Sirte University Scientific Journal Vol. 15, No. 1 (2025) 58-66

Sirte University Scientific Journal (SUSJ)

Journal home page: http://journal.su.edu.ly/index.php/SUSJ/index

DOI: 10.37375/susj.v15i1.3387

A Comparison between steam injection and combined cycle power plant using exergy analysis

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DOI: 10.37375/susj.v15i1.3387

ARTICLE INFO:

Received 26 February 2025.
Accepted 10 May 2025.
Available online 24 June 2025.

Keywords:(Steam injection, combined cycle, gas turbine station, Aspen Plus)

ABSTRACT

The objective of this paper aims is to analyze the performance of a Siemens GT5-2000E gas power plant in West Tripoli using steam injection and combined cycle technologies from an exergy perspective to evaluate energy conversion efficiency and reduce thermal losses. The study relies on real operational data from the power plant. Two gas turbine units were simulated using Aspen Plus to apply the steam injection and combined cycle techniques, while an exergy analysis using the operational data of each system component was performed using Excel. The results showed that the steam injection and combined cycle technologies achieved different exergy efficiencies compared to a standard cycle gas turbine. The exergy efficiency of the two gas units in the conventional cycle was 55.19%. After applying the steam injection technique, the exergy efficiency increased to 74.82% at 15°C, reflecting an improvement of 35.6% compared to the conventional cycle. In contrast, the combined cycle technique recorded an exergy efficiency of 49.10%, representing a lower improvement of 10.1% compared to the conventional cycle. Exergy analysis also revealed that the combustion chamber was the largest contributor to exergy destruction in all cases, accounting for 40–50% of total losses. It can be concluded that the steam injection technique represents the most efficient option from an exergy perspective, as it achieves the highest improvement in energy conversion efficiency and the lowest energy losses compared to the combined cycle and the conventional cycle gas units.

1 Introduction

Gas turbine power plants are among the most efficient electricity generation sources worldwide, known for their high efficiency and ability to respond rapidly to varying energy demands (Livshits, M., & Kribus, A.2012). In Libya, these plants are an integral part of the national electricity generation system. Several gas turbine plants, including the West Tripoli Gas Power Plant and the South Tripoli Gas Power Plant, have been installed. However, the efficiency of these plants is significantly affected by local environmental factors such as high ambient temperature and atmospheric relative humidity, which vary considerably on a seasonal basis Egware, H. O., & Obanor, A. I. (2022).] and(Egware, H. O. 2021) . These factors make it essential to improve the efficiency of gas power plants to reduce fuel consumption and harmful emissions while maintaining high performance levels (Nishida, K.,2005).

. In this context, energy thermal analysis is a fundamental tool for improving the efficiency of gas power plants, providing a comprehensive understanding of the performance of various components. This analysis is a crucial step in the path to improving efficiency and reducing thermal losses (Khademi, M., and Khosravi, A. 2013). Among the advanced technologies that contribute to achieving these goals, combined cycle and steam injection technologies stand out as effective solutions (Mitsubishi Power. Smart-AHAT). The combined cycle technology relies on utilizing the exhaust gas heat generated by the gas turbine to produce steam to operate an additional steam turbine, leading to an increase in energy efficiency and a reduction in thermal losses (Fathy, A. 2023) and Kayhan Kayadelen, H., and Ust, Y.2018).

. Developments in gas turbine design have significantly improved the efficiency of combined cycle plants, with plants using advanced turbines such as the Mitsubishi M501F reaching an efficiency of 57.1%, compared to 37% when operating in simple cycle mode. This improvement is based on maximizing the use of exhaust heat in the combined cycle, which includes heat recovery steam generators (HRSG) and multi-pressure steam turbines (Mitsubishi Power, 2020-2024).

