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Evaluation of Compressor Washing Methods on the Performance Enhancement of Gas Turbine Engines

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Abstract:- Industrial Gas Turbines are subjected to a very harsh operating condition mostly in the oil and gas sector and in the desert environment, thereby causing fouling in the engine component parts, especially the compressor, and the total performance is hence distorted as a result of this degraded engine component. Fouling of the compressor blade is considered in this research. As such, an optimization model for power augmentation was improvised via compressor washing methods. These state-of-the-art washing methods comprises of the online, offline and combination of both methods. This was done to ascertain the most crucial methods to be adopted for further application and advice to gas turbine owners and operators. Here, the operator has the option to select his desired duration for the compressor to be washed between certain intervals while also considering the environment that engine is being operated. The enhancement applied in the work is a computer based linear programming model that is robust and have the ability to investigate the highest and lowest values of the net profit of the project to be determined. Pythia and Turbomatch software of Cranfield University was used for the engine performance simulation, and the outcome appears very accurate since the deviations from existing results do not have much disparity when compared. As such, the engine was validated and hence utilized for the entire research. An investigation of online, offline and a combination of both online and offline compressor washing was evaluated to determine the most economically viable washing method to be implemented to help operators combat the fouling issues and yield profit. This continuous compressor washing does not only extend the engine life, but also optimizes the engine performance, prevent system downtime, and improve the plant operation profit. Implanting a component fault at 15^0 C due to 1% compressor fouling, degradation of about 5% in power output was noticed, 3% reduction in air mass flow and pressure ratio, and about 1.4% reduction in gas generator turbine efficiency was also observed. And for another simulation of 5% compressor efficiency fouling, it was observed that the online compressor washing was able to recover 2.1%, the offline was 2.8%, while the combined method experience a 4.5% performance recovery.

Keyword:- *Compressor Washing, Efficiency, Fouling, Gas Turbine, Performance.*

I. INTRODUCTION

The various types of gas turbines which includes: turbo-prop, turbo-fan, turbo-jet, and the turbo-shaft has different application for variety of purposes such as aircraft, ship propulsion, power generation, oil and gas, and etc. In aforementioned, industrial gas turbines have different uses in most industries in the world, and it is highly sorted for in the electricity industry resulting from the high fluctuations and instability in power supply. These engines have been ensured from research and development to have an economically viable life [1]. There is also a very wide increase in the application of GT in oil and gas industry for power generation, and this increasing popularity has inspired the necessity to determine the means by which these engines can be operated at the lowest possible cost, as it is likely to degradation as a result of unavoidable problems suppressing it smooth operation.

There is a geometric improvement in the GT GT industry for power generation as a result of advances in science and technology into a complex environment that no longer operates from the usual philosophy of demand and supply. The degradation characteristics of this engine resulting from environmental envelop and operating conditions, together with the increasing fuel price globally, has further call for the need to operate the systems more economically without compromising on the supply stability and reliability. It is imperative to consider the safety of the operator and the equipment, because engine component part failure could lead to severe damage of lives and engine components. More so, costs accrue resulting from component degradation can be minimized by adopting efficient compressor water washing method.

Fouling of the GT compressor is unavoidable because the engines operating environment is susceptible to degradation since they ingest some particles alongside air during intake. These particles stick to the compressor blades and causes fouling. These can cause severe damage to the GT major component such as the compressor if not properly maintained. Gas turbine component can also be damaged as a result of contaminants such as; foreign object damage (FOD) and domestic object damage (DOD), particles of sands present in atmospheric air, abrasion, corrosion, and erosion. Amongst all, compressor fouling has been found to constitute the highest amount of loss to the engine power output because it occurs on the surface of the component, system or plant performing a defined and useful function and the fouling process impedes or interfaces with the function. The GT performance modelling tools known as Pythia/Turbomatch was implemented for the simulation of the thermodynamic models of the engine to be evaluated [2, 3]. The data output from the simulation was inputted to economic model similar to [4]. The different wash methods and frequencies were integrated. This study encompasses comparisons amongst three different compressor wash methods which includes: online, offline, and the combination of both methods to achieve the most desirable outcome to adapt for onward application.

