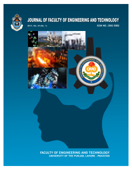
JFET 24(2) (2017) 21-33

Journal of Faculty of Engineering & Technology

journal homepage: www.pu.edu.pk/journals/index.php/jfet/index



ECONOMIC BENEFITS OF A GAS TURBINE COPMRESSOR WASHING AT DIFFERENT INTERVALS

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Abstract

Gas turbine compressor fouling is a major operational issue that affects engine performance. In desert oil and gas, field compressor fouling can be caused by pollution such as airborne ash, smog, hydrocarbons and dust. Accumulation of such pollution in the compressor annulus can lead to sticky fouling. This can ultimately result in the reduction of the compressor mass flow and pressure ratio. In order to maintain constant output power, it is then necessary to increase the turbine entry temperature (TET). The result of such an operational change will cause higher emission rates. In addition, it will decrease the creep life of engine hot components and overall engine thermal efficiency. The investigation of the effect of compressor on-line cleaning leads to the following findings: (i) Frequent cleaning maintains longer creep life of the high-pressure turbine. (ii) More financial benefits due to reduction on fuel flow. (iii) Less cost of cleaning materials per engine, cost of manpower and overheads. In summary from cost aspect with the best frequency of washing intervals (4 weekly), approximately $ 30,000 will be saved annually. On the other hand, in order to attain better engine performance, a weekly washing interval is necessary.

Keywords: Gas turbine, Compressor, fouling, washing.

1. Introduction

Gas turbines have many applications, for examples, in the marine, aero and power industries. Use of gas turbine for power generation in oil and gas applications requires high availability and therefore high reliability. Thus, it is necessary to control power operation and maintenance costs.

The engine model of GT–35 based on desert oilfield environments simulated using the TURBOMACH code. The design point and off design has been considered. Although, filtration can reduce compressor fouling, it has a drawback since fouling of filters can cause a drop in the compressor intake pressure.

This can severely limit the overall engine performance. The creep life of an engine is set by the maximum allowable TET, coupled with the tolerable centrifugal stresses on the rotor blades of the HPT. The Larsson Miller parameter (LMP) is used to calculate the cumulative creep life.

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Meherwan et al. [1] have presented a procedure to find an active on-line and off line water wash program on a 36 small industrial turbines. Tests were developed in order to identify the appropriate water wash frequency and detergents used in water wash. Seddigh et al. has presented and proposed an index which shows the sensitivity of compressors fouling, this might be beneficial in helping operators to control clean up intervals. The framework of three gas turbine engines was widely used for differing performances in developing the appropriate index. Jprdal et al. present an attempt to determine and describe the link between compressor washing and blade lifetime in a gas turbine. Besides the impact of compressor washing intervals on the cost of produced power is studied, based on a thermos-economic method.

In addition, discussed on artificial neural networks (ANN), which should be an economic and efficient technique of on-line condition monitoring, and a valuable tool for optimize compressor washing intervals maintenance. Balevic et al. [4] predicted that the compressor fouling results in reduction of airflow by 5%, which referred to reduce in output and increase in the heat rate. Fortunately, much can be done through proper operation and maintenance procedures to both minimize fouling type losses and to limit the deposit of corrosive elements. On-line compressor wash systems are available that are used to maintain compressor efficiency by washing the compressor while at load, before significant fouling has occurred. Aretakis et al. [5] has analysed and optimised the off-line washing method, parameters taking into many factors that are overlooked in the literature and quantify their economic effect. A method to calculate the specific cost of power production (specific energy cost) and the total profit within a time-period is presented employing a detailed cost function capable to handle maintenance cost's changes related with the washing procedure. The economical method is coupled with a detailed engine model. The detailed engine model allows the accurate simulation of the engine performance under varying rates of fouling and ambient conditions.

This work has investigated the effect of compressor on-line cleaning on cost of engine creep life, cost of fuel flow and cost of cleaning materials per engine. The cost of manpower and overheads was also taken into account. It has been found that cleaning will decrease the cost of the involved processes.. The economic benefits of on-line compressor washing at different frequencies during one year are calculated. Thus, the cost of washing materials, besides the manpower and overheads costs is predicted. These will then be compared with the cost of fuel saved and the cost of increase in creep life.

