Overview the Possible Methods for Increasing the Output Power of Gas Turbines in Al-Quds Power Plant

Ali Najm Abd
M.Tech Thermal Engineering
Engineering Technical College-Baghdad
Al-Quds Power Plant
Baghdad, Iraq
alinajm.an90@gmail.com

Aymen Amer
M.Sc Physics Sciences
Al-Nahrain University
Al-Quds Power Plant
Diyala, Iraq
Aymenamer1993@gmail.com

***Abstract*—This paper presents ways to increase the output power of gas turbines in Al-Quds Power plant, Baghdad, Iraq. There are four LM6000 gas turbines and ten Frame 9E gas turbines with a total load currently about 1200 MWapproximately. We found that the output power of these units can be increased by several methods as follows, Intercooling method between the low pressure compressor and the high pressure compressor to cool the compressed air, which leads to increasethe output power, and there is also a reheating process to heat the combustion gases, which leads to an increase in the overall efficiency by an amount 3%. The most important method that has been produced is to include the whole enhancing method in this plant to increase the electricity power and to reduce the pollution that caused by the combustion gases.**

Keywords—Gas Turbine; Combined Cycle; Output Power; Efficieny

I. INTRODUCTION

Gas turbines installed until the mid-seventies suffered from low efficiency and poor reliability. This limited the use of gas turbines to peak power demand and as a stand-by power unit [1]. However, the recent developments in aerodynamics which led to significant increase in isentropic compressor and isentropic turbine efficiencies (up to 90%), as well as the adventure in material science which came-up with special alloys that can withstand high temperatures, enabled the gas turbine to enter a new competition as a main power plant for generating electricity. Modern gas turbine technology has extensively used compressor intercooling and high turbine temperatures in order to achieve high net power and thermal efficiency requirements. Both of these solutions lead to additional investment cost, but higher turbine inlet temperatures are still limited by turbine blade cooling requirement and metallurgical improvements [2].A more recent gas turbine manufactured by General Electric used a turbine inlet temperature of 1425 ºC and produced up to 282 MW while achieving a thermal efficiency of 39.5% in the simple cycle mode [3]. Accordingly, gas turbines are rapidly becoming the choice for current and future power generation systems because they offer efficient fuel conversion, reduced cost of electricity, low installation and maintenance cost, can be put in service with minimum of delay time, occupy less room than other plants for the same capacity, and the ability to consume wide range of hydrocarbon fuels [4]. Their exhaust gases are relatively less pollutant to the environment, and can be used for preheating air before entering the combustion chamber, or for district heating as in combined heat and power plants [5].

II. THEORY

A. *History of Gas Turbines*

The history of gas turbines with different configurations and for different applications has been detailed in Table I.

TABLE I. HISTORY OF GAS TURBINES

YEAR	DETAILS
1791	The first patent for gas turbine was proposed by John Barber in United Kingdom.
1904	A gas turbine project was attempted unsuccessfully by Franz Stolze in Berlin.
1906	A gas turbine was developed by Armengaud Lemale in France which comprised of a centrifugal compressor but with not useful power generation.
1910	The first gas turbine featuring combustion was developed (constant volume combustion) by Holzwarth. It was of 150 kW capacity.
1923	First exhaust gas turbocharger was developed to increase the power of diesel engine.
1935	Keller and Ackeret patented the first close cycle gas turbine in Switzerland.
1939	World’s first gas turbine for power generation was developed by Brown Boveri Company in Neuchatel, Switzerland.
1972	The biggest and last air close cycle GT was built by Escher Wyss in Vienna.
1995	Siemens becomes the first manufacturer of large electricity producing gas turbines to incorporate single crystalturbine blade technology into their production models, allowing higher operating temperatures and greater efficiency.
2011	Mitsubishi Heavy Industries tests the first >60% efficiency combined cycle gas turbine (the M501J) at its Takasago, Hyōgo, works.
Currently	Several gas turbines with different configurations for power generation and other applications are building by GE and Siemens companies.

B. Frame 9E and LM6000 Gas Turbines

There are ten of Frame 9E and four of LM6000 gas turbines for electricity production in Al-Quds power plant, Baghdad, Iraq. Table II shows the details of these turbines types.

