Effect of Ambient Temperature on Performance of Gas Turbine Engine

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ABSTRACT

Health monitoring data, namely power output and exhaust gas temperature are used for performance analysis of an industrial gas turbine engine. Apart from ambient temperature, influences of fuel consumptions and compressor fouling on the engine performance are also considered in the work. A model-free data analytics approach is used to study the effects of individual governing factors. A performance index (ratio of power generation to fuel consumption) is proposed as the metrics for monitoring the engine performance. The step-by-step analysis suggests that the engine performance shows two opposing trends with the ambient temperature. Fouling is also clearly shown to reduce the engine performance using the proposed indices.

1. Introduction

Gas turbine engine (GTE) performance is conventionally analyzed and measured by several parameters, namely efficiency, output power (PW_{out}), specific fuel consumption. Performance of GTE is greatly influenced by its geographical location besides the internal inputs and its operation is recommended under ISO design conditions e.g. ambient temperature (T_{amb}) of 15°C, relative humidity (H_{rel}) of 60 percent and at ambient pressure (P_{amb}) of mean seal level. However, the local environmental conditions vary widely across the world and considerable studies have been conducted on the GTE performance analysis based on the ambient parameters. GTE performance (Power output, efficiency) depends on T_{amb}, altitude and humidity which a linear function of mass flow of air. Mohanty and Paloso studied effect of the air density and mass flow rate with increase in air temperature, the mass flow rate of air decreases for the same volumetric flow rate (Mohanty and Paloso, 1995; Emughiphel Nelson Igoma, Barinaada Thaddeus Lebele-Alawa, and John Sodiki, 2016). This resulted in reduced power output (PW_{out}) of turbine and increased heat rate as illustrated in Fig. 1

Various studies have looked into the beneficial effects of lowering the ambient temperature by different techniques. Spray cooling lowers the T_{amb} by 3-15°C to increase power output by 1-7 % when the efficiency loss is around 3 % (Boonnasaa, Namprakaia, and Muangnapoh, 2006; Shukla and Singh, 2014; Paula Santos and Andrade, 2012). Evaporative cooling in Iran lowered the T_{amb} by 19°C to increase power by 11MW (Hosseini et al., 2007). Power generation of a GTE and driving power of a compressor were estimated by thermodynamic process of adiabatic expansion and compression using temperature (T), entropy(S) and enthalpy (H-S) diagrams (Taniquichi and Miyamae, 2000; Brooks, 2010). With cooling effects the outlet temperature of the turbine is decreased but its internal efficiency does not, which is due to the fact that less isentropic compression loss can be realized at lower temperature. The effect of ambient temperature on several thermodynamic parameters are clearly displayed in Fig. 1.

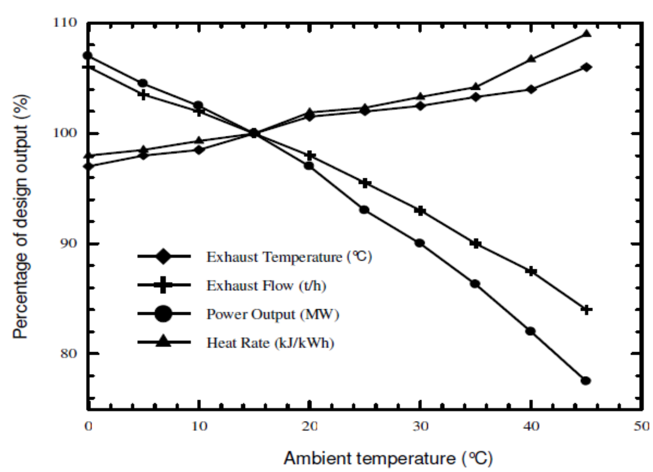

Figure 1.Thermodynamic analysis on the influence of ambient temperature on several gas turbine performance analysis parameters (Taniguchi and Miyamae, 2000).

