} = \frac{(h_{bs} - h_a)}{(h_b - h_a)} \quad (3)$$

The turbine isentropic efficiency is defined as:

$$\eta_t = \frac{w_{actual}}{w_{isentropic}} = \frac{(h_c - h_d)}{(h_c - h_{ds})} \quad (4)$$

The heat liberated due to combustion of fuel is calculated for each unit as:

$$\dot{Q}_f = \dot{m}_f \times LHV \quad (5)$$

This is equal to 282.034MW. The efficiency of the gas turbine unit is therefore:

$$\eta_{gt} = \frac{\dot{W}_{gt-net}}{\dot{Q}_f} \quad (6)$$

The efficiency of the combustion chamber is assumed to be 98%, a typical value of 99% is also adopted in the literature [9]. The isentropic efficiencies of the compressor and gas turbine are assumed equal to 80%, and 85% respectively.

METHOD OF SOLUTION

The fuel mass flow rate at all ambient temperatures must be fed to Hysys in order to initiate the analysis, because of that, fuel mass flow rate must be estimated, we may follow the following steps:

- Equation (1) is used to calculate the density of the ambient air at different temperatures. Since the compressor speed is kept constant, then the volume flow rate of air entering the compressor is also constant [11]. The air mass flow rate at compressor inlet can be calculated at all ambient temperatures.
- Seeking the temperature at combustion chamber outlet, the real time data is fed to Hysys, the output temperature is found equal to 973.6^{o}C.
- Since the pressure ratio is constant and equal to 11, the temperature at compressor outlet can be estimated by using the ideal gas equations.
- The heat librated in the combustion chamber can be calculated, by employing the aforementioned average specific heat, air mass flow rate, temperature difference cross the combustion chamber and the combustion efficiency (98%).
- Knowing the fuel heating value, fixing the temperature at the combustion chamber outlet, the fuel mass flow rate can be estimated at each environmental temperature in the gas cycle.

The estimated fuel mass flow rate together with all other data at different environmental temperatures are fed to Hysys to perform the analysis, the software gives temperatures at combustion chamber temperatures of 976.8^{o}C and 968.8^{o}C at ambient temperatures of 15^{o}C and 40^{o}C respectively, the variations within an acceptable range of $\pm 0.82\%$

MODELING THE PROPOSED DUAL PRESSURE COMBINED CYCLE

A schematic diagram consists of the main components for the proposed dual pressure combined cycle is shown in Figure (2). There are two identical gas turbine units in operation. The hot effluent of the two gas turbine units generates steam in the heat recovery steam generator of the steam cycle, which expands in the steam turbine and generates additional mechanical power. Beside the heat recovery steam generator, the steam cycle contains a high, intermediate and low pressures steam turbines, condenser, pumps, and de-aerator.