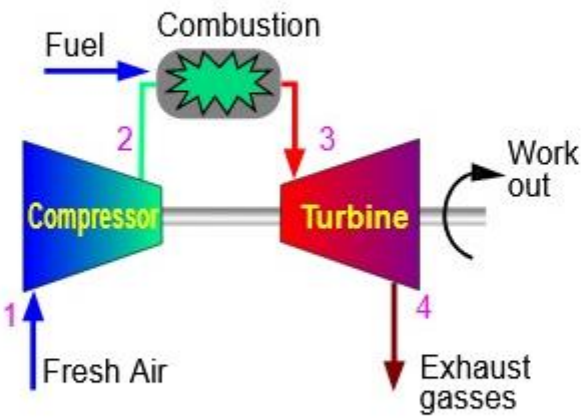
TABLE II.DETAILS OF LM6000 AND FRAME 9E GAS TURBINES

Turbine Model	Frame 9E GT	LM6000 GT
Shaft Configuration	Single	Double
Shaft Speed, (RPM)	3000	1000, 3600
Compression Ratio	10	4.8, 6.1
Compressor Discharge Pressure (CPD), (Barg)	10	29.2
Compressor Discharge Temp. (CTD), (℃)	350	550
Combustors No.	14	1
Nozzles No.	14	30
Inlet Turbine Temperature (T48), (℃)	550	850
Output Power, (MW)	110	44
Efficiency, %	34	38

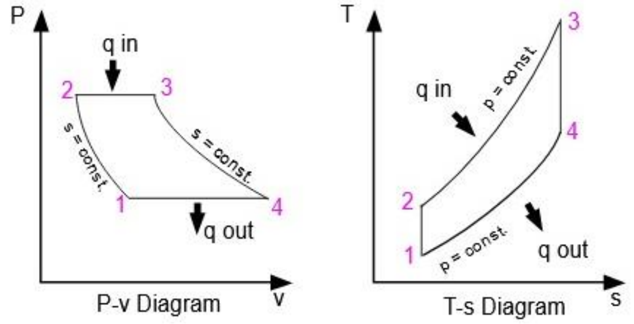
C. Theory of Operation

In a gas turbine, there are four dynamic and thermal processes that gases undergo: an isentropic compression, an isobaric (constant pressure) combustion, an isentropic expansion and heat rejection. Together, these make up the Brayton cycle.

In a real gas turbine, mechanical energy is changed irreversibly (due to internal friction and turbulence) into pressure and thermal energy when the gas is compressed (in the compressor .The specific volume of the gas increases with the increase in the amount of heat in the combustion chambers accompanied by a slight loss in pressure. Then these combustion gasses rotate the turbine during the expansion taken through it. In simple gas turbine, these combustion gasses extract to the ambient while in combined cycle it be used to generate steam to rotate steam turbine.



A. ScheaticLayout



B. P-V and T-S Diagrams

Fig. 1SimpleGas Turbine (Brayton Cycle)

D. Methods for Increasing the Output Power

1. Air Inlet Cooling (Precooling)

This method is currently used in the Al-Quds gas power plant. An evaporator system using for cooling the inlet air in Frame 9E gas turbines, whileinLM6000 gas turbines, the cold water coming from the water chillers cools the air through heat exchange in heat exchanger inside the air filter housing before entering to compressor.

The efficiency of the gas turbine increases when the air is cooled because the air molecules will be more compact because the air density will increase when the air temperature is reduced at constant pressure (Eq.1), and when the air density increases, the mass flow rate of the air will increase with a constant flow rate which equal (6512.8 scmm) approximately for LM6000gas turbines(Eq.2). Thus, the resulting power from the generating unit will increase (Fig.1).

$$p = \rho R T \rightarrow \rho \propto \frac{1}{T} \qquad \text{(Eq. 1)}$$

Mass Flowrate= Density * Volume Flowrate (Eq. 2a)

$$\dot{m}(\frac{kg}{s}) = \rho(\frac{kg}{m^3}) \times \dot{V}(\frac{m^3}{s}) \qquad \text{(Eq. 2b)}$$

Where: R= 287 J/kg K (Constant gas of air)