The maximum influence of T_{amb} on PW_{out} is clearly evident from the figure, while heat rate (HR) and exhaust gas temperature (EGT) tend to increase significantly with T_{amb}. (Rahman, Ibrahim, Taib, Noor, Kadirgama, and Bakar, 2011;

Rahman, Thamir, Ibrahim, and Ahmed, 2011). Relatively limited studies are published on GTE performance analysis using health monitoring data obtained from GTE located in generally cold environments as in North America. $T_{amb.}$ in north-eastern part of North America tend to vary extremely from -35°C to +35°C. The work aims identify a direct and simple performance measuring index derived based on model-free data analysis for turbine performance. In addition, the analysis aims to investigate the influence(s) of fuel consumption on power output in the context of seasonal changes, compressor fouling-washing effects and the operative $T_{amb..}$ This work is our first attempt to use model-free data analysis method to look for an alternative solution for evaluating gas turbine performance. The work can be extended to more comprehensive analysis and prediction for short and long term degradation, which is full of significance to the Prognostics and Health Management of gas turbine engine.

2. AMBIENT AND GAS TURBINE DATA

The data analysed in this work is based on the field data as obtained from a low power gas turbine engine. Performance analysis is carried out using three years' operation-maintenance cycle data. Analysis of the continuous data stream (time series) provides significant clues in advance about any developing faults or deviation in the operating parameters like speed, pressure, temperature, power and any physical damages (e.g. cracks, wear). The data was collected from a power generation turbine located in Ottawa, Canada.

2. 1. Ambient Data

Ambient data were collected from Environment Canada and the three ambient parameters of interests include ambient temperature ($T_{amb.}$), relative humidity ($H_{rel.}$) and ambient pressure ($P_{amb.}$). The compressor of the power plant is located outside, thus the T_{amb} is assumed to be the temperature of air into the compressor.

The data sets were sorted, classified, filtered and processed initially in order to match with the formats of the data sets collected from a gas turbine engines. However, variations in ambient pressure over three years are found to be less than 5 percent and so considered to be insignificant for any meaningful dependency analysis.
Fig. 2 represents the typical time series data for both T_{amb} and H_{rel} over a year of continuous GTE operation. The measured parameters normalized with respective means are shown on y-axis. Typical range of T_{amb} in a year is observed to vary roughly from 252K to 310K with mean around 281K. The mean distribution for T_{amb} over the months is displayed in Fig. 2. Unlike H_{rel}, the T_{amb} tends to vary uniformly over the months and seasons. The T_{amb} is generally coldest in January and February and hottest in July. Effects of $T_{amb.}$ on both $PW_{out.}$ and EGT are analyzed with the data in combination as well in isolation. The $H_{rel.}$ values may be seen to be distributed incoherently with the seasons or month of the year, unlike the distributions for T_{amb}. In view of the lack in any definite trend and variations for H_{rel} this is left out for further analysis.

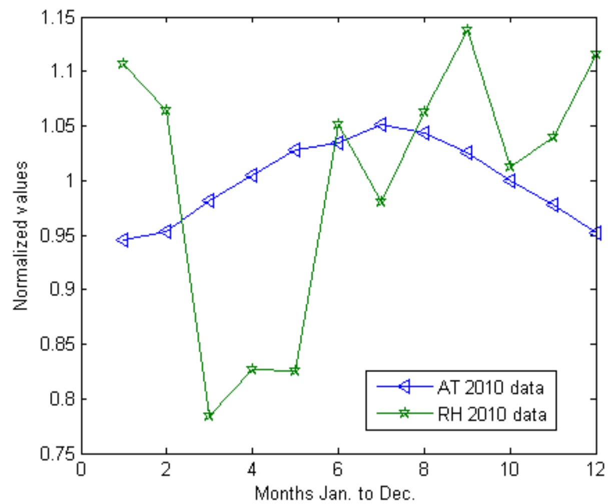

Figure 2. Distribution of monthly means for Tamb. and Hrel. data (in normalized scale) for year 2010

2.2. Gas Turbine Engine Data

Health and condition monitoring data from an industrial gas turbine engine were obtained and used for the analysis.

