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Thermal Analysis of a Combined Cycle Power Plant under Varying Operating Conditions

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Abstract

Combined Cycle Power Plants are preferred for their high efficiency and low pollutant emissions. Combined cycle power plants are becoming increasingly prevalent in the Jordanian electric market place. The output of CCPPs in operation in Jordan counts 2,180 MW which represents 55% out of total installed generation capacity. In this work, the effect of Turbine Inlet Temperature on the net output work and thermal efficiency of the combined cycle are investigated. The power output and thermal efficiency are increasing with increasing Turbine Inlet Temperature. The performance of the power plant was analyzed for two types of fuels; natural gas and fuel oil with 100% and 75% load factors. It was found that Al-Qatrana Power Plant has a maximum efficiency of 43.25% when operated with 100% NG. This produces 374.62 MW total output power. Increasing Turbine Inlet Temperature increased the overall thermal efficiency to 43.69% and the total output power to 378.51MW.

Keywords: CCPP, power plant, TIT;

List of abbreviations

CCPPs	Combined Cycle Power Plants
TIT	Turbine Inlet Temperature
NG	Natural Gas
FO	Fuel Oil
ST	Stem Turbine
GT	Gas Turbine
HRSG	Heat Recovery Steam Generator
AQPP	Al-Qatrana Power Plant
CHP	Combined Heat and Power
OTC	Outlet Temperature Control

1. INTRODUCTION

Combined Cycle Power Plants (CCPPs) are the preferred technology for electricity generation due to its high efficiency and low emitted pollutants. CCPPs' efficiency ranges from 40 - 60%. CCPP consists of a Gas Turbine (GT), Heat Recovery Steam Generator (HRSG), Steam Turbine (ST), condenser, and balance of plant equipment such as fuel system, boiler feed pump, water treatment plant, etc. The major difference between a conventional power plant and a combined cycle power plant is that the CCPP utilizes exhaust gases from GT to turn water into steam inside the HRSG. In the CCPP, both the GT and ST produce electricity, whereas, in conventional power plants, electricity is produced in ST only.

According to thermodynamic principles, inputs and outputs are needed to calculate the efficiency of a system. If the efficiency of the system under study is less than the recommended efficiency by the manufacturer, a deep analysis of the system should be conducted to reduce losses and increase efficiency. Due to the difference between actual and recommended Al-Qatrana Power Plant (AQPP) efficiencies, energy analysis for AQPP is required to improve the power plant performance. This will be reflected on the plant's output power, consumed fuel, and emissions.

There are several methods used to improve power plant efficiency. Energy analysis of the power plant and its operating parameters is one of these methods. In this context, many studies have been delivered in the last few years. Jamnani and Kardgar [1] performed energy-exergy analysis for the gas-fired combined-cycle power plant which will be constructed in Kuantan and Kapar in the Malay Peninsula in 2020. The study revealed that numerous considerations for the CCPPs can be implemented to identify irreversibilities and use several methods to improve plant performance. Suresh et al [2] applied thermodynamic analysis on a Combined Heat and Power (CHP) plant. Energy and exergy analyzes are carried out based on the first and second thermodynamics laws for power generation systems including a 10 MW solar combustion gas turbine, a 4 MW steam turbine, a 100,000 pph heat recovery steam

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generator (HRSG), three 125,000 pph package boilers and auxiliary equipment. They used actual system data to assess the district heating system performance, energy and exergy efficiencies, exergetic improvement potential, and exergy losses. The results showed how thermodynamic analysis can be used to identify the magnitudes and location of energy losses to improve the existing system, processes, or components. Polyzakis et al [3] analyzed a combined cycle power plant describing and comparing four different gas turbine cycles; simple cycle, inter-cooled cycle, reheated cycle and intercooled and reheated cycle. The proposed combined cycle plant would produce 300 MW of power (200 MW from the gas turbine and 100 MW from the steam turbine). They showed that the reheated gas turbine is the most desirable, mainly because of its high turbine exhaust gas temperature which causes the high thermal efficiency of the bottoming steam cycle. They concluded that the optimal gas turbine cycle leads to a more efficient combined cycle power plant (CCPP). Fellah et al., [4] conducted an exergoeconomic analysis for Unit Gt14 of South Tripoli Gas Turbine Power Plant. The analysis assists in the understanding of the cost value associated with exergy destroyed in a thermal system, and hence provides energy system's designers and operators with the information, necessary for operating, maintaining, and evaluating the performance of energy systems.

