Study The Effect of Steam Injection on Gas Turbine Performance

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دراسة تأثير حقن البخار على أداء التوربين الغازي

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Abstract:
This study aims to evaluate the impact of steam injection technology on the performance of the Siemens SGT5-2000E gas power plant in western Tripoli, Libya, using the ASPEN Plus software for performance analysis. The results showed that steam injection increased efficiency by 52.55% and enhanced electrical power output by 53.5% compared to the conventional plant. Specific fuel consumption decreased by 34.76%, while CO_2 emissions were reduced by 34.73%. An analysis of the effect of ambient air temperature (ranging from 15°C to 45°C) revealed that efficiency dropped by 1.3% for every 5°C increase without steam injection, whereas the drop was only 0.9% with steam injection. Regarding specific fuel consumption, it increased by 1.58% without the technology and by 1.01% with it. For CO_2 emissions, the increase was 1.58% without using the technology and 1.01% with its application. Additionally, an availability analysis was conducted to evaluate the system's effectiveness. The results indicated that steam injection technology contributes to improving the overall availability of the plant by reducing exergy losses and enhancing combustion stability, leading to better performance under varying operating conditions.

Keywords: Gas turbines, Steam Injection Technology, Aspen Plus.

الملخص:
تهدف هذه الدراسة إلى تقييم تأثير تقنية حقن البخار على أداء محطة الغاز Siemens SGT5-2000E في غرب طرابلس، ليبيا، باستخدام برنامج ASPEN Plus لتحليل الأداء. أظهرت النتائج أن استخدام حقن البخار زاد الكفاءة بنسبة 52.55% ورفع الطاقة الكهربائية المنتجة بنسبة 53.5% مقارنة بالمحطة التقليدية. كما انخفض الاستهلاك النوعي للوقود بنسبة 34.76% وانبعاثات ثاني أكسيد الكربون بنسبة 34.73%. تم أيضًا إجراء تحليل لتأثير درجة حرارة الهواء المحيط من 15 إلى 45 درجة مئوية، حيث انخفضت الكفاءة بمعدل 1.3% لكل 5 درجات مئوية عند عدم استخدام حقن البخار، بينما كان الانخفاض 0.9% مع استخدامه. بالنسبة للاستهلاك النوعي للوقود، زاد بمعدل 1.58% دون التقنية، بينما كان 1.01% مع تطبيقها. وبالنسبة لانبعاثات ثاني أكسيد الكربون، كانت الزيادة 1.58% دون استخدام التقنية و1.01% مع استخدامها. بالإضافة إلى ذلك، أُجري تحليل الإتاحة لتقييم فعالية النظام، حيث أظهرت النتائج أن تقنية حقن البخار تسهم في تحسين الإتاحة الكلية للمحطة من خلال تقليل الفقد الإكسيرجي وتعزيز استقرار عمليات الاحتراق، مما يؤدي إلى تحسين الأداء في ظل ظروف التشغيل المختلفة.

الكلمات المفتاحية: محطات الطاقة الغازية، تقنية حقن البخار، أسبن بلس.

Introduction:

Gas turbine power plants are among the most effective sources of electricity generation due to their high efficiency and ability to rapidly respond to increasing energy demands [1]. In Libya, these power plants constitute an integral part of the national electricity generation system, with installations such as the West Tripoli and South Tripoli gas power plants, among others. However, the efficiency of these plants is significantly affected by local environmental factors such as temperature and relative humidity, which experience notable variations across seasons [2,3]. These factors necessitate improving gas turbine plant efficiency to reduce fuel consumption and harmful emissions while maintaining high performance levels [4]. The interquartile range and mean vibration values showed variations between winter and summer, reflecting the unit's response to fluctuating operating conditions. Results indicate that the rate of rapid response was consistently lower in summer, pointing to more stable and optimal operational conditions during this period [5]. Using MATLAB, the impact of ambient air temperature and compressor pressure ratio on thermodynamic performance was studied. Energy analysis results revealed that the average net thermal efficiency of the Siemens GT5-2000E gas power plant is 30.21% within an ambient air temperature range of 21°C to 35°C. The net power output ranges from 148.92 MW to 160.70 MW, with 60.16% of the fuel energy input lost as waste heat to the plant's surroundings. Additionally, the results demonstrated that an increase in ambient air temperature by 1°C led to a 1.16% decrease in net power output, a 1.58% reduction in net thermal efficiency, and a 1.58% increase in specific fuel consumption (SFC) and combustion rate [2]. The findings also showed that higher ambient air temperatures and air-fuel ratios resulted in increased carbon dioxide emissions, while higher relative humidity and compressor pressure ratios reduced these emissions. Furthermore, the average carbon dioxide emissions amounted to 644.893 kg of CO_2 per MWh [6]. Low-cost technological cycle modifications to enhance gas turbine performance remain largely underutilized. Among these proven modifications are steam-injected gas turbines. Steam injection is a power generation system that combines the principles of gas turbines and steam turbines to improve overall efficiency and power output. This technique is designed to enhance gas turbine performance by injecting steam into the combustion process [7]. The method involves introducing steam into the combustion chamber, where recovered steam is injected into the heat recovery steam generator (HRSG) by utilizing exhaust gases from the gas turbine combustion chamber [8]. This increases the amount of combustible air, thereby improving performance efficiency and boosting power output. Studies have demonstrated that steam injection can enhance the thermodynamic performance of gas turbine systems, making it a highly significant technology for improving the effectiveness of power plants [9,10]. Steam injection cools the combustion gases, reducing the risk of turbine blade damage caused by high temperatures. Properly treated water used to produce steam has no adverse effect on the lifespan of hot turbine parts. This is supported by numerous units where steam injection has been implemented. Moreover, steam injection allows gas turbines to operate at higher temperatures, improving their efficiency. It also increases the mass flow rate of gases passing through the turbine, which can enhance power output. Additionally, it can help reduce the production of nitrogen oxides (NOx), which are harmful pollutants [7,11]. The study examined the impact of steam injection on the performance of heavy-duty turbines, highlighting its operational benefits in improving system performance [11]. Furthermore, thermodynamic analysis of steam injection technology in gas systems illustrates the effectiveness of this technology in enhancing performance [12]. The SGT5-2000E turbine features a robust design and flexibility to accommodate various types of fuel [13]. It is equipped with a low-NOx emission combustion system and the capability to use water injection technology to boost productivity. This demonstrates the potential for adopting similar technologies, such as steam injection, to enhance performance and efficiency [14]. This study aims to enhance the efficiency of power plants and achieve sustainable development goals by implementing advanced and effective technologies, contributing to energy savings and minimizing environmental impacts. The performance of steam injection technology will be explored and evaluated through a practical study on SGT5-2000E gas turbines in Libya.