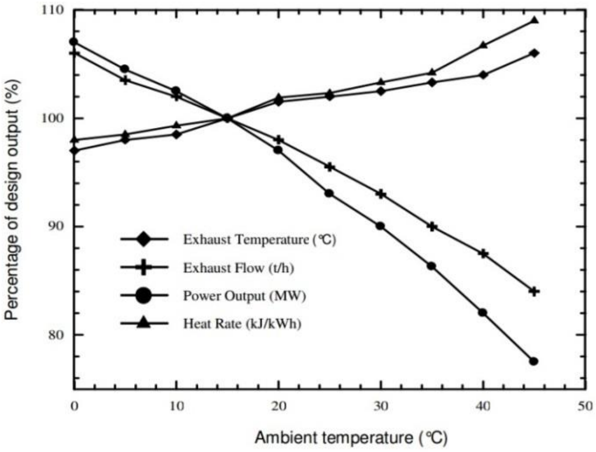


Fig. 3 Effect of ambient temperature on gas turbine performance [6]

2. Intercooling

The cooling of the compressed air between low pressure compressor and high pressure compressor is called intercooling. This method can be applied in LM6000 gas turbines, an intercooler placed between LPC and HPC for cooling the compressed air before entering to the HPC. When an air be cooled, then the work fo compression in the HPC will reduce that's lead to increase in the output power of the LM6000 gas turbine.

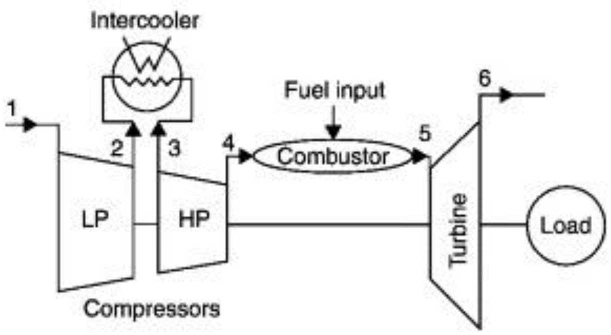


Fig.4 Schematic layout of gas-turbine power-plant with intercooler [7]

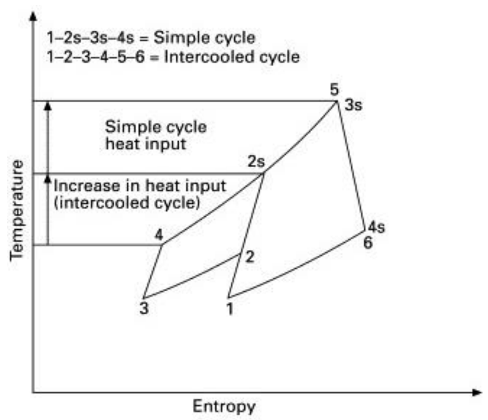


Fig.5 T-S Diagram of gas-turbine power-plant with intercooler [8]

The Work of Low Pressure Compressor:

$$\dot{W}_{LPC} = \dot{m}_{air}(h_2 - h_1) \quad \text{(Eq. 3)}$$

The Work of High Pressure Compressor:

$$\dot{W}_{HPC} = \dot{m}_{air}(h_4 - h_3) \quad \text{(Eq. 4)}$$

The Work of Turbine:

$$\dot{W}_{turb} = \dot{m}_{mix}(h_6 - h_5) \quad \text{(Eq. 5)}$$

The Output Power of Gas Turbine:

$$\text{Output Power} = \dot{W}_{turb} - (\dot{W}_{LPC} + \dot{W}_{HPC}) \quad \text{(Eq. 6)}$$

The compressor compression ratio (r_p):

$$r_P = \frac{P_{Discharge}}{P_{Suction}} \quad \text{(Eq. 7a)}$$

Compression ratio in LPC in LM6000 GT:

$$r_P = \frac{P_2}{P_1} = \frac{4.8}{1} = 4.8 \quad \text{(Eq. 7b)}$$

Compression ratio in HPC in LM600 GT:

$$r_P = \frac{P_4}{P_3} = \frac{29.2}{4.8} = 6.1 \quad \text{(Eq. 7c)}$$

Overall compression ratio in LM6000 GT:

$$r_P = \frac{P_4}{P_1} = \frac{29.2}{1} = 29.2 \quad \text{(Eq. 7d)}$$

The thermal efficiency due to compression ratio:

$$\eta_{th} = 1 - \frac{1}{r_P^{\frac{\gamma-1}{1}}} \quad \text{(Eq. 8)}$$

Where γ=1.4 (constant for air)

The thermal efficiency due to enthalpy:

