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Validation and Parametric Study Using Energy and Exergy Analysis for a Simple Gas Turbine Power Plant

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التحقق من صحة النموذج ودراسة بارامترية باستخدام تحليل الطاقة والإكسيرجي لمحطة توربين غازي بسيطة

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Abstract
This paper presents the model validation and a comprehensive parametric study for the energy and exergy analysis of the Siemens SGT5-2000E gas turbine power plant operating at Al-Ruwais Gas Power Station in Al-Hawamid, Western Mountain region, Libya. Aspen Plus simulation software was employed alongside energy and exergy analyses based on the first and second laws of thermodynamics. The validation results demonstrated excellent agreement between the simulation outputs and the manufacturer's ISO design data, with a maximum power deviation of 0.21%, a thermal efficiency match of 34.7%, and near-perfect agreement in exhaust gas temperature and mass flow rate. The parametric study revealed that increasing the compressor inlet air temperature from 10°C to 50°C causes a significant reduction in net power output and thermal efficiency, accompanied by a corresponding increase in specific fuel consumption and CO_2 emissions. Exergy analysis identified the combustion chamber as the component with the highest exergy destruction rate, rendering it the most critical element affecting energy conversion quality. These findings confirm the operational limitations of the simple gas turbine cycle under hot climatic conditions and support the need for integrated optimization technologies.

Keywords: Gas turbine; Model validation; Exergy analysis; Aspen Plus; Al-Ruwais plant; Libya.

الملخص
تقدم هذه الورقة التحقق من صحة النموذج ودراسة بارامترية شاملة للتحليل الطاقي والإكسيرجي لمحطة قدرة تعمل بتوربين غازي من نوع Siemens SGT5-2000E في محطة الرويس الغازية بمنطقة الحوامد الجبل الغربي ليبيا وقد استخدم برنامج المحاكاة Aspen Plus إلى جانب التحليلين الطاقي والإكسيرجي المستندين إلى القانونين الأول والثاني للديناميكا الحرارية. أظهرت نتائج التحقق توافقا ممتازا بين مخرجات المحاكاة وبيانات التصميم القياسية للشركة المصنعة عند ظروف ISO حيث لم يتجاوز أقصى انحراف في القدرة المنتجة نسبة 0.21% مع تطابق الكفاءة الحرارية عند 34.7% وتوافق شبه تام في درجة حرارة غازات العادم ومعدل تدفقها الكتلي كما كشفت الدراسة البارامترية أن زيادة درجة حرارة الهواء الداخل إلى الضاغط من 10°C إلى 50°C تؤدي إلى انخفاض ملحوظ في صافي القدرة المنتجة والكفاءة الحرارية مصحوب بزيادة مقابلة في معدل استهلاك الوقود النوعي وانبعاثات ثاني أكسيد الكربون. وقد بين التحليل الإكسيرجي أن غرفة الاحتراق تمثل المكون الأعلى من حيث معدل تدمير الإكسيرجي مما يجعلها العنصر الأكثر تأثيرا في جودة تحويل الطاقة داخل المنظومة. وتؤكد هذه النتائج القيود التشغيلية للدورة الغازية البسيطة تحت الظروف المناخية الحارة كما تدعم الحاجة إلى تبني تقنيات تحسين متكاملة لرفع كفاءة الأداء.

الكلمات المفتاحية: التوربين الغازي؛ التحقق من صحة النموذج؛ التحليل الإكسيرجي؛ برنامج Aspen Plus ؛ محطة الرويس؛ ليبيا.

1.Introduction

Gas turbine power stations constitute one of the most prominent sources of electricity generation globally, and in Libya in particular (Gargoum, 2024) owing to their rapid dynamic response and adequate energy conversion efficiency. In Libya, these stations form a fundamental pillar of the national power generation infrastructure, with gas turbine units distributed across several plants including West Tripoli, South Tripoli, Benghazi, Al-Zawiya, and others. However, the operational performance of these units is significantly affected by local atmospheric conditions, particularly the elevated ambient temperatures during summer months, which lead to a reduction in air density at the compressor inlet, a decline in power output, and an increase in fuel consumption (Siemens AG, 2011;Montasser et al, 2024; Alsadaie & Algool, 2024).