Methodology:

This study relies on analyzing the performance of thermal systems using a comparative approach, based on references and technical documents issued by the manufacturer, alongside the use of simulation software to design a higher-performing plant. Aspen Plus is utilized as a powerful tool for mass and energy balance, aiding in the simulation of power generation systems and analyzing the performance of various components. It is instrumental in identifying optimal operating conditions to enhance efficiency and reduce fuel consumption. Additionally, the software allows testing of different scenarios and analyzing their impact on overall plant performance. Aspen Plus is one of the leading tools for simulating and analyzing industrial processes, including power plants, thanks to its advanced mathematical models and ability to deliver accurate analyses.

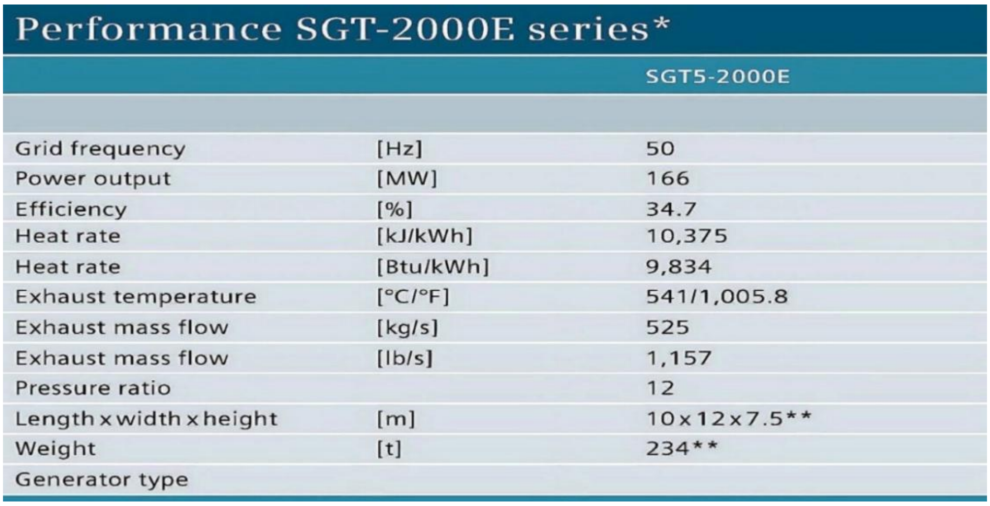
Methodological Steps Followed in the Study:

- Identify the challenges facing gas turbine plants by reviewing documents and previous studies related to the subject.
- Review previous studies analyzing the thermodynamic performance and energy efficiency of gas turbine plants.
- Review prior research on improving and upgrading gas turbine plants to enhance efficiency and performance levels.
- Select the West Tripoli gas turbine plant (Siemens GT5-2000E) as a case study.
- Analyze the documents and operating conditions of the Siemens GT5-2000E gas turbine power plant in compliance with ISO standards.
- Design the target plant (Siemens GT5-2000E) and perform performance analysis. Some real data will be used as stipulated in the operational data of the Siemens GT5-2000E power plant, provided by the manufacturer and verified against ISO standards.
- Simulate the targeted plant’s improvement using the Steam Injection Gas Turbine (STIG) technique and perform a dynamic performance analysis.
- Study the impact of ambient temperature variation on the gas turbine’s performance, before and after applying the steam injection technique, in terms of efficiency, power output, fuel consumption, and emissions.
- Conduct an exergy analysis of the gas turbine plant before and after incorporating the steam injection technique.

Modeling and Simulating the Thermodynamic Operation of the Power Plant

The primary objective of this study is to select the Siemens GT5-2000E gas turbine power plant located in West Tripoli. This model is characterized by a single shaft, two silo-type combustion chambers, a compressor, and a four-stage turbine. The Siemens GT5-2000E is a unique gas turbine model where the generator is coupled with the shaft located on the compressor side. It consists of two combustion silos designed for efficient fuel combustion to reduce nitrogen oxides (NOx) and carbon dioxide (CO_2) emissions. The model also exhibits strong reliability and the ability to burn both liquid and gaseous fuels. The gas turbine power plant operates on the Brayton cycle. To initiate the plant's operation, the axial-flow air compressor is first driven by an electric motor until the turbine shaft reaches 60% of its operational speed. The maximum net thermal efficiency for the simple open cycle plant is always less than 40% because 60% of the turbine shaft's energy is utilized to power the air compressor. Once the turbine starts, the air intake draws in ambient air, filters it, and compresses it in the compressor. The compressed air enters the combustion chamber, where it mixes with fuel and is ignited using a spark plug. When the fuel mixture in one combustion chamber ignites, the fire spreads through interconnected flame tubes to ignite all other chambers. The hot gases then flow into the four-stage turbine. In each turbine nozzle, the kinetic energy of the hot gases increases while pressure decreases across each row of rotating blades. A portion of the burned gas's kinetic energy is converted into useful work on the turbine shaft. The exhaust gases flow through the third stage of the blades, which feature a set of stationary vanes to redirect the gas flow from axial to radial directions with minimal vapor loss. The gases are released with air through the exhaust stack. The turbine uses part of the generated energy to drive the air compressor, while the remaining energy is available as useful work at the gas turbine's output flange, coupled with a generator operating at 3000 rpm. The generator converts mechanical energy into electrical energy [3]. In this study, methane gas was used as the primary fuel for combustion, with natural gas consisting of approximately 98% methane. The proportions of oxygen and nitrogen in the air are $O_2 = 21\%$ and $N_2 = 79\%$. The operational data for the ISO model are presented in Table 1, while Figure 1 shows the simulation of the targeted plant using Aspen Plus.

