



EFFECTS OF ENVIRONMENTAL AND OPERATIONAL PARAMETERS ON A HEAVY-DUTY GAS TURBINE IN A HOSTILE ENVIRONMENT: A GT13E2 CASE STUDY

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Abstract

This study investigates the effects of environmental and operational parameters on the performance of a heavy-duty GT13E2 gas turbine operating under hostile tropical conditions. Using GasTurb14 and validated operational data from a Nigerian power plant, the impacts of ambient temperature, relative humidity, altitude, air density, fuel mass flow, and turbine inlet temperature (TIT) were quantified. Results show that increasing ambient temperature from 15 °C to 40 °C reduces power output by 20.5% (180-143 MW), decreases thermal efficiency by 1.56 percentage points, and increases specific fuel consumption (SFC) by 4.7%. A 150 K rise in TIT enhances power by 12.7% and efficiency by 2.7 points, while reducing SFC by 7.6%. These findings provide site-specific performance insights for gas turbines in hostile environments.

Keywords: Ambient, Environmental, Gas turbine, humidity, efficiency

1.0 Introduction

Gas turbines constitute one of the most vital technologies in modern industrial civilization. They are widely utilized in electric power generation, aviation, marine propulsion, oil and gas processing, and mechanical drives due to their high efficiency, compactness, and operational flexibility. The increasing global energy demand, together with the pursuit of cleaner and more efficient technologies, has positioned gas turbines as a cornerstone in the

world's energy infrastructure [1]. In electricity generation, gas turbines play a central role both in simple-cycle and combined-cycle configurations, often serving as the backbone of peak-load and base-load operations. Their modular design and fast start-up capability make them particularly suitable for integration with renewable energy systems such as solar and wind, providing grid stability and dispatchable backup during periods of intermittency [2].

In

developing countries like Nigeria, gas turbines are indispensable to national energy security. They power most thermal power stations that contribute to the national grid, such as Afam, Egbin, Omotosho, and Geregu plants. However, the performance of these turbines is often constrained by harsh climatic and environmental conditions, including high ambient temperatures, elevated humidity, and airborne particulates. These factors significantly influence turbine efficiency, reliability, and lifespan. For instance, as ambient temperature increases, the density of intake air decreases, reducing the mass flow rate through the compressor. This leads to lower power output and efficiency. Studies indicate that for every 1 °C rise above ISO reference conditions, gas turbine output decreases by 0.5-1.5 MW and thermal efficiency by 0.1-0.2% [3,4]. In contrast, cooler conditions promote higher air density, improve combustion efficiency, and yield higher power output.

Gas turbines are often deployed in hostile environments, characterized by extreme temperatures, high salinity, dust concentration, or pollutant-laden atmospheres. These conditions induce complex thermo-mechanical and chemical degradation mechanisms. In coastal areas, salt-laden air accelerates hot corrosion, while desert environments introduce fine dust particles that foul compressor blades, erode turbine vanes, and disrupt airflow [5]. The presence of sulphur dioxide (SO₂), nitrogen oxides (NO_x), and volatile organic compounds (VOCs) further contributes to chemical attack and material fatigue [6]. Moisture ingress into the combustion

chamber can degrade insulation materials and destabilize flame structures, thereby increasing emissions and maintenance frequency.

Evaluating the operational performance of gas turbines enables the detection of efficiency gaps and performance bottlenecks. Continuous monitoring of critical parameters such as turbine inlet temperature, compressor efficiency, and exhaust gas temperature, facilitates predictive maintenance, allowing operators to address potential issues before they escalate into costly failures or unscheduled outages [7]. Gas turbines functioning in harsh or contaminated environments encounter distinctive operational constraints that hasten component wear and impair overall efficiency. Exposure to extreme thermal conditions, corrosive gases, elevated humidity, and airborne particulates collectively contribute to declining turbine reliability and accelerated performance deterioration [8].