In a desert environment the ambient temperature reaches its highest point in summer. The gas turbine engines are very sensitive to changing ambient temperature and the best engine performance always obtained on cool days.

2. Compressor Fouling

The definition of fouling is the deposition process of airborne particles on the compressor blades surfaces. This will change blades airfoil shapes. Compressor fouling degradation can occur on annulus surfaces due to the adherence of particles entering the axial compressor. This adherence is caused by the presence of oil, water mists, salt, etc.

In summary, the material build up in compressor blades results in an increase in blade surface roughness, a change in airfoil shape and aerodynamic profile and a reduction in pressure ratio. Consequently, this leads to an increase of firing temperature and increase in fuel flow. This will also increase emissions rates and a reduction in both the compressor surge margin and power output. In summary, it represents a reduced flow capacity at component and reduction in the component isentropic efficiency [2]. The aerodynamic performance of each stage depends on the earlier stage. Fouling occurs in inlet guide vanes and for the first few stages can result in a dramatic drop in compressor performance [3].

It has commonly found that deposits of oil and gases in industrial area cause fouling. In particular local emissions from refineries and oil plants can create deposits which basically act as a glue and entrap other materials . Compressor fouling rates are then very high during the weather seasons of sand and dust storms. Figure (1) shows compressor blade fouling.

In coastal areas, the ingestion of sea salt and in desert areas dry sand and dust particles are predominant. Also in agricultural areas, chemical fertilisers can also cause heavy fouling [3]. Fouling can also be caused by environment conditions such as fog, rain, humidity, as well as wide range of industrial pollutants [4].

Compressor fouling is mainly classified as oil soluble, water-soluble and water settable. Sometimes it is referred as a combination of all three types. Although sea salt is essentially water-soluble during its retention within the compressor. In addition, the compressor might be influenced by significant trace quantities of oil and grease [5].

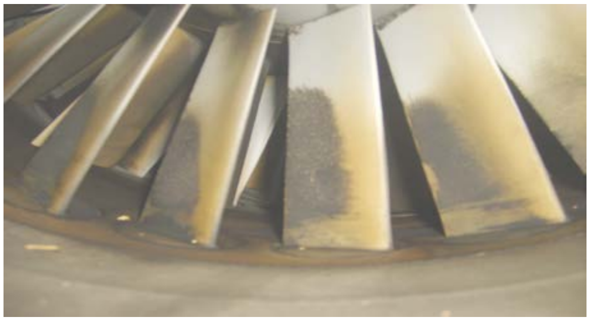

Figure 1: Compressor fouling on first stage (Inner Guide Vane (IGV) after 8000 firing hours.)

The majority of compressor fouling degradation can be recovered by frequent compressor washing. However, a small amount of non- recoverable performance degradation with washing requires overhaul to restore losses. After complete major overhaul and refurbishing of the flow path parts, the permanent performance short fall will be eliminated [14].

3. Engine Configuration

The current engine GT-35 is based in desert for power generation. The engine component consists of two axial flow compressors LPC, HPC and seven combustion chamber-cans. The hot section had HPT, LPT and Power turbine. The engine is operating in off design condition, thus higher ambient temperature on summer period. The Altitude above sea level is 250 ft and with increase in altitude the air density will increase and vice versa. Table (1) shows gas turbine engine design data.

Table 1: datum engine data.

Description	Value	Units
Shaft power	16.8	MW

Ambient temperature	15	^{o}C
Ambient pressure	101.3	KPa
Thermal Efficiency	31.6 %	-
Inlet mass flow	92.3	Kg/s
Firing temperature	1123	K
Compressor Pressure ratio	12.6	-

4. Frequency of Compressor Washing

On line compressor washing is carried out to recover performance degradation occurring due to build up of deposits in flow path. In the oil and gas industry, application on-line cleaning is utilized to increase reliability and achieve high availability. In order to achieve high engine performance, it is essential to schedule compressor washing as frequently as possible [4].

