Performance improvement of the combined cycle power plant by intake air cooling using an absorption chiller

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Abstract

This paper studies how to improve the capacity of the combined cycle (CC) power plant which has been operated for 8 years. The most popular way is to lower intake air temperature to around 15 °C (ISO) and 100% RH before entering the air compressor of a gas turbine (GT). Thailand has 3 seasons: winter, summer and rainy season. According to 2003 Bangkok monthly weather data, all year ambient temperature is higher than 15 °C. This research proposes a steam absorption chiller (AC) to cool intake air to the desired temperature level. It could increase the power output of a GT by about 10.6% and the CC power plant by around 6.24% annually. In economic analysis, the payback period will be about 3.81 years, internal rate of return 40%, and net present value 19.44 MUS$.

Keywords: Air cooler; Economics; Monthly analysis; Uncertainty; Gas turbine

1. Introduction

The performance improvement of a power plant has been presented in literature [1,2]. Ameri et al. [3] proposed the improvement of the new power plant (16.6 MW) and focused on the gas turbine (GT) unit. The study showed that the power output could be increased by about 11.3%. Mohanty et al. [4] analytically studied the GT power plant enhancement in Bangkok, Thailand, and found that 11% increase in power was observed. Both used absorption chiller (AC) units without a cooling water storage system to solve their problem. The Toshiba Corporation [3] used a hybrid system: an AC with a thermal energy storage system for a small power plant (5.42 MW). They increased the power output of their systems by cooling the intake air entering the GT unit using a steam AC. Cooling inlet air would increase air mass flow then increase the power output [5]. The existing system in this current study is an 8-year combined cycle (CC) power plant (336 MW, ISO). Unfortunately, the ambient temperature all year in Bangkok is very high. This will lower the system output substantially. So a steam AC will be introduced in order to cool a compressor intake air to the desired condition. The AC has a certain advantage, since it does not need additional power for the compressor as the

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Nomenclature

A	size of a heat exchanger (m^2)
F	correction factor (dimensionless)
h	specific enthalpy (kJ/kg)
h_{fg}	latent heat of vaporization of water (kJ/kg)
Q_{CL}	total cooling load (kW, RT)
m	mass flow rate (kg/s)
T	temperature (°C)
U	overall heat transfer coefficient ($W/m^2 K$)
V	volume of a stored water (m^3)

Greek symbols

η	efficiency (%)
ω	humidity ratio (kg of moisture/kg of dry air)

Subscripts

a,b,c,d	state points
amb	ambient
CHW	chilled water
CHWR	chilled water return
CHWS	chilled water supply
CL	cooling load
e	electrical
ISO	international standards organization
th	thermal

Acronyms

AC	absorption chiller
CC	combined cycle
Comp	air compressor
ECON	economizer
EVAP	evaporator
G	generator
GT	gas turbine
HE	heat exchanger
HP	high pressure
HRSG	heat recovery steam generator
LHV	low heating value
LP	low pressure
NG	natural gas
RT	ton-refrigeration
ST	steam turbine

mechanical chiller does. It has a very few moving parts so that a standby unit is not necessary. Although the AC may use a fraction of low-pressure steam, this amount in term of energy is less than that used by a mechanical chiller. Then we technically analyze the improvement in the output of the combined system after using the AC. To ensure that this improvement is more appropriate, we analyze the economics of the system and compare it to the past studied system. Monthly average of hourly ambient temperature and relative humidity in 2003 are used as an input climatic data.

1.1. The combined cycle power plant (CC)

The CC consists of 2 GT units, 110.76 MW (ISO) each, and one steam turbine unit (ST), 115.14 MW (ISO), as shown in Fig. 1. Accordingly, we can economically analyze only half of the CC which represents one GT and half of ST units. But actual output from the CC was less than the total installed capacities and will be used as a reference in this analysis. It is the 2003's data (75.5% of full load) from which each component's efficiency was calculated as shown in Table 1.

The most important parameter that affects the performance of a GT is the intake air temperature. Changes in the humidity ratio have a negligible effect on the power output of the power plant [4,6]. Air mass flow rate entering a GT as a function of an ambient temperature can be simply calculated based on an actual data. Higher air mass flow rate also increases fuel consumption and exhaust gas.

