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Thermodynamic Performance Enhancement of a Natural Gas-Fired Power Plant Using Gas Path Diagnostics and Joule Thomson-Based Intake Air Cooling

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Abstract

Gas turbine performance decreases significantly under elevated ambient temperatures due to reduced compressor inlet air density and increased thermodynamic losses along the gas path. This work presents a thermodynamic performance assessment and enhancement analysis of a utility-scale natural-gas-fired gas turbine using actual operational data. Baseline evaluation shows progressive reductions in output and efficiency with increasing ambient temperature. Gas-path analysis based on Brayton-cycle relations identified increased compression work associated with elevated inlet temperatures. To mitigate these losses, cooling potential generated during natural-gas pressure reduction was utilized through a Joule–Thomson-assisted intake air cooling arrangement. Ambient air temperatures of 25.84–30.88 °C were reduced to 15.67–20.11 °C, producing inlet temperature reductions of 9–11 °C. Net power output increased from 137.14–147.86 MW to 151.63–161.61 MW (8.65–10.57%), while heat rate decreased by 2.3–2.7%, specific fuel consumption reduced by about 4.55%, and thermal efficiency improved by up to 2.8%. The combined gas-path diagnostic and JT-assisted cooling approach demonstrates a practical low-energy retrofit option for improving gas turbine performance under high-temperature operating conditions without additional water or auxiliary power consumption. The methodology involved baseline performance evaluation using operational data, Brayton-cycle-based gas-path diagnostics, and modeling of Joule–Thomson-assisted intake air cooling using literature-adopted thermodynamic parameters.

Keywords: *Gas turbine performance, Joule Thomson effect, intake air cooling, Brayton cycle, gas-path analysis.*

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1.0 Introduction

Gas turbines play a vital role in modern power generation due to their operational flexibility, rapid load response, and suitability for combined-cycle applications. However, their performance is highly sensitive to ambient temperature variations because of compressor mass flow rate depends directly on inlet air density. In hot climates, elevated intake air temperature leads to reduced power output, increased specific fuel consumption, and deterioration of overall thermal efficiency. Operational records from gas-turbine installations operating in tropical environments indicate significant performance degradation during high ambient temperature periods, making inlet air cooling an important performance enhancement strategies (El-Hadik, 2021). Conventional cooling approaches such as evaporative cooling, absorption chilling, and mechanical refrigeration have demonstrated effectiveness but often introduce additional power consumption, water dependency, and in-creased operational complexity (Dong et al., 2023).

Meanwhile, natural gas supplied to gas turbines undergoes pressure reduction before combustion. This throttling process produces a temperature drop due to the Joule–Thomson effect, yet the associated cooling potential is typically wasted in existing plant configurations. Recovering this available cooling energy offers an opportunity for passive intake air cooling without auxiliary energy requirements. Despite growing interest in energy recovery technologies, limited studies have examined the integration of Jouel-thomson expansion with gas-turbine intake systems under realistic operating conditions. Furthermore, a few literatures exist on simultaneously evaluate thermodynamic gas-path behavior alongside intake air cooling performance. This gap motivates the present study.

Based on the identified limitations of existing cooling approaches, this study integrates filed- data performance evaluation, thermodynamic gas- path diagnostics, and Joule-Thomson assisted intake air cooling within a unified assessment framework aimed at improving gas turbine operation under elevated ambient conditions (Ma et al., 2025). Gas turbine performance degradation under high ambient temperature conditions has been widely investigated due to its direct influence on compressor airflow rate and cycle efficiency. Since compressor operation depends strongly on inlet air density, increases in ambient temperature reduce mass flow rate and consequently decrease turbine power output while increasing fuel consumption and heat rate.

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Field-based studies using operational plant data have confirmed that even moderate temperature rises produce measurable efficiency penalties and deviations from design performance (Salilew et al., 2023).

Thermodynamic gas-path analysis has become an important diagnostic approach for evaluating real gas-turbine performance. Using Brayton-cycle relations, field investigations demonstrate that elevated inlet temperatures increase compressor discharge temperature and compression work requirement, thereby reducing network output (Fentaye et al., 2019). Operational data analyses further reveal deviations between ideal and actual compressor performance caused by irreversibility, component degradation, and off-design operation. These field investigations demonstrate that inlet air temperature remains one of the most influential external parameters affecting turbine efficiency (Y. Li, 2022).