The higher the frequency of washing, the nearer the turbine entry temperature will be to a constant value. Fundamentally, on-line washing preformed regularly to extend continuous operating period of the engine between shutdowns [16]. This period will of course, also depend on the particular engine’s running schedule. For example washing two or three times a week, for between 20 and 30 minutes [8].

In addition, ambient conditions have strong effects on engine performance of compressor washing system .For example, in a desert area in spring season, typically from February to June, severe sand storms mean weekly washing is required to restore losses.

Economic factors are also very important when implementing frequent washing. The cost of cleaning agents is one factor and this depends on whether the cleaning product is water based or solvent based cleaners. Additionally cost of labour will get high. Furthermore, there is the cost of extra fuel which varies according to the price of oil or gas. Finally, the additional of creep life consumed varies inversely with washing frequency. Low creep life is extremely expensive in replacement of engine part.

The TURBOMACH software is used to simulate gas turbine power loss at constant TET. It also predicts compressor-fouling rate against frequency of washing over the year. The following are degradation rate results.

- (Weekly) washing over the year will keep power loss at 0.5%.
- (4 weekly) washing over the year will keep power loss at 1.5%.
- (13 weekly) washing over the year will keep power loss at 3 %.
- (26 weekly) washing over the year will keep power loss at 4.5%.
- (Annually) washing over the year will keep power loss at 6 %.

Simulation results at constant shaft power over the year TET will increase to maintain constant power. Figure (3) shows power loss versus frequency of washing.

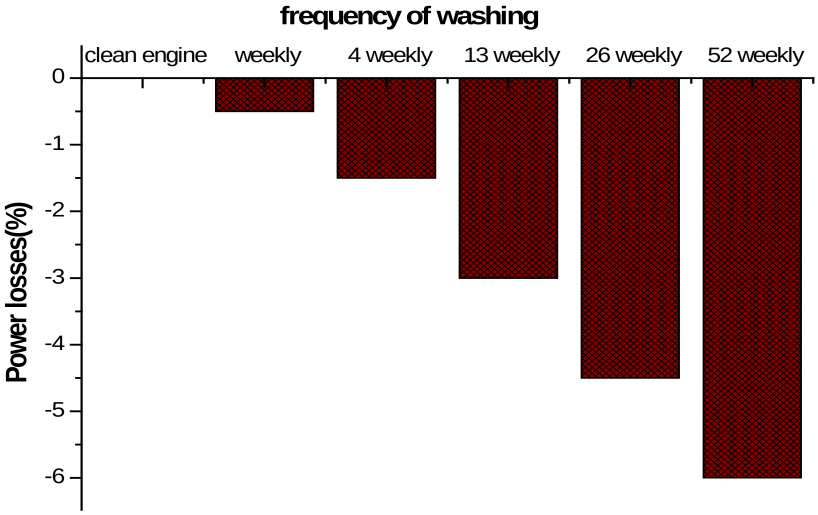

Figure 3: Power loss versus frequency of washing.