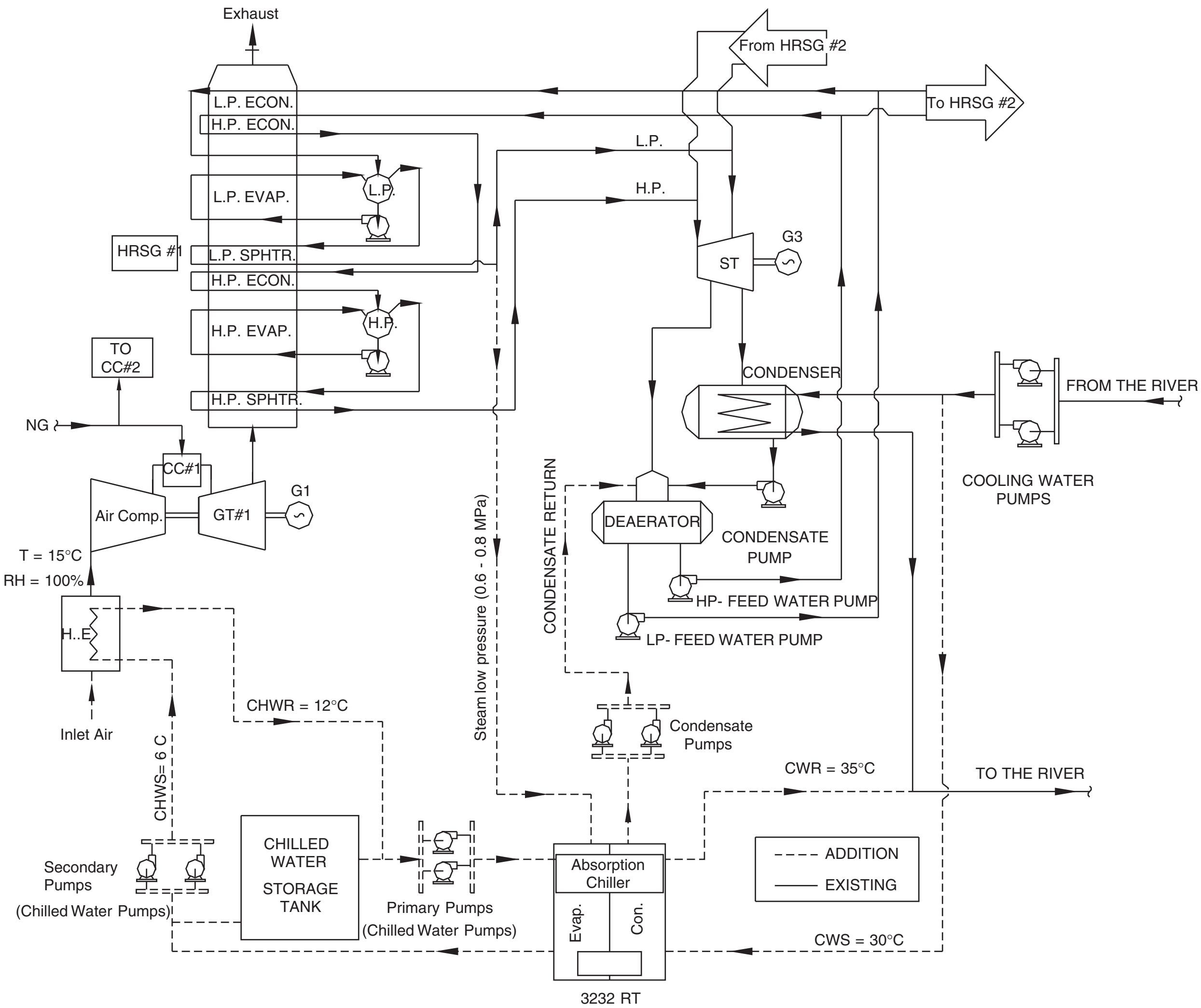

Fig. 1. Schematic diagram of the combined cycle power plant and the addition of the inlet air-cooling system.