. One study addressed the thermodynamic simulation of combined cycle power plants (CCPP). The results showed that changes in economic parameters affect the balance between cash flows and fixed costs at the optimal point, reducing carbon emissions, fuel consumption, and increasing exergy efficiency by about 6%. Thermal calculations for both the gas and steam turbines showed improvements in energy efficiency and operational flexibility (Khan, O., Khalid, F., & Parvez, M. 2020). In contrast, the steam injection technique involves injecting a specified amount of steam into the combustion chamber of the gas turbine, increasing the volume and density of the gas flowing through the turbine, thus contributing to improving output power and thermal efficiency (Livshits, M., & Kribus, A.2012, Ust, Y.2018 and (Ahmed et al, 2011) . This technique has proven successful in improving performance and reducing harmful emissions Livshits, M., & Kribus, A.2012 . Steam injection cools the combustion gases, reducing the risk of turbine blade damage due to high temperatures, and helps decrease the production of nitrogen oxides (NOx). It also allows gas turbines to operate at higher temperatures, improving efficiency and demonstrating better performance at partial load compared to the simple cycle (Abd El-Fattah et al, 2015), Khademi, M., and Khosravi, A. 2013 and . (Ahmed et al, 2011).

Studies indicate that the thermal efficiency of steam-injected gas turbine cycles (STIG) increases with higher pressure ratio and turbine inlet temperature. The results showed that the STIG cycle efficiency is always higher than the simple cycle under the same operational conditions, as it increases the network output and reduces specific fuel consumption (Agarawal et al, 2017).

.Analysis shows that steam injection does not affect compressor performance (Kim, K. H., & Kim, G., 2010 and . (Popli, S.,2013).

Using Aspen Hysys, it was found that when applying a 10% steam-to-air ratio, the power and efficiency of the gas turbines reach 134% and 112% of the design base load values, respectively. Additionally, steam injection from properly treated water does not affect the lifespan of the turbine's hot parts (Jouhara, H., and Khordehgah, N. 2018) and (doe, j and smith, 2019).

This paper will study the performance of the simulated gas turbine configuration in terms of efficiency and exergy loss for each component to evaluate and compare the performance of the combined cycle and steam injection technologies on the gas turbine power plants (SGT5-2000E) in Libya. The study includes performance analysis under identical operating conditions for both technologies.

2. Methodology

Aspen Plus Software:

Aspen Plus is a comprehensive simulation tool widely used in engineering applications for modelling and analyzing dynamic thermodynamic processes, especially in energy and industrial sectors. This software enables users to simulate a wide range of systems, including power plants. Aspen Plus is characterized by its ability to simulate complex processes, evaluate performance, and optimize designs, making it a powerful tool for studying energy systems and their environmental impacts Aspen tech, 2020). It offers a detailed and systematic approach for simulating the various components and processes in power plants. The program includes a set of thermodynamic models and physical properties that allow for precise mass, energy, and exergy balance calculations. These capabilities are crucial in designing and improving power plants, particularly those incorporating advanced technologies like steam injection and combined cycles (doe, j and smith, 2019). Aspen Plus supports a wide range of libraries that enable users to simulate specific components in complex systems. These libraries are fundamental for representing physical processes and engineering applications, ensuring that simulations reflect real-world conditions as accurately as possible. The program uses precise mathematical models to simulate fluid dynamics, heat transfer, chemical reactions, and mechanical processes, providing accurate predictions and insights into system performance (Jouhara, H., and Khordehgah, N. 2018).

In power plant simulations, Aspen Plus is commonly used to model both simple and combined cycles, as well as steam injection in gas turbines and other advanced technologies that enhance efficiency and reduce emissions. This ensures that engineers can assess operational strategies and configurations to achieve the best economic and environmental results (Lee, D., and Turner, E. 2017).

Aspen Plus employs advanced mathematical techniques to solve equations governing system behaviour, ensuring that the simulations converge to accurate solutions, even for complex systems with intertwined components. Its set of properties also allows for precise dynamic thermodynamic calculations, ensuring that the models reflect real-world behaviour and provide accurate predictions regarding system performance (Zhang, X., et al, 2019).

In addition to thermodynamic calculations, Aspen Plus also offers tools for economic analysis, allowing users to evaluate cost changes associated with design choices and different operational strategies. This economic flexibility makes Aspen Plus an essential tool for assessing the feasibility of integrating advanced technologies such as steam injection and combined cycles (Lee, D., and Turner, E. 2017). In this study, Aspen Plus was used to simulate a turbine-based power plant supported by a combined cycle. The program's robust libraries enabled the simulation of steam injection, providing a comprehensive understanding of system performance under different operational conditions (Jouhara, H., and Khordehgah, N. 2018).