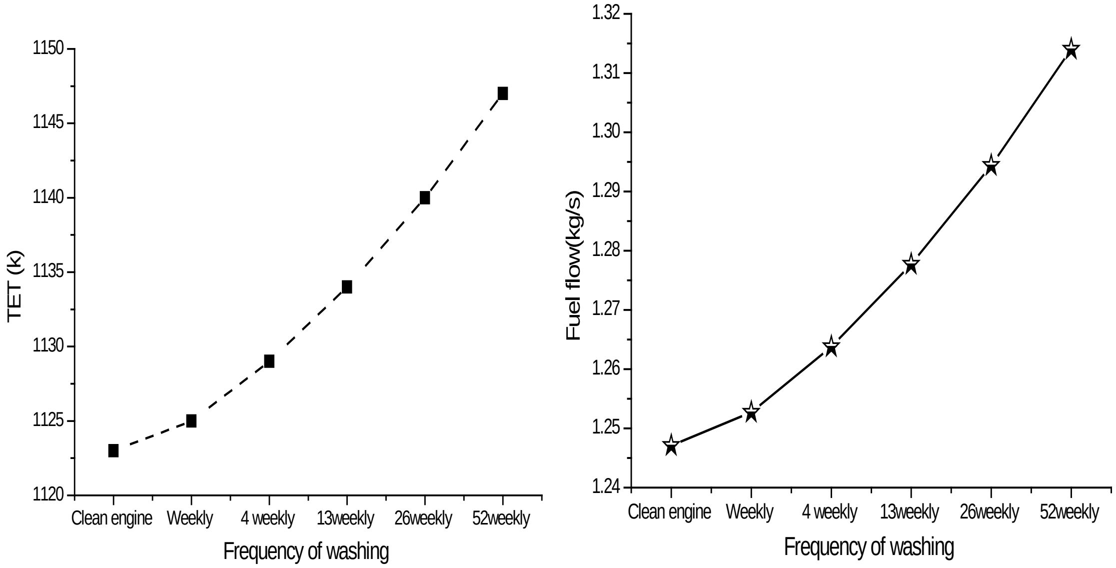

Figure 4: (a) TET versus frequency of washing, (b) Fuel flow versus frequency washing.

Results of compressor fouling by the end of the year without compressor washing TET increases and the fuel flow will increase from 1.23 kg/s to 1.31 kg/s. Hence, high frequency of washing causes a reduction in fuel flow; figure (4-b) shows frequency of washing versus fuel flow and figure (4-a) shows frequency of washing versus TET.

5. Estimation of HPC blade Creep life

Even though turbine-cooling techniques are utilized, performance degradation results in an increase of turbine entry temperature. Metal temperature will increase as well, which is proportional to turbine entry temperature. This results in high stress because of increase in aerodynamic load. Ultimately, leading to early creep failure.

The HPT blade temperature influenced by, (i) flow gas around the blades, (ii) Coolant temperature at inlet and out let from the blade, (iii) The cooling effectiveness of rotor blades depends on total gas and coolant temperature [17]. It is assumed that coolant gas temperature does not change as exit temperature; it also assumed the cooling effectiveness would not change.

The following factors affect metal blade distribution: Blade coolant through multiple pass convection cooling, leading edge and film cooling. Thus, relative air effect increases blade resistance of creep and thermal fatigue. Air cooling which is blade from the last stage of HPC. Furthermore, air cooling which is injected into the blades near leading and trailing edges [17, 18]. Blades metal temperature is given by equation (1).

$$\varepsilon = \frac{T_g - T_b}{T_g - T_{c1}} \qquad (1)$$

Therefore, $T_b = T_g - \varepsilon(T_g - T_{c1})$

Where 'ε' is effectiveness = 0.5, 'T_g ' is the relative gas temperature, 'T_{c1} ' is an initial coolant temperature and 'T_b ' is a maximum allowable metal temperature. In order to estimate engine creep life, it is essential to obtain blade metal temperature by using expression in equation (2)

$$B_{stress} = \frac{m.r.\left(\frac{2.\pi.V}{60}\right)^2}{A} \qquad (2)$$

Where 'B_{stress} ' is blade stress, 'm' is mass of the blade, 'r' is radius, 'V' is speed and 'A' is cross section area.

Equation (3) represents the relationship of Larson Miller parameter (LMP), which is used to calculate the estimation of engine creep life. In terms, the peak of compressor fouling results in increase of TET.

$$LMP = \frac{T}{1000}.(20 + \log_{10} Tf) \qquad (3)$$

Where 'T_f' = lifetime by hours and 'T' = 'T_b' = 'metal temperature at design point'. Even with turbine blade cooling, TET increases coupled with metal temperature. So over period of 12 months in order to maintain constant power, thus effects of compressor fouling peak. The creep life calculated is factored for safety reasons to a level of 60% of the predicted magnitude. The TET increases from 1123K to 1147K. Figure (6) shows turbine blades failure after40, 000 firing hours.

Figure 6: Shows turbine blade failure HPC after 24,000h firing hours.