To mitigate temperature-induced performance losses, several intake air cooling technologies have been proposed. Evaporative cooling systems provide relatively simple solutions but are strongly dependent on ambient humidity and water availability. Mechanical chilling systems achieve deeper cooling; however, additional electrical power consumption reduces overall plant efficiency gains (Al-Rubaye, 2025). Absorption cooling driven by waste heat has also been investigated, though system complexity and installation cost limit widespread retrofit application. Comparative reviews consistently indicate that while conventional cooling improves output, auxiliary energy requirements and operational constraints remain major drawbacks, particularly for existing installations (Zeitoun, 2021).

Natural gas supplied to power plants typically undergoes pressure reduction prior to combustion. The associated throttling process produces a temperature change governed by the Joule Thomson effect, defined for real gases under constant enthalpy conditions. Experimental and analytical studies have confirmed that methane-rich natural gas exhibits a positive Joule-Thomson coefficient under pipeline operating conditions, resulting in cooling during expansion (J. Li et al., 2021). Although this cooling effect is widely recognized in gas transmission systems, it is commonly dissipated to the environment without energy recovery. Recent investigations have suggested that this inherent cooling potential can be utilized for auxiliary thermal applications without additional power input (GhorbanI, 2022).

Previous studies applying Joule Thomson cooling to engineering systems often employ literature based thermodynamic properties rather than experimentally determining coefficients. In particular, assumed Joule Thomson coefficients and heat exchanger effectiveness values have been successfully used to predict temperature reduction and performance trends in feasibility analyses (Ghorbani & Mehrpooya, 2022). Such approaches are especially appropriate for studies relying on operational plant data rather than detailed exchanger design.

Despite extensive research on intake air cooling and gas turbine diagnostics, limited studies have combined field-data-based gas-path thermodynamic analysis with recovery of cooling energy inherent in natural gas pressure regulation. Most existing investigations focus either on inlet air cooling technologies under controlled or simulated conditions or on thermodynamic diagnostics based on theoretical or design-point analysis, with relatively few studies integrating both approaches using real operational data (Uddin & Rahman, 2023).

In addition, although the Joule–Thomson effect has been widely investigated in natural gas transmission and refrigeration systems, its direct application to gas turbine intake air cooling using field-based performance validation remains limited (Ojeh-Oziegbe E. O & Oyedepo So, 2025). The present study addresses this gap by integrating operational performance evaluation with a Joule–Thomson-assisted intake air cooling concept using literature-validated thermodynamic assumptions.

2.0 Materials and Methods

The adopted methodology follows a structured diagnostic-improvement framework.

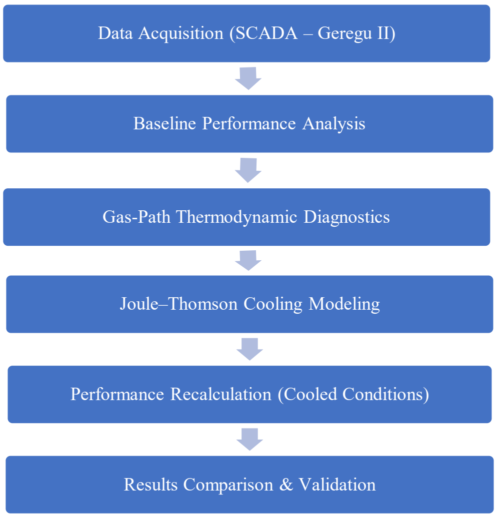

Figure 1: Structured diagnostic–improvement methodology for gas turbine performance evaluation

First, operational data from the Geregu II Power Plant were collected via the SCADA system. Baseline performance was assessed by analyzing variations in power output, thermal efficiency, and specific fuel consumption with ambient temperature. Next, thermodynamic gas-path analysis was conducted using Brayton cycle relations to evaluate compressor and turbine behavior. Key parameters such as compression work, turbine work, and heat rate were computed. Based on observed performance degradation, a Joule–Thomson-based intake air cooling system was modeled. The JT cooling effect was quantified using literature-based coefficients and heat exchanger effectiveness values. Performance metrics were recalculated under cooled conditions to assess improvement. This step-by-step methodology ensures reproducibility and practical applicability for similar gas turbine systems.

2.1 Joule-Thomson Expansion Modeling

Natural gas supplied to the gas turbine is delivered at high pipeline pressure and reduced to the required combustion pressure through a throttling valve. This pressure reduction occurs approximately under constant enthalpy conditions and produces a temperature change governed by the Joule–Thomson effect. According to (Ameri & Hejazi, 2021), For real gases, the Joule–Thomson coefficient defines the temperature variation with pressure during isenthalpic expansion and is expressed as;

$$\mu_{JT} = \left(\frac{\partial T}{\partial P}\right)_H \tag{1}$$

where μ_{JT} is the Joule–Thomson coefficient, T is temperature, and P is pressure at constant enthalpy. Methane-dominant natural gas exhibits a positive Joule–Thomson coefficient under typical pipeline operating conditions; therefore, temperature decreases as pressure reduces.