In this context, the importance of conducting rigorous thermodynamic and exergy analyses to evaluate the performance of gas turbine power stations and to identify locations of energy losses in a scientifically systematic manner becomes evident. Model validation is an indispensable methodological step prior to any parametric or optimization study, as it ensures the reliability of simulation outputs and their ability to represent the actual physical behavior of the system (Eshoul et al., 2025; Khademi & Khosravi, 2013; Boyce, 2011)

This paper aims to validate an existing simple cycle power plant (Siemens SGT5-2000E) using Aspen plus software, Al-Ruwais Gas Power plant. The study also encompasses a comprehensive energy and exergy analysis of the system components, a comparison of results with the manufacturer's ISO data, and a parametric investigation of the effect of ambient air temperature on key performance indicators.

2. Target Gas Power Station

2.1 Description of the SGT5-2000E Gas Turbine

Al-Ruwais Gas Power Station operates with Siemens SGT5-2000E units, a single-shaft gas turbine comprising a multi-stage axial compressor, a combustion chamber, and a gas turbine directly coupled to an electric generator. This model is characterized by high design efficiency and notable operational flexibility when using both liquid and gaseous fuels. The turbine operates on an open Brayton cycle and is among the most prominent models used in Libyan power stations (Gargoum, 2024; Siemens AG, 2011)

Table 1 presents the operating data of the gas power station under ISO conditions according to the technical specifications issued by the manufacturer.

Table (1): Siemens Gas Power Plant Operating Results at ISO Conditions

Siemens Gas Turbine	SGT5-2000E	SGT6-2000E
Grid frequency (Hz)	50	60
Gross power output (MW)	168	113
Gross efficiency (%)	34.7	34
Gross heat rate (kJ/kWh)	10,366	10,606
Gross heat rate (Btu/kWh)	9,825	10,052
Exhaust temperature (°C/°F)	536/998	543/1,009
Exhaust mass flow (kg/s)	531	369
Exhaust mass flow (lb/s)	1,170	813
Pressure ratio	11.7	11.8
Length x width x height (m)	10x12x7.5	8.3x10x6.25
Weight (t)	234	163

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3. Methodology and Thermal Modelling

3.1 Aspen Plus Software

Aspen Plus is an advanced engineering simulation tool widely used in the analysis and modelling of complex thermal systems. The software provides an integrated environment for simulating thermodynamic processes in energy and industrial applications, and is distinguished by its ability to represent various system components and analyse their performance under diverse operating conditions, making it an essential tool in engineering studies related to power generation plants (AspenTech, 2020).The software relies on precise mathematical models for simulating fluid dynamics, heat transfer, and chemical reactions, thereby ensuring the reliability of simulation results (Al-Malah, 2016).

3.2 Thermal Model Equations

The thermodynamic analysis of the gas turbine is based on modelling the open Brayton cycle under the assumption of steady-state flow, neglecting kinetic and potential energy effects, and treating air and combustion gases as ideal fluids. Table 2 presents the principal equations employed in the thermodynamic analysis of the gas power station according to the reference studies (Alsadaie & Algool, 2024; Khademi & Khosravi, 2013; Ibrahim, 2010) .

Table (2): Thermal Model Equations for the Gas Power Plant (Alsadaie & Algool, 2024; Khademi & Khosravi, 2013; Ibrahim, 2010)

Parameter	**Equation**
Net Thermal Power (GT)	$\dot{W}net(GT) = \dot{W}thermal(GT) - \dot{W}loss(GT)$
Net Thermal Efficiency	$\eta net(GT) = \dot{W}net(GT) / (\dot{m}f \cdot LHV)$
Specific Fuel Consumption	$HR = 3600 / \eta net(GT)$
CO_2 Emissions	$CO_2EMISSION = \dot{m}EMISSION / \eta net(GT)$
Model Error Ratio	Model Error = [(Actual – Model) / Actual] × 100

3.3 Exergy Analysis

The exergy analysis is based on the general exergy principle, in which the total exergy of a flow stream comprises physical exergy and chemical exergy. The exergy efficiency of each component is defined as the ratio of useful output exergy to input exergy. The exergy destruction resulting from irreversibilities within each component is determined through an exergy balance applied to the respective component (Elwardany et al., 2024; Dincer & Rosen, 2013).