2.2.1. PW_{out} and EGT

Out of a host of parameters, two most significant ones are considered here, namely Power output (PW_{out}) and exhaust gas temperature (EGT). Two observations on the data trends are distinctly noticeable. Firstly, the PW_{out} continuously and sharply reduces with operating time as the EGT tends to increase sharply from start-up and get flatten quickly beyond 100 hrs. Secondly, fouling and subsequent washing effects on both $PW_{out.}$ and EGT are also clearly evident. Fouling is caused by the adherence of particles typically smaller than 2 to 10µm to airfoils and annulus surfaces (Badamasi Maiwada et. al., 2016).

2.2.2. Fuel Consumption

Power generation in gas turbine depends on the quantity, quality and type of fuel used and so the performance and efficiency strongly depends on fuel consumption. The supply and day-to-day demand of power can be met with the control of fuel consumption (FC). The fuel consumption (FC) is adjusted at the end of the day for the GT system and maintained constant for a day (24 hrs.). Filtered and grouped data as discussed in earlier section from fouling-washing cycles are used to analyze the effects of fuel consumption in presence as well as absence of fouling.

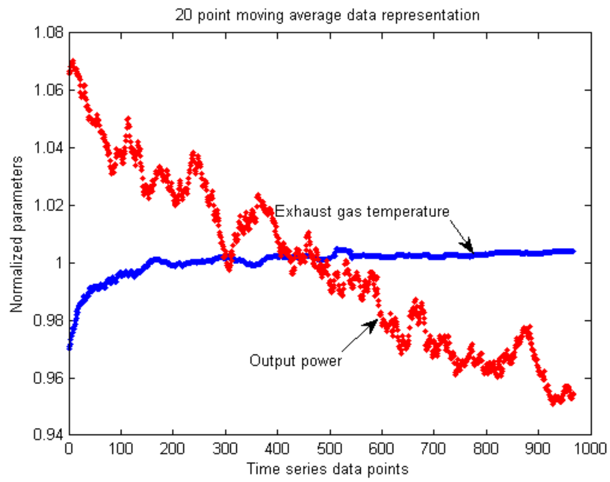

Figure 3. Moving average representation of $PW_{out.}$ and EGT data as used in the analysis

3. DATA ANALYTIC APPROACH

Following sections will present the various analysis performed with both T_{amb} and GTE data sets, results and trend obtained and followed by discussions. A few major factors that strongly influence the performances of gas turbines as measured by two outputs, PW_{out} and EGT are identified. The other operational hazard i.e. fouling effects are also considered to influence significantly the performance of GTE and addressed.

3.1. Methodology

All the input parameters have individual and combined effects on the performance and output parameters. Attempts are made here to isolate effects of individual input parameters or phenomenon for a meaningful analysis and functional relationships of the desired input and output parameters.

Step 1: Collect and clean data

In this step, the measured data is collected from the gas turbine and the data is cleaned of any obvious noises. The data is arranged in hourly, daily and monthly basis to make observations at different levels.

Step 2: Isolate the effect of the fuel

In this step, the effect of fuel is isolated from the measured power by introducing a term power output/gas consumed which indicates the amount of fuel consumed to generate unit power and is directly proportional to the efficiency of the gas turbine.

Step 3: Isolate the effect of ambient conditions

In this step, the change of the power generated by unit gas consumed with ambient temperature is studied to identify its effect on the performance of the gas turbine.

Step 4: Study the effect of fouling

The loss of power due to compressor fouling is studied by taking samples corresponding to after washing the compressor to neglect fouling effects.