The study of [9] investigated the effects of ambient temperature (20-60 °C), altitude (0-2000 m), and relative humidity (0-100%) on gas turbines with turbine inlet temperatures of 1000-1600 K. The study showed that increasing ambient temperature causes sharp declines in thermal efficiency and net power output, with severe degradation at 60 °C, particularly in hot Gulf climates. Similarly [10] reported that each 1 °C rise in ambient temperature reduced power output by about 0.74%. Conversely, [11, 12] demonstrated that intake cooling techniques improved performance under hot conditions. Exposure

to these conditions often results in compressor fouling, turbine blade erosion, corrosive pitting, and thermal fatigue, which collectively reduce power output and increase maintenance frequency [13]. Understanding these environmental influences is therefore essential for optimizing turbine operation, especially in regions characterized by extreme climatic variations [14].

The current study reinforces and localizes global findings by quantifying the decline in power output and efficiency with rising ambient temperature and environmental contamination, validating reported ranges (e.g., power loss per °C rise) for real operating conditions in tropical power plants. The study also, provides one of the few detailed, case-study-based assessments of a GT13E2 heavy-duty gas turbine operating under Nigerian hostile climatic conditions, addressing a critical gap in the literature that is often dominated by simulations or temperate-climate studies. The objective therefore is to quantitatively evaluate the operational performance of a observed from the operational log sheet.

heavy-duty GT13E2 gas turbine under hostile environmental conditions, focusing on variations in ambient temperature, humidity, and particulate-laden air typical of tropical and coastal regions such as Nigeria.

2.0 Method and system modelling

This research targets power generation in high-temperature tropical environments where operational simplicity and robustness are critical. The single-shaft configuration offers a compact, integrated system that is easier to control and maintain under such conditions. The selected case study the Afam GT13E2, already operates in single-shaft mode, ensuring the modelled system reflects actual field practice and allowing reliable use of available operational data. While multi-shaft plants may deliver marginal efficiency gains, their greater complexity and footprint are less suitable for Nigerian power sector needs prioritizing reliability and maintainability. Figure 1 shows the schematic of the combined cycle configuration. While the GT13E2 design conditions are presented in Table.1. The average operational data were also

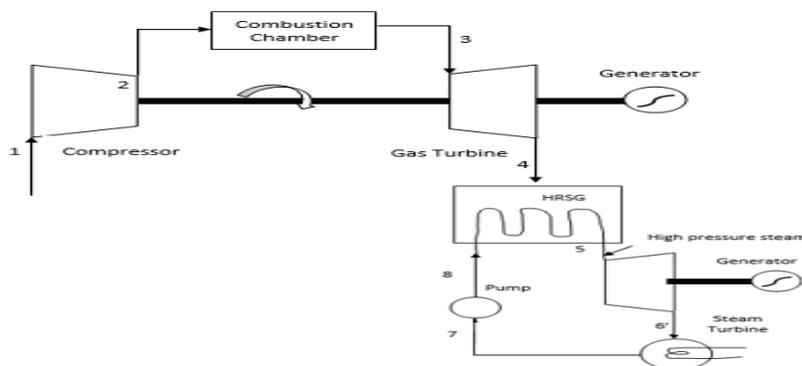


Figure. 1. Schematic of the Single Spool Combined Cycle Configuration

2.1 Assumptions and simulation approach

The analysis of the gas turbine (GT) system was carried out under the following assumptions [15].

1. Air and combustion products are assumed to behave as perfect gases with constant specific heats, except where GasTurb14 applies temperature-dependent corrections, while natural gas is assumed to have a uniform composition with a constant lower heating value of 32.736 MJ/kg.
2. All simulations are conducted under steady-state conditions, neglecting transient effects such as load variations, start-up, and shut-down dynamics.
3. Ambient temperature, pressure, humidity, and contaminant levels are assumed to be spatially uniform at the engine inlet, with hostile operating environments represented using a limited set of parameters.

4. mechanical losses and turbine cooling air extraction are treated as constant fractions within the model.
5. Materials, and configuration are assumed to remain unchanged throughout the analysis period.

This research employed GasTurb14, a professional thermodynamic cycle modeling software widely applied in the analysis, design, and performance evaluation of aero-engines and industrial gas turbines. It offers predefined engine configurations, customizable cycle components, and a range of analysis options, including design-point calculations, off-design performance predictions, degradation modeling, and transient simulations. The software integrates intuitive graphical outputs, parametric analysis tools, and a formula editor that allow researchers to explore the impact of ambient conditions, design parameters, and component efficiencies on overall engine .