Table (3): Exergy Analysis Equations for the Gas Power Plant [4,6,10]

Parameter	**Equation**
Total Exergy of Flow Stream	$\dot{E}x = \dot{E}x\_ph + \dot{E}x\_ch$
Physical Exergy	$\dot{E}x\_ph = \dot{m}[(h - h_0) - T_0(s - s_0)]$
Chemical Exergy of Gas Mixtures	$\dot{E}x\_ch = \dot{n}[\Sigma\, x_i\, \bar{e}x\_ch,i + R\, T_0\, \Sigma\, x_i \ln(x_i)]$
Exergy Efficiency (Compressor/Pump)	$\eta\_ex = (\dot{E}x\_out - \dot{E}x\_in) / \dot{W}\_in$
Exergy Efficiency (Turbine)	$\eta\_ex = \dot{W}\_out / (\dot{E}x\_in - \dot{E}x\_out)$
Exergy Efficiency (Combustion Chamber)	$\eta\_ex = \dot{E}x\_out / (\dot{E}x\_fuel + \dot{E}x\_air)$
Exergy Efficiency (Heat Exchanger)	$\eta\_ex = (\dot{E}x\_cold,out - \dot{E}x\_cold,in) / (\dot{E}x\_hot,in - \dot{E}x\_hot,out)$
Exergy Destruction (Compressor/Pump)	$\dot{E}x\_D = \dot{E}x\_in + \dot{W}\_in - \dot{E}x\_out$

Exergy Destruction (Turbine)	$\dot{E}x\_D = \dot{E}x\_in - \dot{E}x\_out - \dot{W}\_out$
Exergy Destruction (Combustion Chamber/HEX)	$\dot{E}x\_D = \Sigma\dot{E}x\_in - \Sigma\dot{E}x\_out$
Component Exergy Destruction Ratio	$t_i = (\dot{E}x\_D,i / \dot{E}x\_D,total) \times 100$
Overall Plant Exergy Efficiency	$\eta\_ex,total = \dot{W}\_net / \dot{E}x\_fuel$
Exergy Destruction Percentage	$\%t = (\dot{E}x\_D,component / \dot{E}x\_D,total) \times 100$

4. Model Validation

4.1 Gas Power Station Simulation Using Aspen Plus

A detailed simulation model of Al-Ruwais Gas Power Station, operating with a Siemens SGT5-2000E gas turbine, was developed using Aspen Plus software, based on standard design data under ISO conditions. The open gas cycle was represented within the Aspen Plus environment, with air admitted to the compressor at a temperature of 15°C and a pressure of 1.013 bar, with a mass flow rate of 520.328 kg/s, and a mass composition of 21% O_2 and 79% N_2.

Following the compression process, the simulation results indicated that the air temperature rose to approximately 349.6°C at a pressure of 11.7 bar. The combustion chamber was modelled with natural gas (CH_4) introduced as fuel at a flow rate of 10.762 kg/s and a pressure of 20 bar. After expansion within the turbine, the exhaust gas temperature dropped to approximately 536.6°C at a pressure of 1.013 bar, with a mass flow rate of 531.09 kg/s. The performance coefficients were specified as follows: isentropic compressor efficiency of 85%, turbine efficiency of 90.5%, mechanical efficiency of the turbine-compressor shaft of 99%, and generator efficiency of 98.5% (Siemens AG, 2011: Gargoum, 2024)

Table 4 presents the detailed flow stream data of the gas power station obtained from the simulation, while Figure (1) illustrates the design model of Al-Ruwais Gas Power Station.