Ankur Geete and A.I.Khandwawala [5] generated correction curves for power and heat rate. The thermodynamic analysis of 120 MW thermal power plant has been done at particular inlet pressure and at different inlet temperatures. Mohanty and Venkatesh [6] studied the effect of various operating parameters such as TIT and pressure ratio of the Brayton cycle on the net output work and thermal efficiency of the combined cycle. They found that TIT of Brayton cycle has significant effects on the performance of the CCPP. Also, they found that the power output of Rankine cycle is strongly affected by TIT. Lebele-Alawa and Asuo [7] studied the effect of the variation of power turbine inlet temperature on the performance of a gas turbine. They found that when TIT was reduced, the turbine efficiency and power output were reduced. Ersayin and Ozgener [8] implemented a performance analysis of an operating power plant with actual operating data acquired from the power plant control unit. Energy and exergy efficiencies of each component of the power plant system were calculated. They applied the first law and the second law of thermodynamics, energy and exergy efficiencies of the combined cycle power plant were found as 56% and 50.04% respectively. Kumar and Singh [9] developed a general model of a combined cycle performance for varying TIT. They found that by increasing TIT from 1600 K to 1800 K, the combined cycle efficiency increases by 2.37%, and the combined specific work increases by 185.42 kJ/kg. Recently, several researchers studied the use of solar energy for integration with power-plant units. Ahmadi et al., [10] investigated a full repowering simultaneously with merging solar energy in 200 MW units of Montazeri steam power plant in Iran. The study indicated that the energy and exergy efficiencies have increased.

Due to the difference between actual and recommended Al-Qatrana Power Plant (AQPP) efficiencies, energy analysis for AQPP is required to improve the power plant performance. In this work, the actual performance of Al-Qatrana Power Plant (AQPP) has been calculated using data extracted from the plant's control system and compared with the theoretical ones. The difference between the actual and theoretical performance measures the potential for future improvements. Furthermore, the performance of the AQPP has been evaluated under the variation of two operating parameters; fuel types and power output factor. The study analyzed the effect of these variations on power output and thermal efficiency. These parameters were selected because they are the main parameters that affect the operation performance. After performance evaluation under these parameters completed, the effect of increasing TIT on actual power output and thermal efficiency has been studied as a suggested improvement.

2. THEORETICAL BACKGROUND

Thermodynamic principles are used to determine the energy content of a system and to calculate system efficiency.

Energy balance for a system undergoing any kind of process is expressed in Equation 1 [11, 12]

$$E_{in} - E_{out} = \Delta E_{system} \quad (1)$$

Equation 2 is the control volume energy rate balance for a steady state steady flow process, [11, 12]

$$\dot{Q}_{C.V} + \sum \dot{m}_i \left(h_i + \frac{V_i^2}{2} + g.Z_i\right) = \sum \dot{m}_e \left(h_e + \frac{V_e^2}{2} + g.Z_e\right) + \dot{W}_{C.V} \quad (2)$$

Figure 1 illustrates the energy flow in CCPP. The energy chain at CCPP is divided into two areas; GTG and STG. In GTG, fuel burns inside combustion chambers and produces heat that drives the turbine and generator where the work is produced. The flue gas leaves the GTG at a temperature of 500 °C or more. Flue gas is directed to HRSG to produce superheated steam which drives the STG to generate the second portion of work. As a result, the total work produced from CCPP is the work from GTG and STG.