Table 1
Simulation Parameters for the Single Spool (Afam power plant Operational Manual) ISO data

Parameters	Value	
Ambient Conditions	Total Temperature T1	288.15 K
	Total Pressure P1	101.325 kPa
	Ambient Pressure Pamb	101.325 kPa
	Relative Humidity	60 %
	Inlet pressure	93 kPa
	Airflow rate	70 kg/s
	Absolute Inlet Press Loss	6 kPa
	Absolute Exhaust Press Loss	0 kPa
Compressor	Pressure ratio, P2/P1	13.5
	Stages	18
	Speed	3099 rpm

	Type	axial flow, heavy duty
	Air compressor efficiency, η_c	0.8771
	Rel. Enthalpy of Interst Bleed	0.712
	Compr Interstage Bleed/W2	0.0485
Combustor	Fuel net calorific value, NCV	32.736 MJ/Kg
	Fuel	Natural gas
	Combustion efficiency, η_{comb}	0.9999
	Mechanical efficiency	0.9999
	Burner Pressure Ratio	0.9872
	Burner Exit Temperature	1650.29 K
Turbine	Stages	1
	Speed	3099 rpm
	Inlet turbine temperature	1350 K
	Turbine efficiency, η_t	0.87
	Turbine Exit Duct pressure ratio	1.01
	Exhaust Pressure ratio/Pamb	1.01
	NGV 1 cooling air/W2	0.09426
	Rotor 1 cooling air/W2	0.145
HRSG	Design Steam Temperature	800k
	Steam Exit Pressure	10000 Kpa
	Econ and Evap H2O pressure ratio	0.980769
	Superheater H2O pressure ratio	0.980392
	Rel. heat to ambient	0.01
	Feed water Temperature	567.42 K
	Pinch Delta T at Evaporator	10 K
	Evaporator Approach Delta T	10 K
	Rel. Steam Bleed Evaporator	0.01
	Duct burner exit temperature	1300 K
	Duct burner efficiency	0.9
	Design Pressure ratio	0.98
	Design inlet Mach No	0.1

2.2 System modelling equations

The compressor efficiency is expressed in equation (1)

$$\eta_c = \frac{\text{Isentropic compression work}}{\text{Actual compression work}} = \frac{W_c}{W_{ca}} = \frac{T_2 - T_1}{T_2' - T_1} \quad (1)$$

Where η_c compressor isentropic efficiency, T_1 and T_2 are compressor inlet and exit temperature.

The compression process in stage 1-2 is given as equation (2).

$$T_2 = T_1 (p_2/p_1)^{(\gamma-1)/\gamma} \quad (2)$$

Where $\gamma = 1.4$ for air and p_2/p_1 is compressor pressure ratio

$$T_2 = T_1 (r_p)^{((\gamma-1)/\gamma)} \quad (3)$$

$$\text{Where } r_p = \frac{p_2}{p_1}$$

$$T'_2 = T_1 + \frac{T_2 - T_1}{\eta_c} \quad (4)$$

The combustion process is expressed as equation 5.

$$T_3 = \frac{C.V.*\eta_{comb} + c_{pa}*\frac{A}{F}*T'_2}{c_{pg}*(\frac{A}{F}+1)} \quad (5)$$

Where $C.V.$ is calorific value of fuel, $\frac{A}{F}$ is air fuel ratio and C_{pg} specific heat capacity of gas

The turbine efficiency is expressed as equation 6.

$$\eta_t = \frac{\text{Actual turbine work}}{\text{Isentropic turbine work}} = \frac{W_{ta}}{W_t} = \frac{T_3 - T'_4}{T_3 - T_4} \quad (6)$$

$$\frac{T_3}{T_4} = (p_3/p_4)^{((\gamma-1)/\gamma)} \quad (7)$$

Where $\gamma = 1.34$ for gas

$$T'_4 = T_3 - \eta_t(T_3 - T_4) \quad (8)$$

The expansion process is given as equation 9.

$$\frac{T_3}{T'_4} = (p_3/p_4)^{((\gamma-1).\eta_t/\gamma)} \quad (9)$$

The thermal efficiency (η_{tha}) is given as the ratio of the net work done to the heat supplied, and this is given as equation 10 [15]

$$\eta_{tha} = \frac{\{c_{pg}(T_3 - T'_4) - c_{pa}(T'_2 - T_1)\}}{c_{pg}.T_3 - c_{pa}.T_2^1} \quad (10)$$

$$\text{Actual compressor work} = W'_{ca} = h'_2 - h_1 = C_{pa}(T'_2 - T_1) \text{ kJ/kg} \quad (11)$$