Figure (1): Simulation Model of the Gas Power Station (Siemens GT5-2000E)

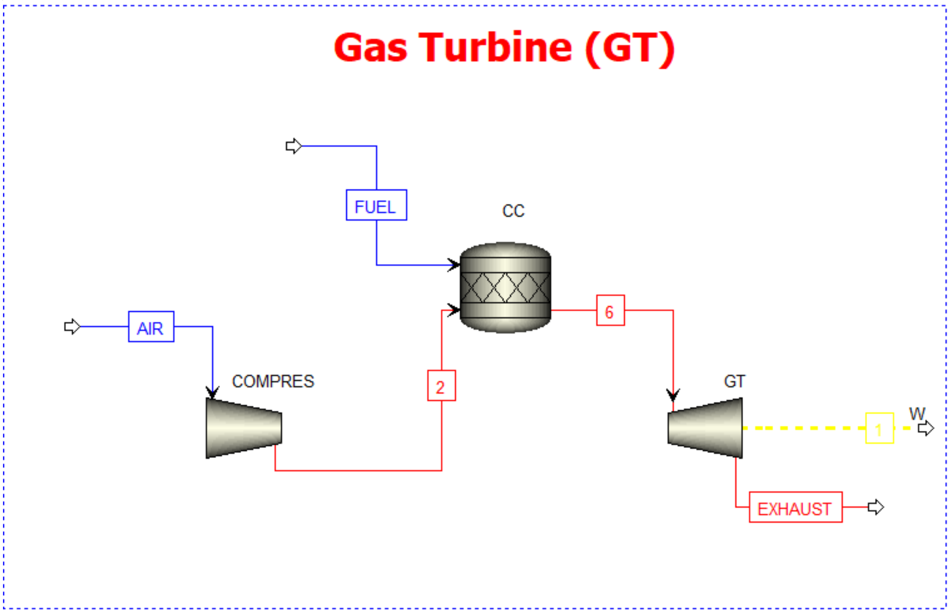

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Table (4): Inputs and Simulation Results of Gas Power Station Flow Streams

Parameter	Unit	Stream 1 (Air Inlet)	Stream 2 (Compressor Outlet)	Stream 3 (Fuel)	Stream 4 (Turbine Inlet)	Stream 5 (Exhaust Gas)
Temperature	°C	15	349.6	15	1081	536.6
Pressure	bar	1.013	11.7	20	11.699	1.013
Mass Flow Rate	kg/s	520.328	520.328	10.762	531.09	531.09
O_2 Fraction	-	0.21	0.21	0	0.124	0.124
N_2 Fraction	-	0.79	0.79	0	0.773	0.773
CO_2 Fraction	-	0	0	0	0.0555	0.0555
H_2O Fraction	-	0	0	0	0.0455	0.0455

4.2 Model Validation Results

Table 5 presents a comparison between the simulation results obtained using Aspen Plus and the design data issued by the manufacturer Siemens under ISO conditions, in order to verify the accuracy of the developed model.

Table (5): Validation Results of the Gas Power Plant Model

No.	Parameter	ISO Design Data	Aspen Plus Model	Difference	Error (%)
1	Power Output (MW)	168	167.65	0.35	0.21
2	Thermal Efficiency (%)	34.7	34.7	0	0.00
3	Exhaust Gas Temperature (°C)	536	537	1	0.19
4	Exhaust Mass Flow Rate (kg/s)	531	531	0	0.00

The validation results demonstrate a high degree of agreement between the simulation outputs and the ISO data. The model power output reached 167.65 MW compared to a design value of 168 MW, with an error ratio not exceeding 0.21%. A complete match was achieved in thermal efficiency at 34.7%, with a zero error ratio. The exhaust gas temperature from the simulation was 537°C, compared to the design value of 536°C, with a marginal deviation of 0.19%. The exhaust gas mass flow rate matched exactly at 531 kg/s. These results confirm the reliability of the Aspen Plus model and its capability to represent the actual performance of the station with high accuracy.