Overall, Aspen Plus is a reliable and powerful tool for simulating energy systems, optimizing performance, and evaluating the environmental and economic impacts of various technologies.

Microsoft Excel Software:

Excel is a popular and efficient tool for data analysis and performing complex calculations in various engineering applications. In this study, Excel was primarily used to analyze data related to efficiency, generated energy, emissions, and specific fuel consumption rates for gas-fired power plants utilizing steam injection and combined cycle technologies. Additionally, Excel was employed in these processes due to its extensive capabilities in performing advanced calculations and data analysis quickly and flexibly, making it easy to handle large and complex data sets (Microsoft. 2020). In energy analysis, Excel was used to calculate the efficiency of gas-fired power plants with steam injection and combined cycle technologies, as well as the energy generated in the system. Excel was also used to calculate emissions resulting from various processes in the plants, allowing for accurate computations of emission levels according to different environmental standards. By using advanced mathematical formulas and charts, Excel provided accurate predictions regarding the environmental and energy performance of the plants Doe, J., & Smith, J. (2019. Microsoft Excel was also used to calculate the specific fuel consumption rate of the gas-fired plants, a critical computational process for understanding fuel efficiency and overall system performance. Excel's capabilities enabled processing data for calculating the thermal efficiency of these systems and analysing their impact on the plant's overall performance. It was also used for exergy calculations in the plants, which allows for determining energy conversion efficiency and offering insights into lost thermal processes (Turner, E., and Lee, D. ,2018).

Exergy Analysis:

Exergy is a vital concept in thermodynamics used to analyse and design thermal systems more efficiently. 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 an essential tool for identifying losses and inefficiencies 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. Through exergy analysis, thermal design engineers can effectively optimize systems, pinpoint areas of waste, and focus efforts on improving efficiency and reducing costs, making it a key element in modern energy system design and minimizing their environmental impact. In the absence of nuclear, magnetic, electrical, or surface tension effects, the total exergy of a 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) (1995. Bejan, 1995).

Thermal Model Equations for Power Generation Plants:

Using Microsoft Excel, an exergy analysis was conducted to assess system losses by focusing on the energy in each energy stream to evaluate the performance of gas-fired power plants, combined cycles, and gas turbines with steam injection in terms of overall exergy efficiency for each plant. The analysis also involved evaluating the performance of each component

in terms of exergy efficiency and the destructive energy to identify inefficiencies and their impact on the plant as a whole. Table 1 illustrates the exergy equations for the gas-fired power plant and the impact of steam injection and combined cycle technologies on the gas-fired power plant (1995. Bejan, 1995).

Table1: Exergy Equations for power plants

Exergy Equations for Power Plants	
$\dot{E} = \dot{E}_{Ph} + \dot{E}_{ch} + \dot{E}_{Po} + \dot{E}_{ken}$	Main Exergy Equation
$\dot{E} = \dot{E}_{Ph} + \dot{E}_{ch}$	Exergy Equation Neglecting Potential and Kinetic Energy
$\mathcal{E}_{(\mathrm{compressor,pump})} = \frac{\dot{\mathrm{E}}_{\mathrm{out}} - \dot{\mathrm{E}}_{\mathrm{in}}}{\mathrm{WC}} * 100$	Exergy Efficiency of the Compressor and Pump
$\mathcal{E}_{(Turbine)} = \frac{W_T}{\dot{E}_{in} - \dot{E}_{out}} * 100$	Exergy Efficiency of the Turbine
$\mathcal{E}_{(combustor)} = \frac{E_{out}}{\dot{E}_{out}} * 100$	Exergy Efficiency of the Combustion Chamber
$\mathcal{E}_{(Heat\ \dot{E}xchanger)} = \frac{\dot{E}_{outc} + \dot{E}_{inc}}{\dot{E}_{inh} - \dot{E}_{outh}} * 100$	Exergy Efficiency of the Heat Exchanger
$\dot{E}_{d\,(compressor,pump)} = Wc + \dot{E}_{in} - \dot{E}_{out}$	Destructive Exergy of the Compressor and Pump
$\dot{E}_{d\,(Turbine)} = \dot{E}_{in} - \dot{E}_{out} - W_T$	Destructive Exergy of the Turbine
$\dot{E}_{d\,(combustor,heat\ exchanger)} = \dot{E}_{in} - \dot{E}_{out}$	Destructive Exergy of the Combustion Chamber and Heat Exchanger
$t_{\%} = \frac{\dot{E}d_{component}}{\dot{E}_{d\,(total)}} * 100$	Exergy Loss Ratio for the Component Compared to Total Exergy
$f(\%) = \frac{\dot{E}d_{component}}{E_{(f)}} * 100$	Destructive Exergy Ratio in Terms of Total Fuel Energy Input
$\mathcal{E}_{(plant)} = 100(\%) - \Sigma f(\%)$	Total Exergy Efficiency of the Plant
$Model_{Eror} = \frac{(Actual\ data - Model\ data) * 100}{Actual\ data}$	Error Calculation for the Model