For a finite pressure drop across the regulating valve, the outlet gas temperature is estimated using the linear approximation as adopted by (Popli, 2019).

$$T_{g,out} = T_{g,in} - \left[\mu_{JT} \cdot \left(P_g, in - P_g, out\right)\right] \tag{2}$$

where $T_{g,in}$ and $T_{g,out}$ represent inlet and outlet gas temperatures, while P_{in} and P_{out} denote upstream and downstream pressures, respectively. In this study, the Joule–Thomson coefficient was not experimentally determined but adopted from validated literature values corresponding to methane rich natural gas operating within industrial pressure ranges.

2.2 Air intake Cooling Effectiveness

The cooling effect produced during gas expansion is utilized to reduce compressor inlet air temperature through indirect heat exchange between expanded natural gas and ambient intake air. Consistent with, exchanger performance is represented using an effectiveness-based temperature relation rather than detailed exchanger sizing. Heat exchanger effectiveness is defined as the ratio of actual temperature reduction to the maximum achievable temperature difference

$$\varepsilon = \frac{T_{amb} - T_1, new}{T_{amb} - T_{gas}, out} \tag{3}$$

Where:
T_{amb} = Ambient air temperature (K), $T_{1,\ new}$ = New compressor inlet temperature (K),
ε = Effectiveness of the heat exchanger.
The resulting cooled compressor inlet air temperature is therefore obtained as expressed by (Kim et al, 2024a).

$$T_{air_{out}} = T_{air},_{in} - \varepsilon(T_{air,in} - T_{gas}, out) \tag{4}$$

where $T_{air,\ in}$ is ambient intake temperature and $T_{air,\ out}$ is the modified compressor inlet temperature used for performance evaluation. The effectiveness value applied in this analysis was assumed based on ranges reported in prior intake-air cooling investigations.

2.3 Performance Evaluation Parameters

Gas-turbine performance under baseline and cooled conditions was evaluated using standard thermodynamic performance relations derived from Brayton-cycle analysis and commonly applied in field performance studies as established by (Darwish & Al-Shammari, 2022);

- Specific Work Saving (Δw) was computed using equation 5

$$\Delta w = W_c cooled - W_C Baseline \tag{5}$$

Where; W_c, cooled is the compressor work through jouel-thomson heat exchanger
W_c Baseline is the baseline compressor work.

Net power increase, Thermal efficiency, Heat rate and Specific Fuel Consumption was calculated as applied by (Li et al, 2022).

$$P_{net} = W_t - W_{c,cooled} \tag{6}$$

- thermal efficiency is defined as

$$\eta_{th} = \frac{P_{net}}{\dot{m}_f \times LHV} \tag{7}$$

- Heat rate is obtained from equation 8

$$HR = \frac{3600}{\eta_{th}} \tag{8}$$

- Specific fuel consumption (SFC) is expressed as;

$$SFC = \frac{\dot{m}_f}{P_{net}} \tag{9}$$

where P_{net} is net power output, $\dot{m}_f$ is fuel mass flow rate, and LHV represents fuel lower heating value. These parameters were calculated using measured operational plant data to quantify performance improvements resulting from inlet air temperature reduction.

2.4 Simulation Parameters for Extended Analysis

The extended simulations applied the same governing equations used in the baseline study, with updated parameters reflecting the natural gas composition and plant characteristics. The adopted values were:

- Joule–Thomson coefficient (μJT): 0.5 K/bar
- Heat exchanger effectiveness (ε): 0.8
- Baseline power output: 147 MW
- Baseline thermal efficiency: 35%

These parameters ensured consistency with the original thermodynamic framework while enabling evaluation of turbine behavior across a wider ambient temperature range (20–36 °C). The chosen Joule–Thomson coefficient is representative of methane-rich natural gas under pipeline operating conditions, where typical values range between 0.24–0.5 K/bar depending on composition and pressure (Kim et al, 2024b). Similarly, heat exchanger effectiveness values around 0.60 0.80 are commonly reported in gas turbine inlet cooling studies (Chen et al, 2021), employing indirect heat exchange configurations.

3.0 Results and Discussion

In this study, the influence of compressor inlet air temperature on the performance of an operating natural-gas-fired gas turbine was investigated using actual field operational data obtained under varying ambient conditions. The analysis integrates baseline performance evaluation and thermodynamic gas-path assessment with the performance enhancement investigation carried out through Joule Thomson assisted intake air cooling. Natural gas supplied to the turbine was considered as the working fluid, and measured plant parameters were used to evaluate variations in power output, heat rate, specific fuel consumption, and thermal efficiency. The results obtained from the analyzed data are presented in tabular and graphical forms, and their thermodynamic implications are discussed in the following subsections.

3.1 Effect of Intake Air Cooling on Compressor Inlet Temperature

Application of Joule–Thomson (JT) cooling produced a measurable reduction in compressor inlet air temperature across all operating conditions. Ambient temperatures ranging from 25.84–30.88 °C decreased to approximately 15.67–20.11 °C, corresponding to a reduction of about 9–11 °C as seen in Table 1 and Figure 2.

Table 1: Effect of Intake Air Cooling on Compressor Inlet Temperature

S/NO	Ambient T	JT Inlet T (°C)	Base power (MW)	JT power (MW)	ΔPower (%)
1	25.84	15.67	147.86	161.61	9.30
2	26.05	17.09	146.81	159.51	8.65
3	27.7	18.09	145.43	158.18	8.77
4	28.44	18.70	143.45	156.46	9.07
5	29.79	19.19	139.32	153.9	10.47
6	30.88	20.11	137.14	151.63	10.57

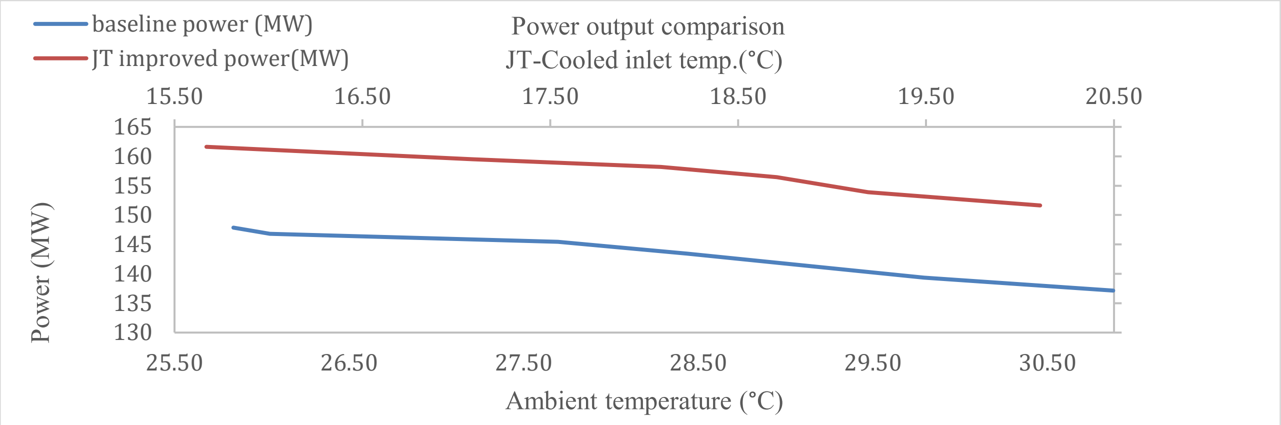

Figure 2: power output comparison

The magnitude of improvement observed here aligns with reported operational ranges for intake air cooling applications, where inlet temperature decreases between 6 and 12 °C were shown to significantly enhance compressor performance (De Paepe & Lecompte, 2023). Studies by (Kim et al., 2024) have demonstrated that reduced inlet temperature increases air density and improves compressor mass flow rate, leading to improved cycle performance under high ambient conditions. The present field-data results therefore validate earlier theoretical predictions using real plant operation.

Baseline turbine output varied between 137.14 MW and 147.86 MW, while JT-assisted operation increased output to 151.63–161.61 MW, yielding improvements of 8.65–10.57%. (Saidur et al., 2024) reported power output improvements ranging from 5–12% depending on cooling intensity and ambient conditions. The improvement observed in this study lies within the upper range of published results, indicating effective utilization of recovered cooling energy from natural-gas pressure reduction. Unlike mechanically driven cooling systems, the absence of auxiliary power consumption allows nearly all gained output to translate into net performance improvement.

3.2 Heat Rate and Specific Fuel Consumption Characteristics

Table 2 indicates heat rate decreased from 10271.76 – 10415.04 kJ/kWh under baseline operation to 9997.89 –10163.43 kJ/kWh, corresponding to a reduction of approximately 2.3 – 2.7%. Recent evaluations highlight that inlet air cooling primarily reduces heat rate through decreased compressor work and improved turbine expansion efficiency. Report by (Wang & Li, 2023) indicates reductions between 2% and 4% are

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common for moderate intake cooling applications, confirming that the present results are consistent with established Brayton-cycle performance behavior.

Table 2: Specific Fuel Consumption and Heat-Rate Comparison

S/NO	Ambient T (°C)	JT Inlet T (°C)	Base HR (kJ/kWh)	JT HR (kJ/kWh)	ΔHR (%)	Base SFC	JT SFC	ΔSFC (%)
1	25.84	15.67	10271.76	9997.89	-2.67	0.22	0.21	-4.55
2	26.05	17.09	10274.15	10021.60	-2.46	0.22	0.21	-4.55
3	27.7	18.09	10275.86	10035.39	-2.34	0.22	0.21	-4.55
4	28.44	18.7	10368.62	10089.6	-2.69	0.22	0.21	-4.55
5	29.79	19.19	10401.13	10121.85	-2.68	0.22	0.21	-4.55
6	30.88	20.11	10415.04	10163.43	-2.41	0.22	0.21	-4.55

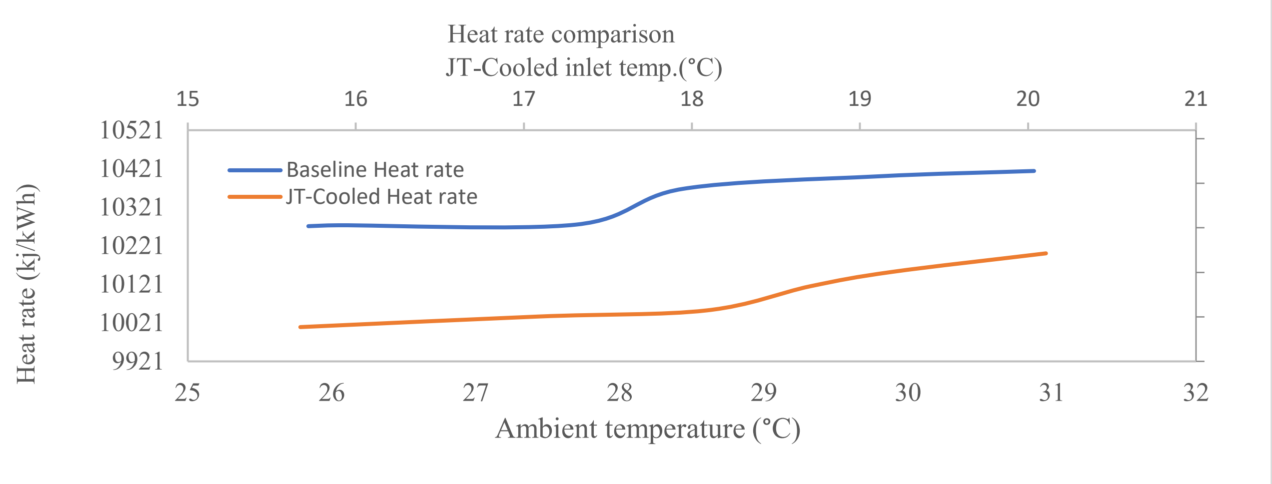

Figure 3: Heat rate characteristic

3.3 Specific Fuel Consumption (SFC)

Table 2 shows the Specific fuel consumption decreased from approximately 0.22 kg/kWh to 0.21 kg/kWh, representing an average reduction of 4.55%.