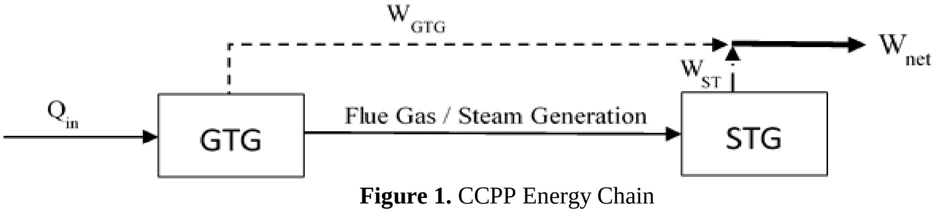

Figure 1. CCPP Energy Chain

Combined cycles have separate cycles with different fluids; air and flue gases inside Brayton cycle and water or steam in Rankine cycle. The enthalpy of each fluid is calculated as follows:

1. The enthalpy of the ideal gas mixtures is determined as the sum of the particular properties of the component gases as shown in Equation 3

$$h = \sum_{i=1}^{k}(mf_i * h_i) \tag{3}$$

where $h_i = c_{pi}dt$, $cp = \sum_{i=1}^{k}(mf_i . cp_i)$

mf_i is a practical mass fraction of ideal gas, c_{pi} is obtained from the table of each gas at a certain temperature.

2. The thermodynamic properties of the water and steam are obtained from steam tables at a certain pressure and temperature

The thermal efficiency of CCPP is calculated using equation 4 [11, 12], where the W is the output work in and Q is the heat added by burning the fuel, either in terms of kJ or kJ/kg.

$$\eta_{th} = \frac{W_{net}}{Q_{in}} \quad or \qquad \eta_{th} = \frac{w_{net}}{q_{in}} \tag{4}$$

One of the methods used to improve the efficiency of a gas turbine is to increase the turbine inlet temperature. TIT is one of the most critical parameters which influence the gas turbine performance. Usually, TIT is kept constant during GT operation. Increasing TIT will be reflected on CCPP efficiency and power output. It should be ensured that TIT temperature increase has no negative impact on GT's material strength and burner's performance.

The basic principle of combustion chamber operation is based on the energy balance principle. The direct effect of TIT on flue gas energy is calculated using Equation (5) [6],

$$m_a C_{pa} T_2 + m_f \times LHV + m_f C_{pf} T_f = (m_a + m_f) C_{pg} \times TIT \tag{5}$$

Where m_f is the mass flow rate of the fuel (kg/s), m_a is the mass flow rate of air (kg/s), LHV is low heating value, TIT is the turbine inlet temperature, C_{pa}, C_{pf} and C_{pf} are the specific heat of air, fuel and flue gases respectively, and T_f is the temperature of the fuel.

Increasing TIT should be within the acceptable range of the GTG manufacturer. Moreover, the effect on HRSG and STG should also be evaluated and consulted with the manufacturers. It should also be ensured that increasing TIT will not affect GTG and HRSG materials and burner's performance

3. PLANT DESCRIPTION AND ANALYSIS

Al-Qatrana electric power company (AQPP) is a private shareholding company producing 373 MW in Al-Qatrana town. AQPP consists of two GT, two HRSG, one ST, an air-cooled condenser (ACC), and a balance of plant equipment such as fuel systems, boiler feed pumps, water treatment plant, etc. as shown in figure 2 [13]. AQPP uses Natural Gas as a primary fuel, and Fuel Oil as a backup fuel. The GTs used in AQPP are Siemens SGT5-2000E. They are using Outlet Temperature Control (OTC) that controls (but not measure) temperature inside GT combustion chamber. OTC value depends on GT exhaust temperature and ambient temperature. TIT can be increased by increasing OTC value. A standard combined cycle is considered for the present analysis. Air after compression in the compressor enters the combustion chamber where its temperature is raised by the combustion of fuel. The gases then expand in the turbine and produce the work output part of which is supplied to run the compressor. The heat carried by the exhaust gases is recovered in the HRSG to generate steam for expansion in the steam turbine.

