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EVALUATION OF OFFLINE COMPRESSOR WATER WASHING AND ITS EFFECT ON SIEMENS SGT-400 GAS TURBINE PERFORMANCE

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Abstract

Compressor fouling is a major cause of performance degradation in industrial gas turbines operating in humid and particulate-laden environments. This study evaluates the effect of offline compressor water washing on the performance of a Siemens SGT-400 gas turbine operating in the Niger Delta region of Nigeria. Operational data were obtained from plant station log sheets and analyzed by comparing six months of pre-wash performance with results from a 72-hour post-wash reliability test following offline compressor cleaning. Key performance indicators including compressor pressure ratio, generated power output, thermal efficiency, specific fuel consumption, and heat rate were calculated using standard gas turbine performance relations to quantify the impact of compressor fouling and the effectiveness of the washing process. Statistical evaluation was conducted using a paired-sample t-test to determine the significance of performance changes before and after washing. The results show that offline compressor washing resulted in a 19.8% recovery in generated power and a 16.9% increase in compressor pressure ratio. Thermal efficiency improved by 26.4%, while specific fuel consumption and heat rate decreased by approximately 20.9%. Statistical analysis confirmed that these improvements were significant at the 95% confidence level ($p < 0.05$). The findings demonstrate that offline compressor water washing is an effective maintenance strategy for restoring both aerodynamic and thermodynamic performance of industrial gas turbines operating under severe fouling conditions and provide field-based evidence to support maintenance planning in high-humidity oil and gas environments.

Keywords: Compressor efficiency, gas turbine, offline compressor, power generation, Siemens

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1. Introduction

Industrial gas turbines operating in coastal and humid environments are highly susceptible to compressor fouling caused by airborne salts, hydrocarbons, and particulate matter. Fouling increases blade surface roughness, reduces effective flow area, and elevates aerodynamic losses, leading to reductions in compressor pressure ratio, mass flow rate, and overall cycle efficiency, with consequent increases in fuel consumption, turbine firing temperatures, and reduced power output (Diakunchak, 1992; Cohen et al., 1996; Kurz and Brun, 2012).Compressor water washing is widely used to mitigate fouling-induced performance degradation. Online washing allows partial contaminant removal during operation but is limited by droplet size, residence time, and compressor operating temperature. Offline washing, performed during planned shutdowns, enables complete rotor wetting, extended soak times, and more thorough deposit removal, offering superior restoration of compressor performance (Meher-Homji & Bromley, 2004; Sayma et al., 2000; Ogaji et al., 2002).

Previous research has extensively documented fouling mechanisms and cleaning strategies. Studies have shown that environmental factors such as high humidity and salt-laden air accelerate deposit formation and performance degradation (Chaker and Meher-Homji, 2003; Syverud and Bakken, 2007; Mohammed et al., 2023). Experimental and field studies on offline washing have reported performance recovery ranging from 70% to 95% of fouling-induced losses, depending on fouling severity and washing procedure (Aretakis, 2012; Kuenkel and Kurz, 2014; Li et al., 2016; Tarabrin et al., 2018). However, most of these studies are either model-based, conducted on generic turbines, or performed under non-tropical conditions, limiting their applicability to Siemens SGT-400 turbines in high-humidity tropical coastal environments such as the Niger Delta (Malaysia offshore study, 2016; Nigeria Port Harcourt study, 2020). Despite manufacturer guidance and case reports demonstrating effective performance restoration following offline washing (Siemens Industrial Application Services, 2018; Siemens Energy, 2019), there remains limited turbine-specific, long-term empirical validation.

Specifically, structured multi-month pre- and post-wash field datasets for SGT-400 turbines under tropical coastal conditions are scarce, leaving uncertainties about the magnitude and consistency of performance recovery.This study addresses these gaps by presenting a field-based evaluation of offline compressor water washing applied to a Siemens SGT-400 gas turbine in the Niger Delta region of Nigeria. The objectives are to quantify pre-wash performance degradation, evaluate post-wash performance recovery, and statistically validate the effectiveness of offline compressor washing as a maintenance intervention under real operating conditions.

2. Materials and Methods

2.1. Gas Turbine Description and Operating Environment

The study was conducted on a Siemens SGT-400 industrial gas turbine installed at an integrated oil and gas facility in the Niger Delta region of Nigeria. The turbine operates in simple-cycle configuration and is exposed to a humid, coastal environment characterized by high particulate concentration, salt aerosols, and hydrocarbon contamination conditions known to accelerate compressor fouling.

2.2. Data Acquisition and Test Periods

Operational data were obtained from daily plant log sheets and the turbine control and monitoring system. Two distinct datasets were analyzed to evaluate the effects of offline compressor water washing:

1. Pre-wash Operational data:Pre-wash data consisted of six months of averaged operating records collected between February and July 2025, representing progressive compressor fouling under continuous base-load operation.
2. Post-wash Operational data**:** A 72-hour reliability test conducted immediately after offline compressor water washing, representing near-restored compressor operating conditions.