Table 1
The present description of the CC system (yearly average in 2003)

Descriptions	Data
Gas turbine (GT1 = GT2)	
Natural gas flow (kg/s)	6.65
Air flow (kg/s)	292.5
Air/fuel mass ratio	44
Power output (MW)	84.7
Natural gas input (MW)	295.2
Natural gas-LHV (MJ/kg)	44.4
Gross efficiency (%)	28.7
Heat rate (kW_{th}/kW_e)	3.5
Steam turbine (ST)	
Steam input LP&HP (MW)	123.2
Power output (MW)	42.4
Gross efficiency (%)	34.4
Heat rate (kW_{th}/kW_e)	2.9
Combined cycle (CC)	
Natural gas input (MW)	295.2
Power output (MW)	127.1
Gross efficiency (%)	43.1
Heat rate (kW_{th}/kW_e)	2.3

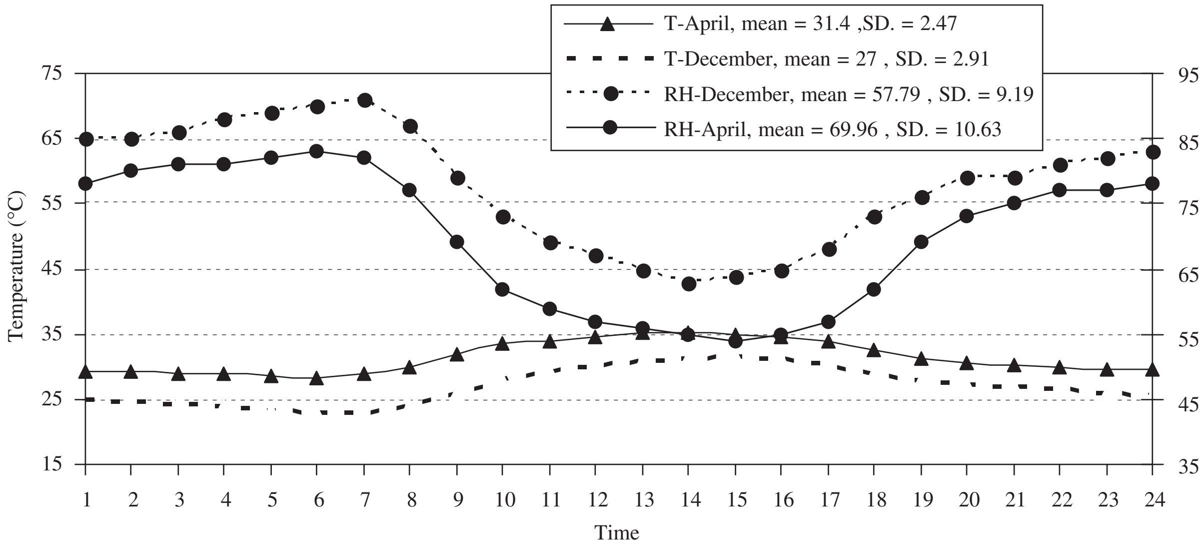

Fig. 2. Hourly average ambient temperature and relative humidity profiles in April and December for Bangkok—Thailand (2003).

Fig. 2 shows the monthly average of hourly ambient temperature and relative humidity of Bangkok (Thailand) in April 2003. April is the hottest month while the temperature is lower in December in which their maximum and minimum average ambient temperatures are 35 and 23 °C, respectively. It is evident that the ambient temperature is always higher than 15 °C. These data will be analyzed in order to find the final net change in the power output of the turbines.

2. A schematic diagram of the proposed system

Established in Bangkok, the capital of Thailand, the CC power plant has been operated since 1995. The system schematic diagram is shown in Fig. 1. This research will suggest a way to improve the performance of one GT unit (GT1) using one lithium-bromide AC (double effect). This chiller is used to produce chilled water. It will use heat input from a low-pressure steam (about 0.6–0.8 MPa) from a heat recovery steam generator (HRSG). The storage tank that stores chilled water will be installed between the AC and the compact heat exchanger (HE). Chilled water pump consists of two groups. The first group is a primary pump which circulates chilled water between the storage tank and the AC. The second group is a secondary pump which circulates chilled water between the storage tank and the HE as shown in Fig. 1.

3. Cooling load calculation

The cooling load was calculated where the compressor inlet humid air is cooled by rejecting its total heat to the chilled water. As the air temperature drops, its relative humidity would continually rise to 100% RH. This load can be calculated in terms of ton refrigeration (RT) or energy per hour, which will be extracted from an inlet compressor air to meet the 15 °C (ISO), 100% RH. In this cooling process, it consists of two steps, which are latent heat (a–d) and sensible heat (d–c) which is shown in Fig. 3. There are some water vapors condensing on the cooling coils. To avoid damage to the system, this condensate has to be eliminated by adding a separation system at the entrance of the air compressor. The total cooling load can be calculated by using energy balance as follows:

$$Q_{CL} = m_{air}[(h_a - h_c) - h_{fg,c}(\omega_a - \omega_c)]. \tag{1}$$

Once the cooling load was known, the size of a HE could be found [7]:

$$A = \frac{Q_{CL}}{U \Delta T_{ln} F}, \tag{2}$$

when

$$\Delta T_{ln} = \frac{(T_{amb} - T_{CHWR}) - (T_{ISO} - T_{CHWS})}{\ln[(T_{amb} - T_{CHWR})/(T_{ISO} - T_{CHWS})]}, \tag{3}$$

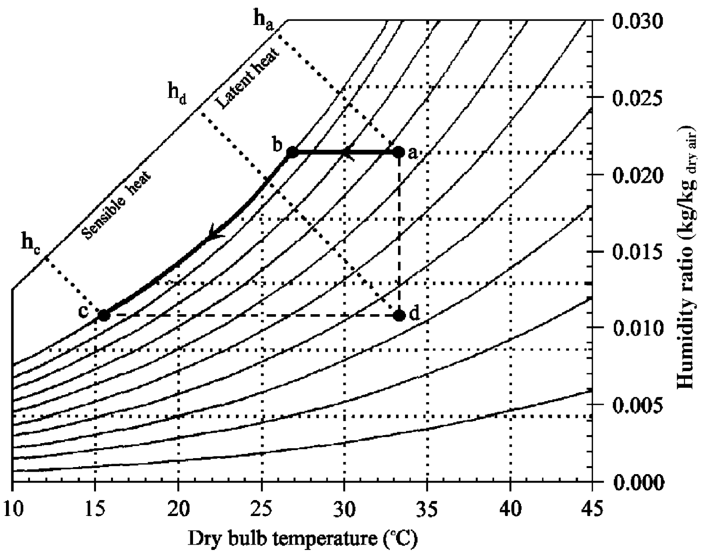

Fig. 3. Air cooling process in psychrometric chart [3].

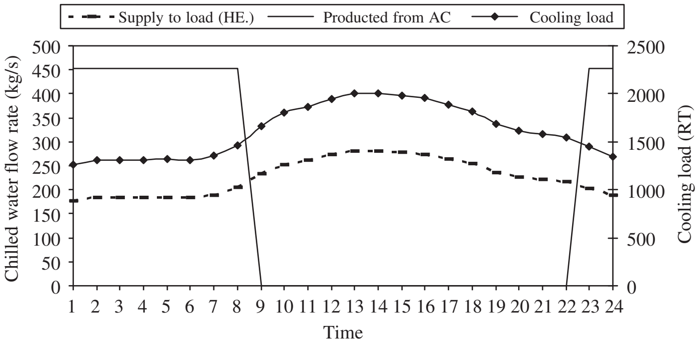

Fig. 4. The flow rate of chilled water from absorption chiller and to heat exchanger and cooling load in April for Bangkok—Thailand (2003).

Table 2
The capital cost of an inlet air-cooling system

Component	Unit	Price (MUS$)
Absorption chiller (3232 RT)	1	1.79
Compact heat exchanger (7544 m^2)	1	0.313
Chilled water pump	4	1.3
Condensate pump	2	0.097
Control system	1	0.81
Storage tank (24 432 m^3)	1	3.2
Miscellaneous	1	0.9
Total capital cost		8.41

Table 3
The auxiliary power consumption

Component	kW
Absorption chiller	19
Chilled water pump	259
Condensate pump	32
Total auxiliary power	310

U is the overall heat transfer coefficient (U) which is $64\,W/m^2\,°C$ [8], F the correction factor which is 0.98 [7] and $T_{ISO} = 15\,°C$.