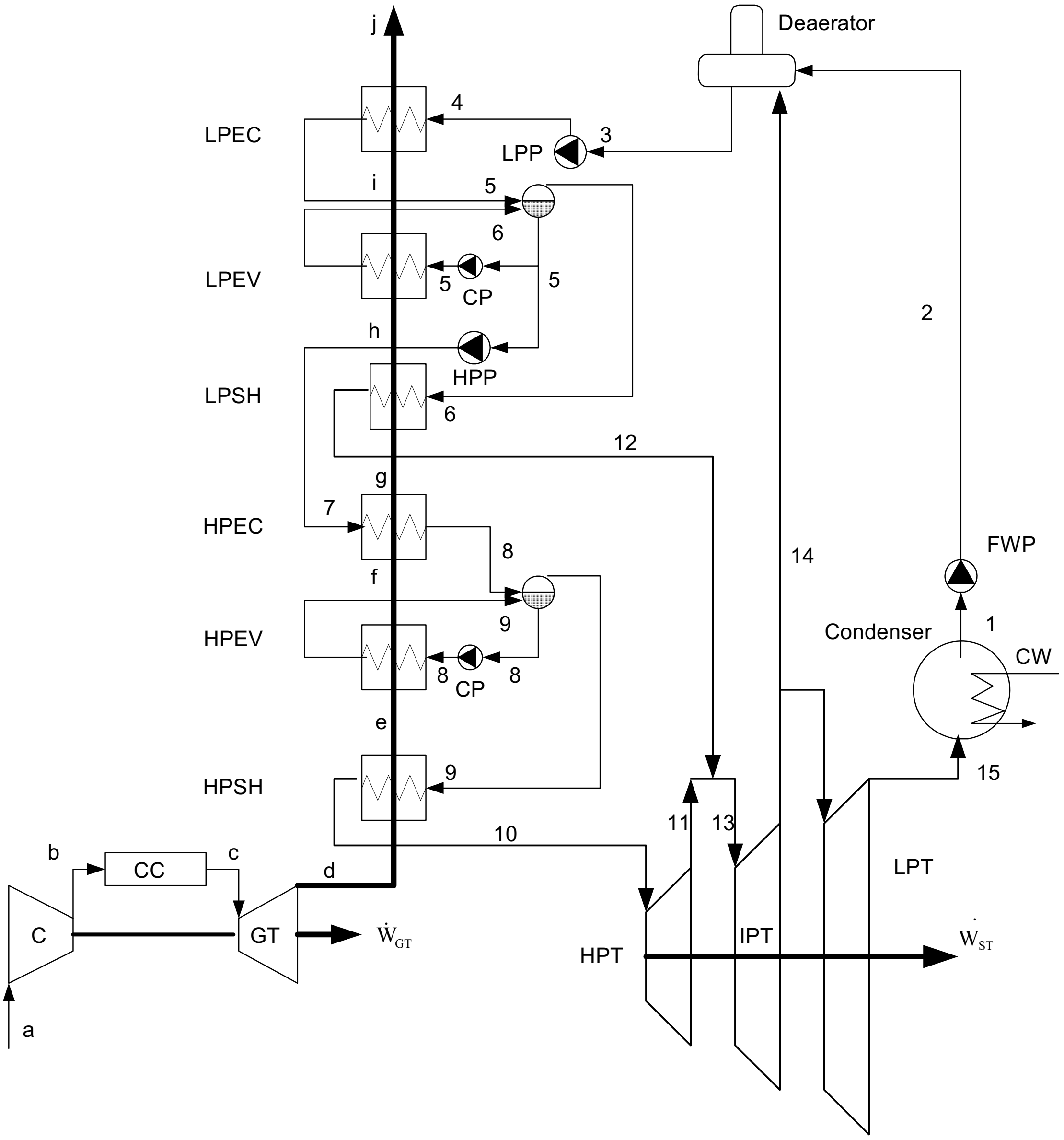

Figure 2: Schematic of the proposed combined cycle

The following assumptions are made for the steam cycle:

- The isentropic efficiencies of pumps and steam turbine are assumed equal to 75%, and 88% respectively.
- The efficiency of the heat recovery steam generator is 100%.

- The condenser pressure, the de-aerator pressure, and the maximum pressure in the steam cycle are set equal to 0.07 bar, 10 bar, and 60 bar respectively.
- The maximum steam temperature is 400^{o}C.

The steam flow rates are set such that energy balance in different sections of the heat recovery generator is insured. Pressure and heat loss are neglected during the simulation process.
The heat supplied to steam cycle can be calculated as:

$$\dot{Q}_{steam} = \dot{m}_{exh}\left(\Delta h\right)_{HRSG-exh} \tag{7}$$

The first law efficiency is calculated by:

$$\eta_{st} = \frac{\dot{W}_{net}}{\dot{m}_f LHV \eta_{cc}} \tag{8}$$

The second law efficiency (effectiveness) is calculated by:

$$\eta_{2nd} = \frac{\dot{W}_{net}}{\dot{\Psi}_f} \tag{9}$$

Where fuel exergy can be approximated as [15]:

$$\dot{\Psi}_f = 1.065 \times \dot{m}_f \times LHV \tag{10}$$

The specific fuel consumption is calculated as:

$$sfc = 3600\frac{\dot{m}_{fl}}{\dot{W}_{net}} \ \left(\frac{g}{kWh}\right) \tag{11}$$

HYSYS [6]

HYSYS is professional simulation software, with tools that are applied to many chemical and thermal engineering processes. Other softwares with similar capabilities, e.g. PRO II and CHEMCAD, could be used in the simulation, with variable degree of difficulty but giving the same solutions. It is interesting to observe that HYSYS is a software package that can simulate various types of processes, but does not have the specific function to simulate and evaluate thermoelectric plants, fuelled by natural gas or other fuels.

INPUT DATA

For simulation the following data must be fed to HYSYS software:

Gas turbine side data

- Gas turbine and compressor efficiencies, environmental condition, air mass flow rate and fuel flow rate, as in Table (1).

Steam turbine side data

- Steam turbines and pumps efficiencies, condenser pressure, de-aerator pressure and maximum pressure.
- Steam flow rate is estimated and fed to HYSYS until energy balance is reached for all heat recovery steam generator components.

RESULTS AND DISCUSSION

The air density and hence the mass flow rate at the compressor entrance vary with the change in ambient temperature. Table (1) shows the variation of air density, mass flow rates, and exhaust temperature at gas turbine exit with the variation in ambient temperature.

The air mass flow rates for the two gas turbine units at 15°C and 40°C ambient temperatures are 816.3402kg/s and 751.1686 kg/s respectively. This would certainly affect the thermodynamic performance of the combined cycle as the amount of heat transfer to steam cycle would also be altered.

Table 1: variation of density, mass flow rates, and the gas turbine exhaust temperature with change in the ambient temperature

t (°C)	$\rho\left(\frac{kg}{m^3}\right)$	$\dot{m}_{air}\left(\frac{kg}{s}\right)$	$\dot{m}_{fuel}\left(\frac{kg}{s}\right)$	$T_{exhaust}\left({}^{o}C\right)$
15	1.2092	816.3402	6.8287	503.8
20	1.1886	802.4166	6.5847	502.5
25	1.1686	788.9600	6.3488	501.2
30	1.1494	775.9473	6.1207	500.0
35	1.1307	763.3569	5.9000	498.7
40	1.11267	751.1686	5.6864	497.4

At constant compressor speed, the rise in ambient temperature reduces the inlet air mass flow rate [11]. Reduction in the inlet mass flow rate with increase in the ambient temperature reduces the power of gas turbine. It is found that the compressor power is almost constant, while the gas turbine power decreases with the increase in the ambient temperature, and a reduction in the net power of the gas cycle is noticed as shown in Figure (3).

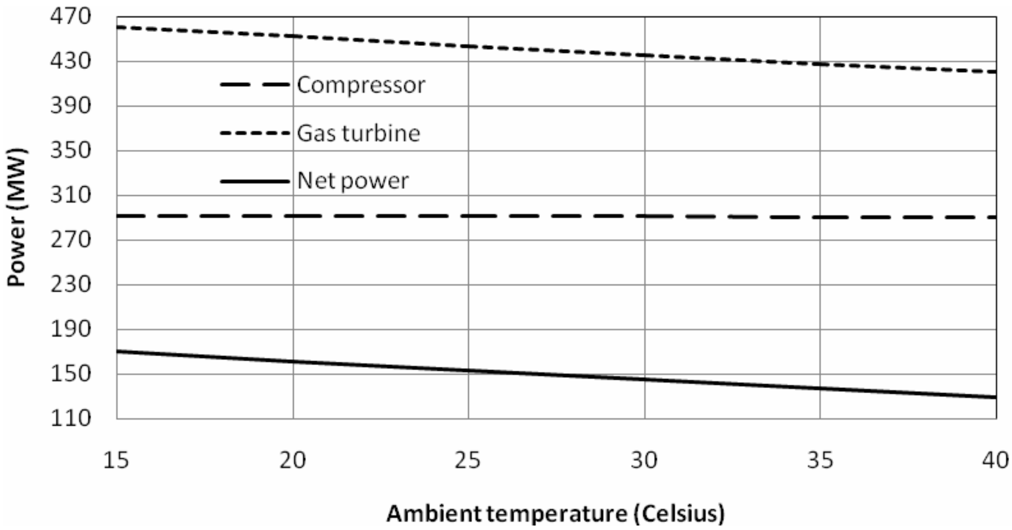

Figure 3: Effect of ambient temperature on power output

The analysis shows that the net power output of the gas cycle, for the two units, is 169.8MW, and 129.6MW at ambient temperatures of 15°C and 40°C respectively. In other words, through this range of temperature, there would be 23.7% reduction in the net power of the gas cycle. This result is in a good agreement with what is given in the literature [7, 8, 12, 14].

The increase in the ambient temperature would reduce the air mass flow rate to gas cycle, fuel mass flow rate, and the exhaust temperature. Hence the rate of heat transfer to the steam cycle decreases with the increase in the ambient temperature as shown in Figure (4). The rate of heat transfer decreases from 300.63 MW to 271.90 MW as the ambient temperature increases from 15°C to 40°C. In other words, in this range of temperature, there will be a 9.6% drop in the rate of the heat transfer inside the heat recovery steam generator.

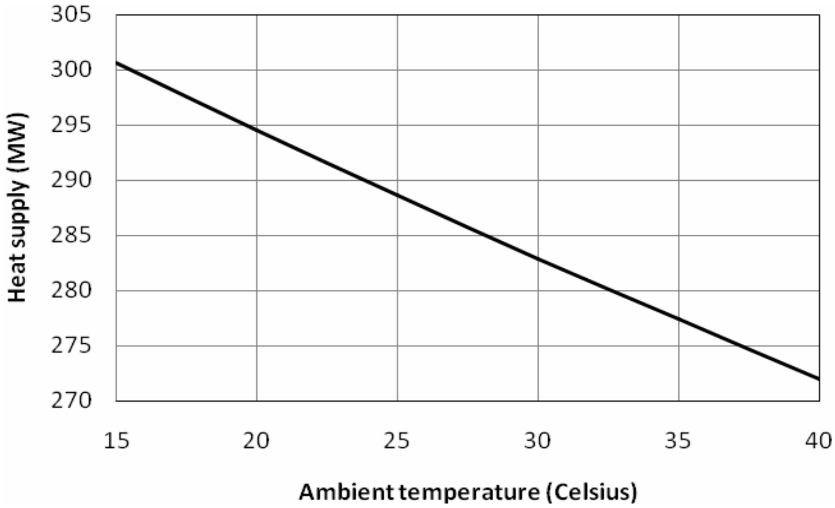

Figure 4: Effect of ambient temperature on heat supply

Effect of ambient temperature on the power output of gas, steam and combined cycles, is shown in Figure (5).

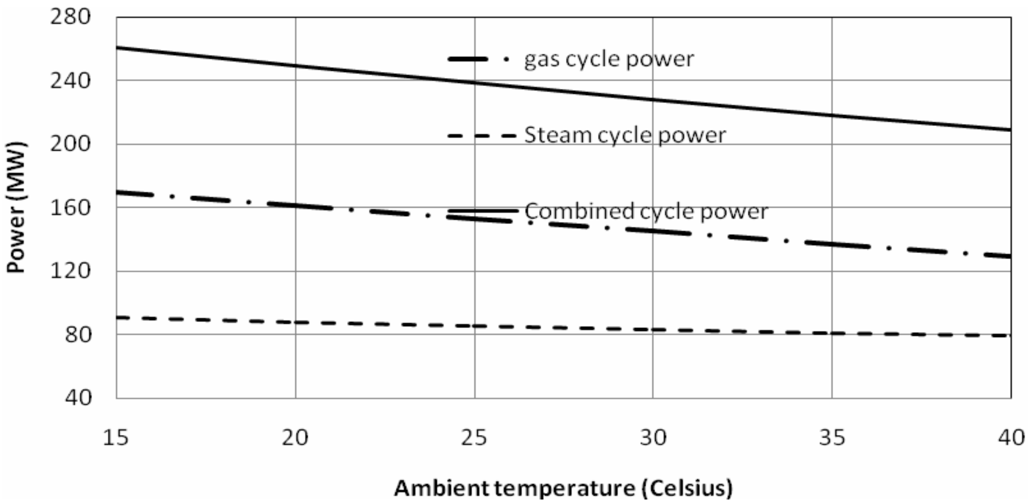

Figure 5: Effect of ambient temperature on power

It is found that the power output of the steam cycle decreases slightly whereas the power output of the gas cycle decreases substantially with an increase in the ambient temperature. Therefore, the output of the combined cycle drops from 260.58MW at 15°C to 208.6242MW at 40°C, that is, at this range of ambient temperatures, about 20% reduction in combined cycle power is noticed.

The percentage gain in net power utilizing the combined cycle is shown in Figure (6). Since the rate of decrease of power in gas turbine side is greater than that of the combined cycle, the percentage increase in net power raises from 53.46% at 15°C to 60.98% at 40°C.

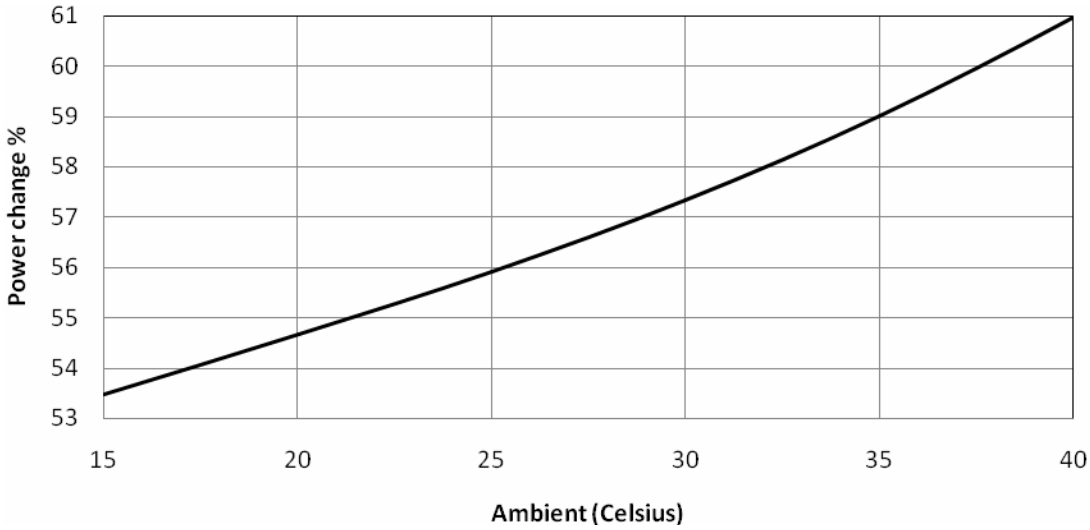

Figure 6: Effect of ambient temperature on power change

Figure (7) shows effect of the ambient temperature on the efficiency of the gas, steam, and combined cycles. As the ambient temperature increases from 15^{o}C to 40^{o}C, the efficiency of the gas turbine unit drops by 8.3%. This is in a good agreement with the results of Mahmoudi et al [14].