Actual turbine work is given as equation 12.

$$W_{ta} = h_3 - h'_4 = C_{pg}(T_3 - T'_4) \text{ kJ/kg} \quad (12)$$

Actual network is given as equation 19.

$$W_{net} = W_{ta} - W_{ca} = C_{pg}(T_3 - T'_4) - C_{pa}(T'_2 - T_1)$$

2.3 Design-Point Performance analysis and validation

The baseline combined-cycle (CC) configuration was simulated using GasTurb 14 under ISO reference conditions, namely an ambient temperature of 15 °C, pressure of 1.013 bar, and relative humidity of 60%. The simple-cycle (SC) gas turbine simulation produced a gross power output of 235.96 MW, with a net heat rate of 9,051 kJ/kWh and a thermal efficiency of 40.4% on a lower heating value (LHV) basis. When integrated

with a heat recovery steam generator (HRSG) and a single-pressure steam bottoming cycle, the plant generated an additional 68.87 MW, resulting in a total combined-cycle output of 304.83 MW and an overall net efficiency of 51.4%. Comparison with the OEM reference data for the Siemens GT13E2-210 gas turbine shows good agreement, with only modest deviations. While the OEM-rated simple-cycle output is 210 MW, the simulated model predicts 235.96 MW, corresponding to an overestimation of approximately 12.4%. Likewise, the simulated heat rate of 9,051 kJ/kWh is about 4.5% lower than the OEM

value of 9,474 kJ/kWh, indicating a slightly optimistic thermal performance.

At the combined-cycle level, the OEM design rating specifies a net output of 305 MW and a net efficiency of 55.1%, equivalent to a heat rate of 6,530 kJ/kWh. The simulated configuration closely matches the OEM output at 304.83 MW but yields a lower efficiency of 51.4%, corresponding to an approximately 7.0% higher heat rate. This difference is primarily attributable to simplifications in HRSG modeling, the omission of detailed heat-exchanger pressure losses, and the use of idealized steam-cycle

boundary conditions. Overall, the baseline model demonstrates strong fidelity in reproducing OEM design-point performance. The modest overprediction of simple-cycle output and underestimation of combined-cycle efficiency remain within acceptable limits (less than 10%) for standard GasTurb models. As summarized in Table 2, these results confirm the model’s suitability for subsequent off-design, degradation, and ambient-condition sensitivity analyses, particularly for tropical and high-temperature operating environments.

Table 2
Comparison of Baseline Simulation with OEM GT13E2

Performance Metric	GT13E2	GasTurb15 Simulation	% Deviation
SC Net Output (MW)	210.0	235.96	+12.4%
SC Net Heat Rate (kJ/kWh)	9474	9051	-4.5%
SC Net Efficiency (%)	38.0	40.4	+6.3%
CC Net Output (MW)	305.0	304.83	-0.1%
CC Net Heat Rate (kJ/kWh)	6530	6987	+7.0%
CC Net Efficiency (%)	55.1	51.4	-6.7%

Note: SC = Simple Cycle, CC = Combined Cycle

3.0 Results and Discussion

3.1 Effect of Ambient Temperature on GT13E2 Performance

The effect of ambient temperature is presented in Figure 4.2. The thermodynamic baseline parameters required for cycle simulation: ambient temperature = 288.15 K (15 °C), pressure ratio = 13.5, air mass flow = 70 kg/s, compressor efficiency = 0.8771, turbine efficiency = 0.87, and TIT = 1350 K (ISO data Table 1). The results show that a 25 °C rise in ambient temperature (15-40 °C) decreases the turbine power by 20.5% (180-143 MW). Thermal efficiency declines by 1.56 percentage points (32.68 -31.12%), while specific fuel consumption (SFC) rises by 4.7% (0.337-0.353 kg/kWh). Hence, for every 1 °C increase in ambient temperature, the average power loss is 1.5 MW and efficiency drops by 0.06 %. This demonstrates a clear inverse relationship between inlet air temperature and mass flow, directly affecting output and fuel economy [16. 17].