5. Results and Discussion

5.1 Effect of Air Temperature on Thermal Efficiency

The parametric study demonstrated that increasing the compressor inlet air temperature from 10°C to 50°C results in a decline in the net thermal efficiency from 35.28% to 30.17%, representing an overall reduction of approximately 11.31%, with an average rate of 1.3% per 5°C increment. This decline is attributed to the reduction in inlet air density and the increase in compressor work, which diminishes the energy available for effective conversion.

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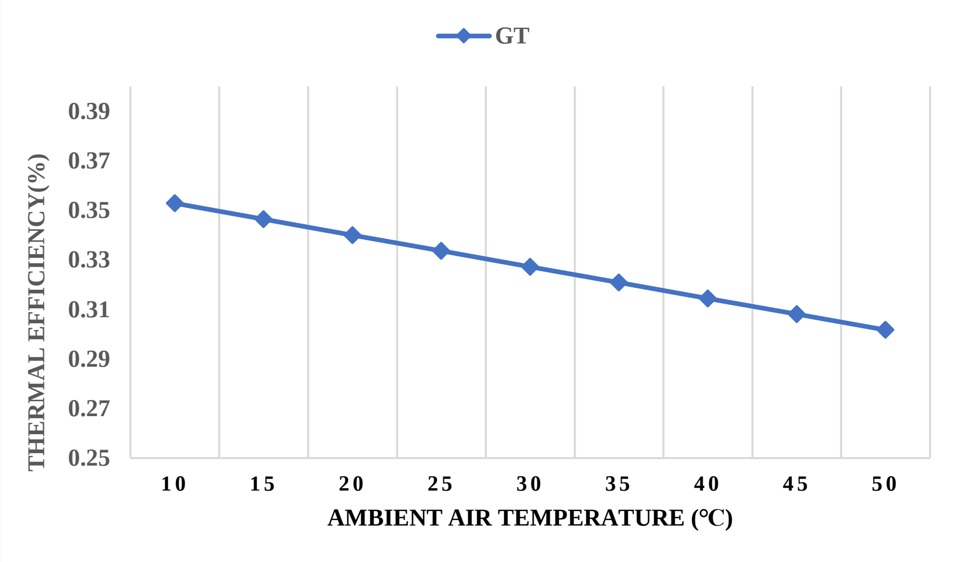

Figure (2): Effect of Compressor Inlet Air Temperature on Thermal Efficiency

5.2 Effect of Air Temperature on Net Power Output

The increase in inlet air temperature led to a reduction in the net electrical power output of the two gas turbine units from 341.68 MW at 10°C to 292.16 MW at 50°C, representing an overall decline of 14.49%. This reduction reflects the impact of elevated temperatures on turbine performance, whereby higher temperatures increase compressor work and reduce net power output. These findings confirm the sensitivity of gas-fired power stations operating in hot climates to ambient air conditions.