2.3. Offline Compressor Water Washing Procedure

Offline compressor water washing was performed, during a planned turbine shutdown using demineralized water and approved cleaning agents, as presented in Table 1. The procedure included the following steps:

i. Water Wash Module Connection: Water wash module was connected to the turbine, which serves as the central system for delivering cleaning fluids. The module allows precise regulation of injection pressure, flow rate, and timing, ensuring that the cleaning solution reaches all compressor stages evenly. Instrumentation and safety interlocks integrated into the module prevent overpressure, thermal shock, or inadvertent contamination during the wash process.

ii. Detergent Injection**:** Using the water wash module, a controlled mixture of demineralized water and approved detergent was introduced into the compressor inlet. This step targets the dissolution and removal of accumulated salts, hydrocarbons, and particulate matter from blade and vane surfaces.

iii. Soaking Period: The injected solution was allowed to soak for a predetermined duration to ensure complete wetting of all aerodynamic surfaces. This facilitates thorough removal of stubborn fouling while minimizing the risk of uneven cleaning.

iv. Rinse Cycles**:** Successive rinse cycles with demineralized water were executed through the water wash module. The system monitors rinse water clarity and pH, continuing the rinse process until acceptable standards are achieved, ensuring that all detergent residues and contaminants are removed.

v. Qualitative Inspection: Visual inspection of the rinse water served as a practical verification of cleaning effectiveness. The transition from dark, oil-laden water to clear, neutral-pH water confirmed successful contaminant removal. Borescope inspections were performed when necessary to verify cleanliness in internal stages not visible from the compressor inlet.

Table 1: Rinse water quality assessment during offline compressor water washing

Rinse Stage	Water Color Appearance	Oil Dust Presence	Clarity Level	pH (Measured)	Remarks
Rinse 1	Dark brown to black	High oil film, heavy dust	Very low (opaque)	5.8	Highly contaminated, confirms severe fouling accumulation
Rinse 2	Brownish	Moderate oil, visible dust	Low	6.2	Contamination still present but reduced
Rinse 3	Light brown	Reduced oil traces	Medium	6.5	Considerably improved, most deposits flushed out
Rinse 4	Faint coloration	Minimal oil/dust traces	High	6.8	Nearly clean, residual impurities only
Final Rinse	Clear/transparent	Negligible	Very high (clear)	7.0	Acceptable cleanliness achieved, compressor restored

This procedure ensured comprehensive cleaning of the compressor, maximizing aerodynamic and thermodynamic recovery while minimizing the risk of blade erosion or water ingestion.

2.4. Performance Indicators and Calculations

Key gas turbine performance parameters were evaluated using standard thermodynamic and gas turbine performance relationships derived from measured field data. Comparative analysis between averaged pre-wash and post-wash operating conditions quantified the effects of compressor fouling and the recovery achieved through offline compressor water washing. These were the key performance indicators (KPIs) evaluated:

1. Compressor pressure ratio
2. Compressor isentropic efficiency and compressor work
3. Thermal efficiency
4. Specific fuel consumption (SFC)
5. Heat rate
6. Generated electrical power output

2.5. Statistical Analysis

To ensure that observed performance improvements were attributable to compressor washing rather than operational variability, a paired-sample t-test was applied to select KPIs at a 95% confidence level ($p < 0.05$). The analysis compared pre-wash and post-wash values for these parameters, compressor pressure ratio, compressor efficiency, thermal efficiency, specific fuel consumption (SFC), heat rate, compressor work, and generated electrical power output. Also, the paired t-test was chosen because it accounts for repeated measurements on the same turbine under different operating conditions, allowing robust assessment of statistical significance. KPI changes were considered significant if p-values were below 0.05, confirming that observed improvements were not due to random operational fluctuations.

3. Results and Discussion

3.1 Pre-Wash Performance Degradation

The results of the pre-wash operational data are presented in Table 2, Figures 1 and 2. Prior to offline compressor water washing, the Siemens SGT-400 turbine operated continuously

under normal base-load conditions during the six-month pre-wash monitoring period. Measured parameters included compressor inlet and discharge pressures and temperatures, exhaust gas temperature (EGT), fuel flow rate, and generated power output. These data provided the basis for quantifying progressive compressor fouling, assessing its impact on thermodynamic and aerodynamic performance, and establishing a reliable baseline against which post-wash performance recovery was evaluated.

Table 2: Pre-Wash Operational data

Month	Avg T_1 (°C)	Avg T_2 (°C)	Avg P_1 (barA)	Avg P_2 (barA)	Avg EGT (°C)	Avg Gen Power (kW)	Avg Fuel Energy (kW)
Feb	30.3	399.0	1.00	13.38	499.0	10,250.05	27,313.20
Mar	29.5	406.4	0.979	12.29	511.5	9,967.50	27,600.03
Apr	28.6	408.0	0.978	12.54	523.1	9,684.04	27,900.05
May	27.5	414.3	0.977	12.17	533.2	9,401.50	28,200.50
Jun	26.9	417.6	0.976	11.80	542.6	9,118.06	28,500.20
Jul	25.6	422.8	0.970	11.08	557.5	8,553.05	28,800.00