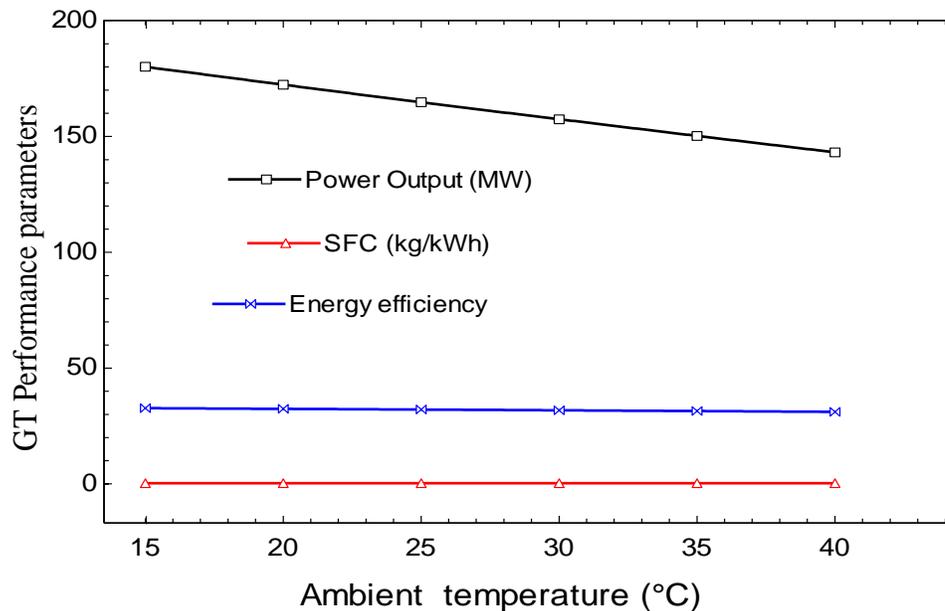


Figure 2. Effect of Ambient Temperature on GT13E2 Performance

3.1.2 Effect of Relative humidity (RH) on GT13E2 Performance

The effect relative humidity of turbine performance is shown in Figure 3. Increasing

Thus, while humidity alone is a minor factor in dry operation, it becomes significant when combined with evaporative cooling or fogging systems, which depend on ambient dew point.

RH from 20 to 80% reduces density by 0.7%, causing 0.8 MW drop in power. Thermal efficiency changes by less than 0.02 %; SFC variation is negligible (± 0.0005 kg/kWh).