AQPP has been operating for ten years as a baseload power plant. The plant is always in-operation except for the annual maintenance. Table (1) shows the operation parameters such as energy consumption, production, and performance indicators for the AQPP power plant for three years. The actual performance is compared with the theoretical one. The energy analysis is performed on the power plant using two types of fuels; natural gas (NG) and fuel oil (FO) with 100% and 75% load factors.

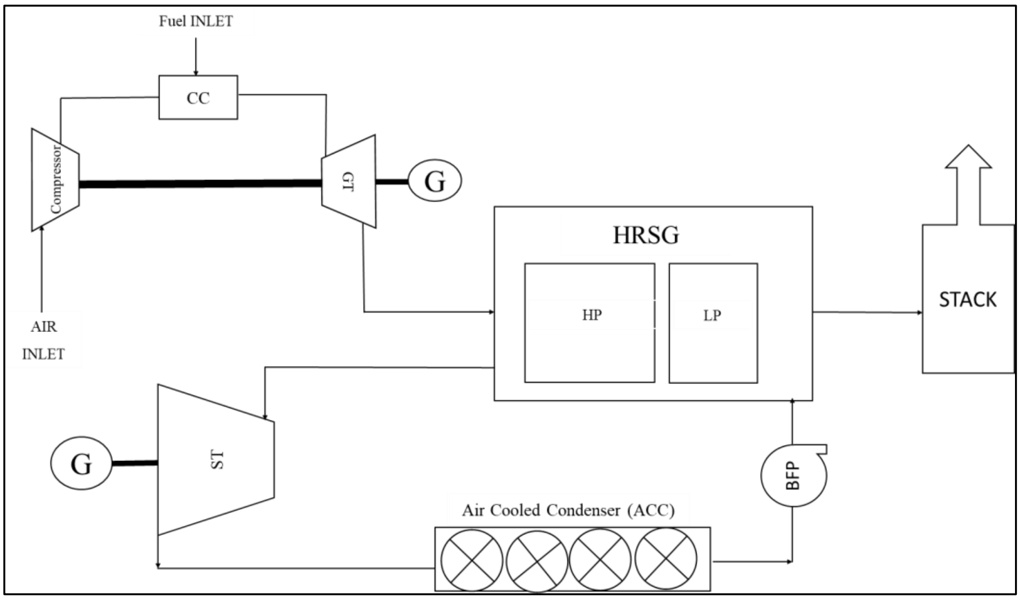

Figure 2. Schematic diagram of AQPP

Table 1. AQPP Operation Parameters

Item	Year 1	Year 2	Year 3
Generated Energy (MWh)	2,436,533	1,509,033	2,274,288
FO Consumption (GJ)	11,150,879	2,489,148	15,196,597
NG Consumption (GJ)	9,105,093	10,523,838	3,934,116
Internal consumption Rate (%)	1.70%	1.89%	1.62%
Plant Availability (%)	97.46%	92.59%	92.70%
Utilization Factor (%)	73.43%	45.63%	68.60%
Actual Efficiency (%)	39.56%	37.95%	38.96%

In Table 1, the fuel used over the period is a mix of NG and FO, due to a shortage in NG supply. In the second year, the planned maintenance was longer than the other two years. The effect of this breakdown is shown in the reduction in the generated energy, plant availability, and utilization factor percentage. The actual efficiency is calculated annually when AQPP is operated using both fuel types and various power output ranges.

The data required to calculate the theoretical performance of AQPP is taken from the manufacturers of the power plant equipment (GT, STG, and HRSG) at AQPP reference conditions. The actual performance of AQPP is conducted in normal operation days. The actual performance is corrected to reference conditions because values are related to reference conditions such as site conditions and the operational parameters of plant equipment. The corrections curves are usually supplied by the original equipment manufacturers. Table 2 presents AQPP reference conditions.