3.2. Data Collection and Trend

The data was collected and monitored at a frequency of every 2 hours from a power generating GTE operating in Ottawa, Canada. The generated power is usually a function of mass flow of air, temperature difference and specific heat of air. On the other hand, the thermal health condition in a GTE is measured by EGT which is a measure of the engine's efficiency in producing its design level of PW_{out}. The EGT gives an indication of performance deterioration and its prediction in advance estimates the remaining Time-between-overhauls (TBO). Higher EGT indicates more structural degradation of engine components and deterioration lowering engine performance. As the engine structural health degrades due to service-exposed wear and tear, on rotating parts, the engine's fuel consumption increases. Consequently, the EGT increases (and EGT margin decreases). The EGT was monitored by twelve K-type thermocouple annular arrangement as a part of gas path analysis. An average of 12 EGT measurements are considered in the present analysis with EGT data.

Fig. 4 displays the trend and distribution of all input and output data in normalized scale. Mean of the respective data for each day is determined to display as shown for three years period corresponding to a complete TBO. The T_{amb} data is most symmetrically and uniformly distributed with peak during the summer months and lowest during the winter months; while the EGT shows the opposite trend with some degree of irregularities and disturbance. PW_{out} appears to shows similar fluctuations in terms of peaks and valleys over a year, though these do not match precisely with those observed for T_{amb} on time scale (x-axis). Also, FC seems to closely follow the trend of PW_{out}. While the variation of the PW_{out} is less than that of the FC.

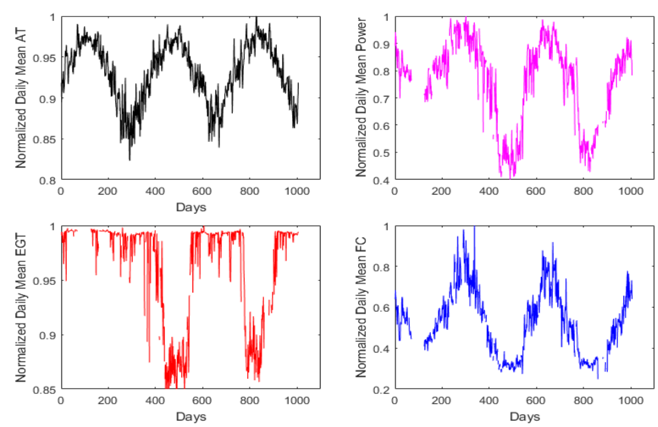

Figure 4. Daily trend of $T_{amb,}$ EGT, PW_{out} and FC for 3 years

The monthly means of the measured parameters for three years is shown in Fig. 5. Interestingly, the trend is quite smooth and uniform in all cases. As expected, the T_{amb} shows peak during summer seasons (months June to Aug.) and has a bell shape, while the other three parameters, namely EGT, PW_{out} and FC show opposite trend. The main reason of the opposite trend of power is when ambient T is higher, the density of air decreases, so the mass flow rate of air decreases leading to lower thermal efficiencies. Thus, higher the T_{amb}, the lower is the power. For EGT, from the viewpoint of thermodynamics, lower mass flow and power leads to higher EGT. All GTE are designed to have an EGT limit during operation, to ensure the engine performance reliability and durability of failure critical components. For most of the range of the T_{amb}, the EGT is controlled to keep it stable. At peak T_{amb}, the EGT is kept low.