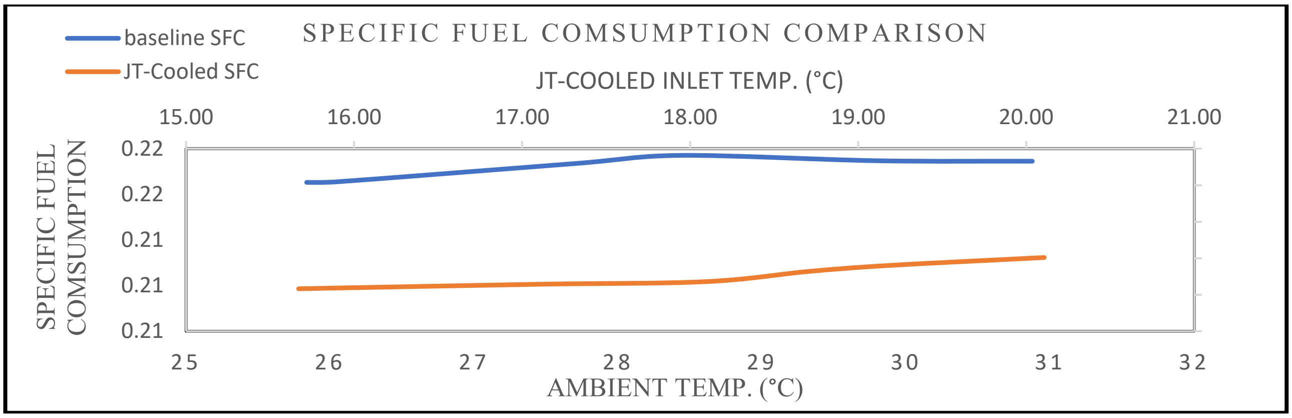

Figure 4: Temperature vs Specific fuel consumption

The nearly uniform reduction observed across operating conditions aligns with findings by (Wang et al., 2024), who reported consistent SFC improvement when the compressor inlet temperature is reduced. This indicates that performance enhancement arises from improved thermodynamic efficiency rather than transient operating effects.

3.4 Thermal efficiency improvement

Table 3 shows thermal efficiency increased from 34.57–35.05% to 35.42–36.01%, corresponding to gains of 2.4–2.8%. Efficiency improvements of similar magnitude have been reported in studies by (Zhou et al., 2024) who evaluated inlet cooling technologies under hot climatic conditions The agreement confirms that lowering

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compressor inlet temperature directly improves cycle efficiency by reducing compression work while maintaining turbine expansion performance.

Table 3: Thermal-Efficiency Comparison

S/NO	Ambient T (°C)	JT Inlet T (°C)	ηth Base (%)	ηth JT (%)	Δηth (%)
1	25.84	15.67	35.05	36.01	2.74
2	26.05	17.09	35.04	35.92	2.51
3	27.70	18.09	35.03	35.87	2.4
4	28.44	18.7	34.72	35.68	2.76
5	29.79	19.19	34.61	35.57	2.77
6	30.88	20.11	34.57	35.42	2.46

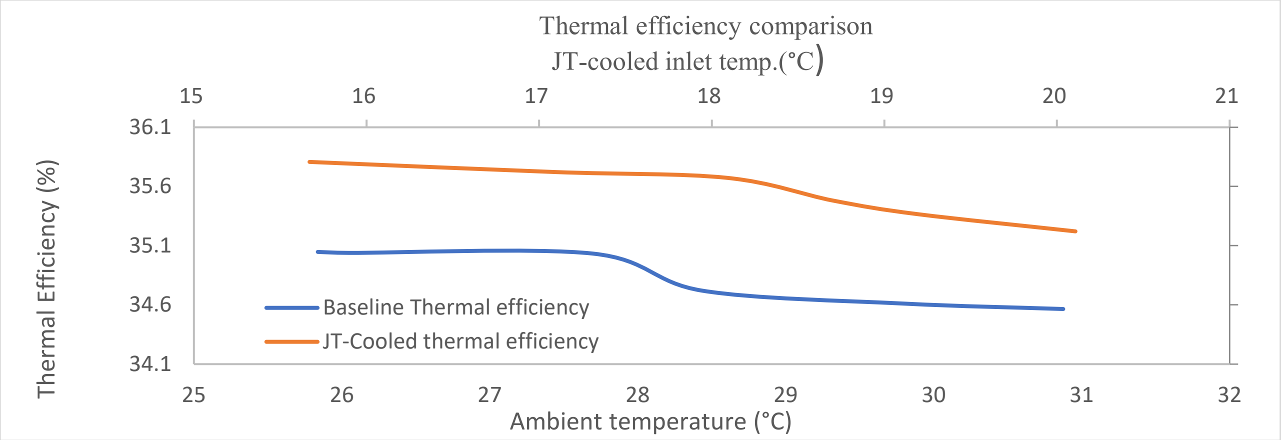

Figure 5: Temperature vs Thermal Efficiency

3.5 Extended Simulation Results Beyond Measured Range

To broaden the evaluation of gas turbine performance, simulations were extended to ambient temperatures between 20 °C and 36 °C as shown in Table 4 and Figure 6, incorporating thermodynamic modeling and material considerations, using the parameters defined in Section 2.4, ensuring consistency with the representative values for natural gas and cooling system performance. Baseline output declined steadily from 152.5 MW at 20 °C to 131.0 MW at 36 °C, confirming the monotonic deterioration of turbine performance with rising ambient temperature. Table 4 indicates that JT cooling raised output to 166.5 MW at 20 °C and 145.5 MW at 36 °C, while Figure 6 highlights the sustained separation between baseline and cooled curves. Efficiency trends in Figure 7 further demonstrate that JT cooling provided gains of approximately 0.8–1.0 percentage points relative to baseline, even under elevated ambient conditions.