Thermal Dynamic Simulation of the Gas Power Plant Operation:

The Siemens GT5-2000E gas turbine features a single shaft, two types of combustion chambers for efficient fuel burning to reduce nitrogen oxide and carbon dioxide emissions, as well as a compressor and a four-stage turbine. The Siemens GT5-2000E gas turbine is a unique model among gas turbines as the generator is connected to the shaft next to the compressor. The model also has high operational reliability and the ability to burn both liquid and gaseous fuels. The Siemens GT5-2000E gas power plant operates on the Brayton cycle. The manufacturer's operational data for the ISO (International Organization for Standardization) conditions are shown in Table (2).

Table (2): Operational Data for the Siemens GT5-2000E Gas Power Plant under ISO Conditions [28]

Siemens Performance SGT5-2000E Series	*ISO Conditions*
Grid Frequency (Hz)	50
Power (MW)	166
Thermal Efficiency (%)	34.7
Heat Rate(kJ/kWh)	10,375
Heat Rate(Btu/kwh)	9,834
Turbine Exhaust Temperature (°C/°F)	541/1,005
Exhaust mass flow rate (kg/s)	525
Pressure ratio	12

4. Validation of the Gas Power Plant Model:

When the gas turbine operates in the design condition, it is referred to as the ISO condition. When the power plant operates under any condition other than the ISO specifications, it is known as off-design performance. To validate the model, a model for energy production and thermal efficiency was designed using the professional (Aspen Plus) program for the power plant. A simulation of the Siemens GT5-2000E turbine was conducted using values for ambient air temperature, pressure, pressure ratio, exhaust gas flow rate, and exhaust gas temperature from Table (2), while the pressure ratio in the gas turbines was adjusted. The isentropic efficiency of the compressor and turbine were set at 85% and 90%, respectively. The mechanical efficiency of the turbine and compressor shaft was 98.5%, and the mechanical efficiency of the generator shaft 99%, as specified by the manufacturer and used in previous studies. Table (3) presents the validation data for the target gas power plant model.

Table (3): Gas Power Plant Model Validation Results Based on the Manufacturer's Operational Data [28]

NO	*Parameters*	ISO Conditions	Aspen Plus	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

Simulation of the Target Gas Power Plant Using Steam Injection (STIG) and Combined Cycle (CCPP).

The two Siemens GT5-2000E gas turbines that are the subject of this paper are located west of Tripoli. They are combined with Heat Recovery Steam Generator (HRSG) units that utilise the exhaust gases from the two units for steam generation. The steam injection technology (as shown in Figure 1) and the combined cycle technology (as shown in Figure 2) were applied to improve performance efficiency and increase power output. were applied to improve performance efficiency and increase power output.