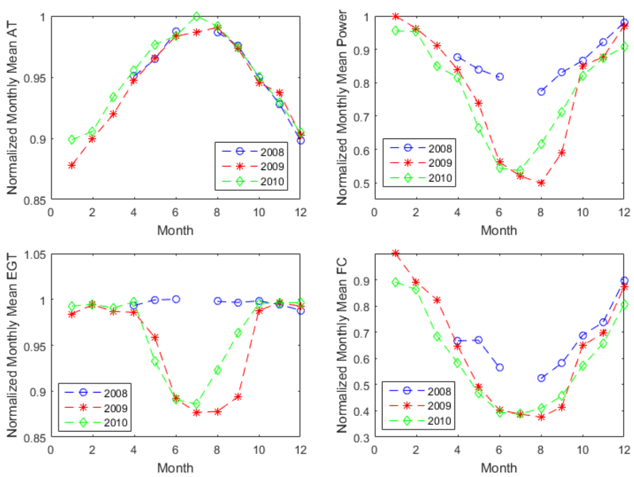

Figure 5. Monthly trend of T_{amb}, EGT, PW_{out} and FC for every year

3.3. Performance Index

The power requirement for the gas turbine under consideration varies seasonally with maximum in summer and minimum in winter months. The FC has the most significant effects on PW_{out} from GT. The ratio of PW_{out} to FC may be considered as the effective performance measuring index (PI). A higher PW_{out}/FC would indicate higher efficiency due to higher output power for the same fuel consumption. The PI also helps to isolate the effect of running the engine under partial load by reducing the fuel flow due to seasonal fluctuations in the power demand. The PI is a simple and direct term which can be used to stand for the efficiency of the turbine. The actual thermal efficiency is more difficult to estimate directly from the GTE parameters. Our subsequent analysis is directed towards assessing the effectiveness of this performance measuring index.

3.4. Consideration of Fuel Consumption

Fig. 6 presents the distribution of daily mean data for T_{amb} and ratio of PW_{out} to FC or power index (PI) for over three years. It can be seen that the distribution of PI shows similar trend as T_{amb}. Decreasing T_{amb} reduces PI, which means the efficiency of the system decreases. While it should be noted that when $T_{amb.}$ keeps increasing, the ratio of PI initially increases and then decrease. It might be caused due to the fuel gas loss in hot days (Hawthorne and Olson, 2015) and the fuel density change. Similar trend can be seen from the Fig.7, which is the monthly distribution of PI (the ratio of $PW_{out.}$ to F_C). PI tends to be increasing and decreasing continuously in all seasons and months except summer (months 5 to 8).

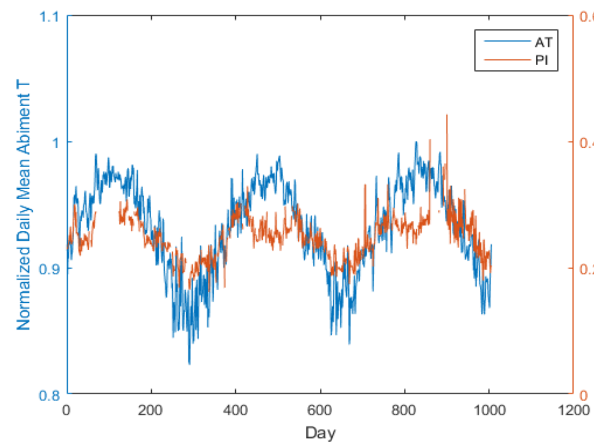

Figure 6. Distribution of daily mean data for T_{amb} and the proposed PI

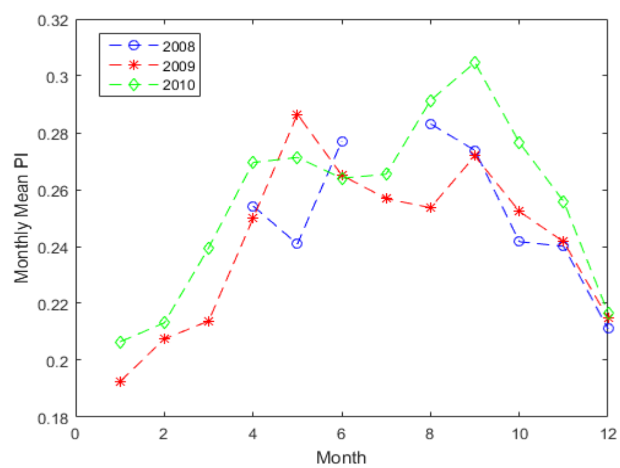

Figure 7. Distribution of monthly data of PI (PW_{out} /FC)

