SYMPOSIUM OF THE INDUSTRIAL APPLICATION OF GAS TURBINES COMMITTEE
BANFF, ALBERTA, CANADA
OCTOBER 2017

17-IAGT- 203

AIR FILTRATION STUDY FOR THE OPTIMUM PERFORMANCE OF GAS TURBINE

†Syed Hasan
svhasan@uniongas.com
Union Gas Limited – An Enbridge Company

†Joshua Kohn
joshua.kohn@camfil.com
Camfil Power Systems

Keywords: *RB211 DLE, Soakwash, Efficiency, Fuel, Air Filters*

Abstract

This paper compares the performance of M6 and F9 (EN779:2012) inlet air filters installed in two Siemens RB211 G DLE gas turbine compressor sets installed at the Union Gas Bright Compressor station near Waterloo, Ontario. For testing purposes, the compressor efficiency of each gas turbine was calculated, normalized and monitored. In addition to compressor efficiency, filter pressure drop, filter efficiency, and the cleanliness level of compressor wash fluids were also measured. The test was conducted over two winter operational seasons and the results indicate that upgrading the inlet air filtration had a positive effect on compressor efficiency. Furthermore, a correlation between the cleanliness of the compressor wash fluids and compressor efficiency were noted giving rise to the concept of using this correlation to predict when a soak wash is required as opposed to performing soak washes on fixed time intervals. Choosing the appropriate level of air filtration based on site specific environmental conditions and implementing a soak wash strategy based on compressor performance are cost effective strategies that will help keep your turbine fleet in top operating shape.

Introduction

Storage Transmission and Operations (STO) System of Union Gas Limited is spread over a wide area within Ontario with the main hub being at Dawn.

Figure 1: Transmission System – UGL

The total compression capacity is 435 MW (627,127 HP) with 23 centrifugal units and 14 reciprocating engines located at different locations. The centrifugal units ranging from 746 kW (1,000 HP) to 33,184 kW (44,500 HP) are mostly located within the Dawn- Parkway corridor (Figure 1). The air filtration system of these units vary in terms of number of elements, style, type and brands; basically, having different construction and efficiencies, with several different filter media technologies used across the corridor. Air filters per unit varies from as low as 18 to as high as 244 filter elements, with roughly 4,190 total elements across all units.

Table 1: Filters in Use

Camfil Tenkay Hemipleat HE / GTC, with optional Gold cone	Donaldson Synthetic Spider-Web XP / Duratek	AAF ASC II

Figure 2: Bright Station

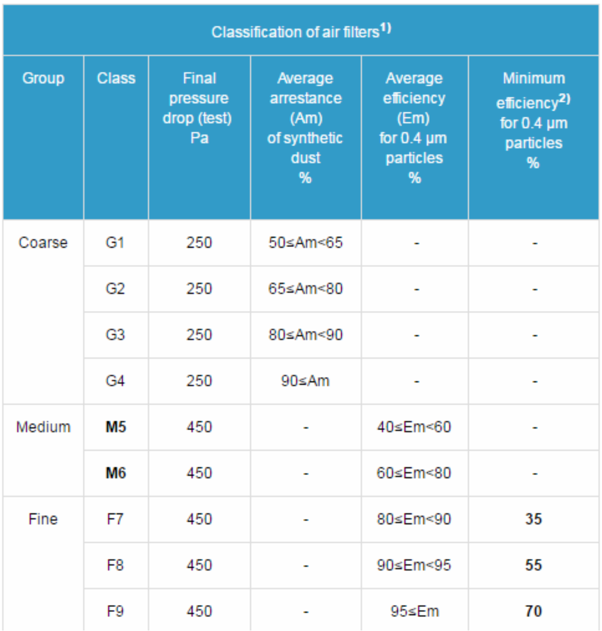
Operations and Maintenance Engineering Group at STO identified an opportunity to evaluate the existing air filtration system, determine the most efficient air filters applicable; and bring about consistency in air filtration system across the board, if possible. One of the by-products of the study was the opportunity to evaluate the selection process of air filters as well; selection process becomes even more critical especially in the light of different and new air filters being offered by companies due to advancement in technology. Most of the publications on new products are from OEMs and research companies but there is little contribution in terms of information from operators [1]. The paper also discusses the performance improvement with new filters and the overall cost benefit comparison over the lifecycle of filters.

The study was carried out at Bright station (Figure 2), part of Dawn-Parkway system. The station has two RB211 machines (RB211 G DLE RT 62) side by side which made it very convenient for comparative analysis (same environment). Every effort was made to collect the data for the same operating conditions on both machines over two seasons of winter.

Importance of Air Quality

Gas turbines ingest a large quantity of air during operation, with a typical 33 MW unit ingesting 300,000 m^3/h (175,000 CFM) of air. Of importance in this study is the effect particle ingestion can have on reducing the operating efficiency of the gas turbine, as particles smaller than 2.5µm have been previously identified as a key factor in compressor fouling of gas turbines [2], which can lead to detrimental effects such as a reduction in compressor efficiency, lower power output and an increase in heat rate over time. Note such performance loss can be treated in two ways: frequent compressor soak washes or upgraded air filtration. Gains in performance can be rather large, with a typical industrial gas turbine losing up to 6.8% power output per year with a low grade F8 air inlet filter per EN779:2012, and losing up to 4.7% power output per year with enhanced F9 filtration [1]. This increase of 2.1% in power output is quite substantial, as increasing the level of inlet air filtration will not only cause an effective increase in the yearly power output of the gas turbine, but will also cause a corresponding reduction in the heat rate of the engine.

As the air quality at Bright Station is relatively clean, analysis was performed to determine if a change in filtration efficiency would be beneficial. As the cause of compressor fouling and performance degradation is the quantity of particles penetrating into the engine, of interest is whether at a site with relatively clean air a relatively low performance air filter with a low airflow restriction would prove optimal. Typically, cellulose/synthetic or fully synthetic canister air filters in the range of class M6 to F7 per EN779:2012 are used across the Bright-to-Parkway corridor, which should provide 60 to 90% efficiency on submicron particles. In comparison, the upgraded fully synthetic class F9 filter per EN779:2012 should provide over 95% efficiency on submicron particles.



Classification of air filters$^{1)}$

Group	Class	Final pressure drop (test) Pa	Average arrestance (Am) of synthetic dust %	Average efficiency (Em) for 0.4 µm particles %	Minimum efficiency$^{2)}$ for 0.4 µm particles %
Coarse	G1	250	50≤Am<65	-	-
	G2	250	65≤Am<80	-	-
	G3	250	80≤Am<90	-	-
	G4	250	90≤Am	-	-
Medium	**M5**	450	-	40≤Em<60	-
	M6	450	-	60≤Em<80	-
Fine	F7	450	-	80≤Em<90	**35**
	F8	450	-	90≤Em<95	**55**
	F9	450	-	95≤Em	**70**

Figure 3: EN779:2012 Filtration Classification

Measurement Equipment Used at Bright Station

To understand the environment at Bright Station as well as the state of the installed equipment, three types of measurements were collected:

- Air analysis, using Lighthouse particle counter. