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the Life Cycle Assessments of Gas Turbine using Inlet Air Cooling System

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ABSTRACT
The achievement of life cycle assessments of energy systems with both maximum power output and economical profits is considered as the main objective of operations management. This paper aimed to evaluate both of the performance of a gas turbine using an inlet air cooling system as well as its life cycle cost. Accordingly, a thermodynamic model and an economic model are developed respectively to derive an analytical formula for calculating the cooling loads and life cycle cost. The major results show that, the output power of gas turbines power plant with a cooling system is (120MWh) which is higher than that of gas turbines power plant without the cooling system (96.6 MWh) at peak condition; while the life cycle cost is lower in the case of gas turbines power plant with cooling system. Thus, the proposed methods show a potential cost reduction and achievable through changing the structure of the system.
Keywords: life cycle cost, gas turbine, cooling system, power output.

تحسين أداء ودورة حياة التربينات الغازية باستخدام منظومة تبريد الهواء الداخل

ان تحقيق دورة حياة أنظمة توليد الطاقة يعتبر الهدف الرئيسي لإدارة العمليات للوصول إلى أقصى إنتاج للطاقة والأرباح الاقتصادية . هذه الدراسة تهدف لتقييم كل من أداء التربينات الغازية بدون ومع أضافة نظام تبريد الهواء الداخل، فضلا عن تكلفة دورة حياتها. وفقا لذلك، تم بناء نموذج للحسابات الحرارية ونموذج اقتصادي على التوالي لاشتقاق صيغة تحليلية لحساب الأحمال التبريد وتكلفة دورة الحياة. أظهرت النتائج الرئيسية في هذه الدراسة إلى إن إنتاج الطاقة لمحطة كهرباء التربينات الغازية مع نظام التبريد كان (120 MWh) ولكن هذه القيمة تنخفض في محطات التربينات الغازية دون استعمال نظام التبريد الى (96.6MWh) في قمة مستواه. في حين أن تكلفة دورة حياة المحطات الغازية مع استعمال منظومات تبريد الهواء الداخل هي أفضل من تلك الأخيرة. وبالتالي، فإن الأساليب المقترحة بينت تحسينات فعالة من حيث التكلفة المحتملة ويمكن تحقيقها من خلال تغيير بنية النظام.

Introduction

Nowadays, under the heightened awareness of the global warming issues with increasing demand for cost effective power generation, extensive research activities are currently devoted onto new technologies to boost up the performance of gas turbine generators [1].

Malewski and Holldorft[2] analyzed the performance of a gas turbine generator fitted with aqua-ammonia absorption chiller to cool the inlet air. In their system, the generator received the required heat from the exhaust gases through a direct contact heat exchanger. Johnson[3] suggested the use of evaporative coolers in an effort to boost the performance of gas turbine generators. De Lucia et al.[4] examined the differences between the operation of cogeneration gas turbine power plant with and without air cooling system. Ondryas and Haub[5] investigated the various options for cooling the inlet air, including vapor compression chillers and aqua-ammonia absorption chillers. Jan[6] studied the influence of ambient temperature on the operational indices of the gas turbine set and reported that the lowering inlet air temperature leads to the increase of flow rate of combustion gases, which results in the increase of power output. McDonalds[7] also carried out studies on the turbine performance with optional power booster including mechanical chillers with the thermal storage system. Valdes et al.[8] showed a possible way to achieve an optimal operation of combined cycle gas turbine power plants by using a genetic algorithm. Accadia and Vanoli[9] applied the structural method into the operational optimization of the condenser of a vapor compression heat pump. Amongst all those, the inlet air cooler is expected to result in a boosting of power output of the gas turbine, as well as a fashion of a noticeable improving in efficiency[10], which seems more valuable as the price of energy and investment cost continue swelling. And since operation analysis facilitates the determination of the optimum design parameters of gas turbine power plant systems under a set of operating conditions, this paper focuses on the operation evaluation of the gas turbine power plant systems. And by adding an inlet air cooler to the gas turbine power plant, it develops a new analyzing method for the inlet-air cooling technologies under ambient conditions. More importantly, a detailed economic appraisal analysis for the performance of the entire cogeneration plant is also elaborated. The derived results reveal that the performance variations that the gas turbine inlet-air cooling produces could generate cash flows and other relevant economic variables to maximize the profit of the integrated system. This paragraph should explain the objective of present work not the content or work flowchart.

Thermodynamic and Economic Modelling

This study deals with single shaft gas turbine power plant type Siemens V94.2 which is used at Baiji Gas Turbine Power Station. As shown in Fig.1, single shaft gas turbines are constructed in one continuous shaft. Therefore, all stages operate at the same speed (3000 RPM). These types of units are typically used for electricity generation. The absorption refrigeration cycle is show in Fig.1.

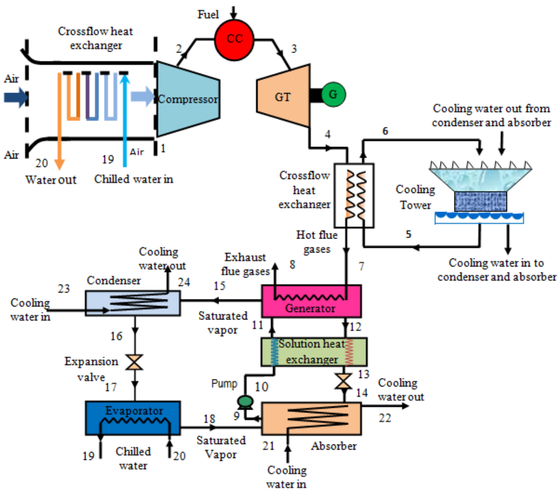


Fig.1: Gas turbine with effect absorption cooling system

Thermodynamic Model

Using the first law of thermodynamic and knowing the air inlet temperature to compressor, pressure ratio (r_p) and isentropic efficiency of the compressor, the compressor exit temperature is expressed as[11].

$$T_2 = T_1\left(1 + \frac{r_p^{\frac{\gamma_a - 1}{\gamma_a}} - 1}{\eta_c}\right) \tag{1}$$

Where η_c, r_p are the compressor efficiency and pressure ratio respectively, $\gamma_a = 1.4$ and $\gamma_g = 1.33$.

The compressor work (W_c) can be calculated as.

$$W_c = \frac{c_{pa} T_1 \left(\left(r_p^{\frac{\gamma_a - 1}{\gamma_a}} - 1\right) \Big/ \eta_c\right)}{\eta_m} \tag{2}$$

Where η_m is the mechanical efficiency of the compressor and c_{pa} is the specific heat of air which can be calculated as below for the range of 200 K° < T < 800 K° [1].

$$c_{pa} = 1.0189 \times 10^3 - 0.13784 T_a + 1.9843 \times 10^{-4} T_a^2 + 4.2399 \times 10^{-7} T_a^3 - 3.7632 \times 10^{-10} T_a^4 \tag{3}$$

Where

$$T_a = \frac{T_2 - T_1}{2} \text{ in K}^o.$$

The specific heat of flue gas is given as[12].

$$c_{pg} = 1.8083 - 2.3127\times10^{-3}T + 4.045\times10^{-6}T^2 - 1.7363\times10^{-9}T^3 \quad (4)$$

The equation of energy balance in the combustion chamber is expressed as[13].

$$\dot{m}_a c_{pa} T_2 + \dot{m}_f \times LHV + \dot{m}_f c_{pf} T_f = (\dot{m}_a + \dot{m}_f) \times c_{pg} TIT \quad (5)$$

Where, $\dot{m}_f$ is fuel mass flow rate (kg/s), $\dot{m}_a$ is air mass flow rate (kg/s), *LHV* is low heating value, T_3 = *TIT* = turbine inlet temperature C_{pf} is specific heat of fuel and T_f is temperature of fuel.

After rearrange Eq. (5), the fuel air ratio (f) is expressed as.

$$f = \frac{\dot{m}_f}{\dot{m}_a} = \frac{c_{pg} \times TIT - c_{pa} T_2}{LHV - c_{pg} \times TIT} \quad (6)$$

The heat supplied is expressed as:

$$Q_{add} = c_{pg_m}\left(TIT - T_1\left(1 + \frac{r_p^{\frac{\gamma_a - 1}{\gamma_a}} - 1}{\eta_c}\right)\right) \quad (7)$$

The shaft work of the turbine is given by:

$$W_t = c_{pg} TIT.\eta_t \left(1 - \frac{1}{r_p^{\frac{\gamma_g - 1}{\gamma_g}}}\right) \quad (8)$$

The network of the gas turbine (W_{net}) is calculated from

$$W_{net} = W_t - W_c \quad (9)$$

The gas turbine efficiency is also expressed as

$$\eta_{th} = \frac{W_{net}}{Q_{add}} \quad (10)$$

The first thermodynamic law is used to determine the cooling load of refrigeration cycle, the heat rejected from cooling air is given by[14]:

$$Q_{air} = \dot{m}_a c_{pa}\left(T_{a,in} - T_{a,out}\right) = Q_e \quad (11)$$

Where:

$T_{a,out}$=Desired inlet air temperature, let be 25ºC.

$T_{a,in}$=Air inlet mean temperature at summer condition=45ºC.

Q_e=is the heat transferred through the evaporator.

Economic Model

The life cycle cost (*LCC*) is based on the actual power output that produced by the gas turbine throughout the year and which can be written as[15]:

$$LCC_{nc} = \left\{IC_{gt} + E_{ncAnu} \times (PWF) + M_{gt} \times (PWF) - Sal_{gt} \times (SPW)\right\}_{original} \quad (12)$$

Where

LCC_{nc} : Life Cycle Cost without cooling

IC_{gt}: Initial Cost of the gas turbine

E_{ncAnu}: Annual Energy cost without cooling

M_{gt} : Maintenance cost of the gas turbine

Sal_{gt} : Salvage value of the gas turbine

PWF: Present worth Factor

SPW: Single Present Worth

Equation (12) can be rewrite as.

$$LCC_{nc} = IC_{gt} + \sum_{1}^{12} \frac{P_{ncm} \times F_p}{\eta_{gt}} \times \left[\frac{1+f}{i-f}\left(1 - \left(\frac{1+f}{1+i}\right)^n\right)\right] + M_{gt} \times \left[\frac{1+f}{i-f}\left(1 - \left(\frac{1+f}{1+i}\right)^n\right)\right] - Sal_{gt} \times \left(\frac{1+f}{1+i}\right)^n \quad (13)$$

Where

F_p : Fuel price

P_{ncm}: Monthly power output without cooling

f :Inflation rate

i : Interest rate

n : Period of investment

The single stage LiBr absorption system is used to enhance the power output nearly to the design value by cooling the inlet air to 15˚C which create the gas turbine operates at the ISO design conditions (Ibrahim et al. 2011)[15]. Thus, the life cycle cost of the combined system can be written as Eq. (14) [16,17, 18]:

$$LCC_{wc} = \left[IC_{gt} + E_{wcAnu} \times (PWF) + M_{gt} \times (PWF) - Sal_{gt} \times (SPW)\right]_{original} + \left[IC_{abs} - P_{adp} \times (PWF) + M_{abs} \times (PWF) - Sal_{abs} \times (SPW)\right]_{absorption} \tag{14}$$

Where

LCC_{wc}: life cycle cost with cooling
IC_{abs}: initial cost of the absorption system
E_{wcAnu}: annual energy cost with cooling
P_{adp}: additional power output price
P_{wcm}: monthly power output with cooling
P_{adt}: additional power produced due to the using of cooling system
M_{gt}: maintenance cost of the gas turbine
m: absorption life time.
Sal_{abs}: salvage value of the absorption system

After manipulations, Eq. (14) can also be written as Eq. (15) [16]:

$$LCC_{wc} = \left[IC_{gt} + \sum_{1}^{12} \frac{P_{wcm} \times F_p}{\eta_{gt}} \times PWF + M_{gt} \times PWF - Sal_{gt} \times \left(\frac{1+f}{1+i}\right)^n\right]_{original} + \left[IC_{abs} - \frac{P_{adt} \times F_p}{\eta_{gt}} \times PWF + M_{abs} \times PWF - Sal_{abs} \times \left(\frac{1+f}{1+i}\right)^m\right]_{absorption} \tag{15}$$

Where
LCC_{wc}: life cycle cost with cooling
IC_{abs}: initial cost of the absorption system
E_{wcAnu}: annual energy cost with cooling
P_{adp}: additional power output price
P_{wcm}: monthly power output with cooling
P_{adt}: additional power produced due to the using of cooling system
M_{gt}: maintenance cost of the gas turbine
m: absorption life time.
Sal_{abs}: salvage value of the absorption system

Results and Discussion

Absorption cooling system with single stage LiBr-water was used to reduce the inlet air temperature of the compressor of gas turbine of power plants in order to increase the net power output. The absorption cooling system is driven by recovering the heat energy from the exhaust gases of the gas turbine. Gas turbines are constant volume machines at a given shaft speed which is always move the same volume of air. However, the power output of a turbine depends on the flow of mass through it. This is precisely the reason why on hot days, when air is less dense, power output falls off. A rise of 1°C temperature of inlet air decreases the power output by 1% and at the same time, the heat rate of the turbine also goes up which is a great concern of power producers. A simulation code was developed for life cycle modeling using MATLAB software to investigate the effect of using the inlet air cooling system on the thermal and economic performance of gas turbine power plant. The daily net power output for gas turbine power plant with and without cooling for the January is found to be almost constant and parallel to the design value of 2870 MWh as shown in Figure 2. This is due to the low ambient temperature that remains constant during the month of January. It can also be seen that at early day hours, the net power output is high (until 121 MW/h). Then, a significant reduction is recognized (until 118 MW/h) in the midday hours due to the increase in ambient temperature. Then, it is enhanced again at the late hours of the day when the ambient temperature goes down.

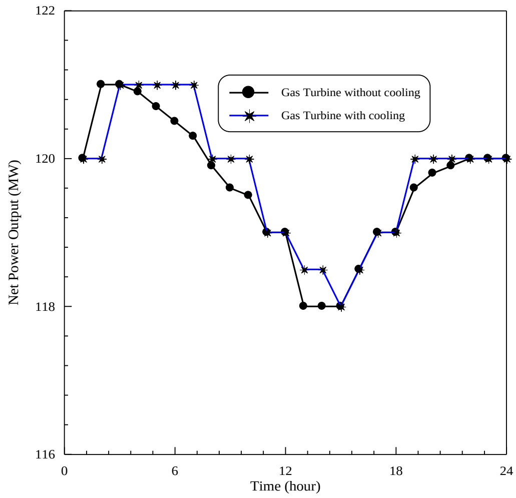
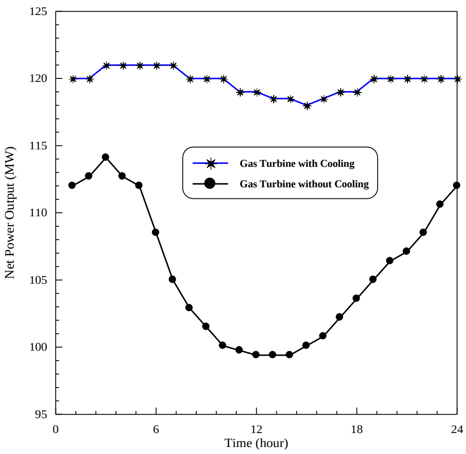
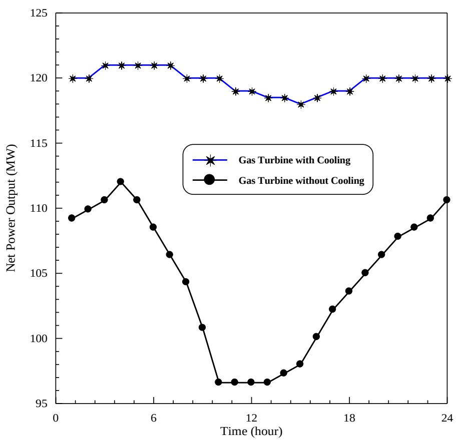


Fig.2: Gas turbine net power output with and without cooling system for January.

The degradation in power output was observed to occur during the hot season months of May to October in Iraq. Figure 3 shows the effect of the daily time on the net daily power output for the gas turbine power plant with cooling and the gas turbine power plant without cooling for the month of June and August. Fig.3 (a) shows the net power output when the gas turbine power plant without cooling was found to be 2535.75 MWh which represent an average reduction in daily power out of 11.9%, while the maximum reduction in net daily power output was obtained to be about 17.2%. This reduction is noticed due to the high disproportion in the temperature of Baiji City ambient. The temperature increases considerably in the midday hours in June in Baiji city.



(a) For Month of June

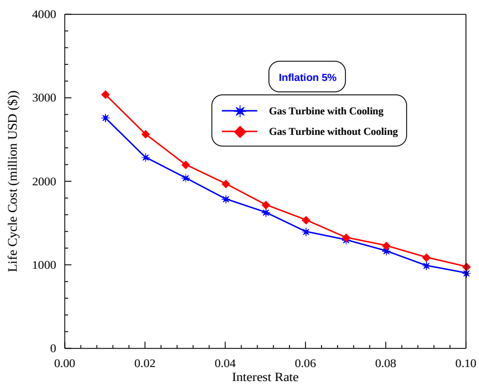


(b) For Month of August

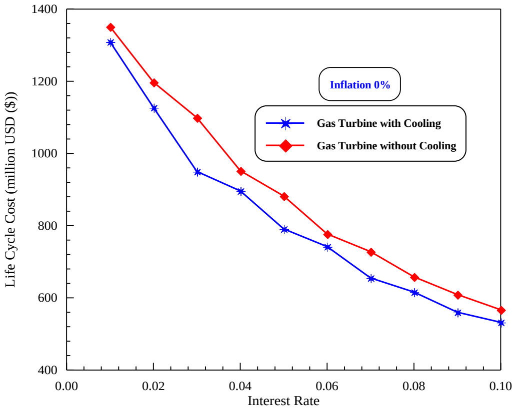
Fig.3: Gas turbine net power output with and without cooling system for the month of (a) June; (b) August.

Fig. 3(b) shows the effect of the daily time on the net daily power output for the gas turbine power plant without cooling and the gas turbine power plant with cooling for August. The daily net power output was found to be 2507.4 MWh which indicates an average reduction in daily power out of 12.7% compared to the design value of 2871 MWh. The maximum reduction in daily power output was obtained to be approximately 19.5%.Moreover, June, July and August are surely the hottest months in the year where the ambient temperature reaches over 45 ˚C. Therefore, the cooling system should operate at 100% capacity and 24 hours a day in order to boost the power production to near design value.

The lifetime of the gas turbine power plant as well as the single stage absorption system is considered to be 30 years. The values for interest rate were varied in the range of 0% to 10%, as the inflation rate varies from 0% to 5%. Two main cases as the gas turbine with and without cooling were considered. The life cycle cost is based on the annually net power output produced by the gas turbine power plant without using the cooling system and then is calculated when the cooling system is used with gas turbine. Subsequently, a comparison is made with and without cooling system. Fig. 4 shows the life cycle costs for gas turbine power plant with and without cooling system for various values of interest rate at 0 % and 5% inflation rate. It can be seen from Fig.4(a) the life cycle cost of the gas turbine power plants with the cooling system is lower than without cooling by approximately 4% for inflation rate of 0%, however, Fig. 4(b) approximately 12% for the inflation rate of 5% at 0.01% interest rate then decrease as the interest rate in increase, i.e. life cycle cost are 1356 M$ and 3020 M$ at 0.01 interest rate. Furthermore, it is also observed that the life cycle costs increase as the inflation rate increases. A 38 M$ and 260M$ saving occurs with cooling system utilization for interest rate of 0.01% at 0 % and 5% inflation rate respectively.



(a) Inflation rate of 0%



(b) Inflation rate of 5%

Fig.4: Life cycle costs for gas turbine power plant with and without cooling system for various interest rates

Conclusions

The life cycle costs based on both the gas turbine power plant with and without the cooling system are presented. The calculated costs included the capital investment, maintenance costs and energy costs, incurred throughout the lifespan of the gas turbine power plant. Finally, it is difficult to measure sizably correct life cycle costs for both the two cases since the gas turbine power plant equipment cost information is restricted and hard to acquire. The summary of the major findings of this analysis are as follows:

1. The life cycle cost is decreased by a corresponding decrease in the compressor inlet air temperature with the other factors remaining unchanged.
2. A minimum 4% decrease in the life cycle cost is observed in gas turbine power plants utilizing cooling technologies, compare to units without these technologies.
3. The economic facts and figures document the benefits of utilizing a single stage LiBr in gas turbines. Such usage should be analysed in greater detail, and should be incorporated in power plant design.

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