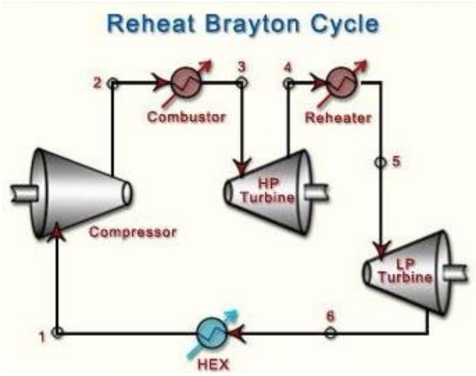
$$\eta_{intercooling} = \frac{\dot{W}_{turb} - (\dot{W}_{LPC} + \dot{W}_{HPC})}{\text{Heat added}} \quad \text{(Eq. 9a)}$$

$$\eta_{intercooling} = \frac{(h_6 - h_5) - ((h_2 - h_1) + (h_4 - h_3))}{h_5 - h_4} \quad \text{(Eq. 9b)}$$

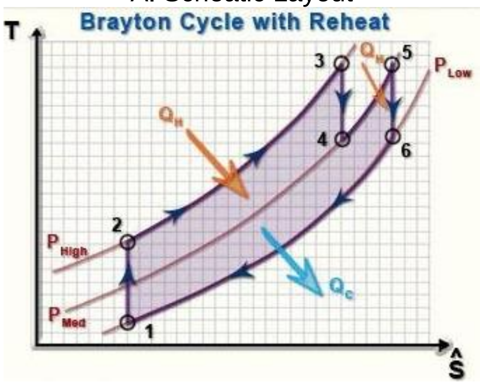
3. Reheating

Gas turbine reheating is applied in such a way as to increase the turbine work without increasing the compressor work or melting turbine materials.When gas turbines consist of two turbines, one of them is of high pressure and the other is low pressure as in LM6000 gas turbines, then the use of the reheating process will be successful.

Reheating can increase the efficiency of the gas turbine unit up to 3%.The reheating process is generally a combustion device that heats the combustion gases which leaving the high pressure turbine, and it is located between a high pressure turbine and a low pressure turbine.In this process, the fuel consumption is more, which means that the operational cost will be higher, but the unit output power will be more due to the increasing in low pressure turbine.



A. Scheatic Layout



B. T-S Diagrams

Fig. 6 Gas Turbine with Reheating [9]

Heat added in combustion chamber:

$$Q_{c.ch} = h_3 - h_2 \quad \text{(Eq. 10)}$$

Heat added in reheater:

$$Q_{reheat} = h_5 - h_4 \quad \text{(Eq. 11)}$$

The thermal efficiency of gas turbine with reheating:

$$\eta_{reheating} = \frac{(W_{HPT}+W_{LPT})-W_{comp}}{Q_{c.ch}+Q_{reheat}} \quad \text{(Eq. 12a)}$$

$$= \frac{((h_4-h_3)+(h_6-h_5))-((h_2-h_1)}{(h_3-h_2)+(h_5-h_4)} \quad \text{(Eq. 12b)}$$

4. Regenerating

The regeneration process involves the installation of a heat exchanger in the gas turbine cycle. The heat exchanger is also known as the recovery device. This process uses the combustion gases leaving the turbine to heat the compressed air leaving the compressor in Frame 9E gas turbine. Then this preheated compressed air enters the combustion chambers. When this heat exchanger is well designed, its efficiency is high in the heat exchange process with very little pressure losses. When using this heat exchanger in the generating unit, an improvement in thermal efficiency is observed. It can improve the efficiency by more than 5%, and reduce the amount of fuel spent in the combustion chambers. The regeneration process also reduces the emission of combustion gases to the atmosphere and thus is beneficial to the ozone layer.

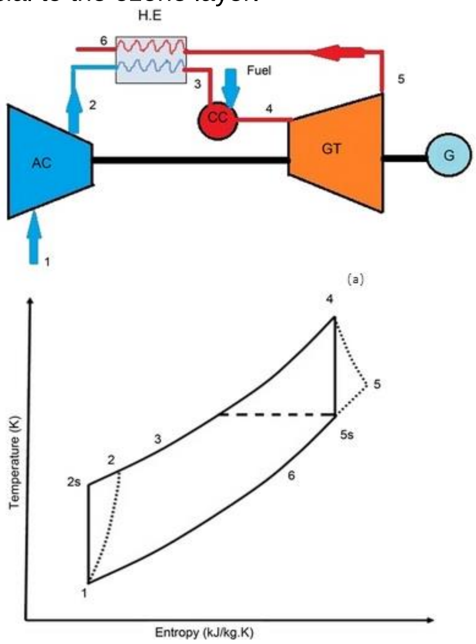


Fig. 7 Gas Turbine with Regenerating [6]