3.5. Effects of Ambient Temperature

As discussed in previous section, T_{amb} has noticeable influence on GTE operating parameters. Fig.8 presents the dependency of the PI (P_{out} /FC) on T_{amb}. It can be seen that the PI increases with increasing T_{amb} till 288K, and the empirical relationship between PI and T_{amb} can be considered as linear function as below,

$$PI = 0.003 \times T_{amb} - 0.5832 \quad (1)$$

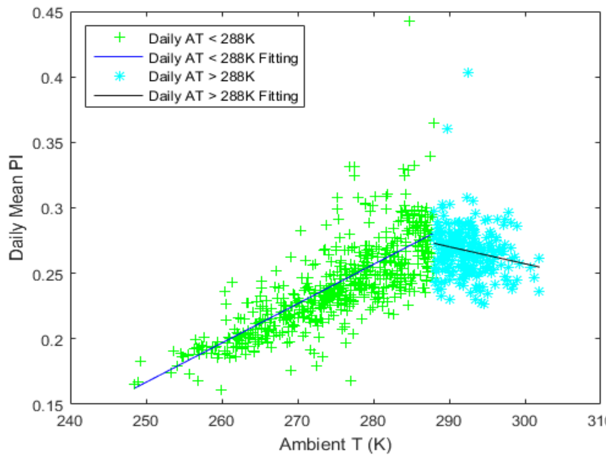

Figure 8. Dependency of PI (PW_{out} /FC) on $T_{amb.}$

For $T_{amb.}$ above 288K, the trend of the PI is reversed and it reduces with further increase of T_{amb}. The empirical relationship of PI with $T_{amb.}$ can be expressed as below,

$$PI = -0.0013 \times T_{amb} + 0.6473 \quad (2)$$

The PI reaches peak when $T_{amb.}$ is around 288K, which matches the fact that for this turbine, the value of $T_{amb.}$ at design point is 288.15K. As discussed in previous section, both PW_{out} and FC decrease with increasing T_{amb}. And the variation of PW_{out} is less than that of the FC when T_{amb} below 288K. Thus the gas turbine power plant reaches its highest efficiency and then begins to decrease. One of the possible reason for it is the specific fuel consumption increases with the increase of $T_{amb.}$ due to the fuel gases losses. Also, when less than full power is required from a gas turbine, the output is reduced by lowering the turbine inlet temperature. In addition to reducing power, this change in operating conditions also reduces efficiency.

3.6. Fouling Isolation and Effects

The data analytics approach used has so far ignored the detrimental effects of fouling on GTE performance. Compressor fouling is one of the causes of performance deterioration of industrial gas turbines (Maiwada, IsyakuMu'az, Ibrahim, and Musa, 2016). Airborne particles such as dust and moisture in the ambient air enter through the intake of the gas turbine and adhere on compressor blades. The attached particles on compressor blades increases the surface roughness and reduce air flow passage between blades. Those phenomena bring to the reduction of air flow rate, decrease of pressure ratio and compressor efficiency. In spite of the possible removal of foulants by the on/off-line washings, some parts of them cannot be eliminated. The influence on the long-term performance fouling of air-path surfaces in the turbine compressor occurs, leading to performance loss and increased fuel consumption. Of the total gas turbine performance loss approximately 70% can usually be attributed to compressor deterioration due to blade fouling. Fouling of axial flow compressor blades is generally attributed to airborne particulate in the sub-micron to 10 micron size range and this will be the major source of fouling. Another possible source of compressor fouling is oil leakage from the compressor rotor inlet bearing.

Washing to remove the fouling of compressor system is normally carried out at an intervals of 5-6 weeks for the system under study. The washing schedule followed during the operation-maintenance cycle for the GT was made available and used to extract the required data. For each of the fouling (operational) stage in between two washes, monitoring data set for just 5 days (i.e. 120 hrs.) at the beginning of a cycle was selected and combined to create a separate group for analysis. It is assumed that these data set are from fouling free condition of the compressor (start of fouling). In addition, data for 5 days was also collected from the end of the cycle (prior to next washing cycle) and this is assumed to be from fully fouled stage (end of fouling). This approach facilitates meaningful comparison of fully fouled and no-fouled conditions.