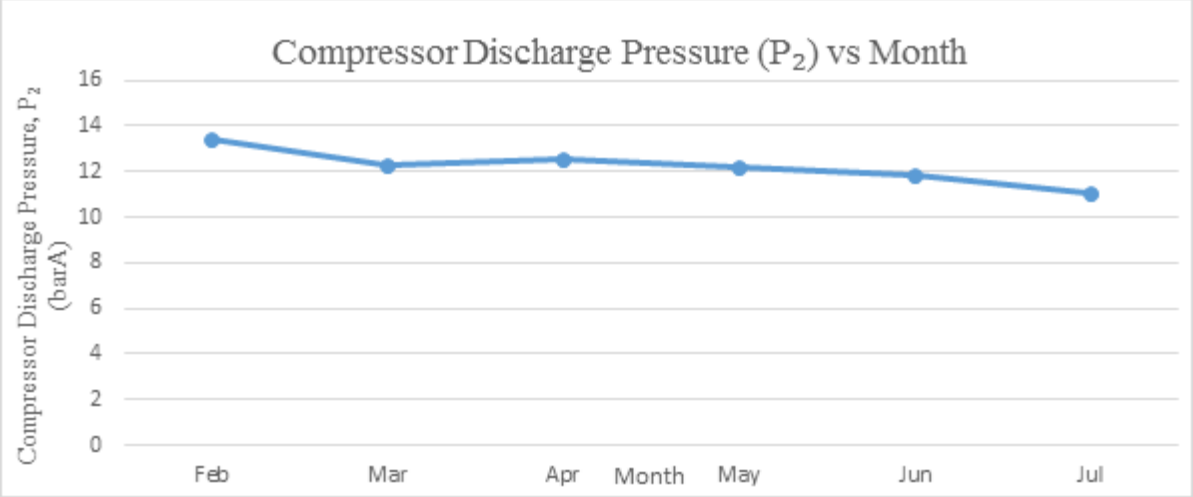


Figure 1: Compressor discharge pressure (P_2) of GTG 2 over six months prior to offline washing

Figure 1 shows the compressor discharge pressure (P_2) of GTG 2 over six months of operation prior to offline washing. The data indicate a gradual decline in P_2, reflecting cumulative performance degradation due to compressor fouling in the humid, particulate-laden environment of the Niger Delta. This trend is consistent with previous studies demonstrating that fouling reduces mass flow and pressure ratio in axial compressors over time (Diakunchak, 1992; Cohen et al., 1996; Mohammed et al., 2023). The progressive drop in discharge pressure highlights the need for scheduled maintenance interventions, such as offline water washing, to restore aerodynamic performance and prevent further efficiency losses.

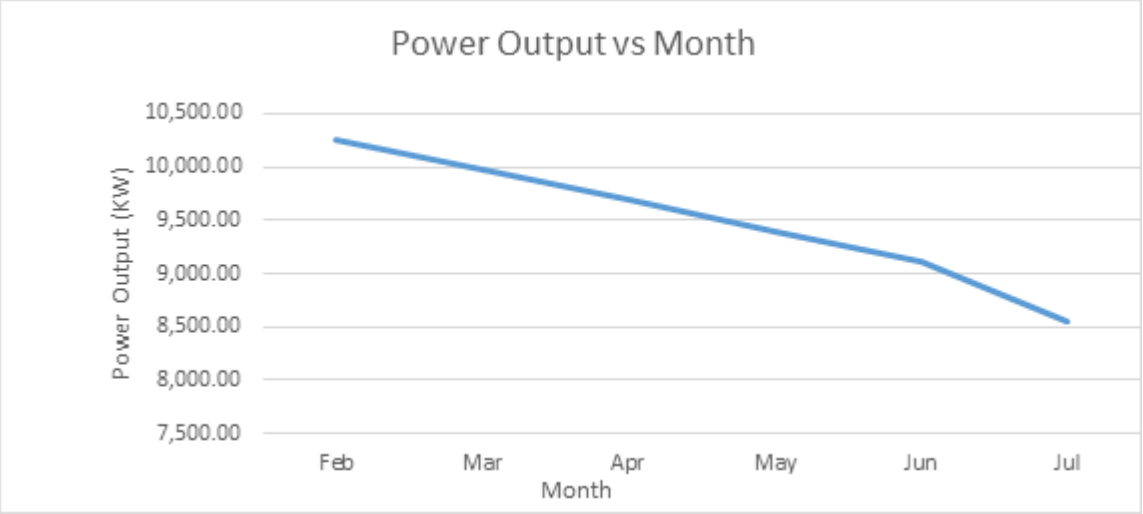


Figure.2: Generator power output of GTG 2 over six months prior to offline washing

Figure 2 shows the generator power output of GTG 2 over six months of operation prior to offline compressor washing. The data reveal a gradual decline in power output, corresponding to the observed reduction in compressor discharge pressure (Figure 1) and consistent with fouling-induced performance losses reported in axial compressors (Diakunchak, 1992; Cohen et al., 1996; Meher-Homji & Bromley, 2004). The declining trend emphasizes the cumulative effect of airborne particulates and high humidity on turbine efficiency, underlining the importance of maintenance interventions such as offline washing to restore both aerodynamic and thermodynamic performance.