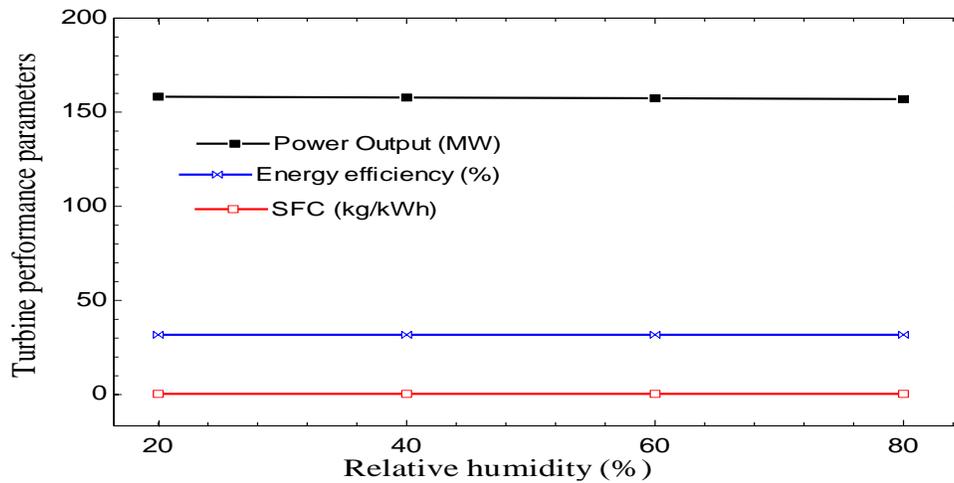


Figure 3. Effect of Relative humidity on GT13E2 Performance

3.1.3 Effect of Altitude on GT13E2 Performance

Atmospheric pressure drops by 21% from sea level to 2000 m (At 2000 m altitude, the standard atmospheric pressure =79.5 kPa (approximately 0.785 atm), causing a 12.4% reduction in mass flow and power output (180-157.8 MW). Efficiency improves slightly (0.71 %) due to lower compressor inlet temperature and reduced work ratio. SFC declines from 0.337 to 0.329 kg/kWh (2.4%), reflecting marginal thermodynamic gain but significant capacity penalty. The average loss rate is about 1.1 MW per 100 m elevation gain, critical for site selection in highland regions. kWh. The exhaust behaviour: While exhaust temperature rises by 32 K (+ 3.8 %), mass flow falls 18 %. The hotter but lighter exhaust stream reduces downstream heat-recovery potential.

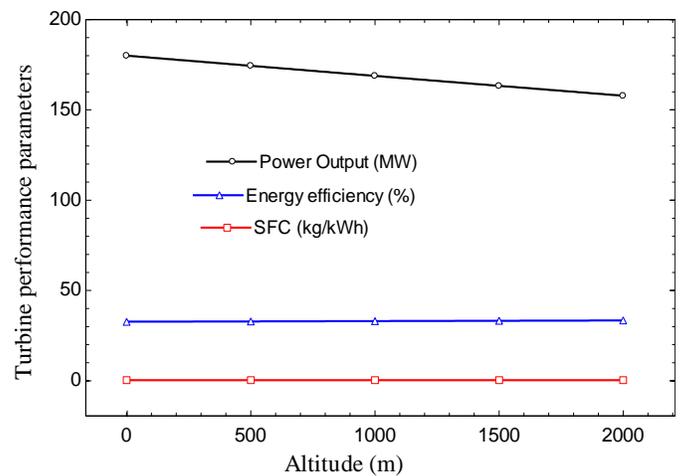


Figure 4. Effect of Altitude on GT13E2 Performance

3.1.4 Effect of Air density on GT13E2 Performance

Figure 5 shows the effect of air density on GT13E2 Performance. As ambient temperature rises from 15 °C to 45 °C, the air density drops by about 9-10 % (from 1.225-1.11 kg/m³). Over the same range, thermal

efficiency remains essentially constant at 34.9 %; the variation is less than $\pm 0.01\%$, which is negligible. Likewise, the specific fuel consumption stays at about 0.315 kg/kWh, with changes smaller than 0.001 kg/kWh (less than 0.3 %). This behaviour is consistent with Brayton-cycle theory: For a fixed pressure ratio and turbine inlet temperature, the temperature ratios across

compressor and turbine do not change when density changes; hence the cycle efficiency is almost unaffected. Lower density simply reduces the mass flow rate through the compressor, so net power output falls, but the ratio of fuel input to useful work (SFC) and the fraction of fuel energy converted to work (thermal efficiency) stay practically the same