The effectiveness of regenerator:

$$\varepsilon_{regen} = \frac{h_3-h_2}{h_5-h_2} \quad \text{(Eq. 13)}$$

The thermal efficiency of gas turbine with regeneration:

$$\eta_{regenrating} = \frac{W_{turbine}-W_{comp}}{Q_{c.ch}} \quad \text{(Eq. 14a)}$$

$$= \frac{(h_5-h_4)-((h_2-h_1)}{(h_4-h_3)} \quad \text{(Eq. 14b)}$$

5. Overall Enhancing

Overall enhancing is a combination of (precooling, intercooling, reheat and regeneration methods).

Brayton cycle With cooling, heating and regeneration, the net work for a gas turbine cycle is the difference between (sum of work of high pressure turbine and work of low pressure turbine) and (sum of work of low pressure compressor and work of high pressure compressor), and the work of the compressor can either be reduced, or Increase turbine work, or both can increase.

The intercooling process between the low pressure compressor and the high pressure compressor will reduce the compressed air temperature, which leads to reducing the work required for air pressure in the high pressure compressor stage, and as a result, the output power from the turbine unit will increase.

Similarly, the work produced by the low pressure turbine can be increased by using the heater between the high pressure turbine and the low pressure turbine to heat the combustion gases, thus increasing the temperature .for next use in heating compressed air from high pressure compressor in the regenerator.

The combination of internal cooling and reheating can greatly increase the net output power of gas turbine (Brayton cycle).

Working Principle of Gas Turbine With Overall Enhancing

1. The gas (air) enters the low pressure compressor and is compressed by an isentropicprocess, where both the air temperature and pressure will rise.

2. Then this compressed air will enter to heat exchanger is called (Intercooler), where this intercooler cools the compressed air with constant pressure.

3. Thenit enters to the high pressure compressor with high pressure and temperature less compared to the simple cycle, where the air is compressed to a pressure and temperature much higher than the exit point from the intercooler.

4. After that, the compressed air enters the regenerator, where it is heated at constant pressure by heat exchange with combustion gases from the low pressure turbine in closed system. In ideal regenerator, the air leaving the regenerator will be at temperature equal to the temperature of the combustion gases leaving the low pressure turbine.

5. Then the air that coming from the regenerator enters the combustion chambers (air+fuel+ignitor), where the combustion process takes at constant pressure, then the combustion gases will be produced with a pressure equal to the pressure of the air coming out of the regenerator and the high pressure compressor respectively and at a very high temperature.

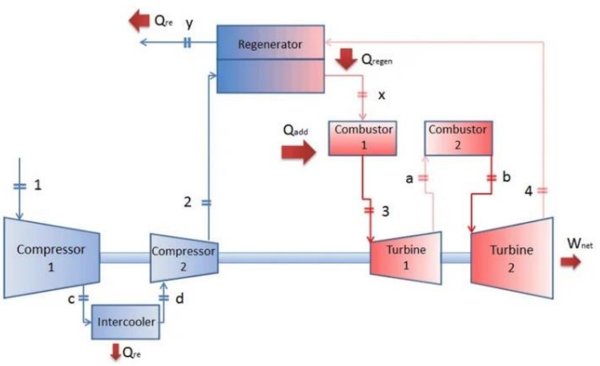
6. These combustion gases with high pressure and temperature will rotate the high pressure turbine and the low pressure turbine, which in turn rotate the high pressure compressor and the high pressure compressor, as the two compressors are considered as lost energy according to the law of thermal efficiency of the gas turbine.

In the high pressure turbine stage, during the combustion gases are expanded by isentropicprocess, then the temperature and pressure will decrease.

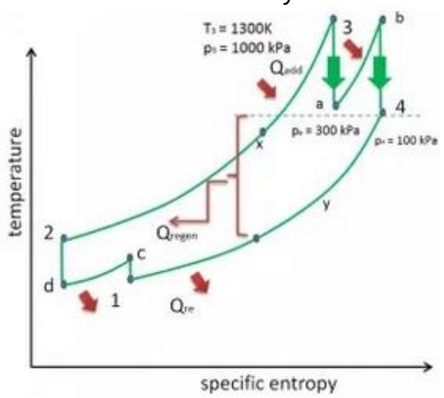
7. Then the combustion gases enter the heater to reheat the combustion gases at constant pressure. Then the combustion gases enter the low pressure turbine, where the expansion is also done by an isentropicprocess to a pressure and temperature lower than the exit point from the heater.