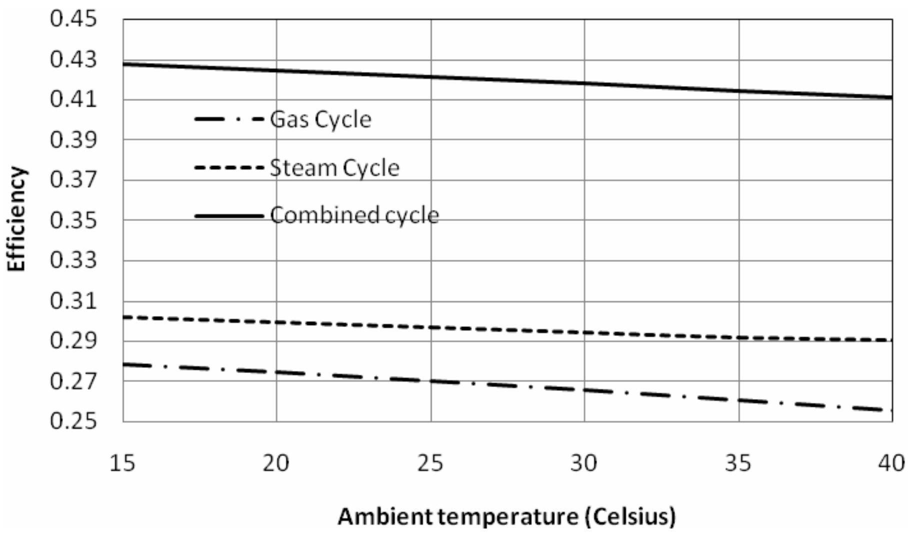

Figure 7: Effect of ambient temperature on efficiency

Nevertheless, a drop of 10% has also been reported by Al-Tobil Is'haq [12]. The reduction in the gas turbine efficiency is due to the drop in the net power of the gas cycle as the ambient temperature increases. Since the rate of the decrease of the net power of the combined cycle is greater than that of the heat supplied to steam cycle, the anlaysis shows a drop on combined cycle efficiency. The analysis shows that the efficiency of the selected combined cycle is about 43%. However, due to the different conditions prevailing at the site, values between 46.8 and 50.1% have been reported [13].

The variations in specific fuel consumption for both gas and combined cycles are shown in Fig. 8. For the gas turbine cycle the specific fuel consumption increases from

289.56 to 315.91 g/kWh as the ambient temperature increases from 15 to 40^{o}C, which presents 9.1% rise in the specific fuel consumption. For the combined cycle the specific fuel consumption increases from 94.34 to 98.10 g/kWh as the ambient temperature increases from 15 to 40^{o}C, which presents only 1.28% rises in the specific fuel consumption.

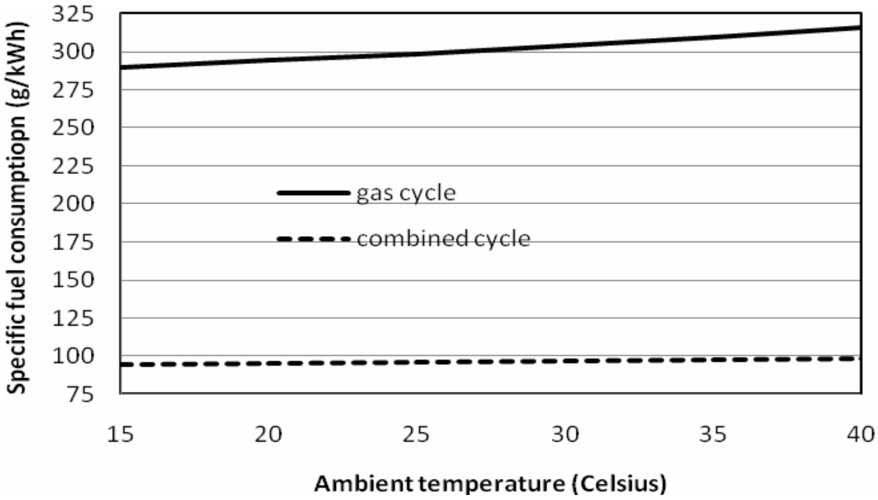

Figure 8: Effect of ambient temperature on specific fuel consumption

Figure (9) shows that there is a drop in the effectiveness of gas cycle and combined cycle as the ambient temperature increases. It can also be observed that the effectiveness of the combined cycle is higher than that of the gas cycle, and at 25^{o}C ambient temperature it can be enhanced by about 55.8%. An improvement of 40% has been reported by Somkiat and Pichai [10].