April was used as a key design month as it is the hottest month and from Eq. (1) the maximum cooling load at 14:00 is around 2005 RT (see Fig. 4). According to Eq. (2) the heat transfer area of the HE is $7544\,m^2$. The pressure drop due to the HE is $65\,mmH_2O$ which can be negligible [3,8,9]. Then, a storage tank, an AC, a HE and pumps can be designed as shown in Tables 2 and 3.

4. Thermal energy storage system (TES)

The storage system uses chilled water to store the sensible heat of water. Water is cooled by the AC and stored in a tank for later use to meet the cooling needs. The amount of stored cooling energy depends on ton-hours and temperature difference between the inlet (CHWR) and outlet (CHWS) chilled water of the storage tank. The typical gross volume of a stored water for chilled water storage in cubic meter is as follows [10,11]:

$$V_{\text{gross}} = \frac{V_{\text{theory}}}{0.8}, \tag{4}$$

where

$$V_{\text{theory}} = \frac{\text{TES capacity in ton-hours}}{T_{\text{CHWR}} - T_{\text{CHWS}}} \times 3.024. \tag{5}$$

4.1. *Operating strategy*

In this case the power plant operates for 24 h every day. Figs. 4 and 5 show an analysis result in April. Because the off-peak period energy charges are low in Thailand, the AC can be run at its full load, i.e. 3232 RT (453 kg/s) between 22:00 and 9:00 (off-peak) (see Fig. 4). It will supply chilled water for both the storage tank and the HE. The AC needs a constant low-pressure steam with a mass flow rate of 4 kg/s (4.5 kg/h-RT). During the on-peak period the AC will be stopped and a secondary pump will supply chilled water from the storage tank to the cooling coil, while in December the AC will produce 2140 RT instead.

5. Technical analysis

According to Sections 3 and 4 it was found that fuel consumption after an improvement was increased by about 0.4 kg/s. Fig. 5 shows the power output of the GT, the ST and the CC before and after improvement in April. The power output of the GT increases by around 10.8 MW (10.16%) and the power output of the ST decreases by around 1.25 MW (2.85%).

The combined power of the GT and the ST annually increases by 8 MW (6.24%) after supplying an auxiliary power (Table 3). The heat rate decreases by 0.85%.

It was observed that the power output of the GT and the CC reach a maximum at the highest ambient temperature according to a national demand curve. The same trends are also shown in Fig. 6 for the rest of the months.

The economic analysis is based on the retail prices of electricity and demand charges for the time of use tariff (TOU):

on-peak = 0.06534 US$/kWh and 1.8535 US$/kWh,

off-peak = 0.029315 US$/kWh

(currency exchange rate used is 40 Baht/US$).

6. Economic analysis

The economic feasibility analysis of this project considers the additional system efficiency in producing the electricity and the capital costs of the project. It is a cost-benefit analysis. The analysis is based on 12% Thailand's tax rate, 5% interest rate and the salvage value about 15% of the initial investment costs. The cost of a natural gas is 0.125 US$/kg.

Table 2 shows the capital cost for the AC inlet air-cooling system. It includes the cost of components and the installation cost. Table 3 shows the auxiliary power consumption and Table 4 shows the annual operating and maintenance costs of the system components. In addition, Table 5 shows the final economic result in which the additional fuel cost was subtracted from the annual profit.

It was found that the internal rate of return (IRR) is 40%. This is due to the low investment. Payback period is within 3.81 years. As compared to Amari et al. [3], their system has IRR of 23.4% and payback period of 4.2 years.