A high frequency of washing leads to an increased engine creep life, figure (7) shows frequency of washing versus engine life. Cleaning the engine frequently can prolong engine life. In table (2) summary of estimated creep life, hence increase of TET and metal temperature utilized to calculate creep life.

Table 2: Summarized calculation of creep life versus frequency of washing

Frequency washing	TET (k)	Metal temperature (k)	Life hours	Life years	Factored of 60%
Clean engine	1123	879.5	226629	25.8	15.5
Weekly	1125	880.5	212089	24.2	14.4
4weekly	1129	882.5	185832	21.2	12.3
13weekly	1134	885	157666	17.9	10.2
26weekly	1140	888	129602	14.7	8.5
52weekly	1147	891.5	103281	11.7	7

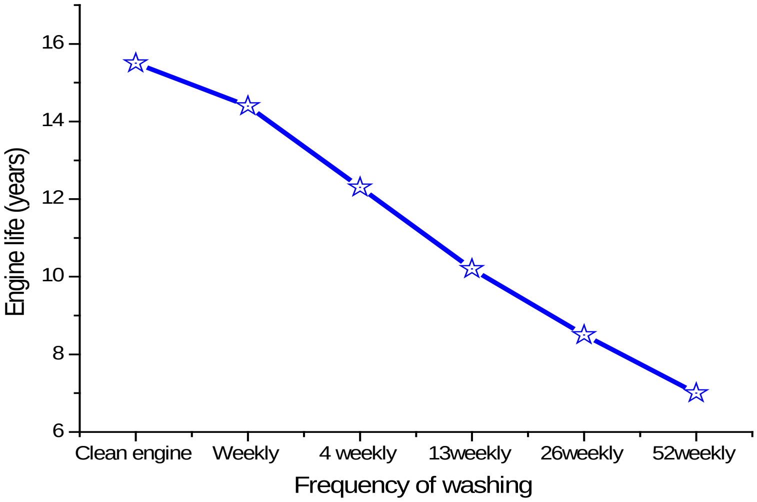

Figure 7: Engine life versus to frequency of washing.

6. Analysis of Economic Benefits

Basic assumption

Capital cost of equipment at plant of three engines is $ 75000.

Capital cost of equipment of one engine $25000.

The equipment cost amortised at the end of 5 years $5000.

6-1. Cost of cleaning materials

Engine such as, GT–35 consumes 40 litres of cleaning fluid, which will be diluted with fresh water. The cost of one litre is ≈ $5 / litres. Based on that the cost of one engine cleaning is about = $ 200.

Cost of clean = (N * $ 200)

Where, 'N' is number of weeks washing per year

Washing once a week over the year, N = 52

Washing every 4 weeks over the year, N = 12

Washing every 13 weeks over the year, N = 4

Washing every 26 weeks over the year, N = 2

Washing every 52 weeks over the year, N = 1

6-2 Cost of manpower and overheads

For manpower and overhead costs, the assumption has been made that it is $ 50 per cleaning.

Man-power cost = (N * $50)

6-3. Cost of excess fuel

This depends on oil and gas price market. Fuel consumption increases because of TET increasing due to performance degradation. To keep constant power, the fuel flow also increases as TURBOMACH results have shown. Figure (6) shows fuel flow versus Frequency of washing.

In order to gain optimal saving of extra fuel some data is obtained from using in this oil field natural gas Lower Heating Value 44650 MJ/kg, which converts to 42230 Btu /m^3. The natural gas density is 0.83 kg/ m^3. Cost of natural gas $7.4 / M Btu, which is available at daily gas Natural Gas Future prices (NYME).

Fuel gas flow = $1.25/0.83 = 1.506\ m^3/s$

Increase in fuel flow for weekly wash = 1.506 *60 m^3/h * 42230 Btu / m$_3$ * 168 h = 64 MBtu

4 weekly wash = 1.518 *60 *42230 * 720 = 276 MBtu

13 weekly wash = 1.530 * 60 * 42230 * 2160 = 837 MBtu

26 weekly wash = 1.554 * 60 * 42230 * 4320 =1701MBtu

52 weekly wash = 1.578 * 60 * 42230 * 8640 = 3455MBtu

Where, weekly washing there are 168 hours, 4weekly washing there are 720 hours, 13 weekly washing there are 2160 hours, 26 weekly washing there are 4320 hours and 52 weekly washing there are 8640h hours [19]. Table (3) summarises the cost of extra fuel consumption.