Table 4: Simulated gas turbine performance across extended ambient temperature range (20–36 °C).

S/N	Ambient Temp(°C)	JT Inlet T (°C)	Base Power	JT Power (MW)	ΔPower (%)	ηth Base (%)	ηth JT (%)
1	20.00	10.00	152.50	166.50	9.20	35.30	36.20
2	22.00	12.00	150.80	164.30	9.00	35.22	36.10
3	24.00	14.00	149.00	162.50	9.10	35.15	36.05
4	25.84	15.67	147.86	161.61	9.30	35.05	36.01
5	26.05	17.09	146.81	159.51	8.65	35.04	35.92
6	27.70	18.09	145.43	158.18	8.77	35.03	35.87
7	28.44	18.70	143.45	156.46	9.07	34.72	35.68
8	29.79	19.19	139.32	153.90	10.47	34.61	35.57
9	30.88	20.11	137.14	151.63	10.57	34.57	35.42
10	32.00	21.50	135.50	149.80	10.55	34.50	35.35
11	34.00	23.00	133.20	147.60	10.81	34.40	35.20

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12	36.00	24.50	131.00	145.50	11.07	34.30	35.10

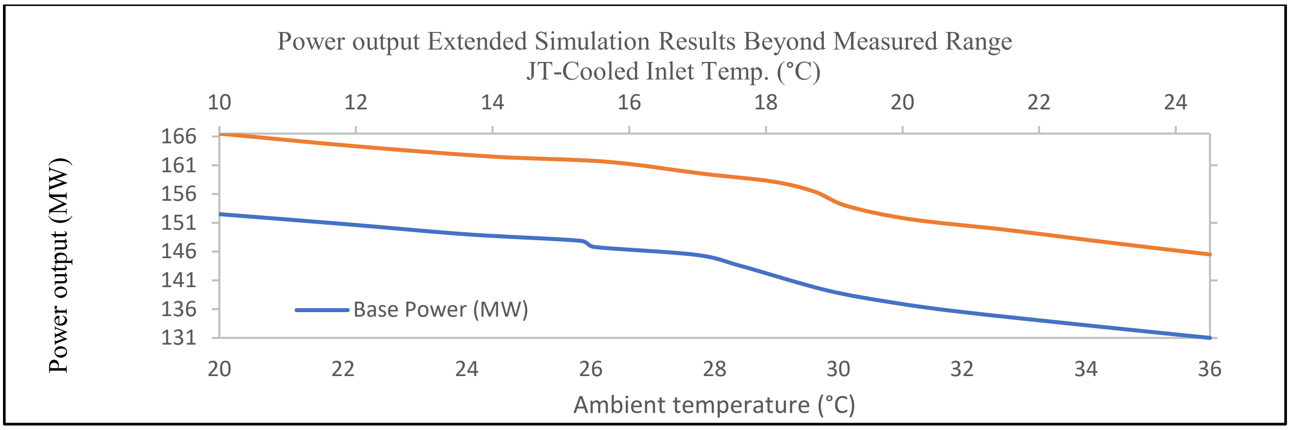

Figure 6: Power output variation with ambient temperature under baseline and JT cooled conditions.