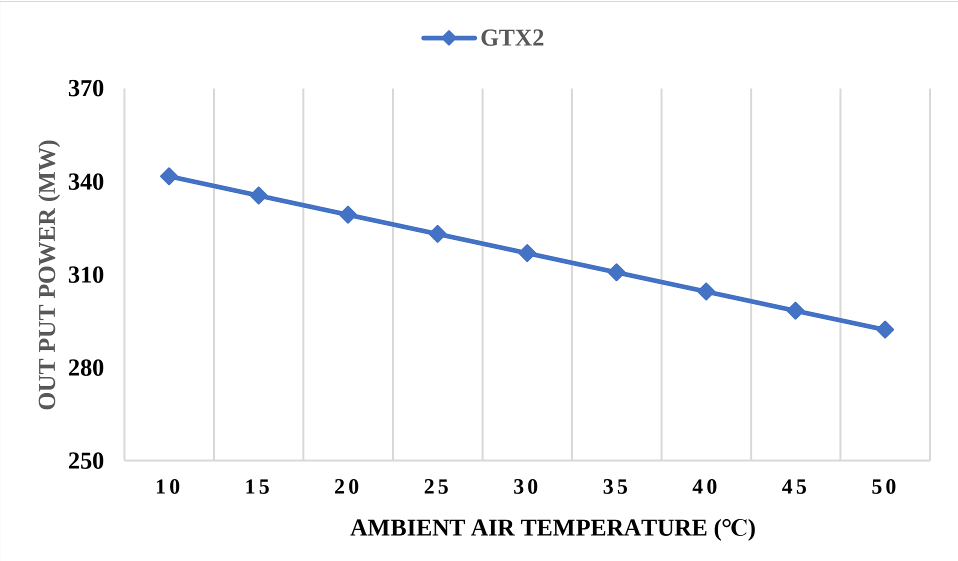

Figure (3): Effect of Compressor Inlet Air Temperature on Net Electrical Power Output

5.3 Effect of Air Temperature on Specific Fuel Consumption

Specific fuel consumption increased from 226.73 kg/MWh at 10°C to 265.16 kg/MWh at 50°C, representing an overall increase of 16.95%, at an average rate of 2.12% per 5°C. This effect is interrelated with the decline in thermal efficiency, indicating that the thermal load required to produce a unit of energy increases simultaneously with the degradation in performance.

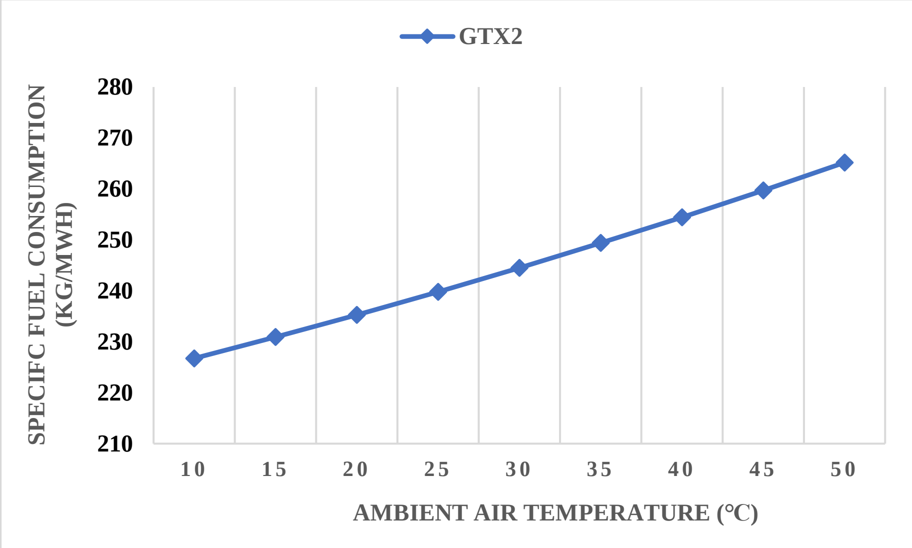

Figure (4): Effect of Compressor Inlet Air Temperature on Fuel Consumption Rate

5.4 Effect of Air Temperature on CO_2 Emissions

Increasing the air temperature from 10°C to 50°C resulted in an increase in CO_2 emissions from 622.04 kg/MWh to 712.64 kg/MWh, representing an overall increase of 14.56%, at an average rate of 1.82% per 5°C. This rise demonstrates the dual effect of elevated temperatures on specific fuel consumption and the associated emission intensity.