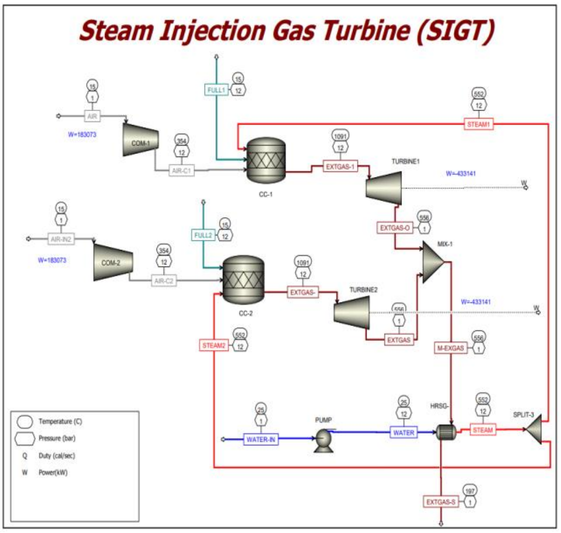

Figure (1): Simulation Model of the Target Plant (SGT5-2000E) with Steam Injection Technology (SIGT

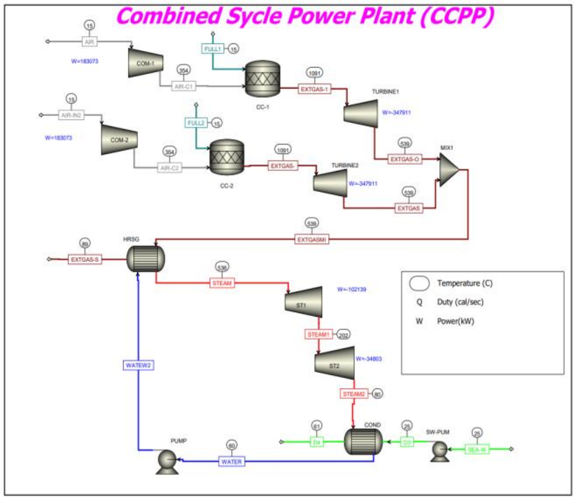

Figure (2): Simulation Model of the Target Plant (SGT5-2000E) with Combined Cycle Technology (CCPP

5. Results and Discussion

Exergy Analysis of the Impact of Combined Cycle and Steam Injection Technologies on the Two Gas Units.

When comparing steam injection technology and the combined cycle with the simple cycle in terms of exergy efficiency, as shown in Table (4), it is clear that the effect of the technologies on the two gas units in the simple cycle differs significantly between the technologies. The overall exergy efficiency increased from 55.19% in the two gas units to 74.82% with steam injection, reflecting an improvement of 19.63%. In contrast, in the combined cycle, the exergy efficiency dropped to 49.18%, reflecting a decrease of 6.01%. This is due to the different impacts of each technology on the system's core components: combustion chambers, turbines, compressors, and the Heat Recovery Steam Generator (HRSG). In the combustion chambers, a significant improvement in efficiency was observed after applying steam injection. The exergy efficiency increased from 70.62% in the two gas units to 92.49% after applying steam injection. This reflects a significant reduction in exergy loss, which decreased from 210.46 MW to 53.80 MW per combustion chamber, as shown in Table (5). The exergy wastage ratio in the combustion chambers decreased from 42.79% to 19.41% of the total available exergy in the system, reflecting greater efficiency in utilizing available energy. In the combined cycle, the combustion chambers did not show any change in exergy efficiency, as the exergy efficiency remained at 70.62%, with no change. Moreover, the exergy loss in these components remained high, at 210.46 MW per combustion chamber. This suggests that the combined cycle did not have an effect in reducing exergy loss in the combustion chambers. Regarding the turbines, the exergy efficiency in the turbines of the two gas units increased after applying steam injection to 94.71%, compared to 94.63% in the combined cycle. However, despite the slight increase in efficiency, the exergy loss in the turbines slightly increased with steam injection from 19.79 MW to 24.25 MW, while in the combined cycle, the exergy loss in the turbines remained at 19.80 MW. This indicates that steam injection improved combustion conditions, raising the pressure within the turbines due to the additional mass flow, but slightly increased exergy loss in the turbines. of the thermal energy, contributed to the increase in generated power. The first steam turbine (ST1) added 127.91 MW of power, with an exergy efficiency of 90.63%, while the second steam turbine (ST2) added 9.58 MW with an exergy efficiency of 90.43%. However, this addition to the complex system did not compensate for the increase in exergy loss, leading to a decrease in overall exergy efficiency from 55.19% in the two gas units under the simple cycle condition to 49.18% in the combined cycle.

Table (4): Exergy Efficiency Results for the Two Gas Units without and with Combined Cycle and Steam Injection Technologies.