II. LITERATURE REVIEW

Gas turbine (GT) breathe in large amount of air during intake, and if the air is not properly filtered, the contaminants from the environment known as Foreign Object Damage (FOD) will enter into the engine and cause distortion (fouling) to the components parts known as Domestic Object Damage (DOD). The thermodynamic and aerodynamic design of the components parts greatly affect the performance of the GT engines resulting from the complexity of it frame, condition of operations etc [5]. The major component parts such as Compressor, Combustor and Turbine are very reliable. Continuous operation of this engine will lead to deterioration of the components parts, as such, results to degradation in engine performance [6- 8]. The following factors affects the performance of a GT engine: Fuel flow, mass flow rate, pressure ratio, etc [9], because disruption in the free flow of air along the engine component parts will lead to engine deterioration [10]. A Solar Titan 250 GT with 22.37 MW capacity has a reported exhaust flow of 245,660 kg/hr [11], at this air flow rate, one ppm of particles penetrating into in the ambient air is equivalent to 5.9kg of particles entering GT without filtration each day. Degradation mechanisms and rates for GT that can be used to estimate a rate of degradation for LCC have been discussed in several researches which comprises of compressor fouling, and washing reviewing different models and experimental data of the GT rates of deterioration [12]. Syverud et al [13] presented the degradation of axial compressor from fouling resulting from ingestion of saltwater. Kurz and Brun [14] also review the mechanism responsible for GT model degradation and investigate the effects of these mechanism on the performance of the GT. A detailed review on fouling effects on 92 different GTs were carried out by [15], and Zaba [16] determined the effects of debris on the blade and present a theoretical model comparing with experimental data. Different washing intervals was investigated by [17] to determine the most economical wash intervals to be implemented. The fouling effect on compressor as presented in figure 1 below was carried out by [18], they investigated that a 3% fouled compressed requires cleaning to avoid damage to the component part as is enough sign for obvious damage.

They also show that as efficient as a GT inlet could be, there is still room for particle penetration into the engine, which will clog on the compressor blades, build up and cause distortion to smooth engine operation. The current research intends to compare the most viable method amongst online, offline, and combination of both methods.

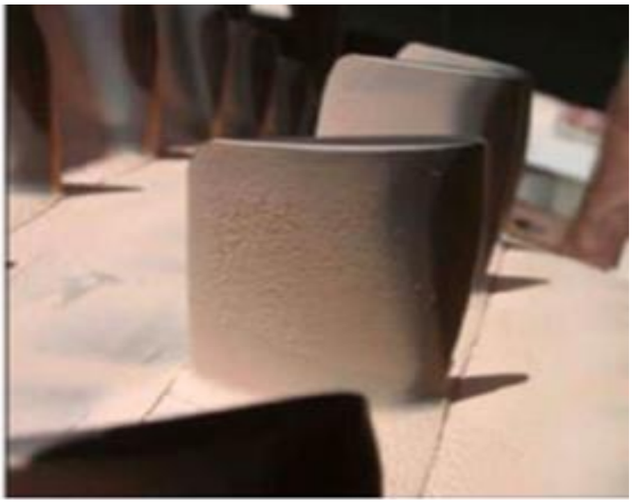

Fig 1 Fouled Compressor [18]

III. RESEARCH METHODOLOGY

Gas turbine owners are facing serious challenges from operating and maintaining the GT efficiently to meet external needs, adhering to environmental conditions and economic stability for maximum profit, as such, it has become imperative to apply a more sophisticated technique in the maintenance of such engines. In this case, the compressor online and offline washing is introduced. The methods used here involves washing the compressor online with intervals of 7days wash frequencies. The offline compressor water wash is assumed to be administered quarterly per annum, which amount to a total of four offline washes in a year and, a combination of both online & offline washing was also used. In the case of combination, the offline wash was assumed to be done as a major wash after equal interval of online wash, which enables more power augmentation. The reason is to make comparisons of these wash intervals at the most reasonable wash effectiveness to obtain the most economically viable means of compressor washing, to help minimize operating and maintenance cost, so as to optimize profits in all possible aspects of the operations. The figure 2 below indicates the assembling of each component part that made up the entire performance model. The components, its functions and inter-connectivity are all thermodynamic processes. The given inputs and outputs of the model are described standards taken as reference from the operating environment for the operation of the engine, and the results are described thereafter.

Turbomatch and Pythia software which are in-house software for gas turbine engine simulation in Cranfield University are both applied for the performance simulations in this research with the application of a hot climate condition having an average temperature of 30^0C. The performance parameters of the GT that requires evaluation were predicted for the design point (DP) and off design point (ODP) possible for the operating conditions. The data were sourced and applied into the performance simulation model, the outputs were validated, and the results were assumed to be the DP performance of the GT, which is referred to as baseline performance. The ODP performance for the GT was also evaluated for the different cases to be investigated. The parameters considered during the evaluation were ambient temperature (T_{amb}), ambient pressure (P_{amb}) and turbine entry temperature (TET). TET and (T_{amb}) were varied while (P_{amb}) was kept constant in the investigation. The Pythia software was applied for the investigation of ODP performance parameters which produces the performance parameters for corresponding values of TET and (T_{amb}). These are to obtain the predicted ODP parameters for the GT in investigation, and were further tabulated in dimensional look-up tables where fuel flow, mass flow, power output, compressor temperature, etc, were being obtained and applied into other sub-models to achieve the required engine parameter output.