The three correction factors listed below are the most important factors which indicate the operational effects on thermal input and power and thus requiring all measured values of the thermal input and power to be corrected to reflect the accurate analysis and results; these factors have been considered for the energy analysis of this work:

1. Ambient temperature
2. Ambient pressure
3. Ambient humidity

Table 2. AQPP reference conditions

Item	Reference value
Barometric Pressure	0.9270 bar
Inlet Air Temperature	36 °C
Relative Humidity	55 %
Frequency	50 H z
Power Factor	0.85

The cycle thermal efficiency and output power were calculated using two fuels; NG and FO with different load factors. The operation matrix is presented in Table 3.

Table 3. Operation Matrix

Fuel type	Output load factor	
NG	100 % of full output power	75 % of full output power
FO	100 % of full output power	75 % of full output power

The actual thermodynamic properties of each stream are shown in Table 4. These properties were collected from AQPP control system. Equation 3 is used to calculate the enthalpy of each stream. It is more accurate to calculate the enthalpy of the mixture as a summation of individual species enthalpies rather than taking a rough estimation that the whole mixture behaves as air [14]. In this work, the enthalpies for each case under study were calculated based on exhaust gas percentages presented in Table 4.

Table 4. Plant Streams Thermodynamic Properties

NG Operation											
Power Output Factor			100 %					% 75			
	Component	State	T [˚C]	P [kPa]	m [kg/s]	h [kJ/kg]		T [˚C]	P [kPa]	m [kg/s]	h [kJ/kg]
1	Compressor	Inlet air	5.85	91.43	1030.00	280.02		15.78	92.25	945.00	288.94
2	Compressor	Outlet air	332.00	1110	1030.00	613.21		314.60	901.76	945.00	626.33
3	Turbine	fuel inlet (NG)	52.04	1999.52	20.00	4605.00		117.30	2053.65	15.00	878.94
4	Turbine	Turbine outlet	527.64	137.60	1050.00	958.92		529.21	110.00	960.00	954.93
5	HRSG	Main stack	132.38	101.00	1050.00	442.61		123.25	101.00	960.00	431.90
6	HRSG	inlet Water	48.26	2389.90	125.01	204.10		45.75	2385.37	102.24	193.60
7	STG	HP Steam	506.15	7009.32	106.15	3425.12		511.25	6606.00	84.00	3442.00
8	STG	LP Steam	193.76	465.18	17.04	2844.00		194.69	317.20	15.38	2854.00
9	STG	Exhaust steam	52.89	15.00	123.20	2362.00		45.10	10.00	99.38	2345.00
10	ACC	Condensate	47.07	37.36	123.20	197.10		44.20	35.64	99.38	185.10
FO Operation											
Power Output Factor			%100					%75			
	Component	State	T [˚C]	P [kPa]	m [kg/s]	h [kJ/kg]		T [˚C]	P [kPa]	m [kg/s]	h [kJ/kg]
1	Compressor	Inlet air	30.12	91.39	866.33	309.82		11.69	92.62	791.82	309.82
2	Compressor	Outlet air	355.04	1013.98	866.33	673.74		289.60	830.59	791.82	673.74
3	Turbine	fuel inlet (FO)	33.05	516.01	18.67	535.58		28.77	313.40	14.18	528.10
4	Turbine	Turbine outlet	518.01	121.68	885.00	944.64		484.37	104.53	806.00	944.64
5	HRSG	Main stack	172.44	101.30	885.00	488.16		165.86	101.30	806.00	488.16
6	HRSG	inlet Water	52.21	2028.43	97.00	220.30		52.67	2553.09	84.60	222.60
7	STG	HP Steam	501.51	6574.60	94.06	3419.00		494.47	6517.37	79.56	3403.00
8	STG	LP Steam	197.09	279.00	2.68	2861.00		197.87	234.00	4.99	2864.00
9	STG	Exhaust steam	50.18	10.14	96.74	2354.00		51.20	10.25	84.55	2595.00
10	ACC	Condensate	50.06	38.74	96.74	209.60		51.06	40.22	84.55	213.80