3.2 Post-Wash Operational Reliability and Stability

Following offline compressor water washing, the Siemens SGT-400 turbine maintained stable operation throughout the 72-hour post-wash reliability test.Table 3 presents the post-wash 72-hour reliability test data for GTG 2 following offline compressor water washing. The test monitored key operational parameters—including compressor inlet temperature (T_1), compressor discharge temperature (T_2), inlet pressure (P_1), compressor discharge pressure (P_2), exhaust gas temperature (EGT), generator power output, and fuel energy input to confirm the stability of turbine performance over the 72-hour period.

Table 3: Post-Wash Operational Parameters

Time (h)	T_1 (°C)	T_2 (°C)	P_1 (barA)	P_2 (barA)	EGT (°C)	Gen Power (kW)	Fuel Energy (kW)
00–12	25.6	399.4	1.000	13.38	489.9	10,250.0	27,313.20
12–24	25.6	399.5	1.000	13.38	489.9	10,250.0	27,313.22
24–36	25.6	399.6	1.000	13.38	499.0	10,249.5	27,313.25
36–48	25.7	399.5	1.000	13.38	489.9	10,250.0	27,313.23
48–60	25.7	399.4	0.999	13.20	499.5	10,249.8	27,313.23
60–72	25.6	399.5	1.000	13.38	489.9	10,250.2	27,313.20

Figure 3 illustrates the compressor discharge pressure (P_2) of GTG 2 during the 72-hour post-wash reliability test conducted after offline compressor water washing. The data show that the compressor discharge pressure remained nearly constant at approximately 13.38 bar throughout the monitoring period, indicating stable compressor operation following the cleaning process.The consistency of P_2 suggests that the removal of fouling deposits restored the effective flow area of the compressor blades and reduced aerodynamic losses, allowing the compressor to operate closer to its design pressure ratio. Similar stabilization of compressor operating parameters following cleaning has been reported in previous studies on gas turbine compressor fouling and recovery (Meher-Homji & Bromley, 2004; Kurz & Brun, 2012). The observed stability therefore confirms the effectiveness of offline washing in restoring compressor performance under the humid and particulate-laden environmental conditions typical of the Niger Delta.

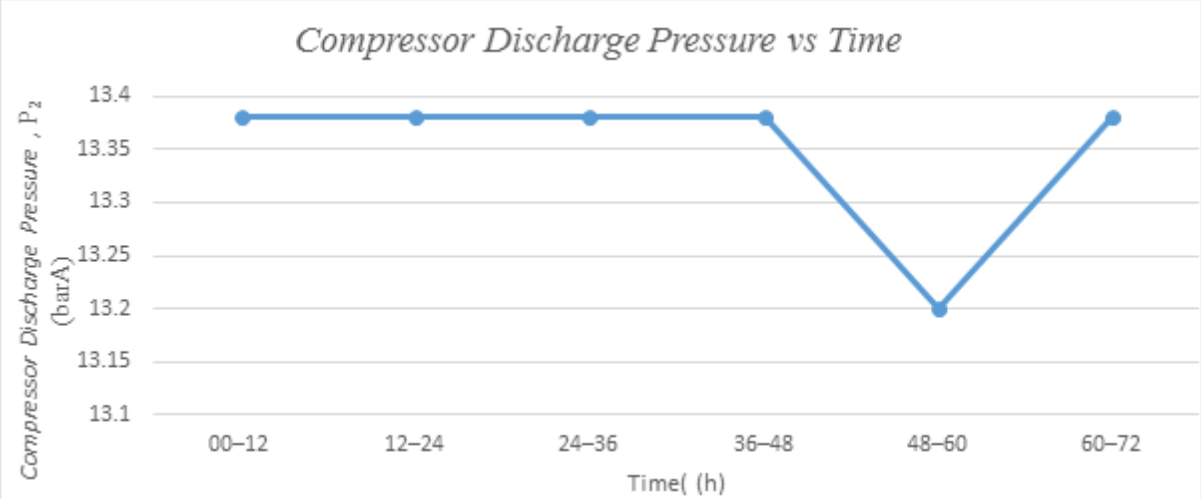


Figure 3: Variation of compressor pressure ratio (PR) of GTG 2 over six months prior to offline Washing

Figure 4 illustrates the generator power output of GTG 2 during the 72-hour post-wash reliability test conducted after offline compressor water washing. The data show that the generator power remained nearly constant at approximately 10,250 kW throughout the monitoring period, indicating stable turbine operation following the cleaning process.

The consistency of generator output suggests that the removal of fouling deposits restored the compressor's aerodynamic efficiency and stabilized airflow through the turbine, allowing the generator to produce power close to its design value. Similar stabilization of gas turbine

performance parameters following cleaning has been reported in recent studies on compressor fouling and recovery (Ahmed et al., 2021; Zhang et al., 2022). The observed stability therefore confirms the effectiveness of offline water washing in restoring turbine performance under the humid and particulate-laden environmental conditions typical of the Niger Delta.

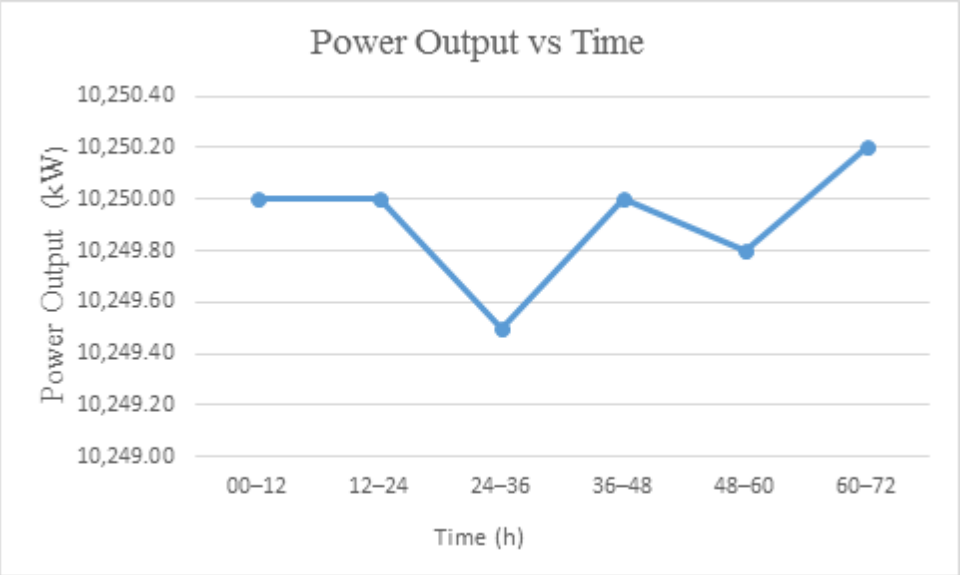


Figure 4: Generator Power Output with Time during the 72-hour Post-Wash Reliability Test

3.3. Comparative Analysis of Pre- and Post-Wash Operational Parameters

This section presents a comparative evaluation of key operational parameters of the Siemens SGT-400 (GTG 2) before and after offline compressor water washing. The analysis highlights changes in turbine operational parameters, particularly compressor discharge pressure (P_2), compressor discharge temperature (T_2), and exhaust gas temperature (EGT), as well as other relevant operational parameters. By examining pre- and post-wash data, the effectiveness of the cleaning process in restoring turbine performance under the humid and particulate-laden environmental conditions of the Niger Delta is assessed.

Table 4 provides a comparative summary of the operating conditions, including compressor inlet temperature (T_1), compressor discharge temperature (T_2), compressor inlet pressure (P_1), compressor discharge pressure (P_2), exhaust gas temperature (EGT), generated power, and fuel energy input, illustrating the impact of offline water washing on turbine performance.

Table 4: Pre- and Post-Wash Operational Parameter Comparison

Parameter	Pre-Wash Avg Jul	Post-Wash Avg (0–72 hrs)	Improvement	% Change	Remarks
T_1 (°C)	25.60	≈ 25.65	+0.05	+0.20%	Slight increase in compressor inlet temperature; negligible impact on air density.
T_2 (°C)	422.80	399.48	−23.32	−5.52%	Lower compressor discharge temperature indicates reduced fouling and improved airflow.
P_1 (barA)	0.970	0.9998	+0.0298	+3.07%	Slight rise in inlet pressure due to restored suction flow uniformity.
P_2 (barA)	11.08	13.35	+2.27	+20.50%	Significant increase in discharge pressure → improved pressure ratio and compressor performance.
EGT (°C)	557.50	493.02	−64.48	−11.56%	Substantial drop in exhaust gas temperature → better thermodynamic efficiency and reduced fouling losses.
Generated Power (kW)	8,553.05	10,250.00	+1,696.95	+19.83%	Major recovery in turbine output following compressor washing.
Fuel Energy (kW)	28,800.00	27,313.22	−1,486.78	−5.16%	Reduced fuel input reflects improved combustion efficiency and better energy conversion.