The aim is to determine the health condition of a single IGT engine of 29MW in three different conditions of health in its clean, fouled and washed conditions throughout a period of one year. The difference in temperature for this part of the country selected, ranges between 20^0C and 40^0C. These was absorbed and integrated into the off design engine while the behaviours were carefully studied in different cases of: Clean, Fouled, and Washed behaviour. The temperatures provided were the highest and lowest experienced temperatures throughout a year period in the region. The baseline engine behavior is assumed to be the clean engine and the fouled engine is the highest power attainable without wash been carried out. The online wash was taken at different intervals of 7days throughout the one-year period. The offline wash was carried out quarterly in the year, making a total of four offline compressor water washes per annum, and lastly, both online and offline wash was combined and carried out. In all, the highest recoverable energy was recorded for each case and combination of cases as well. The recoverable power (MW) achieved was converted into energy (kwh), since this energy will be sold as electricity for consumption.

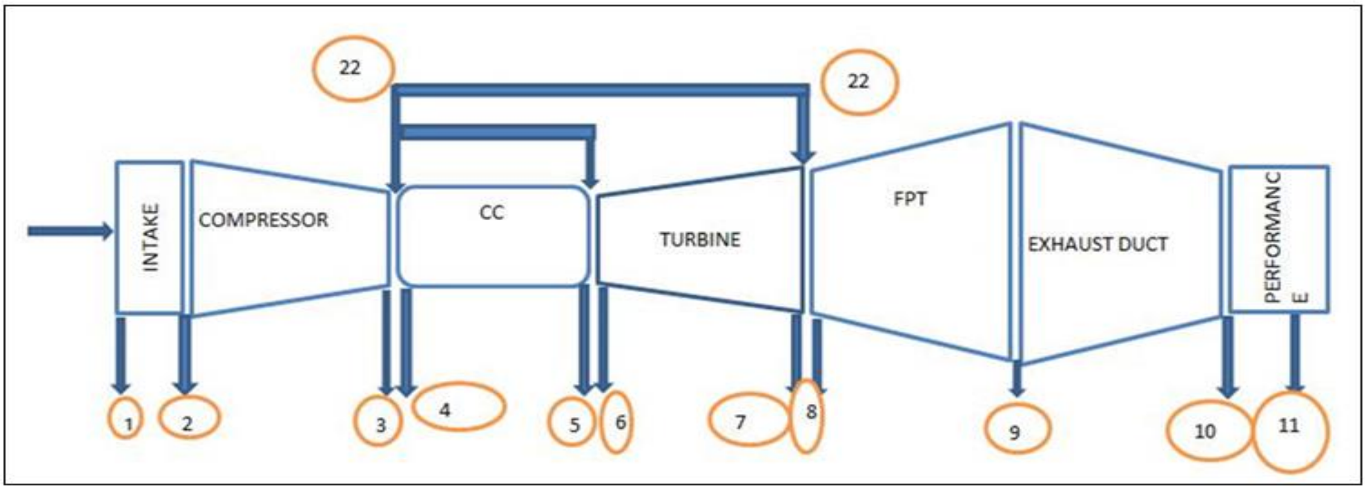

Fig 2 Schematic Engine Layout for GE LM2500+

The engine selected for simulation in this research is a simple cycle LM2500+ similar to that of General Electric (GE), an industrial and co-generation two shaft GT. It is applied in a wide range of power generation as simple or combined cycle but can also be applied as mechanical drive. The components were built in Turbomatch model engine as could be seen schematically in figure 2. The Turbomatch simulation procedures have been followed to carry out the engine modelling. The objective was to simulate the engine behaviour at varying ambient conditions a particular year. The output result was assumed to be that of the clean (baseline engine), and the degradation resulting from fouling was inputted afterward. Later, compressor water wash methods were carried out to show the effects of washing on power output and other parameters affected.

The design point DP of a GT engine could be defined as the actual point in the operating range of an engine where it is running at a particular speed, mass flow, power output, and pressure ratio for which it is originally designed [8]. The DP performance of the engine applied herein is determined from the Pythia output file of the simulated engine similar to that of GE's LM2500+ engine in the sense of it characteristics. Considering the given simulation, the stipulated operating envelop, the output results compared reasonably with that of the real engine, as such, it was adopted and assumed to be the reference point (baseline engine) for further discussions in this work.

In the performance simulation of the GT, pressure and TET affects thermal efficiency and specific power adversely. But the highest specific power and the highest thermal efficiency do not occur at the same pressure ratio. This indicates that during the designing of a GT, the design pressure ratio should be a compromise between the highest specific power and the highest thermal efficiency which means minimum specific fuel consumption to enable informed decision whether to use a small engine with high specific power or an efficient engine with low specific fuel consumption and this directly relates to the capital cost and annual cost for the engine.

The major considerations are the effects of ambient conditions effects on the engine performance applied for the off-design point of this research. Afterwards, the effect of fouling to compressor deterioration on engine performance. The performance is generally given based on the environment that the engine is operated. The change in steady state performance is evaluated. Since the operational conditions have been investigated, it is possible to determine the different behaviours of the engine performance, which includes; mass flow, power output, fuel flow, thermal efficiency, etc.

IV. RESULTS AND DISCUSSIONS

The GT performance of the given engine is based on a particular site location in Maiduguri, Nigeria, with given ambient conditions as could be seen in table 1. The data provided indicates annual ambient temperature fluctuation, which is applied for the GT performance simulation to demonstrate the effects of ambient conditions on the performance parameters of the engine for a given year period as could be seen in table 1 below.

Table 1 Weather Condition for Maiduguri, Nigeria [19]

Climate data summary for Maiduguri, Nigeria		
Months	**Temperature (^{0}C)**	**Temperature (^{0}K)**
January	21	294
February	22	295
March	26	299
April	31	304
May	37	310
June	40	313
July	41	314
August	40	313
September	38	311
October	34	307
November	29	302
December	23	296

Table 1 shows the twelve months in the year with its corresponding temperatures in Celsius and kelvin conversion. It is obvious that the temperature is higher during the dry season and lower during the raining season. Thus, affecting the engine performance output accordingly as presented in figure 3 below for the thermal efficiency.

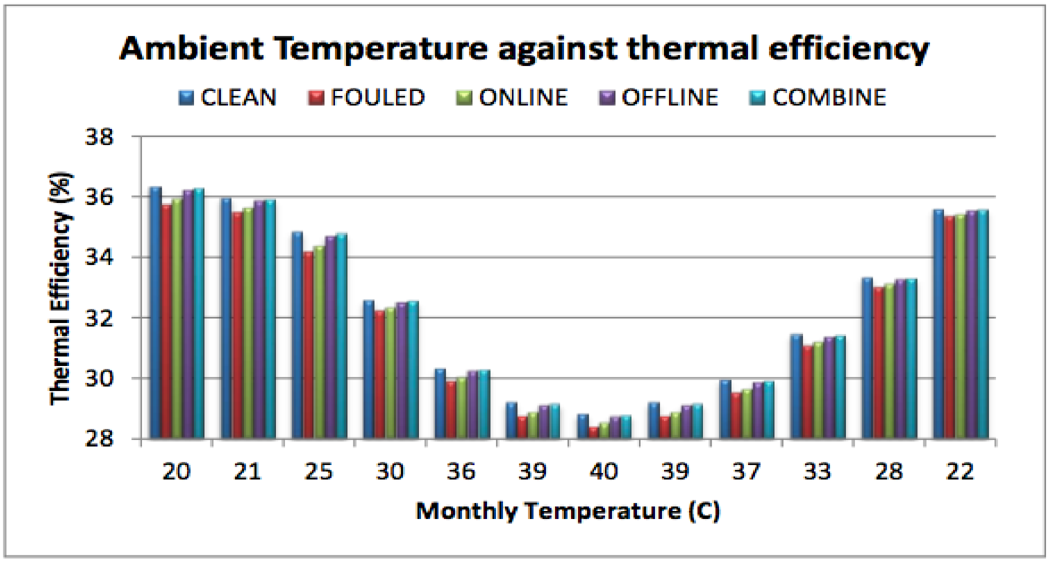

Fig 3 Effects of Ambient Temperature on Thermal Efficiency.

The fluctuations in thermal efficiency results from the varying ambient temperature all through the year. An increase in ambient temperature causes reduction in thermal efficiency, and vice-versa. It is indicated in figure 3 that between the first and the seventh months, the thermal efficiency increases, which is due to the decrease in ambient temperature, and between the seventh month and the twelfth month, there is an increase in thermal efficiency resulting from decrease in ambient temperature, leaving the seventh month of the year as least efficient since it has the highest ambient temperature of 41^{0}C. It was determined that the thermal efficiency for the online washed engine is better compared to the fouled engine. On average through the whole year (twelve months' period), there was a drop in thermal efficiency of about 1.32% for the fouled engine, 0.40% was recovered from the online compressor washed, while the offline and combine offline and online compressor washed experienced 1.06% and 1.19% recovery respectively. There was a 4.15% drop in pressure ratio from the fouled engine, and after the incorporation of online compressor water wash, a regain of 1.28% was experienced, in a similar way, the offline and the combination of both offline and online water experienced a sound recovery of 3.34% and 3.75% respectively. The pressure ratio, like the thermal efficiency reduces with increase in ambient temperature and increases with decrease in ambient temperature. The first to seventh months indicates decreases, as seventh to twelfth month shows increase in PR with the seventh month being the least as a result from the highest ambient temperature. Increase in PR result in increase in the thermal efficiency and vice versa, in the same way, the engine conditions behavior, with mass flow against ambient temperature. Averagely, the disparity of the fouled condition deviated by about 5.67%, and 1.77% was recovered from online compressor water wash, while the offline and combination of offline and online recovered about 4.58% and 5.13% respectively. The mass flow reduces the GT output power because it is less dense with hot air. The percentage disparity is high with mass flow, because GT's are air breathing engines and as such the quality of air intake really matters a whole lot to the performance output of the engine health. The cleaner and colder the air, the better the output power and vice versa. In a similar method, the fuel flow is also affected by ambient conditions, because high temperature reduces fuel flow, while lower temperatures increases fuel flow and keep the engine more efficient, and operating in a better condition, working better for the operator, and yielding profit for the engine owner in longer lasting years.

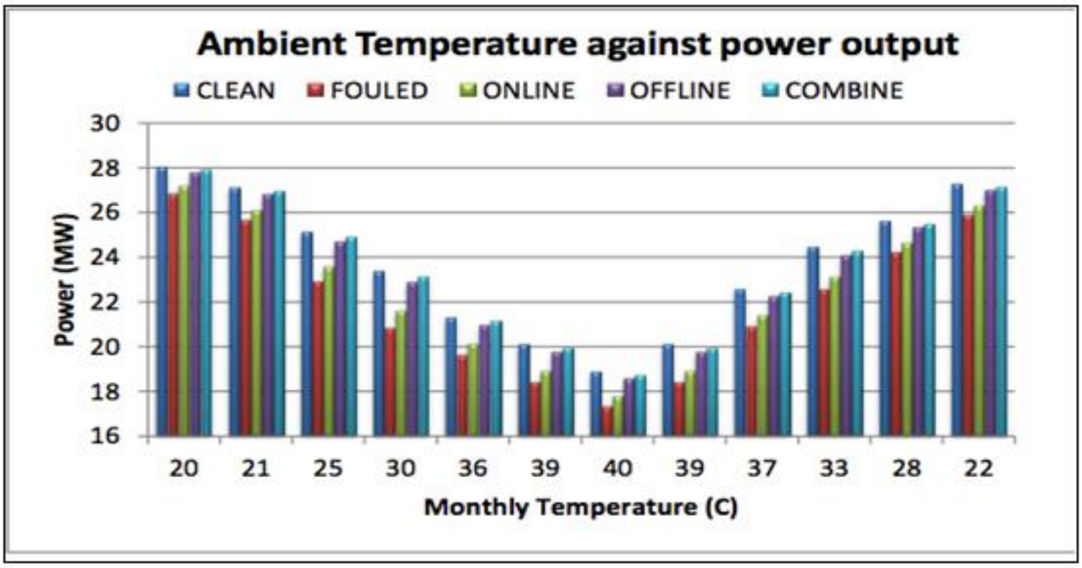

Fig 4 Effects of Ambient Temperature on Shaft Power

It is deduced from figure 4 that the turbine output power has the most disparity amounting to about 7.20% as a result of the compressor fouling, of which about 2.28% was regained from the online compressor water wash. However, a recovery of about 5.85% and 6.50% was realized from the offline and combination of both offline & online compressor water wash. The power loss from a GT engine could be regained in different methods, such as; increase in fuel flow & TET, injection of water, supercharging, inlet fogging etc.

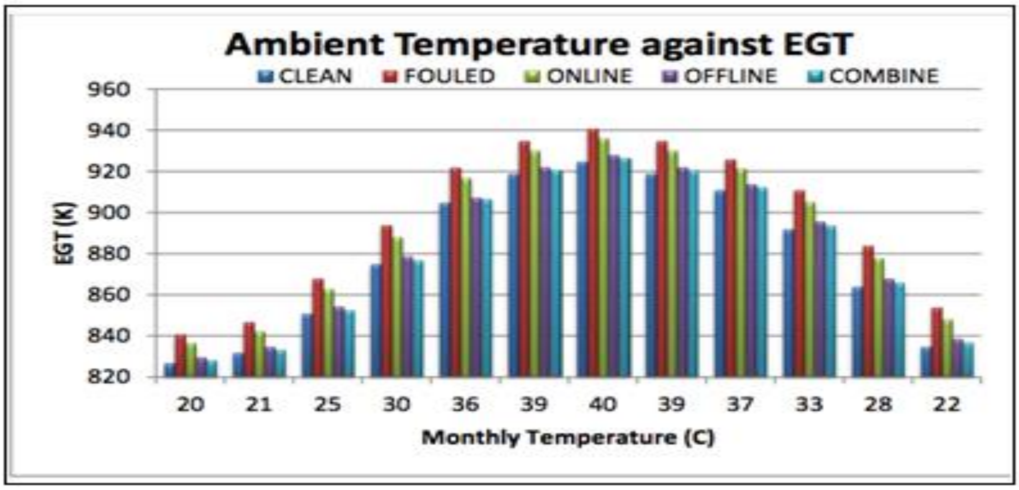

Fig 5 Effects of Ambient Temperature on Exhaust Gas Temperature.

It is obvious that figure 5 took a different dimension opposite to figure 3 and 4 for the thermal efficiency and shaft power respectively. Obviously, the fouled engine has the most value while the clean engine has the least value. This signifies that an increase in ambient temperature results to increase in exhaust gas temperature (EGT). Increased EGT will decreases fuel efficiency, which leads to reduction in GT output power. The EGT for the clean engine is better compared to that of the fouled engine because it has better fuel efficiency as could be seen in figure 5. A 6.8% increase in ambient temperature leads to 1.92% increases in EGT. Application of the online compressor wash reduces the temperature by 0.57% effectiveness. On the other hand, the offline and combination of offline and online compressor water wash recovered 1.54% and 1.73% respectively.

- *Engine Performance Recovery Rate from Compressor Washing*

It was determined in this research that at the beginning of service life, fouling increases faster, and afterwards, there is a reduction in the rate of debris build-ups or in a more or less constant form. There are some considerations put in place while trying to mitigate this compressor degradation issues to the lowest point. These includes; a more frequent but very moderate maintenance methods, increased compressor water wash intervals, strategic location of the inlet filter system to mitigate too much debris at the entry to the compressor during suction, reducing hot section fouling by treating the fuel extensively before use, strict adherence to the original manufacturers engine maintenance instruction and recommendation about operations and maintenance guideline. The cases for compressor water wash in this research as earlier emphasized involves; online water wash only, for an interval of 7 days'. Offline compressor water wash instituted quarterly in a year period. A combined online & offline compressor water wash involves carrying out the regular weekly water wash and then an offline compressor water wash to be administered twice a year at equal interval.

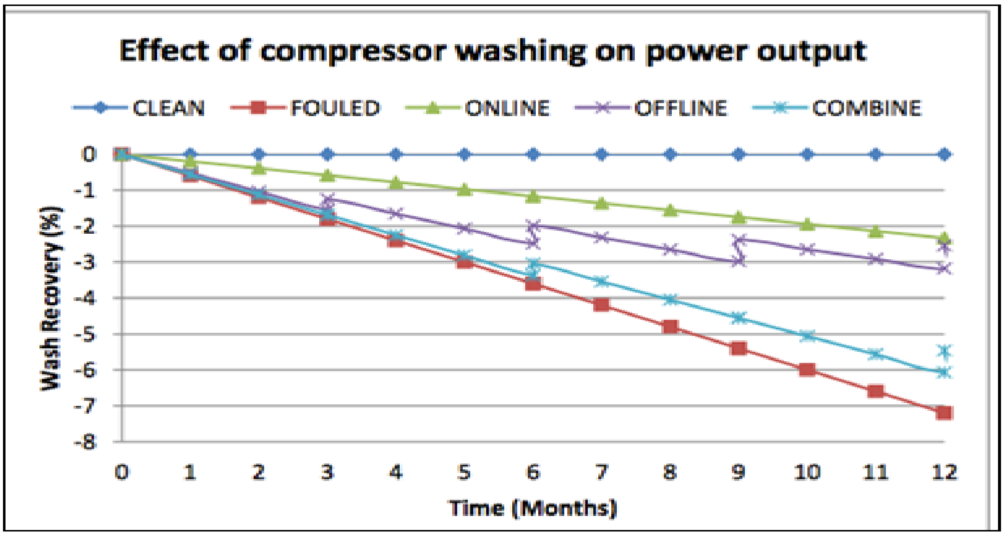

Fig 6 Effect of Compressor Washing on Power Recovery

It is displayed in Figure 6 that the cumulative percentage deviation of all the wash case for power output were detected distinctively. It is evaluated that the combinations of both online and offline compressor water wash deviated more. The engine output power was fouled with about 7% , but the online water wash was able to recover 2.5%, the offline recovered 3.2%, and the combined methods recovered about 5.5% of the lost power from the engine.

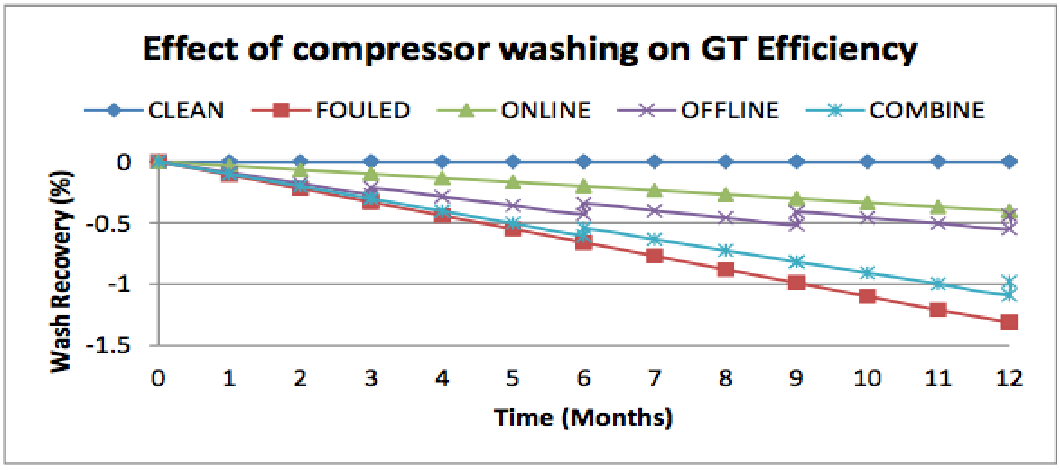

Fig 7 Effect of Compressor Washing on Efficiency

In addition, the GT efficiency was degraded by about 1.3%, and after the online water wash, it experienced 0.4% recovery, it was 0.6% for the offline and 1.1% for the combined method.

It could be noticed that aside the EGT which is increasing, all other parameters decreased. It is obvious that the combination of both wash cases deviated more, which indicates that it recovered more efficiency which in turn yielded better performing of the engine output. The EGT was degraded by about 2%, the online water wash recovered 0.5%, the offline recovered0.9%, while the combined method amount to about 1.5% recovery.

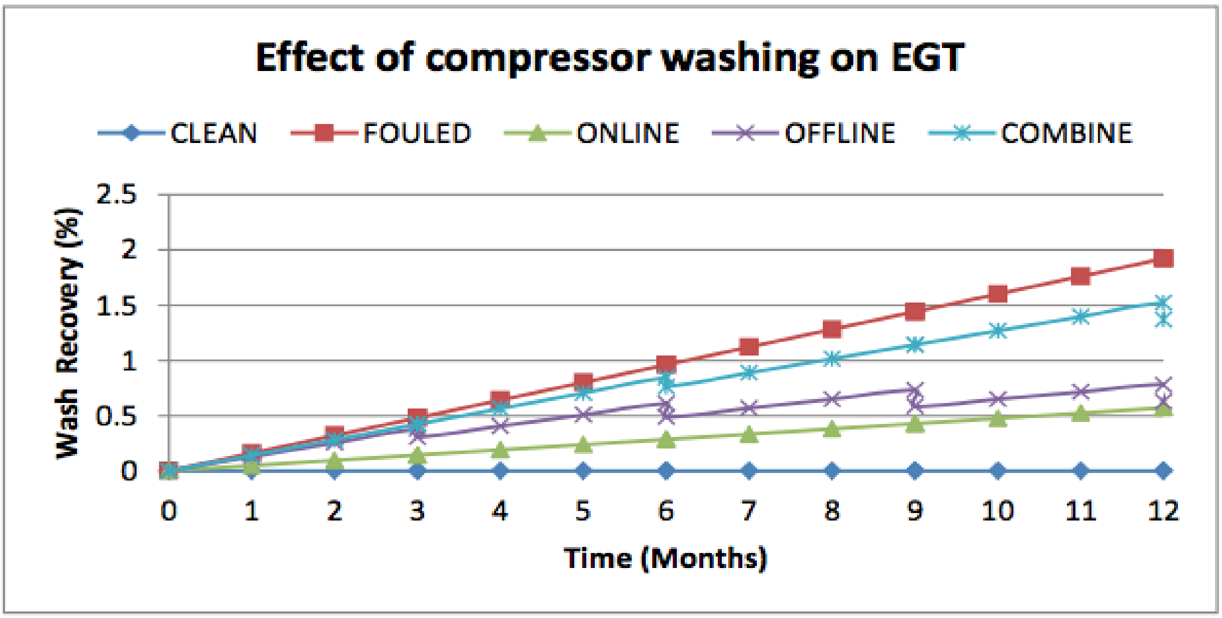

Fig 8 Effect of Compressor Washing on EGT

V. CONCLUSION AND RECOMMENDATIONS

Compressor water wash methods have been applied to solve the problem of compressor fouling which have been in existence for some decades now to the engine operators. Adequate selection for it application offers many technical and economic Importance to the GT operators. It has been investigated that compressor fouling does not easily result to engine breakdown, but ignoring the debris and allowing it to accumulate over time can cause reduction in GT performance efficiency and flow capacity of the compressor, thereby affecting total output power of the engine. Therefore, cleaning the engine regular interval, usually by water washing the compressor, is important to enhance production and profitability to the end user. Washing the compressor too often will also lead to high maintenance cost, and loss in profit due to downtime for scheduled washing and unavailability of the engine in the case of offline washing. In the same way, if the washing is infrequent, this will cause more accumulation of dirt clogging the blade which will definitely affect overall GT output performance resulting from the fouling of the component part. The possible mechanism responsible for GT deterioration have been stated and discussed in the body of this research, displaying the various possible physical reasons. The design point was first simulated successfully with very promising outcome and close to the actual characteristics of the engine with error of about 0.01% from Turbomatch software application since the actual map could not be found on public domain for the sensitivity of commercial reasons. A deterioration in the flow capacity and isentropic efficiency was noticed and the output power as well, which is all caused by compressor fouling due to accrued debris on the surface of the compressor blades. The application of Turbomatch and Pythia software which is in-house software available in school of engineering from Cranfield University, for the simulation of the performance of GT, was used to predict the effect of compressor degradation on total performance of the engine, and the result is robust and promising.