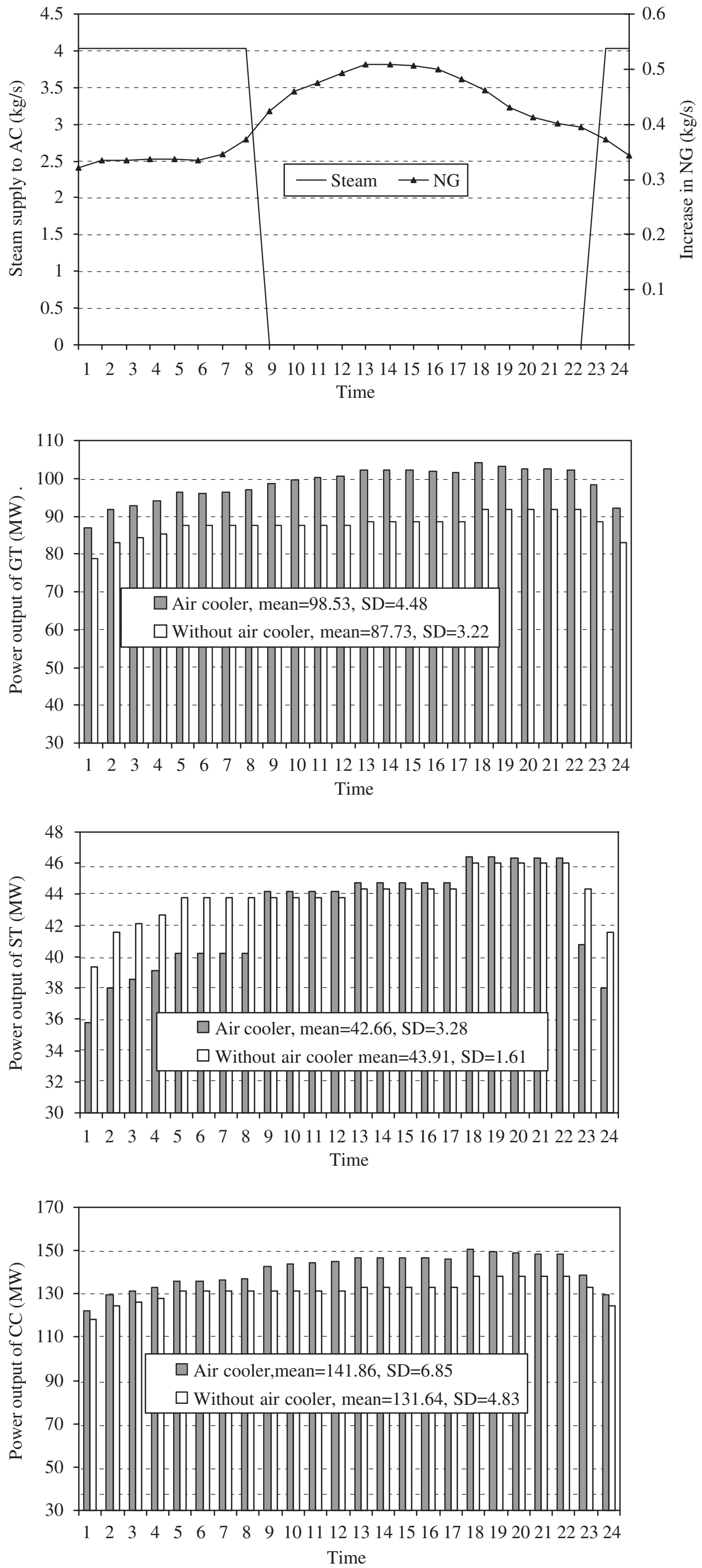

Fig. 5. Technical study applied to April for Bangkok—Thailand (2003) as example.