Table 5. Exhaust Gases Composition

Fuel type	NG		FO	
Output power factor	100%	75%	100%	75%
CO2	3.34%	3.21%	4.15%	3.98%
N2	75.18%	75.27%	76.21%	76.27%
H2O	7.01%	6.76%	4.36%	4.21%
O2	13.60%	13.87%	14.37%	14.63%

Table 5 was used to calculate the actual thermal efficiency and power output. The calculated values were corrected to reference conditions. These values were compared with the theoretical ones that have been calculated using manufacturers' data.

4. RESULTS AND DISCUSSION

AQPP thermal efficiency and power output were calculated and presented in Figures 3 and 4. Using NG (100% load factor) leads to the highest efficiency and power output for theoretical and actual cycles. The maximum difference (4.59%) between theoretical and actual cycle efficiency is obtained when NG 100% load factor is used. The minimum difference (2.88%) between theoretical and actual cycle efficiency is achieved when FO 75% load factor is used. The difference between theoretical and actual output power is around 5 MW for all fuels with different load factors except NG 75% load factor. Operating the power plant using NG is more efficient than using FO due to the fact that GT power output and HRSG efficiency are higher when NG is used. As shown in Table 5 the flue gas leaves the combined cycle at 132 °C and 172 °C when GT operates using NG and FO respectively. This dissipates more energy when the plant is operated using FO. The plant draws hotter flue gases to the atmosphere in case of FO operation to avoid SO_X dew point on the main stack because FO contains more sulfur than NG.

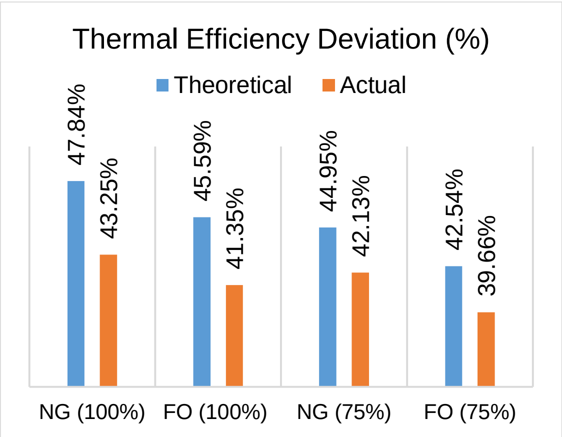

Figure 3. Theoretical and Actual Thermal Efficiency

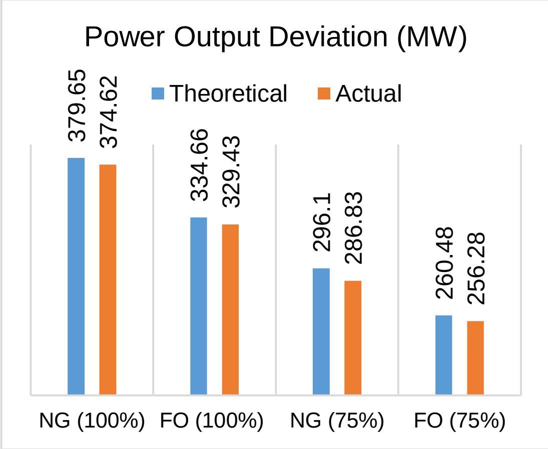

Figure 4. Theoretical and Actual Power Output

The turbine inlet temperature (TIT) plays an important role on the performance of combined cycle. Table 6 presents the effect of increasing TIT on GT power output, GT efficiency, plant overall thermal efficiency, and plant power output. The actual performance of AQPP has been calculated using data extracted from the plant's control system. OTC was increased from 523 °C to 533 °C (10 degrees). The test was conducted at 100% load factor using NG. TIT significantly affects the performance of the gas turbine engine. GT output, GT efficiency, plant overall thermal efficiency, and plant power output are improved by increasing TIT temperature. TIT should be kept higher to minimize losses in the gas turbine system. Increasing the TIT increases the output power and thermal efficiency as a result of increasing the turbine work. For STG, GT flue gas mass flow rate is increased which is reflected positively on steam quantity produced from HRSG. GT power output has a direct relation with TIT. In summary, Power output is increased when TIT is increased due to GT and STG power output increase. Kaviri et al. [15], indicated that increasing the gas turbine inlet temperature decreases the combustion chamber exergy destruction. The reason is due to the fact that this increase leads to the decrease of the entropy generation. Compared to Sanjay [16], the parameter that affects cycle performance most is the TIT (turbine inlet temperature).

Table 6. The effect of increasing TIT on power plant performance

	OTC (523 ºC)	OTC (533 ºC)	Improvement
GT Efficiency (%)	29.35	29.87	0.52
Overall Efficiency (%)	43.25	43.69	0.44
GT power output (MW)	127.14	129.25	2.11
Power plant power output (MW)	372.63	378.51	5.88

The actual results are compared with theoretical ones. The difference between the theoretical cycle efficiency and the actual cycle efficiency was reduced from 4.5% to 4.1% as shown in figure 5. The effect of increasing TIT on the overall power output is presented in figure 6. The calculations revealed that the power output increased from 374.62 MW to 378.51 MW with a difference of 4.1 MW between the theoretical and the improved cycle.

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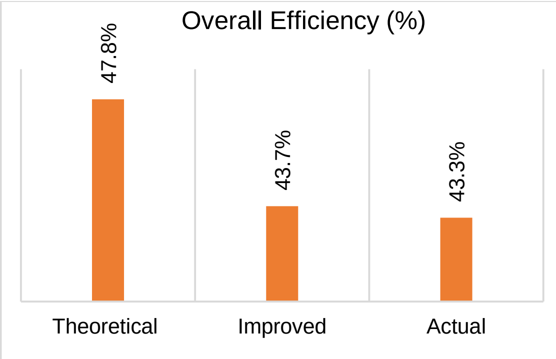

Figure 5. Theoretical and Improved Overall Thermal Efficiency deviation

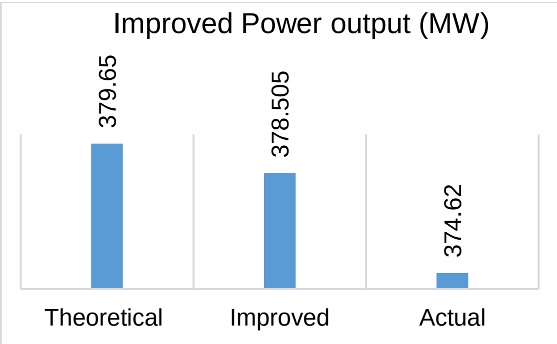

Figure 6. Theoretical and Improved Plant Overall Power output Gap

The study results provide useful information and guidelines to power plant engineers and operators; such as choosing possible performance enhancement modifications to combined cycle power plants.

5. CONCLUSIONS

The current study presents an analysis of Al-Qatrana combined cycle power plant using real data extracted from the plant's control system. The effect of TIT on GT power output, GT efficiency, plant overall thermal efficiency, and plant power output was calculated and compared with the theoretical values. The turbine inlet temperature significantly affects the performance of the combined cycle. It should be kept on the higher side for minimizing the exergy losses. The results obtained were validated against published data. Furthermore, the performance of the power plant was analyzed for two types of fuels; natural gas and fuel oil with 100% and 75% load factors. Operating the power plant using NG is more efficient than FO.

These results are very helpful for future improvements because the difference between the actual and theoretical performance measures the potential for future improvements. This difference could be further reduced by increasing HRSG heat transfer efficiency.

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