Plant	*GTx2*	*CCPP*	*STIG x2*
Components	*Exergy Efficiency (%)*	*Exergy Efficiency (%)*	*Exergy Efficiency (%)*
COMP1	91.43	91.43	91.43
COMB1	70.62	70.62	92.49
TURBINE1	94.63	94.63	94.71
COMP2	91.43	91.43	91.43
COMB2	70.62	70.62	92.49
TURBINE2	94.63	94.63	94.71
HRGS	-	79.69	69.88
Water Pump	-	0.01	0.01
ST1	-	90.63	-
ST2	-	90.43	-
Plant Exergy Efficiency (%)	55.19	49.18	74.82

It is observed that the exergy loss in the compressors remains constant at 15.69 MW per compressor, with an exergy efficiency of 91.43% in both technologies. Therefore, compressors cannot be considered the primary contributor to the significant improvement in efficiency in either of the two technologies. Regarding the steam generator in the steam injection technology, exhaust gases are utilized to generate steam that is injected into the combustion chamber to enhance thermal efficiency. In this technology, the exergy loss in the Heat Recovery Steam Generator (HRSG) was 89.66 MW, while the exergy efficiency in the steam generator was 69.88%. The exergy supplied by the steam generator accounts for approximately 32.35% of the total exergy in the system. This indicates that steam injection technology uses the hot gases produced by the turbines to vaporize water, thereby improving the overall efficiency of the plant. However, the additional steam mass passing through the HRSG leads to an increase in exergy loss, thus escalating energy loss within the system. On the other hand, in the combined cycle, the HRSG is also employed to convert the thermal energy in the exhaust gases into steam. In this technology, the exergy loss in the HRSG was 51.74 MW, with an exergy efficiency of 79.69%. The exergy provided by the steam generator in the combined cycle constitutes about 9.27% of the total exergy in the system. It is evident that the combined cycle makes better use of the thermal energy in the exhaust gases compared to the steam injection technology, as the exergy loss in the steam generator is lower than in steam injection. It is noticeable that the exergy loss in steam injection is higher than in the combined cycle, with 89.66 MW in steam injection compared to 51.74 MW in the combined cycle. This is attributed to the additional steam mass passing through the HRSG in steam injection technology, which increases the exergy loss due to the higher flow rate.

Table (5) Exergy Loss Results for the Two Gas Turbines in the Combined Cycle and Steam Injection Technologies

Plant	*GTx2*	*CCPP*	*STIG x2*
Components	*Ex Destruction (MW)*	*Ex Destruction (MW)*	*Ex Destruction (MW)*
COMP1	15.69	15.69	15.69
COMB1	210.46	210.46	53.80
TURBINE1	19.79	19.80	24.25
COMP2	15.69	15.69	15.69
COMB2	210.46	210.46	53.80
TURBINE2	19.79	19.80	24.25
HRGS	-	51.74	89.66
Water Pump	-	0.20	0.20
ST1	-	13.22	-
ST2	-	1.01	-
Total	491.89	557.89	277.15

In terms of the exergy ratio provided by the steam generator, we observe that steam injection provides a higher exergy ratio (32.35%) compared to the combined cycle (9.27%), as shown in Table (6).

Table (6) Exergy Loss Ratio Results for the Two Gas Turbines in the Combined Cycle and Steam Injection Technologies.

Plant	*GTx2*	*CCPP*	*STIG x2*
Components	*Ex Ratio (%) t*	*Ex Ratio (%) t*	*Ex Ratio (%) t*
COMP1	3.19	2.81	5.66
COMB1	42.79	37.72	19.41
TURBINE1	4.02	3.55	8.75
COMP2	3.19	2.81	5.66
COMB2	42.79	37.72	19.41
TURBINE2	4.02	3.55	8.75
HRGS	-	9.27	32.35
Water Pump	-	0.07	0.07
ST1	-	2.37	100.00
ST2	-	0.18	-
Total	100.00	100.00	100.00

The results indicate that steam injection technology outperforms the combined cycle in improving exergy efficiency. Steam injection achieved an overall improvement of 19.63%, whereas the combined cycle efficiency decreased by 6.01%. The most significant improvement in steam injection occurred in the combustion chambers, where efficiency increased substantially, while no improvements were observed in this stage for the combined cycle. The inclusion of steam turbines in the combined cycle added complexity to the system, contributing to a reduction in overall exergy efficiency. Based on these factors, it can be concluded that steam injection technology performs better than the combined cycle in terms of overall efficiency and energy savings.