Table 1: ISO Conditions for the Gas Turbine Power Plant (Siemens GT5-2000E) [13]



Performance SGT-2000E series*

		SGT5-2000E
Grid frequency	[Hz]	50
Power output	[MW]	166
Efficiency	[%]	34.7
Heat rate	[kJ/kWh]	10,375
Heat rate	[Btu/kWh]	9,834
Exhaust temperature	[°C/°F]	541/1,005.8
Exhaust mass flow	[kg/s]	525
Exhaust mass flow	[lb/s]	1,157
Pressure ratio		12
Length x width x height	[m]	10x12x7.5**
Weight	[t]	234**
Generator type		

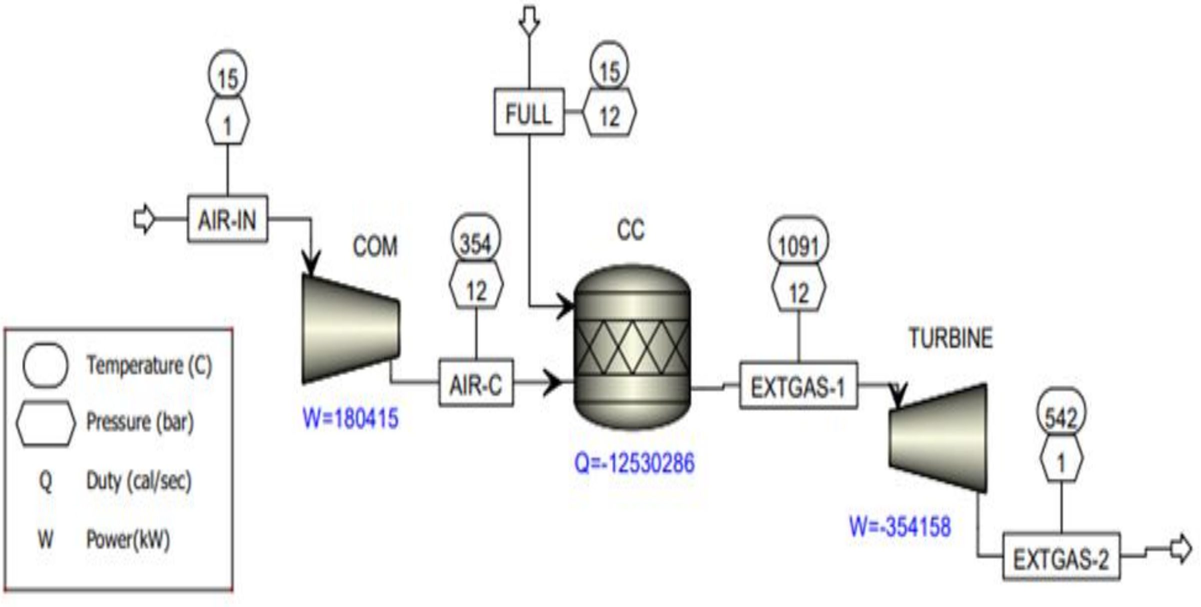


Figure 1: Simulation of the Targeted Gas Turbine Power Plant (Siemens GT5-2000E).

Thermodynamic Model Equations

The compressor discharge temperature T_2 is calculated using Equation (1), and the turbine exhaust gas temperature T_4 is determined using Equation (2), as outlined in [3][2] by Sengel and Boles. The pressure ratios of the compressor r_{PC} and the turbine r_{PT} are evaluated using Equation (3).

$$T_2 = T1[\left(\frac{r_{pc}^{\frac{ya-1}{ya}} - 1}{\eta_C}\right) + 1] \tag{1}$$

$$T_4 = T_3[1 - \eta_T\left(1 - \frac{1}{r_{pt}^{\frac{yg-1}{yg}}}\right) + 1] \tag{2}$$

$$r_{pc} = \frac{P_2}{P_1} \quad , \quad r_{PT} = \frac{P_3}{P_4}, \tag{3}$$

Equations (4) to (10) were used to determine the various performance aspects of the gas turbine model, as obtained from Sengel and Boles.

The work done by the compressor W_C and the turbine W_T can also be evaluated using Equations (4) and (5).

$$W_C = \dot{m}_a \, . cp_a . (T_2 - T_1) \tag{4}$$

$$W_T = \dot{m}_g \, . cp_g . (T_3 - T_4) \tag{5}$$

The thermal power $P_{thermal}$ of the power plant is determined by applying Equation (6).

$$P_{thermal} = W_T - W_C \tag{6}$$

The heat supply HS from the fuel can be determined using Equation (7).

$$HS = \dot{m}_f \cdot LHV \tag{7}$$

The generated electrical power P_{net} is expressed in Equation (8).

$$P_{net} = P_{thermal} - P_{loss} \tag{8}$$

Where P_{loss} represents the total losses, including mechanical losses in the compressor shaft, generator shaft, and auxiliary losses.

The net thermal efficiency η_{net} is determined as shown in Equation (9).

$$\eta_{net} = \frac{P_{net}}{\dot{m}_f \cdot LHV} \tag{9}$$

The Heat Rate HR of the gas turbine power plant can be calculated using Equation (10).

$$HR = \frac{3600}{\eta_{net}} \tag{10}$$

The amount of carbon dioxide (CO2) emissions $C\dot{O}2_{EMISSION}$ can be calculated using Equation (11).

$$C\dot{O}2_{EMISSION} = \frac{\dot{m}_{EMISSION}}{P_{net}} \tag{11}$$

Model Validation

When the gas turbine operates under design conditions, it is referred to as the (ISO) condition. When the power plant operates under any condition different from the (ISO) specifications, it is considered to be operating outside of the design condition. To validate the model, a model was designed to simulate the power generation and thermal efficiency with ambient air temperature using the professional simulation software (Aspen Plus) for the power plant, as shown in Figure (1). Ambient air temperature, pressure, pressure ratio, exhaust mass flow rate, and temperature data from Table (1) were used to model the Siemens GT5-2000E turbine. The input values for the mass flow rate and exhaust gas temperature were used for the (ISO) condition, while the pressure ratio for the gas turbines was adjusted. The isentropic efficiency for the compressor and turbine used is 85% and 90%, respectively. The mechanical efficiency for the turbine and compressor shaft is 98.5%, and for the generator, it is 99%, as specified by the manufacturer for the power plant [2]. The error percentage in the model can be calculated using Equation (12) [3].

$$Model_{Eror} = \frac{(Actual\ data - Model\ data) * 100}{Actual\ data}$$

Table 2: Model Validation Results Based on (ISO) Operating Data.