REFERENCES

[1]. Chen, H. A., Multiscale Forecasting Methodology for Power Plant Fleet Management. Aerospace Engineering. Georgia Institute of Technology; 2005.
[2]. Palmer., The TURBOMATCH Scheme for Gas-Turbine Performance Calculation (Unpublished User's Guid), Cranfield University. Cranfield, UK; 1999.
[3]. Vassilious, P., Gas Turbine Performance Simulation and Diagnostics (Unpublished TURBOMATCH course note), Cranfield University; 2011.
[4]. Ogaji, S. O. T., Pilidis, P., and Hales, R., TERA- A Tool for Aero-engine Modelling and Management. second world congress on Engineering Assest Management and the Fourth International Conference on Condition Monitoring, Harrogate, UK; 11-14 June, 2007.
[5]. Diankunchak, I.S., Performance Deterioration in Industrial Gas Turbine. Journal of Engineering for gas turbine and power, Vol. 114, No. 2, pp. 161-168, 1992.

[6]. Meher-Homji, C. B., Chaker, M. A., and Motiwala, H. M., Gas Turbine Performance Deterioration. Proceedings of the 30th Turbomachinery Symposium, Turbomachinery Laboratory, Texas A & M University, College Station, Texas, pg.139-176, 2001.

[7]. Lakshminarasimha, A. N., Boyce, M.P., and Meher-Homji, C.B., Modelling and Analysis of Gas Turbine Performance Deterioration. Journal of Engineering for gas turbines and power, Vol. 116, No. 1, pp. 46-52, 1994.

[8]. Hamed, A., Tabakoff, W., and Singh, D., Modelling of Compressor Performance Deterioration due to Erosion. International Journal of Rotating Machinery, Vol. 4 Issue 4, pp. 243-248, 1998.

[9]. Tabakoff, W., Lakshminarasimha, N., and Pasin, M., Simulation of Compressor Performance Deterioration due to Erosion. Journal of Turbomachinery 112 (1) pp 78-83, 1990.

[10]. Basrawi, F., Yomada, T., Nakanishi, K., Naing, S., Effect of Ambient Temperature on the Performance of Micro Gas Turbine with Cogeneration System in Cold Region. Applied Thermal Engineering 31 (6-7) 1058-1067. 2011.

[11]. Titan., 2009., "Titan 250 Gas Turbine Compressor Set Datasheet, "Solar Turbines; A Caterpillar Company.

[12]. Meher-Homji, C., and Bromley, A., 2004, "Gas Turbine Axial Compressor Fouling and Washing," Proceedings of the Thirty-Third Turbomachinery Symposium.

[13]. Syverud, E., Brekke, O., and Bakken, L., 2007, "Axial Compressor Deterioration Caused by Saltwater Ingestion," Journal of Turbomachinery, vol. 129, pp. 119-126.

[14]. Kurz, R., and Brun, K., 2001, "Degradation in Gas Turbine Systems," Journal of Engineering for Gas Turbines and Power, vol. 123, pp. 70-77.

[15]. Meher-Homji, C,. Chaker, M., and Bromley, A., 2009, "The Fouling of Axial Flow Compressors – Causes, Effects, Susceptibility, and Sensitivity," GT2009-53239, Proceedings of ASME TurboExpo: Power for Land, Sea, and Air, Orlando, FL, USA.

[16]. Zaba, T., 1980, "Losses in Gas Turbines Due to Deposits on the Blading", Brown Boveri Review, 12-80, pp. 715- 722.

[17]. Enyia, J. D., Li Yiguang., Igbong D. I., Thank-God I. E., 2015. "Industrial Gas Turbine On-line Compressor Washing for Power Generation". International Journal of Engineering Research & Technology (IJERT). ISSN: 2278-0181. Vol.4 Issue 08, August-2015.

[18]. Sampath, S., (2003) "Fault Diagnostics for Advanced Cycle Marine Turbine using Generic Algorithm". School of engineering, Cranfield University, United Kingdom.

[19]. http://www.weather-and-climate.com/average-monthly-rainfall- temperature-sunshine, maiduguri,Nigeria. Accessed August, 2012.