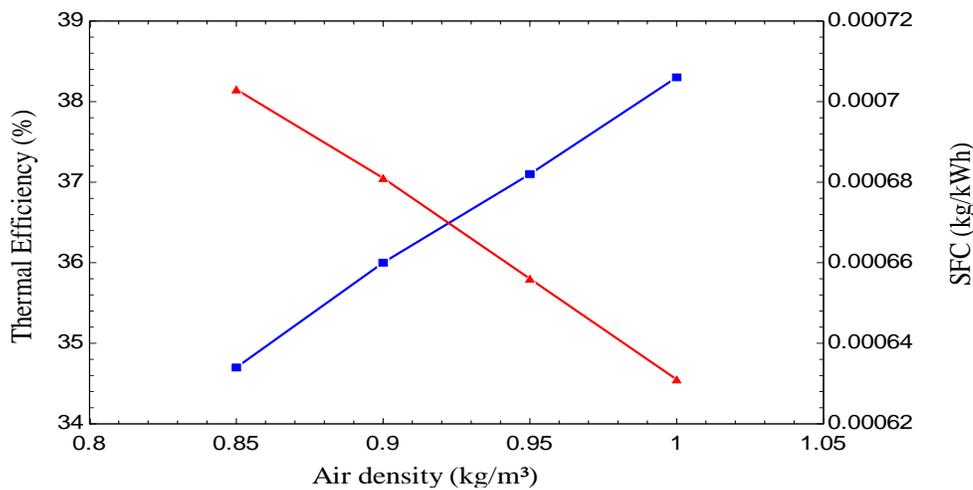


Figure 5. Effect of air density on GT13E2 Performance

3.1.5 Effect of mass flowrate (fuel) on GT13E2 performance

Figure 6 describes the effect of fuel mass flow rate on system performance. The results show that an increase in fuel mass-flow rate raises turbine output almost linearly up to about 2.4 kg/s, after which efficiency saturates. Beyond this point, higher fuel addition yields diminishing returns due to turbine inlet temperature (TIT) and compressor constraints. SFC decreases with increased fuel flow until the optimum efficiency plateau is reached, after which it stabilizes.

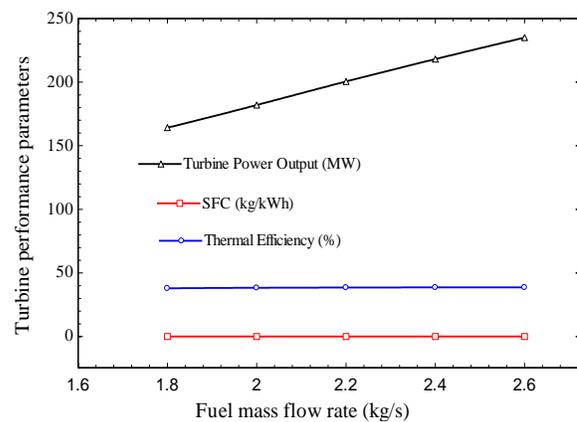


Figure 6. Effect of mass flowrate (fuel) on GT13E2 performance

3.1.6 Effect of turbine inlet temperature (TIT) on GT13E2 performance

Figure 7 shows the effect of turbine inlet temperature (TIT) on GT13E2 performance. Raising TIT significantly boosts turbine output and efficiency due to the larger enthalpy drop across the turbine. A 150 K increase in TIT (from 1350-1500 K) enhances power by 12.7% and efficiency by 2.7 points, while SFC drops by 7.6%. However, higher TIT accelerates blade oxidation and thermal-fatigue degradation, requiring advanced cooling.

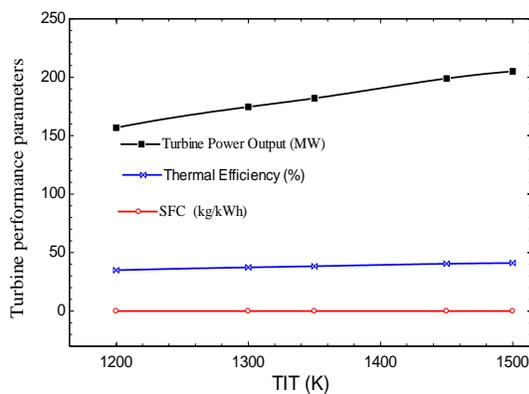


Figure 7. Effect of turbine inlet temperature (TIT) on GT13E2 performance

4.0 Conclusion

This study quantitatively evaluated the influence of environmental and operational parameters on the GT13E2 heavy-duty gas turbine operating under hostile tropical conditions typical of Nigeria. The results demonstrate that ambient temperature is the most critical environmental factor affecting performance. A temperature increase from 15 °C to 40 °C caused a 20.5% reduction in power output (≈37 MW), a 1.56 percentage-

point drop in thermal efficiency, and a 4.7% rise in SFC, corresponding to an average power loss of about 1.5 MW per °C. Relative humidity exhibited minimal standalone influence, with less than 1 MW power variation and negligible efficiency change, although its role becomes important when coupled with inlet-air cooling systems. Altitude effects were significant, with a 12.4% power reduction at 2000 m due to reduced air density and mass flow, despite a slight efficiency improvement of 0.7%. Operational parameters showed strong leverage on performance. Increasing turbine inlet temperature by 150 K improved power output by 12.7% and reduced SFC by 7.6%, albeit with implications for blade life and cooling requirements. Changes in air density primarily affected capacity rather than efficiency, confirming Brayton-cycle behavior. Overall, the findings highlight the necessity of environment-specific performance assessment and adaptive operational strategies to improve reliability, efficiency, and fuel economy of heavy-duty gas turbines in hostile climates.

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