Cost of extra fuel for weekly wash = \$7.4/ MBtu * 64 (MBtu) = \$474

4 weekly wash = 7.4 *276 = \$2049

13 weekly wash = 7.4 *837 = \$6197

26 weekly wash = 7.4 *1701 = \$12589

52 weekly wash = 7.4 *3455 = \$25568

Table 3: Summarized cost of extra fuel flow

Frequency washing	Fuel flow kg/s	Fuel flow m/s	Increase fuel flow MBtu	Cost of extra fuel \$
Weekly	1.25	1506	64	474
4weekly	1.26	5118	276	2049
13weekly	1.27	1530	837	6197
26weekly	1.29	1554	1701	12589
52weekly	1.31	1578	3455	25568

6-4. Creep life cost

Assumed the cost of replacement equipment = \$300,000. Table (4) summarise calculation engine creep life at weekly washing is about 14.4 years. Estimated cost of creep life when weekly washing as follows:

$$\text{Weekly} = {}^{300.000}/_{14.4} = \$\ 20833$$

$$\text{4 weekly} = {}^{300.000}/_{12.3} = \$\ 24390$$

$$\text{13 weekly} = {}^{300.000}/_{10.2} = \$\ 29411$$

$$\text{26 weekly} = {}^{300.000}/_{8.5} = \$35294$$

$$\text{52 weekly} = {}^{300.000}/_{7} = \$\ 42857$$

Table 4: Summarized estimation cost of creep life

Frequency washing	Creep life (years)	Cost of creep \$
Weekly	14.4	20833
4 weekly	12.3	24390
13weekly	10.2	29411
26weekly	8.5	35294
52weekly	7	42857

$$CTC = \sum_{1}^{12} (C_{ef} + C_{cm} + C_{mp} + C_{cl}) \qquad (4)$$

Where ‘CTC’ is the Capital Total Cost, 'C_{ef} ' is the cost of extra fuel, 'C_{cm} ' is cost of cleaning materials per engine, 'C_{mp} ' is cost of manpower and overhead and 'C_{cl} ' is cost of creep life.

The cost analysis shows that a very high frequency of washing results in hundreds of thousands of dollars being saved per year. Against this, the cost of replacement of hot section amounts to $ 42,000 while the cost of excess fuel is about $ 25,000. A weekly washing results in more cleaning cost than an annual washing Figures (8 and 9) summarises the results and shows the corresponding costs against the frequency of washing.

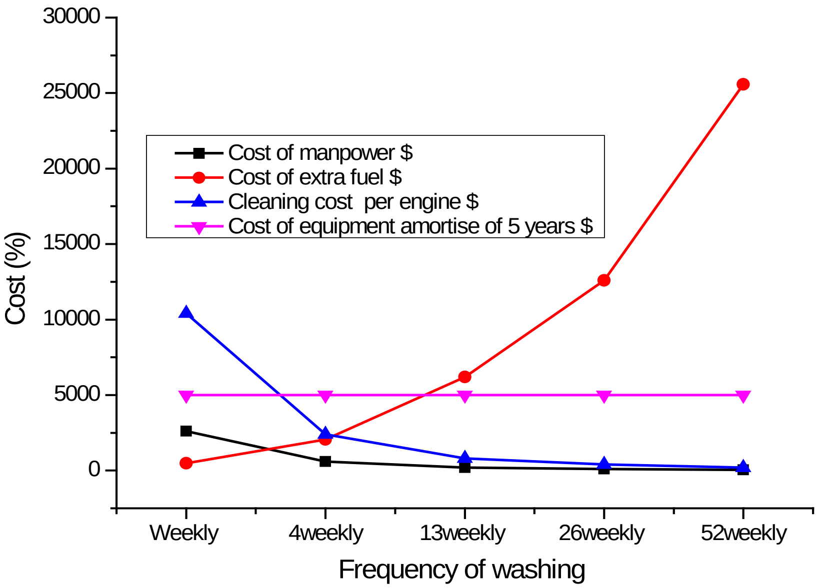

Figure 8: Cost versus frequency of washing.