NO	*Parameters*	*Design*	*Model*	*Diff*	*%Error*
1	***Power (MW)***	166	165.689	0.31134	0.18755
2	***Thermal Efficiency (%)***	34.7	34.7	0	0
3	***Turbine Exhaust Temperature (C)***	541	542	-1	-0.1848
4	***Exhaust mass flow rate (kg/s)***	525	525	0	0
5	***Heat Rate(kJ/kWh)***	10375	10372.4	2.58244	0.02489

After comparing the values obtained with the ISO data and the established SGT5-2000E data, the model validation results showed a good agreement with Siemens' operational data under (ISO) conditions and previous studies by Egwari, Abanour, et al.

Modeling and Simulation of the Target Gas Power Plant Enhancement Using Steam Injection Technology (STIG):

This study focused on the use of two gas turbines at the target power plant located west of Tripoli, model (SGT5-2000E), for water evaporation through Heat Recovery Steam Generator (HRSG) units. This was done by utilizing the exhaust gases produced by the two plants, followed by steam injection into the combustion chambers of both plants to improve performance efficiency and increase power output, as shown in Figure (2). A previous study examined the effect of steam injection in combustion chambers to enhance performance and reduce harmful emissions. The results showed that steam injection at 25% contributed to achieving near-perfect combustion and flame stability, while a 20% steam injection reduced emissions. It was also found that this positive effect is enhanced by increasing the combustion chamber pressure, indicating that steam injection not only reduces emissions but also contributes to performance stability [15]. Table (3) shows the operational data for the two gas turbines.

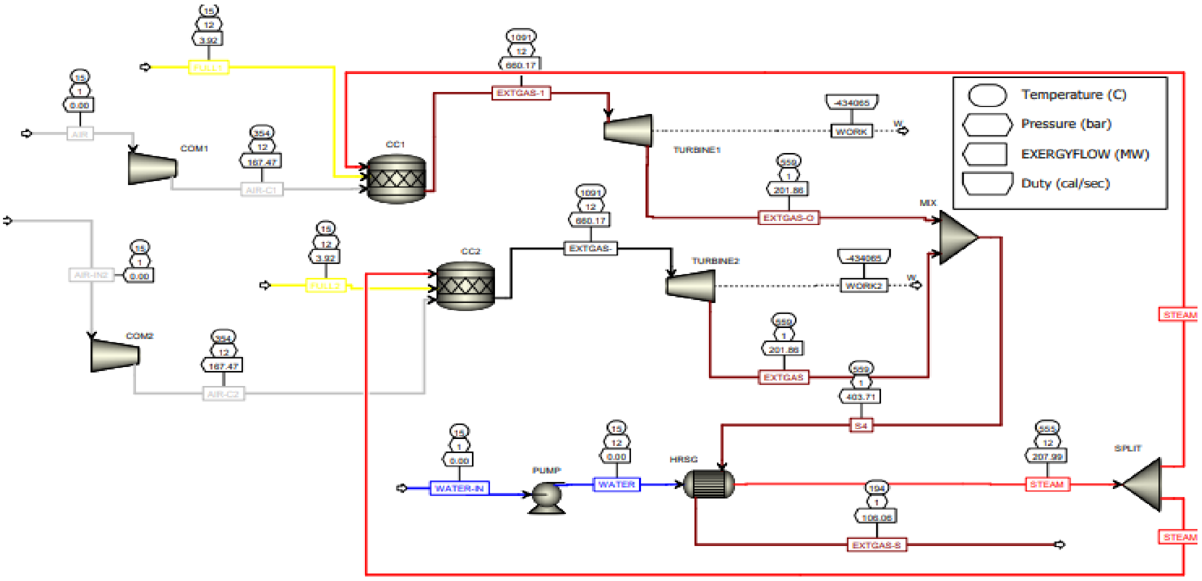


Figure 2 Simulation model of the target power plant design using Steam Injection Technology (STIGT5-2000E).

Table 3: Operational results for two gas turbines of the target model on Aspen Plus.

TEMP	*Pnet*	*Ƞnet*	*SFC*	*HR*	$CO2_{EMISSION}$
C	MW	%	Kg/MWH	KJ/KWh	Kg/MWh
15	331.37	34.70	230.44	10372.41	632.16
20	325.12	34.05	234.87	10571.99	644.33
25	318.87	33.39	239.47	10779.15	656.95
30	312.6	32.74	244.25	10994.33	670.07
35	306.39	32.09	249.22	11218	683.70
40	300.17	31.43	254.39	11450.66	697.88
45	293.95	30.78	259.77	11692.86	712.64

The effect of steam injection on the main characteristics of the Brayton cycle:
When steam is injected, the nominal power of the turbine $WT_{(SIGT)}$ is calculated using the following equation (13).

$$W_{T\,(SIGT)} = \left(\dot{m}_g + \dot{m}_S\right).cp_g.(T_3 - T_4) \tag{13}$$

The steam-to-air ratio f' is calculated by applying equation (14).

$$f' = \frac{\dot{m}_s}{\dot{m}_a} \tag{14}$$

The thermal power $P_{thermal\,(STIG)}$ for the steam injection gas turbine (STIG) power plant is determined by applying equation (15).

$$P_{thermal\,(STIG)} = W_{T\,(SIGT)} - W_C \tag{15}$$

The electrical power generated after applying the steam injection technology $P_{net\,(SIGT)}$ for the steam injection gas turbine (SIGT) is expressed in equation (16).