Fig. 9 illustrates the distribution of 5 day's data of $PW_{out.}$ /FC vs $T_{amb.}$ before and after compressor wash, which represent the fully fouled condition and non-fouled condition, respectively. It is evident that the PI before and after wash show linear trends when fitted as function of T_{amb}:

Before wash (fully fouled condition):

$$PI = 0.0041 \times T_{amb} - 0.9085 \quad (T_{amb} < 288K) \quad (3)$$
$$PI = -0.0015 \times T_{amb} + 0.697 \quad (T_{amb} > 288K) \quad (4)$$

After wash (minimum fouling effect):

$$PI = 0.0034 \times T_{amb} - 0.686 \quad (T_{amb} < 288K) \quad (5)$$
$$PI = -0.0014 \times T_{amb} + 0.6805 \quad (T_{amb} > 288K) \quad (6)$$

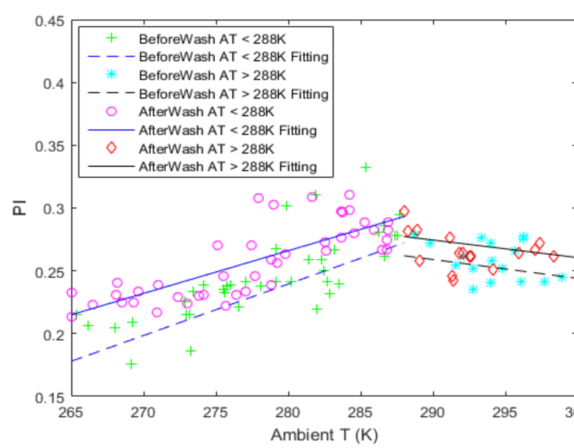

Figure 9. Relationship of PI ($PW_{out.}$ /FC) vs. $T_{amb.}$ before and after wash

By comparing Fig. 9 with Fig. 8, it can be found that for the same value of PI without fouling effect is higher than the raw data with fouling effect. This confirms that the effectiveness of compressor washing can be clearly detected by the introduced engine performance index PI.

4. CONCLUSION

For a low power rating and partially loaded gas turbine engine, the performance analysis is carried out by model-free data analytics approach using typically measured data. Influences of the ambient temperature and fuel supply/consumptions on the power output are studied using a proposed performance index. The effects of compressor fouling has also been considered. Conclusions that emerge from the analysis of the obtained result are as follows

- In a model free approach, it is still important to gather sufficient domain knowledge and propose a systematic data analysis. For gas turbine, this task become even more important, as the output power can varies due to various independent, continuous and simultaneous variations like ambient, operating and structural degradation conditions.
- A performance index (PI) is proposed considering the ratio of power output to fuel consumption. PI can be correlated to the engine performance and trended to study the effect of ambient temperature on engine performance, comparing with the actual thermal efficiency which is more difficult to estimate.
- The PI increases along with ambient temperature up to around 288K, indicating the engine gets relative better performance and high efficiency in this temperature range. While PI decreases for T_{amb} higher than 288K. This is due to the effect of parasitic losses in the pre-cooler used for power augmentation observed during summer months.
- The PI was also clearly able to detect the performance improvements due to compressor washing. Although the effect of ambient temperature over the entire engine operation, with maximum as well as minimum fouled conditions are observed to be consistent. The work will be continued to be advisory on turbine service scheduling.
- The result demonstrates the feasibility of deployment of model-free data analytics using a systematic data manipulation methodology, and applicability of the proposed performance index for performance monitoring. The work can be continued for more comprehensive analysis and prediction for short and long term degradation, which is full of significance to the Prognostics and Health Management of gas turbine engine.

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