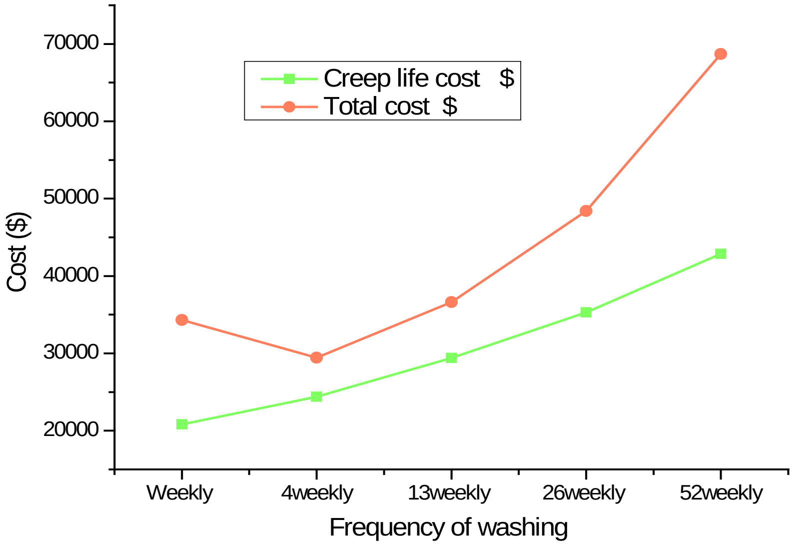

Figure 9: Cost versus frequency of washing.

The high cost of creep life loss is estimated together with corresponding extra fuel costs and compared with lowering costs of manpower and cleaning detergents. The economic benefits of monthly compressor washing are more money savings, in comparison, the weekly washing is better for engine efficiency.

7. Conclusion

The benefit of frequent compressor washing is to maintain engine performance. This also maintains constant turbine entry temperature and reduces operations and maintenance cost and fuel consumption.

The current study has been concentrated on the benefits of different levels of washing frequency intervals over period of one year. While, the high cost of creep life loss is estimated together with corresponding extra fuel costs and compared with lowering costs of manpower and cleaning detergents. The economic feasibility of (4 weekly) compressor washing is more money savings. In contrast, the weekly washing is better for engine efficiency. It has been demonstrated, that engine creep life reduces with increase in turbine entry temperature. Furthermore, even with turbine blades cooling, TET increases as the compressor fouls up. For the particular case considered in this work, engine performance degradation results in an increased TET from 1123k to 1147k. Consequently, HPT rotor life reduces from 15.5 years to 7 years. The economic benefits of frequent compressor washing are compared with the cost of manpower, overheads, and the cost of cleaning. In addition, cost of extra fuel flow and of creep life has been calculated. It is also demonstrated that an increase of frequency washing interval reduces the increase of TET, which needed to maintain output power. From cost point of view, the best frequency of washing intervals is 4weekly. Approximately $ 30,000 will be saved annually. In order to achieve more engine performance enhancement, a weekly wash is desirable.

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NOMENCLATURE

P	Total Pressure
p	Static Pressure
T	Total Temperature
t	Static Temperature
W or m	Mass Flow
ρ	Density
η	Efficiency

ε	Effectiveness
Cp	Specific Heat (at constant pressure)
CV	Specific Heat (at constant volume)
γ =Cp/CV	Specific Heat Ratio

ABBREVIATION AND TERMS

AMB	Ambient
DP	Design Point
GT	Gas Turbine
HPC	High Pressure Compressor
HPT	High Pressure Turbine
IGV	Inlet Guide Vane
LPC	Low Pressure Compressor
LPT	Low pressure Turbine
OD	Off Design
PR	Pressure Ratio
PT	Power Turbine
SFC	Specific Fuel Consumption
TET	Turbine Entry Temperature