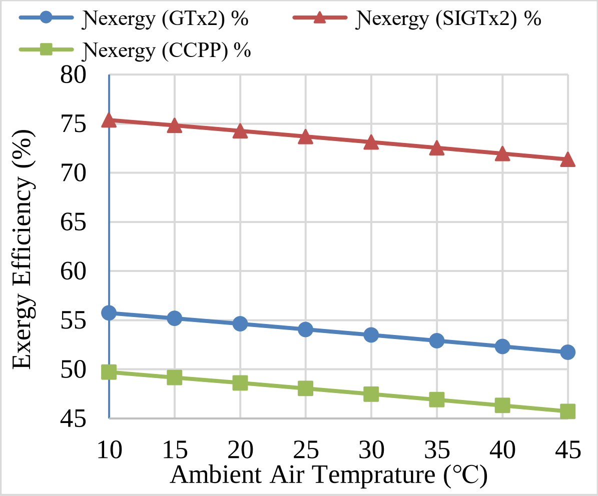

Figure (3) Effect of Compressor Inlet Air Temperature on Exergy Efficiency

Study of the Effect of Compressor Inlet Air Temperature on Exergy Efficiency

As shown in Figure (3), the results demonstrate that when the two gas turbines are operated in the simple cycle, the exergy efficiency is 55.19% at an inlet air temperature of 15°C. This efficiency increases to 74.82% with the application of steam injection technology, due to better utilization of exhaust gas heat in vaporizing water and enhancing the combustion process. In contrast, the exergy efficiency in the combined cycle decreases to 49.16% due to additional components such as the steam turbine, which increases exergy losses in these components, thereby lowering the overall exergy efficiency. As the ambient air temperature increases, a gradual decrease in exergy efficiency is observed across the different systems. In the case of the two gas turbines, efficiency decreases from 55.73% at 10°C to 51.74% at 45°C, reflecting the adverse effect of higher temperature on air density and compressor efficiency. With steam injection, the efficiency begins to decline from 75.37% at 10°C to 71.36% at 45°C, highlighting its effectiveness in reducing exergy losses despite thermal variations. In the combined cycle, the exergy efficiency decreases from 49.72% to 45.72% as temperature rises. Therefore, steam injection technology outperforms the combined cycle in enhancing exergy efficiency, especially in hot conditions, where it maintains a higher proportion of useful exergy and mitigates the impact of temperature on performance.

Study of the Effect of Compressor Inlet Air Temperature on Exergy Energy Loss

From Figure (4), it is observed that for both gas turbines, at a compressor inlet air temperature of 15°C, the exergy energy loss is recorded at 491.87 MW, indicating significant amounts of unused energy. When steam injection technology is used, the loss decreases to 277.13 MW, reflecting a considerable improvement in thermal energy utilization and reduction in energy loss, thanks to enhanced combustion and reduced exhaust gas temperature. On the other hand, when the turbines are operated in a combined cycle, the loss increases to 557.87 MW due to the complexity of the system and the addition of the steam turbine, which increases energy loss compared to steam injection technology that operates on the gas turbines themselves. When analysing the effect of changes in loss with rising compressor inlet air temperature, it is observed that exergy loss increases across all systems. In the case of the two gas turbines operating in simple cycle, the loss rises from 485.95 MW at 10°C to 529.79 MW at 45°C. Meanwhile, in steam injection technology, the loss remains relatively lower, rising from 271.21 MW at 10°C to 315.04 MW at 45°C, highlighting the ability of this technology to mitigate system enhancement even at high air temperatures. In the combined cycle, the loss increases from 551.95 MW at 10°C to 595.78 MW at 45°C. These results confirm that steam injection technology is the most efficient in reducing exergy energy loss and is less affected by temperature changes, making it more suitable for hot environments.

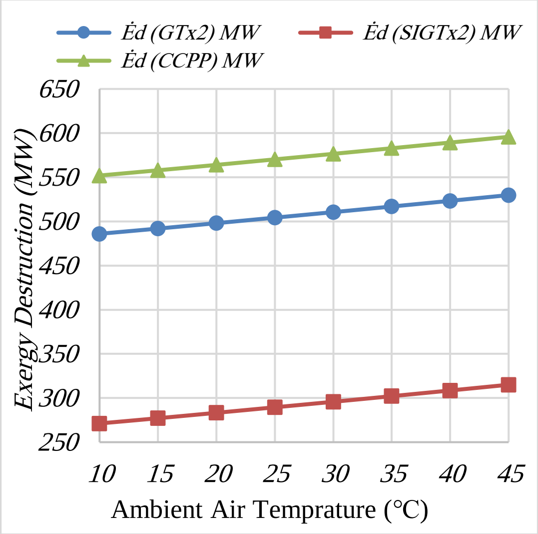

Figure (4) Effect of Compressor Inlet Air Temperature on Exergy Energy Loss

Study of the Effect of Compressor Inlet Air Temperature on Energy Loss Ratio in the System

In the case of the two gas turbines operating in simple cycle at 15°C, the energy loss ratio is recorded at 44.81%. When steam injection technology is applied, this ratio drops to 25.25%. In contrast, the combined cycle registers a loss ratio of 50.82%, as shown in Figure (5). When analysing the changes in loss ratio with varying compressor inlet air temperatures, a gradual increase in loss is observed as temperature increases across the different systems. At 10°C, the energy loss ratio for the two gas turbines in simple cycle is 55.73%, which gradually decreases to 51.74% at 45°C. In steam injection technology, the loss ratio starts at 75.29% at 10°C and decreases to 71.36% at 45°C. In the combined cycle, the ratio starts at 50.28% at 10°C and gradually increases to 54.28% at 45°C. From these results, it is clear that steam injection technology is the most effective in reducing energy loss compared to both the simple cycle and the combined cycle.

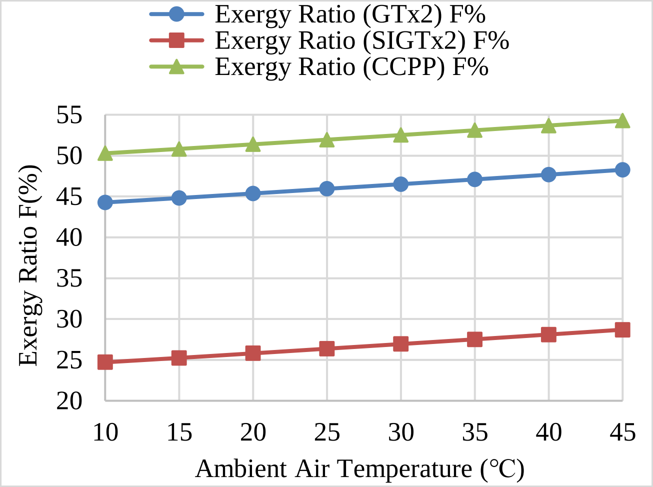

Figure (5) Effect of Compressor Inlet Air Temperature on Energy Loss Ratio in the System

Conclusion:

The following conclusions can be drawn from this work:

1. Steam injection technology has clearly outperformed in improving plant efficiency and reducing exergy loss compared to the two gas turbines in both simple cycle and combined cycle configurations.

2. The combined cycle provided additional power but suffered from a noticeable increase in exergy loss due to the system's complexity and the addition of new components.

3. Compressors and gas turbines demonstrated high stability in performance with elevated exergy efficiency in all scenarios.

4. Combustion chambers significantly benefited from steam injection technology, greatly reducing thermal energy loss.

5. The analysis demonstrates the importance of steam injection technology as the optimal choice for improving overall efficiency and reducing thermal losses compared to the combined cycle.

6. There is a need to improve the design of the combined cycle to minimize exergy energy loss.

7. The importance of adopting the most efficient and effective energy technologies to achieve performance improvement and reduce loss in gas power plants.

Acknowledgements

I would like to thank marine Engineering department for their help to finish this article.

Conflict of interest: The authors declare that there are no conflicts of interest

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