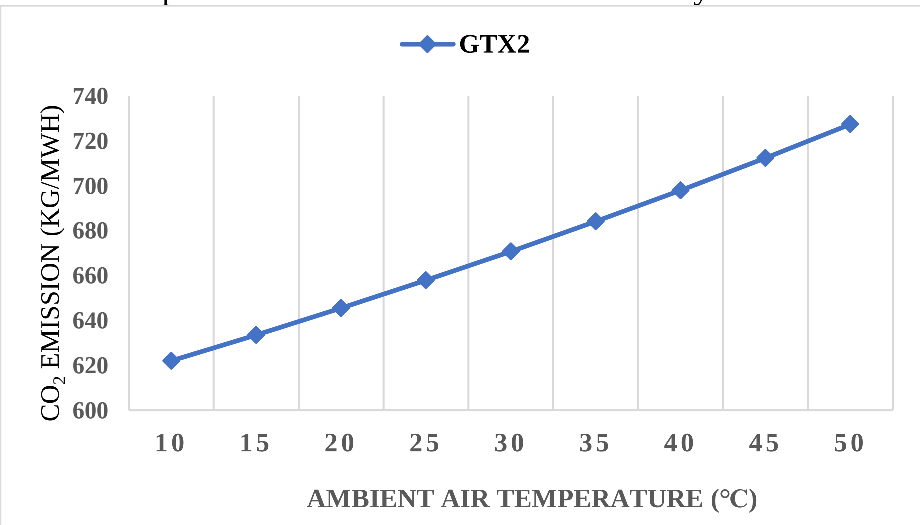

Figure (5): Effect of Compressor Inlet Air Temperature on CO_2 Emissions

5.5 Exergy Destruction Ratio Analysis

The exergy analysis revealed that the combustion chamber accounts for the largest proportion of exergy destruction within the system, due to the high exergy losses arising from the chemical reaction of the combustion process. This is followed by the gas turbine and then the compressor, rendering the combustion chamber the most influential component on energy conversion quality and overall system efficiency.

These findings indicate that improving combustion efficiency and reducing the thermodynamic losses within the combustion chamber represents the most effective pathway for enhancing the overall exergy efficiency of the system, while the gas turbine and compressor remain secondary sources of exergy destruction that can be mitigated through improvements in component efficiencies.

Figure (6) shows that exergy destruction within the gas cycle is predominantly concentrated in the combustion chambers, which accounted for the largest share of total exergy destruction within this part of the system, contributing 82.7%. This reflects the elevated exergy losses associated with the combustion process as a result of chemical reactions, heat transfer across large temperature differentials, and entropy generation within these components. This implies that the largest portion of energy quality degradation within the gas cycle occurs during the conversion of the fuel's chemical energy into thermal energy, making the combustion chambers the most significant source of exergy destruction in this part of the system.

In contrast, the contribution of the gas turbines was considerably lower at 9.0%, a loss associated with the actual expansion process and the accompanying friction and flow losses that reduce the optimal utilization of the available energy in the hot gases. The compressors contributed 8.3%, a proportion lower than that of the combustion chambers, yet still of clear significance due to the non-ideal compression process occurring within the compressor, accompanied by entropy increase. It is therefore evident that the defining characteristic of the gas cycle is that the combustion chambers are the dominant component governing exergy destruction, indicating that any improvement in the thermodynamic performance of this part of the system must first focus on reducing exergy losses in the combustion process and optimizing its operating conditions.