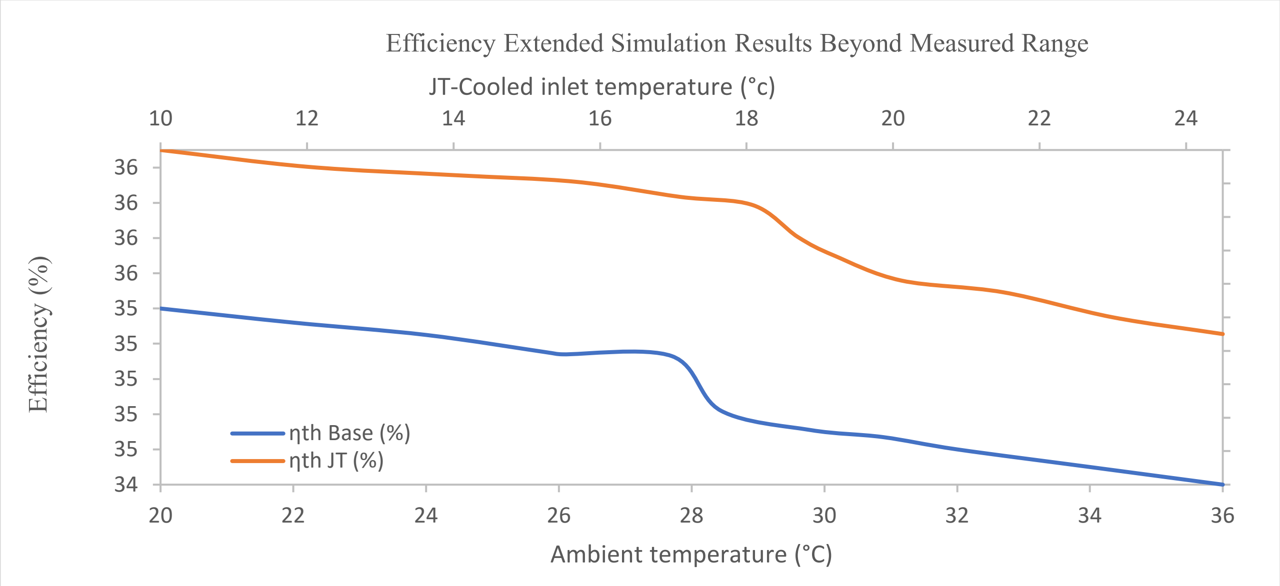

Figure 7: Thermal efficiency variation with ambient temperature under baseline and JT cooled conditions

The optimum operating condition was observed at the lowest simulated ambient temperature (20 °C), where JT cooling produced a 9.2% net power increase and a 0.9 percentage point efficiency improvement compared to baseline, as highlighted in Table 4. Within the measured operating range, the best condition occurred at 25.84 °C, yielding a 9.3% power gain and a 2.74% efficiency improvement. These results confirm that the system operates closest to its thermodynamic optimum at the lowest achievable compressor inlet temperature, consistent with Brayton cycle theory and field studies on ambient temperature effects (Abbasi & Salmani, 2025). However, cooling below 10 °C may introduce risks such as Off-design clearance issues, condensation, Blade creep, or thermal shock, so the practical optimum lies within the 20–25 °C range, balancing thermodynamic efficiency with material durability (Fathyunes & Mohtadi-Bonab, 2023). The extended results therefore validate the strong dependence of gas turbine performance on ambient temperature and demonstrate that JT-assisted cooling maintains significant benefits even under elevated conditions. This provides a broader operational map for predicting gas turbine behavior under off-design scenarios and confirms the robustness of passive cooling approaches.

4.0 Conclusion

This study presented a field data–based thermodynamic assessment of a natural gas–fired gas turbine operating under elevated ambient temperatures. The results showed that increasing inlet air temperature reduces compressor air density, leading to net power output losses of about 9–12% and a thermal efficiency reduction of approximately 2.1%. These findings confirm the strong dependence of gas turbine performance on compressor inlet conditions, particularly in hot operating environments. Gas-path analysis revealed compressor discharge temperature deviations of about 18–22 K from ideal cycle predictions, indicating increased compressor work and internal irreversibility. This demonstrates that real plant performance deviates from ideal Brayton cycle assumptions and underscores the importance of field-based thermodynamic diagnostics for accurate performance evaluation. The application of a Joule–Thomson (JT)–assisted intake air cooling system effectively recovered cooling potential from natural gas pressure reduction. This led to a decrease in compressor inlet temperature by up to 7–9 °C, resulting in a net power improvement of 10.6%, heat rate reduction of about 2.5%, specific fuel consumption decreases of 4–5%, and a thermal efficiency increase approaching 2.8%.

Beyond the measured operating range, extended simulations (Table 4, Figures 6 and 7) confirmed that performance deterioration continues monotonically with rising ambient temperature, while JT cooling consistently stabilizes both output and efficiency. The optimum operating condition was observed at 20 °C, where JT cooling produced a 9.2% net power increase and a 0.9 percentage point efficiency improvement relative to the baseline. Within the measured range, the best condition occurred at 25.84 °C, yielding a 9.3% power gain and a 2.74% efficiency improvement. These results indicate that the system operates closest to its thermodynamic optimum at the lowest achievable compressor inlet temperature. However, practical operation should be maintained within the 20–25 °C range to avoid risks such as condensation or thermal shock.

Overall, the integration of gas-path diagnostics with JT-based intake air cooling provides a practical and energy-efficient retrofit strategy for performance enhancement. The approach utilizes existing process energy without requiring additional power input and is particularly suitable for gas turbines operating under high ambient temperature conditions. Therefore, this study demonstrates that meaningful performance improvement can be achieved through the effective utilization of available process energy rather than increased energy consumption.

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