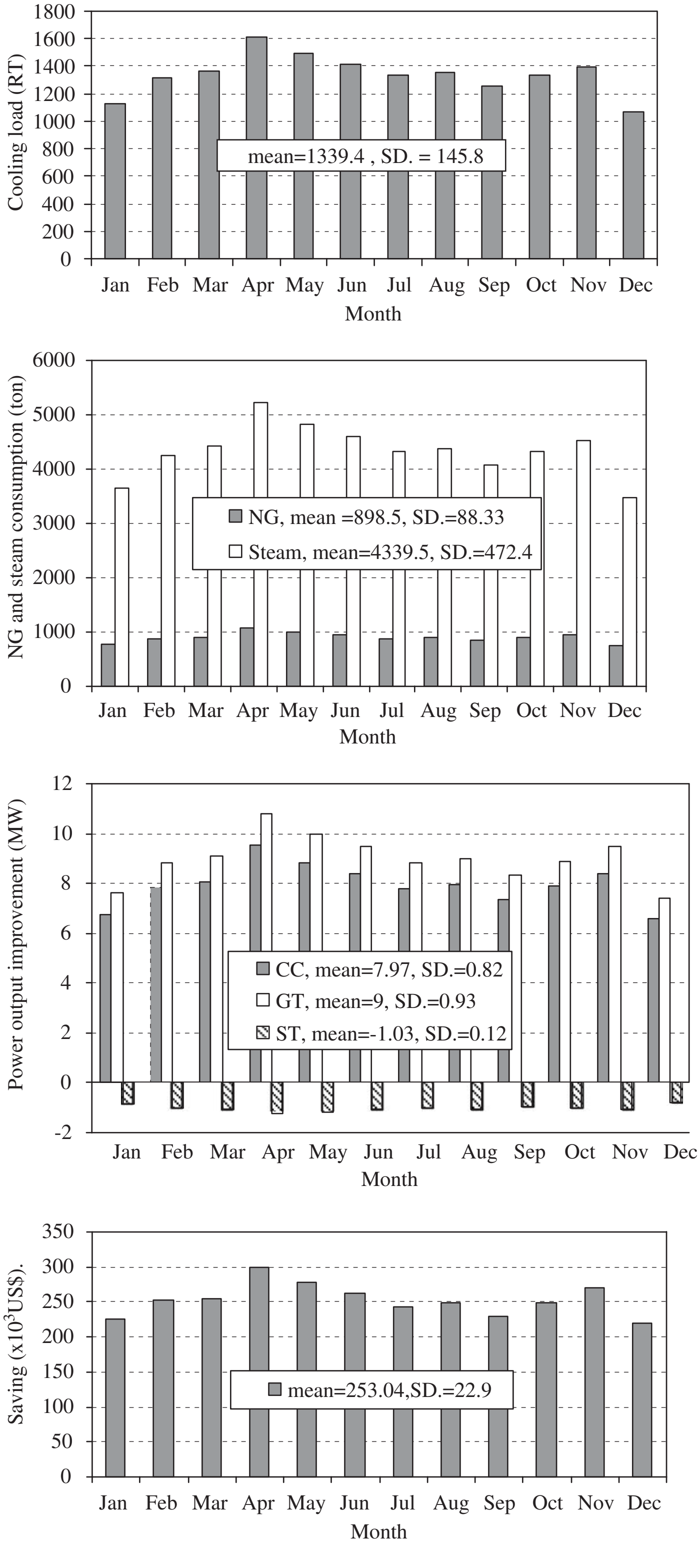

Fig. 6. The results of analysis in monthly for Bangkok—Thailand (2003).

Table 4
The annual O&M costs

Component	O&M costs (US$/yr)
Absorption chiller	39 000
Storage tank	640 000
Compact heat exchanger	4000
Chilled water pump	94 000
Condensate pump	28 000
Control system	25 000
Total annual O&M costs	830 000

Table 5
Final economic analysis

Total capital cost	8.41 MUS$
Annual O&M cost	0.83 MUS$/yr (increase 10%/yr)
Annual benefit	3.036 MUS$/yr (increase 10%/yr)
Life time service	20 yr
Salvage value	1.261 MUS$ (15% of total capital cost)
Taxes	12%
Interest rate	5%
Discount rate	15%
Net present value (NPV)	19.44 MUS$
Payback period	3.81 yr
Internal rate return (IRR)	40%

7. Conclusions

1. In cooling the inlet compressor air, the steam turbine (ST) can produce 0.3 MW more power (0.7%). Due to the chiller steam consumption (which is equivalent to 1.3 MW), the power output from the ST is reduced only by 1 MW. However, the power output of a gas turbine (GT) will increase by around 9 MW. Totally the combined cycle power may increase by about 8 MW (see Fig. 6 annual result).
2. It was concluded that cooling the intake air entering the gas-turbine compressor would increase the power output by about 10.6% for the GT and 6.24% for the CC. Nevertheless, the power of a ST was decreased by about 2.43% (see Fig. 6 annual result).
3. The estimated net electricity production would increase by 70 080 MWh/yr which can save money by around 3.04 MUS$/yr. The internal rate of return is 40%, payback period is 3.81 years and net present value is 19.44 MUS$.

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