$$P_{net\,(SIGT)} = P_{thermal\,(SIGT)} - P_{loss\,(SIGT)} \tag{16}$$

The net thermal efficiency $\eta_{net\,(STIG)}$ for the new plant after applying steam injection technology (SIGT) is determined as shown in equation (17) [16].

$$\eta_{net\,(STIG)} = \frac{P_{net\,(SIGT)}}{\dot{m}_f \cdot LHV} \tag{17}$$

The quantity of carbon dioxide (CO2) emissions, denoted as$C\dot{O}2_{EMISSION(STIG)}$, can be calculated using equation (18).

$$C\dot{O}2_{EMISSION(STIG)} = \frac{\dot{m}_{EMISSION}}{P_{net}} \tag{18}$$

In the context of this study, the maximum heat exchanger in the Heat Recovery System (HRSG) was used to maximize the utilization of exhaust gas heat in the steam generator to evaporate water. The lost heat was converted into steam, which was then injected into the gas turbine at the same pressure as the combustion chamber. The steam-to-air ratio reached 14.96%. This ratio contributed to an overall improvement in performance, as shown in Table (4).

Table 4: Operational Results of the Steam Injection Technology (SIGTx2) on Aspen plus Software.

$TEMP$	$Pnet$	$Ƞnet$	SFC	HR	$CO2_{EMISSION}$
C	MW	$\%$	Kg/MWH	KJ/KWh	Kg/MWh
15	501.80	52.55	152.17	6790.37	417.46
20	495.55	51.90	154.09	5999.58	422.73
25	489.30	51.24	156.06	5188.97	428.13
30	483.06	50.59	158.08	4357.81	433.66
35	476.82	49.94	160.14	3505.34	439.33
40	470.60	49.28	162.26	2630.76	445.14
45	464.38	48.63	164.43	1733.21	451.10

Exergy:

Exergy is a vital concept in thermodynamics used for analyzing and designing thermal systems with greater efficiency. The concept of exergy evaluates the amount of useful work that can be extracted from a thermal system when it interacts with its environment until equilibrium is reached, making it a tool for determining the amount of waste and actual losses within the system. Unlike energy, which remains constant (according to the first law of thermodynamics), exergy can be destroyed in inefficient processes, serving as a measure of energy quality and efficiency. By analyzing exergy, thermal design engineers can effectively improve systems, identify areas of waste, and focus efforts on increasing efficiency and reducing costs, making it a crucial component in the design of modern energy systems and reducing their environmental impact. In the absence of nuclear, magnetic, electrical effects, or surface tension, the total exergy of the system $\dot{E}$ can be divided into four components: physical exergy $\dot{E}_{Ph}$, kinetic exergy $\dot{E}_{ken}$, potential exergy $\dot{E}_{Po}$, and chemical exergy $\dot{E}_{ch}$, as shown in equation (19)[17].

$$\dot{E} = \dot{E}_{Ph} + \dot{E}_{ch} + \dot{E}_{Po} + \dot{E}_{ken}$$

Neglecting the potential exergy $\dot{E}_{Po}$ and kinetic exergy $\dot{E}_{ken}$ due to their small values. (19)

The total exergy E can be calculated using equation (20).

$$\dot{E} = \dot{E}_{Ph} + \dot{E}_{ch} \tag{20}$$

Exergy efficiency for each component $\mathcal{E}_{(component)}$ represents the effectiveness of the component in converting exergy into useful work. It can be calculated using equations (21) to (24) respectively.

$$\mathcal{E}_{(\mathrm{compressor,pump})} = \frac{\dot{\mathrm{E}}_{\mathrm{out}}-\dot{\mathrm{E}}_{\mathrm{in}}}{\mathrm{WC}}*100 \tag{21}$$

$$\mathcal{E}_{(Turbine)} = \frac{WT}{\dot{E}_{in} - \dot{E}_{out}} * 100 \tag{22}$$

$$\mathcal{E}_{(combustor)} = \frac{E_{out}}{\dot{E}_{out}} * 100 \tag{23}$$

$$\dot{\mathcal{E}}_{(Heat\ Exchanger)} = \frac{\dot{E}_{outc} + \dot{E}_{inc}}{\dot{E}_{inh} - \dot{E}_{outh}} * 100 \tag{24}$$

The destructive energy in each component $\dot{E}_{d\,(component)}$ is determined using equations (25) to (27).

$$\dot{E}_{d\,(compressor,pump)} = Wc + \dot{E}_{in} - \dot{E}_{out} \tag{25}$$

(26)

(27)

$$\dot{E}_{d(Turbine)} = \dot{E}_{in} - \dot{E}_{out} - WT$$

$$\dot{E}_{d(combustor,heat\ exchanger)} = \dot{E}_{in} - \dot{E}_{out}$$

The exergy waste percentage for the component compared to the total $t_{\%}$ is given by equation (28).

$$t_{\%} = \frac{\dot{E}d_{component}}{\dot{E}_{d(total)}} * 100 \tag{28}$$

The exergy waste percentage for the component compared to the fuel $f(\%)$ is given by equation (29).

$$f(\%) = \frac{\dot{E}d_{component}}{\dot{E}_{(f)}} * 100 \tag{29}$$

The exergy efficiency of the plant $\mathcal{E}_{(plant)}$ is given by equation (30).

$$\mathcal{E}_{(plant)} = 100(\%) - \Sigma f(\%) \tag{30}$$

Results and Discussion

- **Energy Analysis**
  - Figure (3) shows the effect of steam injection in the combustion chamber on turbine efficiency. The application of steam injection led to an increase in the gas turbine plant's efficiency from 33.39% to 51.24% at 25°C, representing a 53.5% increase. Steam injection in the combustion chamber improves combustion conditions by increasing the pressure and density of the air-fuel mixture, enhancing the effectiveness of the combustion process and achieving more efficient combustion. Steam injection also helps reduce combustion temperatures, which decreases wear and increases flame stability, leading to better fuel consumption efficiency and increased output power, even under partial load conditions.
  - When analyzing the generated electrical power data, steam injection at 25°C increased electrical power from 318.87 MW to 489.3 MW, as shown in Figure (4), representing a 53.5% increase. This improvement is attributed to the effect of steam injection in the combustion chamber, where it increases the mass flow through the turbine, leading to higher net power output and improved productivity compared to the simple cycle. This technique also enhances turbine performance under partial load conditions, allowing for increased power production under varying conditions.