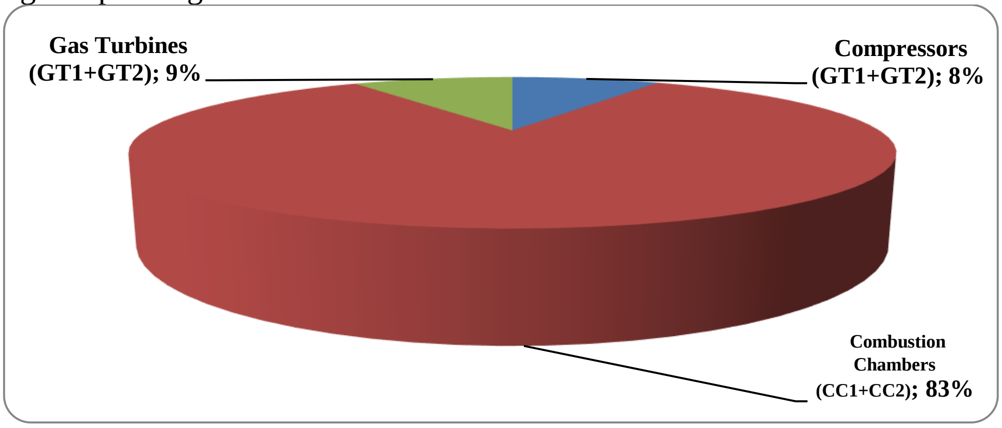

Figure (6): Exergy Destruction Ratio Results for the Gas Power Station

Figure (7) illustrates the effect of increasing ambient air temperature on the exergy efficiency of the gas turbine power plant. It is evident that the exergy efficiency decreases progressively as the temperature rises from 10°C to 50°C, starting at approximately 34.6% and declining to approximately 29.8%. This reduction is attributed to the decrease in air density at the compressor inlet, which leads to increased compressor work and a reduction in net power output. Furthermore, elevated temperature degrades the quality of energy conversion within the gas cycle and increases exergy losses. These findings confirm that the exergy performance of the plant is significantly affected by hot climatic conditions.

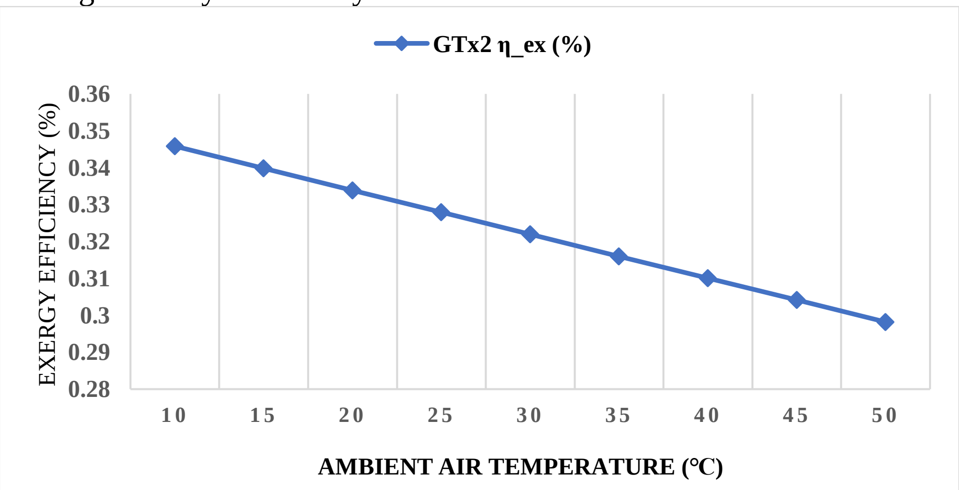

Figure (7): Effect of Compressor Inlet Air Temperature on Exergy Efficiency

6. Conclusions

Through the energy and exergy analysis of Al-Ruwais Gas Power Station operating with the Siemens SGT5-2000E gas turbine, and based on the parametric study conducted using Aspen Plus, it can be concluded that the developed simulation model demonstrated high reliability in representing the actual performance of the plant. The validation results showed very good agreement with the ISO design data, where the error in net power output did not exceed 0.21%, while the thermal efficiency and exhaust gas mass flow rate matched the reference data. This confirms the suitability of the model for conducting detailed thermodynamic and exergy analyses.

The results of the parametric study showed that increasing the compressor inlet air temperature from 10°C to 50°C causes a clear deterioration in the performance of the simple gas turbine cycle. This deterioration is represented by a reduction in net electrical power output and thermal efficiency, where the net thermal efficiency decreases at an average rate of about 1.3% for every 5°C increase in inlet air temperature. At the same time, the specific fuel consumption and CO_2 emissions increase as the ambient temperature rises. This behavior is mainly attributed to the reduction in inlet air density and the increase in compressor work, which confirms the strong sensitivity of gas turbine power plants to hot climatic conditions, particularly in the Libyan environment.

The exergy analysis revealed that the combustion chamber is the main source of exergy destruction within the system due to the irreversibilities associated with the combustion process. Therefore, improving combustion efficiency and reducing exergy losses in this component represent important pathways for enhancing the overall performance of the plant. Based on these findings, the study supports the need to adopt integrated performance improvement technologies, such as inlet air cooling, combined cycle configurations, steam injection, absorption chillers, and waste heat recovery systems. These technologies can contribute to increasing the overall efficiency of gas-fired power generation plants in Libya, while reducing fuel consumption and CO_2 emissions.

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