8. The outside of the low pressure turbine goes to the regenerator to heat the air leaving the high pressure compressor with constant pressure and in an isolated process, after that the combustion gases come out to the atmospheric with low pressure and low temperature as a result of cooling by the air outside the high pressure compressor.

These processes (compression, cooling, regeneration, combustion, expansion and reheating) are shown in the figure below.



A. Scheatic Layout



B. T-S Diagrams

Fig. 8 Gas Turbine with Overall Enhancing [6]

Heat rejected in intercooler:

$$Q_{int} = (h_d - h_c) \quad \text{(Eq. 15)}$$

Heat added in reheater:

$$Q_{int} = (h_b - h_a) \quad \text{(Eq. 16)}$$

The effectiveness of regenerator:

$$\varepsilon_{regen} = \frac{h_x - h_2}{h_4 - h_2} \quad \text{(Eq. 17)}$$

The thermal efficiency of intercooled/reheat/regenerative cycle:

$$\eta_{th} = \frac{(W_{HPT}+W_{LPT})-(W_{LPC}+W_{HPC})}{Q_{c.ch}+Q_{reheat}} \quad \text{(Eq. 18a)}$$

$$= \frac{((h_a-h_3)+(h_4-h_b))-((h_c-h_1)+(h_2-h_d))}{(h_3-h_x)+(h_b-h_a)} \quad \text{(Eq. 18b)}$$

III. Conclusions

It was concluded that it is possible to increase the production of electrical energy from the gas turbines in Al-Quds power plant through several methods, which are: Insert a heat exchanger called the intercooler between the low pressure compressor and the high pressure compressor to reduce the work of high pressure compressor, also insert a heater between the high pressure turbine and the low pressure turbine called reheater to increase the work of low pressure turbine, and also insert a regenerator to increase the temperature of the compressed air, thus reducing the amount of fuel spent. These methods (configurations) are reducing the level of pollution level that come out from the gas turbine, so there are two benefits of this paper; increase the output power of the gas turbines in Al-Quds power plant and decrease the pollution.

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Symbols

GT: gas turbine
LPC: low pressure compressor
HPC: high pressure compressor
HPT: high pressure turbine
LPC: low pressure turbine
CPD: compressor discharge pressure
CTD: compressor discharge temperature
c.ch: combustion chamber
th: thermal
T48: inlet turbine temperature
scmm: standard cubic meter per minute
P: pressure, (kpa)
T: temperature, (℃)
v: specific volume, (m^3/kg)
s: specific entropy, (J/kg K)
Q: heat, (Watt)
$\dot{m}$:air mass flow rate, (kg/s)
ρ: density, (kg/m^3)
R: gas constant of air, (287 J/kg K)
h: enthalpy, (J/kg)
$\dot{W}$: Work, (Watt)
r_p: compression ratio, (-)
η: efficiency, (%)
γ: heat capacity ratio, (-)

References

[1] Taniquchi, H. and Miyamae, S. Power generation analysis for high temperature gas turbine in thermodynamic process. Journal of Propulsion and Power, 16: 557-561. 2000.

[2] Horlock, J.H. Advance gas turbine cycles. UK: Pergamon. 2003.
[3] Cengel, A. Y. and Boles, A.M. Thermodynamics an engineering approach. New York: McGraw-Hill. 2008.

[4] Nag, P.K. Power plant engineering. New Delhi: Tata McGraw-Hill Publishing Company Limited. 2008.

[5] Wang. F.J. and Chiou, J.S.Performance improvement for a simple cycle gas turbine GENSET-a retrofitting example.Applied Thermal Engineering. 22: 1105-1115. 2002.

[6] Rahman et. al. Thermodynamic performance analysis of gas-turbine power-plant. 2011.

[7] MarkDooner, Jihong Wang, in Future Energy(ThirdEdition), 2020.

[8] A.M.Y. Razak,inModern Gas Turbine Systems, 2013.

[9] Antonio Cilindro, UniversitàdegliStudidella Campania "Luigi Vanvitelli, thesis, Performance Analysis and Economic Effects of Maintenance and Hot Gas Path Inspection of a Combined Cycle Power Plant.2015