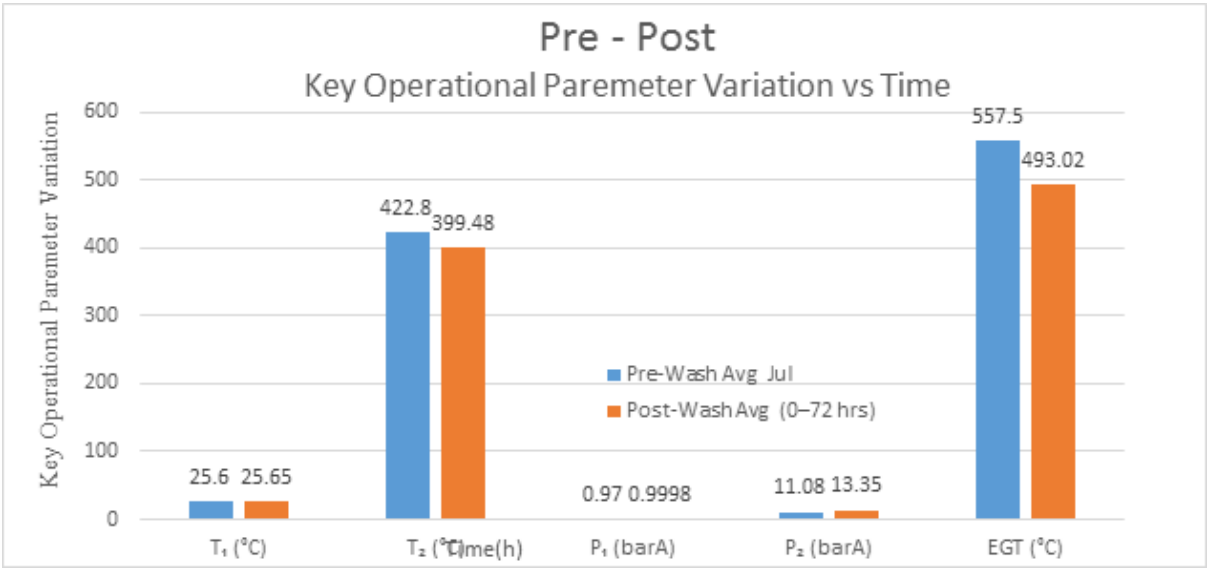


Figure 5: Comparative Trends of Selected Operational Parameters of GTG 2 Before and After Offline Compressor Water Washing

Figure 5 compares selected operational parameters of GTG 2 before and after offline compressor water washing, highlighting variations in T_1, T_2, P_1, P_2, and EGT.As observed, the compressor discharge pressure (P_2) increased significantly after washing, indicating a recovery of the compressor pressure ratio and improved airflow through the stages. Fouling typically reduces the effective flow area of the blades and increases aerodynamic losses, lowering pressure ratio and overall turbine efficiency. The observed improvement suggests that cleaning effectively restored the compressor's aerodynamic performance. Similar gains in pressure ratio following compressor cleaning have been reported in recent studies on gas turbine performance recovery (Alblawi et al., 2021; Tarabrin et al., 2022).

The figure also shows reductions in compressor discharge temperature (T_2) and exhaust gas temperature (EGT) post-wash. Lower values indicate improved compressor efficiency and thermodynamic performance, as the removal of fouling allows higher air mass flow to the combustion chamber, improving combustion efficiency and reducing turbine exhaust temperatures. Comparable trends have been reported in recent investigations on post-wash turbine performance (Meher-Homji & Bromley, 2020; Al-Hussaini et al., 2023).

In contrast, T_1 and P_1 show minimal variation between pre- and post-wash conditions, suggesting stable intake environmental conditions during data collection. Therefore, the performance improvements can primarily be attributed to the cleaning process rather than ambient changes.Overall, Figure 5 confirms that offline compressor water washing significantly improved turbine operation. The increase in P_2 alongside reductions in T_2 and EGT demonstrates restored compressor airflow and enhanced thermodynamic efficiency following the removal of fouling deposits.

3.4. Key Performance Indicator Assessment

Key performance indicators (KPIs) were calculated from the turbine's operational parameters, including compressor pressure ratio (PR), thermal efficiency (ηth), specific fuel consumption (SFC), compressor work (Wc), and compressor efficiency (ηc).Table 5 compares key performance indicators (KPIs) of the Siemens SGT-400 gas turbine before and

after offline compressor water washing, highlighting the immediate effects of the cleaning on turbine operational performance.

Table 5: Pre- and Post-Wash Key Performance Indicators Parameter Comparison

Parameter	**Pre-Wash Avg (Feb–Jul)**	**Post-Wash Avg (0–72 hrs)**	**Improvement**	**% Change**	**Remarks**
Fuel Flow (kg/s)	0.60000	0.56903	−0.03097	−5.16	Lower fuel flow indicates improved energy conversion efficiency
Heat Rate (kJ/kWh)	12,121.99	9,593.01	−2,528.98	−20.86	Reduced heat rate shows better thermal efficiency after wash
SFC (kg/kWh)	0.25254	0.19985	−0.05269	−20.86	Lower specific fuel consumption reflects improved fuel utilization
Pressure Ratio (P_2/P_1)	11.42268	13.35	+1.92732	+16.87	Increased pressure ratio confirms restored compressor performance
Parameter	**Pre-Wash Avg (Feb–Jul)**	**Post-Wash Avg (0–72 hrs)**	**Improvement**	**% Change**	**Remarks**
Thermal Efficiency (ηth, %)	29.70	37.53	+7.83	+26.37	Higher thermal efficiency shows improved cycle energy conversion
Compressor Work (Wc, kJ/kg)	399.186	329.39	−69.796	−17.48	Reduced compressor work indicates lower aerodynamic losses after cleaning
Compressor Efficiency (ηc, %)	75.63	87.67	+12.04	+15.92	Higher compressor efficiency confirms effective removal of fouling
Fuel Energy (kW)	28,800.00	27,313.22	−1,486.78	−5.16	Reduced fuel input reflects improved combustion efficiency and better energy conversion.
Generated Power (kW)	8,553.05	10,250.00	+1,696.95	+19.83	Major recovery in turbine output following compressor washing.

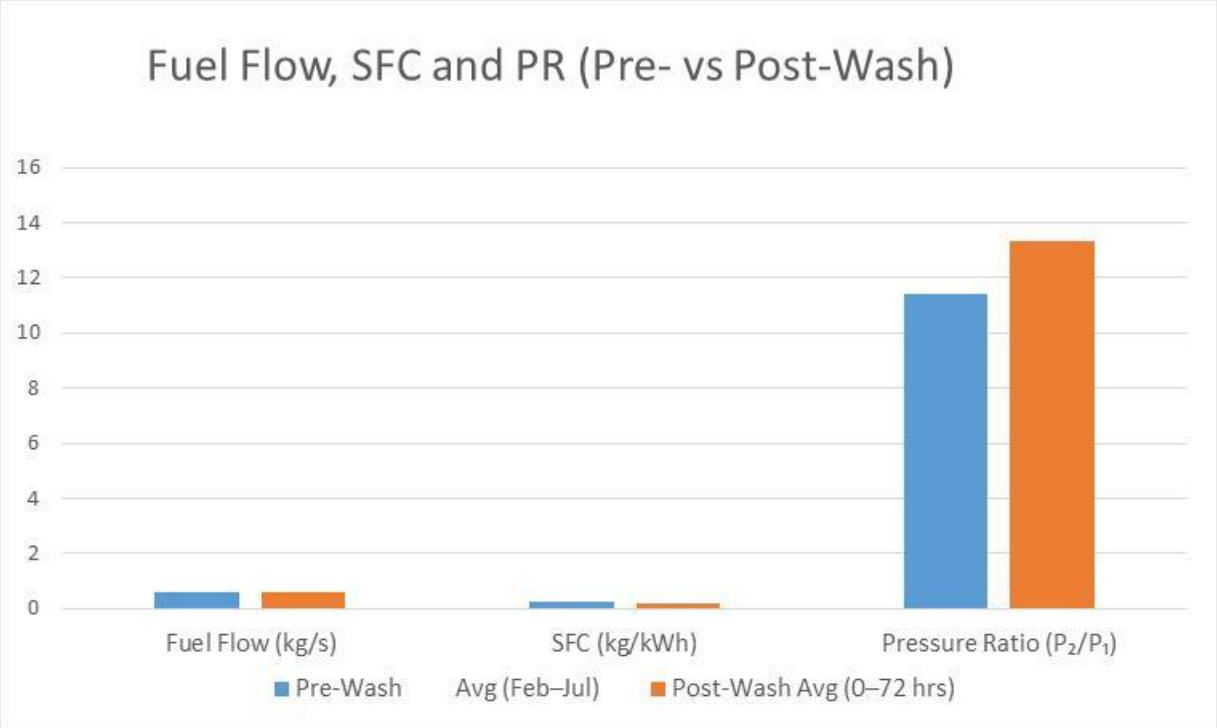


Figure 6: Comparative Trends of Fuel Flow, SFC, and Pressure Ratio (PR) Before and After Offline Compressor Water Washing

Figure 6 shows the comparative behavior of fuel flow, specific fuel consumption (SFC), and compressor pressure ratio (PR) before and after the offline compressor water washing of the Siemens SGT-400 gas turbine. The trends indicate clear performance recovery after the removal of fouling deposits from the compressor section.The fuel flow rate decreases from 0.60000 kg/s to 0.56903 kg/s, representing a 5.16 % reduction after washing. This decrease indicates that less fuel is required to produce the turbine output once the compressor airflow capacity has been restored. Compressor fouling typically restricts airflow and reduces compressor efficiency, which forces the turbine to consume more fuel to maintain load conditions. Cleaning the compressor removes deposited contaminants and improves airflow, thereby reducing fuel demand (Aretakis et al., 2023; Susanto et al., 2025).

A more pronounced improvement is observed in specific fuel consumption, which decreases from 0.25254 kg/kWh to 0.19985 kg/kWh, corresponding to a 20.86 % reduction. Lower SFC indicates improved fuel utilization and more efficient energy conversion during turbine operation. Fouling increases aerodynamic losses within the compressor, leading to higher fuel consumption per unit power output. After washing, the restored blade surfaces improve airflow characteristics and combustion efficiency, resulting in lower SFC (Kurz & Brun, 2022; Susanto et al., 2025).The compressor pressure ratio increases from 11.42 to 13.35, representing an improvement of 16.87 %. Pressure ratio is a key parameter governing the performance of the Brayton cycle, and higher values indicate more effective air compression prior to combustion. Fouling deposits reduce compressor pressure rise by disrupting airflow across the blades. The increase observed after washing confirms that the compressor stages regained much of their aerodynamic efficiency (Aretakis et al., 2023; Kurz & Brun, 2022).

Overall, Figure 6 demonstrates that offline compressor water washing significantly improves turbine performance, as reflected by reduced fuel consumption and enhanced compressor pressure ratio. These improvements confirm the effectiveness of compressor washing in

mitigating fouling effects and restoring gas turbine efficiency, particularly in contaminant-prone environments such as those encountered in the Niger Delta region (Aretakis et al., 2023; Kurz & Brun, 2022; Susanto et al., 2025).

3.5. Statistical Evaluation of Pre- and Post-Wash KPIs

Table 6 summarizes the results of the Statistical Evaluation of Pre- and Post-Wash KPIs. To quantify the effect of offline compressor water washing on turbine performance, a paired sample t-test was conducted on selected Key Performance Indicators (KPIs) at a 95% confidence level ($\alpha = 0.05$).