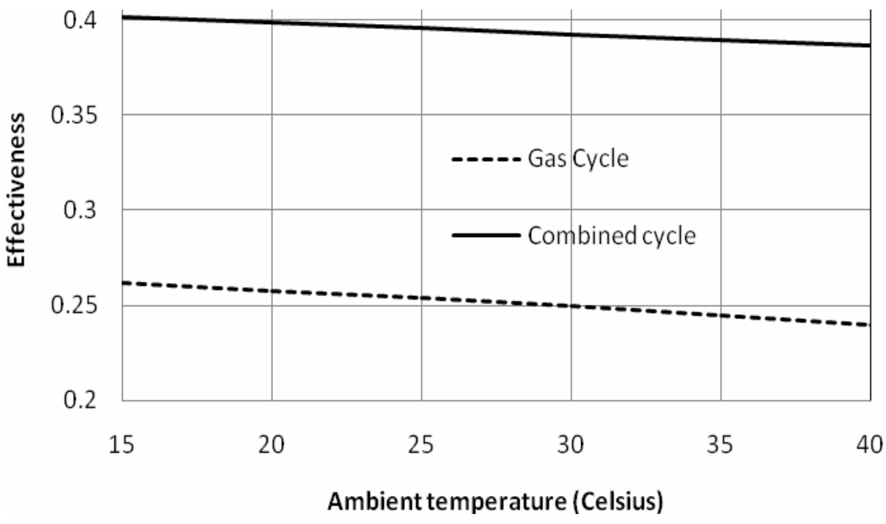

Figure 9: Effect of ambient temperature on effectiveness

CONCLUSIONS AND RECOMMENDATIONS

An analysis based on the first law and the second law of thermodynamics has been performed to find effect of the ambient temperature variation on the thermodynamic performance of a proposed combined cycle. HYSYS software has been used as a tool to perform the analysis. The following conclusions can be drawn:

- The current analysis has been made for almost constant temperature at the combustion chamber outlet and constant pressure ratio. Other analyses could be performed for constant compressor outlet temperature, constant fuel mass flow rate, or constant gas turbine power, and different conclusions may probably be drawn. Hence, the decision maker could decide which scheme is the proper one for controlling and operating the gas turbine units.
- The heat supply to the steam cycle decreases with the increase in the ambient temperature.
- The net power output of the combined cycle varies with the change in the ambient temperature; furthermore the ratio of the combined cycle power to that of the gas cycle increases substantially.
- The first law efficiency of the combined cycle is larger than that of the gas cycle.
- The analysis has also shown that both power and efficiency could be increased substantially by employing a combined cycle.

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NOMENCLATURE

$\dot{m}$	mass flow rate (kg/s)
h	enthalpy (kJ/kg)
s	entropy $(kJ/kg.K)$
$\dot{Q}$	rate of heat transfer (kW)
r_P	pressure ratio
$\dot{V}$	volume flow rate $\left(\frac{m^3}{s}\right)$
C_P	specific heat at constant pressure (kJ/kg.K)
k	specific heat ratio
P	pressure (kPa)
$\dot{W}$	power (kW)
T	temperature (K)
t	temperature $^{o}(C)$
k	index for the isentropic process
sfc	specific fuel consumption (g/kWh)
R	gas constant $\left(\frac{kJ}{kg.^{o}C}\right)$
LHV	lower heating value $\left(\frac{kJ}{kg}\right)$
LPEC	low pressure economizer
LPEV	low pressure evaporator
LPSH	low pressure superheater
HPEC	high pressure economizer
HPEV	high pressure evaporator
HPSH	high pressure superheater
C	compressor
CC	combustion chamber
GT	gas turbine
HPT	high pressure turbine
IPT	intermediate pressure turbine

LPT	low pressure turbine
CW	cooling water
FWP	feed water pump
LPP	low pressure pump
HPP	high pressure pimp
CP	circulating pump

Symbols

$\dot{\Psi}$	exergy rate (kW)
η	efficiency
λ	air fuel ratio
ρ	density (kg/m^3)

Subscripts

a, b, c, d	states in the gas cycle
f	fuel
s	isentropic
cc	combustion chamber
HRSG	heat recovery steam generator
C	compressor
t	turbine
gt	gas turbine cycle
st	steam turbine cycle
exh	exhaust
comb	combined cycle
0	ambient condition
1st	first law
2nd	second law