  - The obtained data also indicates that the specific fuel consumption in the two gas turbines decreases significantly when applying steam injection technology. At 25°C, consumption decreased from 239.47 kg/MWh to 156.06 kg/MWh, as shown in Figure (5), representing a reduction of 34.76%. This improvement is due to the increased pressure and density of the air-fuel mixture inside the combustion chamber, which enhances combustion efficiency and increases energy output with the same amount of fuel. Steam injection also contributes to flame stability, reducing disturbances in the combustion process and improving the overall performance of the system.
  - The results also showed that the application of steam injection at 25°C led to a significant reduction in CO_2 emissions. Emissions decreased from 656.95 kg/MWh to 428.13 kg/MWh, reflecting a reduction of 34.73%, as shown in Figure (6). These results demonstrate that the use of steam injection not only enhances combustion efficiency and power generation but also helps reduce harmful emissions, improving the environmental performance of gas plants and supporting sustainability goals. The decrease in CO_2 emissions is due to the increased pressure in the combustion chamber caused by steam injection, leading to more complete combustion, thereby reducing the amount of fuel required to generate energy. Additionally, the reduction in combustion temperatures as a result of steam injection further contributes to the reduction in emissions.

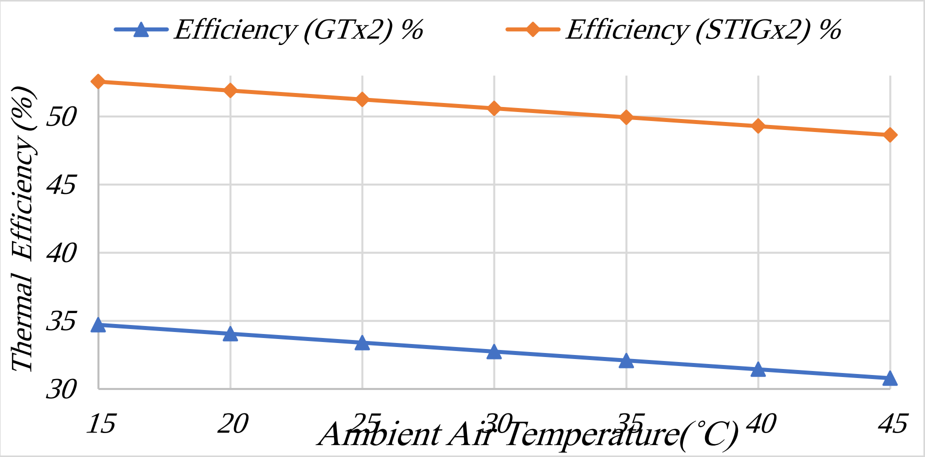


Figure 3: The Effect of Ambient Air on Thermal Efficiency.

Steam injection also reduces the formation of harmful products like nitrogen oxides (NOx) and other pollutants. Therefore, this improvement in air quality reflects the effectiveness of steam injection technology in reducing emissions and achieving better operational efficiency.

When studying the effect of temperature on efficiency, it is noted that in the plant without steam injection, the increase in temperature from 15°C to 45°C leads to a decrease in efficiency from 34.70% to 30.78%, a total decrease of approximately 11.31%, or an average rate of 1.3% per 5°C increase. With steam injection technology, efficiency decreases from 52.55% to 48.63% for the same temperature increase, representing a total decrease of around 7.47%, which is an average decrease of 0.9% per 5°C, as shown in Figure (3).

When examining the impact of temperature on electrical power, it is observed that electrical power without steam injection decreases with increasing temperature, from 331.37 MW at 15°C to 293.95 MW at 45°C, reflecting a total decrease of 37.42 MW, or 11.3%, with an average decrease of about 1.41% per 5°C. In contrast, electrical power with steam injection remains relatively high, ranging from 501.8 MW at 15°C to 464.38 MW at 45°C, with a total decrease of 37.42 MW, or 7.45%, and an average decrease of about 0.87% per 5°C, as shown in Figure (4).

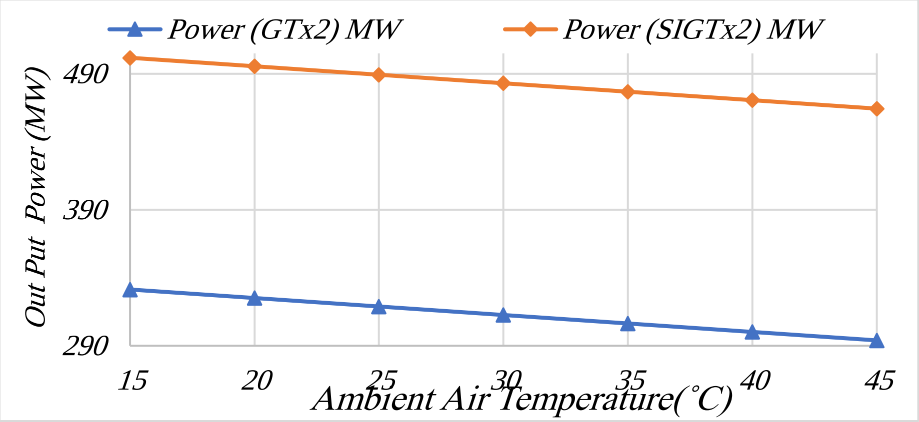


Figure 4: Effect of Ambient Air on Output Power.

The results of the study on the effect of temperature showed that the specific fuel consumption increases with the rise in temperature in the case of no steam injection. The consumption increased from 230.44 kg/MWh at 15°C to 259.77 kg/MWh at 45°C, reflecting an increase of 29.33 kg/MWh, or 12.7%, with an average increase of approximately 1.58% for every 5°C increase. In contrast, the fuel consumption rate with steam injection shows relative improvement, ranging from 152.17 kg/MWh at 15°C to 164.43 kg/MWh at 45°C, with a total increase of 12.26 kg/MWh, representing an 8.05% increase, and an average increase of approximately 1.01% for every 5°C increase, as shown in Figure 5.