Table 6: Statistical Evaluation of Pre- and Post-Wash KPIs

KPI	Pre-Wash Mean	Post-Wash Mean	Mean Difference	t-Statistic	p-Value	Significance (95% CI)
Fuel Flow (kg/s)	0.61030	0.57610	−0.03421	−3.131	0.02593	Significant ↓
Heat Rate (kJ/kWh)	11,651.55	9,398.1	−2,253.5	−5.878	0.00202	Significant ↓
SFC (kg/kWh)	0.24812	0.19949	−0.04863	−8.603	0.00035	Significant ↓
Pressure Ratio (P_2/P_1)	11.23494	13.12543	1.89049	7.015	0.00091	Significant ↑
Thermal Efficiency (ηth,%)	29.31745	38.19324	8.87579	10.306	0.00015	Significant ↑
Compressor Work (Wc, kJ/kg)	396.5294	336.3826	−60.1468	−10.465	0.00014	Significant ↓
Compressor Efficiency (ηc, %)	75.32686	87.08645	11.75959	3.517	0.01697	Significant ↑
Generated Power (kW)	8,547.16335	10,094.57448	1,547.41113	5.810	0.00213	Significant ↑
Fuel Energy (kW)	28,438.00459	27,576.91482	−861.08978	−0.974	0.37492	Not Significant ↓

A paired sample t-test at a 95 % confidence level ($\alpha = 0.05$) was conducted to determine whether the observed changes in key turbine performance indicators after offline compressor water washing were statistically significant. The results presented in Table 6 show that most performance parameters experienced statistically significant improvements after the washing process.For the fuel-related parameters, fuel flow decreased from 0.61030 kg/s to 0.57610 kg/s ($t = -3.131$, $p = 0.02593$). Similarly, heat rate reduced from 11,651.55 kJ/kWh to 9,398.10 kJ/kWh ($t = -5.878$, $p = 0.00202$), while specific fuel consumption (SFC) declined from 0.24812 kg/kWh to 0.19949 kg/kWh ($t = -8.603$, $p = 0.00035$). These statistically significant reductions indicate improved fuel utilization and lower thermodynamic losses after compressor cleaning. Similar improvements in fuel efficiency following compressor washing have been reported in recent gas turbine performance studies (Enyia et al., 2023; Agbadede and Kainga, 2026).

In terms of compressor performance, the pressure ratio increased from 11.23494 to 13.12543 ($t = 7.015$, $p = 0.00091$), while compressor work decreased from 396.53 kJ/kg to 336.38 kJ/kg ($t = -10.465$, $p = 0.00014$). Additionally, compressor efficiency improved from 75.33 % to 87.09 % ($t = 3.517$, $p = 0.01697$). These results confirm that the removal of fouling deposits restored the aerodynamic characteristics of the compressor blades, thereby improving airflow and compression performance. Previous investigations have shown that compressor washing significantly restores compressor efficiency and pressure ratio in industrial gas turbines operating in fouling-prone environments (Enyia et al., 2023).

The improvements in compressor performance also translated into better overall turbine performance. Thermal efficiency increased from 29.32 % to 38.19 % ($t = 10.306$, $p = 0.00015$), while generated power increased from 8,547.16 kW to 10,094.57 kW ($t = 5.810$, $p = 0.00213$). These statistically significant changes demonstrate that restoring compressor aerodynamic performance enhanced the thermodynamic efficiency of the turbine cycle and increased mechanical power output. Similar performance recovery after compressor washing has been documented in industrial turbine studies (Agbadede and Kainga, 2026). However, the change in fuel energy input, which decreased from 28,438.00 kW to 27,576.91 kW, was not statistically significant ($t = -0.974$, $p = 0.37492$). This suggests that the improvements in turbine performance were mainly due to enhanced aerodynamic and thermodynamic efficiency rather than a substantial increase or decrease in fuel energy supply.

Overall, the statistical evaluation confirms that offline compressor water washing produced significant improvements in most turbine performance indicators. The reductions in fuel flow, heat rate, SFC, and compressor work, together with increases in pressure ratio, compressor efficiency, thermal efficiency, and generated power, indicate that the washing process effectively restored compressor performance and improved overall gas turbine efficiency. These findings are consistent with recent research demonstrating that periodic compressor washing is essential for maintaining optimal gas turbine performance in contaminant-prone operating environments (Enyia et al., 2023; Agbadede and Kainga, 2026).

4.0 Conclusions

Compressor fouling in humid, particulate-laden environments reduces turbine efficiency, pressure ratio, and power output while increasing fuel consumption. This study demonstrates that offline compressor water washing effectively restores performance in a Siemens SGT-400 turbine, with statistically significant improvements in pressure ratio, thermal efficiency, compressor efficiency, and generated power. Post-wash monitoring confirmed stable operation and consistent KPI recovery. The results highlight the importance of scheduled offline washing in tropical coastal regions to maintain aerodynamic and thermodynamic performance, prevent long-term degradation and maintain energy conversion efficiency. Combining routine washing with KPI-based monitoring provides a practical strategy for sustaining turbine reliability under severe fouling conditions.

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