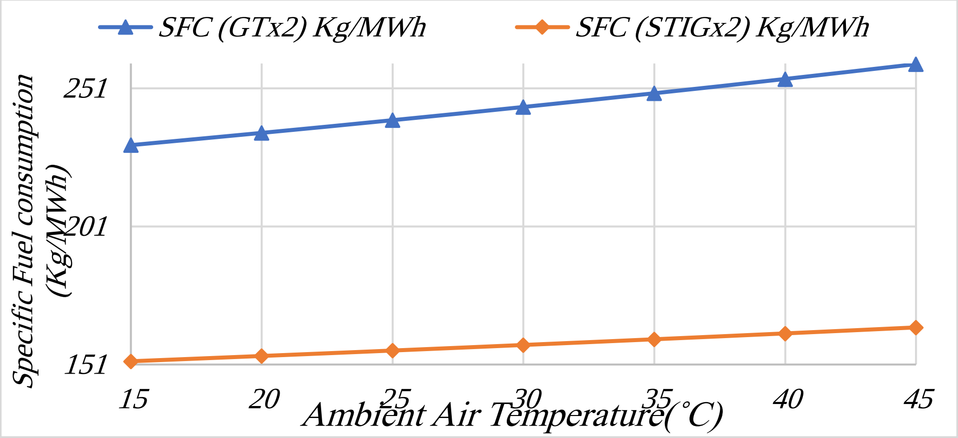


Figure 5: Effect of Ambient Air on Fuel Consumption Rate.

In the study of the effect of temperature on CO_2 emissions, it is evident that emissions increase with rising temperature when steam injection technology is not used. CO_2 emissions increased from 632.16 kg/MWh at 15°C to 712.64 kg/MWh at 45°C, reflecting an increase of 80.48 kg/MWh, or 12.7%, with an average increase of approximately 1.58% for every 5°C increase. In contrast, the CO_2 emissions rate with steam injection shows a smaller increase, ranging from 417.46 kg/MWh at 15°C to 451.10 kg/MWh at 45°C, with a total increase of 33.64 kg/MWh, or 8.05%, and an average increase of approximately 1.01% for every 5°C increase, as shown in Figure (6).

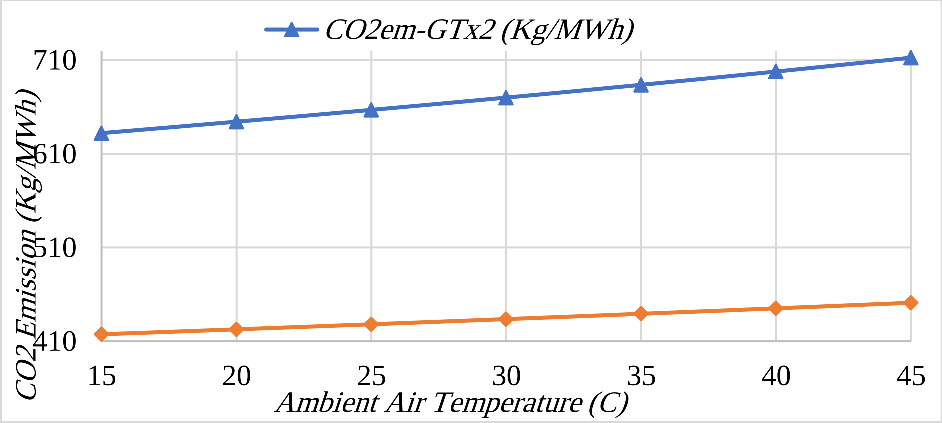


Figure 6: The Effect of Ambient Air on Carbon Dioxide Emissions.

- **Exergy Analysis**

After analyzing the exergy data for the two gas turbines before and after the application of steam injection technology (STIG) using Microsoft Excel, notable improvements in performance and efficiency were observed. This indicates a clear positive effect of this technology on the gas power plant, as shown in Tables 5 and 6.

Table 5: Exergy Analysis Results for the SGT5-2000E Gas Turbine.

GTx2	Power (MW)	Exergy Efficiency (%)	Ex Destruction (MW)	Ex Ratio (%) f	Ex Ratio (%) t
Compressor1	183.16	91.43	15.69	1.42	3.19
Combustor1	/	70.61	210.45	19.17	42.78
Turbine1	348.85	94.63	19.79	1.80	4.02
Compressor2	183.16	91.43	15.69	1.42	3.19
Combustor2	/	70.61	210.45	19.17	42.78
Turbine2	348.85	94.63	19.79	1.80	4.02
Summation	/	/	491.89	44.81	100
Plant Exergy Efficiency (%)	/	55.18	/	/	/

The results show that the combustion chambers were the main source of exergy loss, with a high destruction rate of 210.46 MW per combustion chamber, accounting for 42.78% of the total loss in the plant. After the application of steam injection, this value decreased to 53.80 MW, representing a 74.43% reduction. This decrease indicates that steam injection significantly contributes to reducing the high temperatures in the combustion chambers, thus improving energy utilization and reducing losses.

Table 6: Availability Analysis Results of the Gas Turbine with Steam Injection Technology (SIGT).

STIGx2	*Power (MW)*	*Exergy Efficiency (%)*	*Ex Destruction (MW)*	*Ex Ratio (%) f*	*Ex Ratio (%) t*
Compressor1	183.16	91.43	15.69	1.42	5.66
Combustor1	/	92.48	53.80	4.90	19.41
Turbine1	434.06	94.70	24.24	2.20	8.74
Compressor2	183.16	91.43	15.69	1.42	5.66
Combustor2	/	92.48	53.80	4.90	19.41
Turbine2	434.06	94.70	24.24	2.20	8.74
HRGS		69.87	89.66	8.16	32.35
Water Pump	0.19	0.00619	0.19	0.017	0.071
Summation	/	/	277.15	25.24	100
Plant Exergy Efficiency (%)	/	74.82293184	/	/	/

As for the turbines, the results showed that steam injection contributed to an increase in the power output of each turbine; turbine power increased from 348.86 MW to 434.07 MW after injection, representing a 24.4% increase. Despite this increase, the exergy destruction rate in the turbines slightly increased from 19.79 MW to 24.25 MW, reflecting an interaction between the increase in energy production and the loss rate. Additionally, a heat recovery steam generator (HRSG) was integrated after the application of steam injection, contributing to an exergy efficiency of 89.66%. This led to a reduction in total losses and directed the generated heat toward improving plant efficiency. Although the impact of the water pump on overall performance was minimal, with an efficiency of around 0.006%, it showed a slight contribution to reducing exergy destruction. When analyzing the compressor performance in the gas plant before and after the application of steam injection, there was no significant change in the exergy efficiency of the compressors, remaining around 91.43% per compressor in both cases. This result indicates that the compressor maintained its relatively high efficiency and was not significantly affected by the steam injection process, suggesting that the compressor is not a major area for thermal interactions leading to significant exergy loss, unlike the combustion chambers and turbines. However, the compressor remains crucial for achieving overall plant efficiency, as its high efficiency helps reduce the energy required for compressing the intake air, thereby increasing the overall effectiveness of the gas cycle. Therefore, maintaining compressor efficiency, along with the improved efficiency of other components after the application of steam injection, contributed to enhancing the overall plant performance. This reflects a balanced design that optimizes the utilization of different energies within the plant.

Comparing the two conditions before and after the application of steam injection, there is a clear reduction in losses from the combustion chambers and an increase in turbine productivity, proving the effectiveness of steam injection in improving plant performance and increasing efficiency. It is evident that steam injection not only contributes to improving the overall efficiency of the plant but also helps reduce thermal losses, thus enhancing the utilization of energy resources.

Conclusion:

1. The analysis shows that steam injection technology significantly contributes to improving the efficiency of the gas plant, demonstrating its effectiveness in enhancing performance even at high temperatures.
2. The results confirm that the application of steam injection leads to a noticeable increase in the electrical power produced, reflecting improved generative performance of the plant.
3. The data indicates that steam injection helps reduce specific fuel consumption, meaning that the plant can generate more power with less fuel, thus improving economic efficiency.
4. Emission analysis shows that the use of steam injection helps reduce carbon dioxide emissions, enhancing the plant's environmental performance and meeting sustainability goals.
5. The analysis shows that steam injection reduces the impact of high temperatures on efficiency and power production, making this technology an effective option for improving gas plant performance under varying operating conditions.

6. The analysis indicates that steam injection contributes to stabilizing the combustion process, reducing disturbances, and enhancing combustion effectiveness.
7. The availability analysis shows that steam injection technology enhances efficiency in the gas plant by improving combustion processes and reducing energy losses, leading to a higher conversion of available energy into useful energy, thus reducing waste and increasing fuel utilization efficiency.

It can be concluded that steam injection technology is an effective strategy for improving the overall performance of gas power plants, as it enhances efficiency, increases energy production, reduces fuel consumption, and contributes to improved environmental outcomes.

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Abbreviation:

Symbol	Description
GT	Gas Turbine
$HRSG$	Heat Recovery Steam Generator
Nox	Nitrogen Oxides
ISO	International Standards Organization
$STIG$	team Injection Gas Turbine
$O2$	Oxygen
$N2$	Nitrogen
T_1 (C°)	Compressor Inlet Temperature
T_2 (C°)	Compressor Outlet Temperature
T_3 (C°)	Combustion Chamber Outlet Temperature
T_4 (C°)	Turbine Outlet Temperature
r_{PC}	Compressor Pressure Ratio
η_C (%)	Compressor Efficiency
r_{PT}	Turbine Pressure Ratio
η_T(%)	Turbine Efficiency
$\frac{P_2}{P_1}$	Compressor Inlet and Outlet Pressure
$\frac{P_3}{P_4}$	Turbine Inlet and Outlet Pressure
W_C (MW)	Compressor Work
m_a (Kg/s)	Air Mass Flow Rate
cp_a (J/Kg.k)	Specific Heat Capacity of Air
W_T (MW)	Turbine Work
$\dot{m}_g$(Kg/s)	Exhaust Gas Mass Flow Rate
cp_g (J/Kg.k)	Specific Heat Capacity of Exhaust Gases
$P_{thermal}$ (MW)	Net Thermal Power
HS (MW)	Heat Supply
$\dot{m}_f$ (Kg/s)	Fuel Mass Flow Rate
LHV (MJ/Kg)	Lower Heating Value of Fuel
P_{net} (MW)	Net Electrical Power Output
P_{loss} (MW)	Power Loss
η_{net} (%)	Net Thermal Efficiency
HR (KJ/KWh)	Heat Rate
SFC (Kg/MWH)	Specific Fuel Consumption
$C\dot{O}2_{EMISSION}$ (Kg/MWh)	Carbon Dioxide Emissions
$\dot{m}_{EMISSION}$(Kg/s)	Carbon Dioxide Mass Flow Rate
$Model_{Eror}$ (%)	Model Error Percentage
$Diff$	Difference (-)
$TEMP$ (C°)	Temperature
$\dot{m}_S$ (Kg/s)	Steam Mass Flow Rate
f'	Mass Flow Percentage
$\dot{E}$ (MJ/Kg)	Exergy
$\dot{E}_{Ph}$ (MJ/Kg)	Physical Exergy
$\dot{E}_{ch}$ (MJ/Kg)	Chemical Exergy
$\dot{E}_{Po}$ (MJ/Kg)	Potential Energy Exergy
$\dot{E}_{ken}$ (MJ/Kg)	Kinetic Energy Exergy
$\mathcal{E}_{(component)}$ (%)	Component Exergy Efficiency
$\dot{E}_{in}$ (MJ/Kg)	Input Exergy
E_{out} (MJ/Kg)	Output Exergy
$\dot{E}_d$ (MJ/Kg)	Destroyed Exergy
$t_{\%}$	System Exergy Percentage
$f(\%)$	Fuel Exergy Percentage
$\mathcal{E}_{(plant)}$ (%)	Plant Exergy Efficiency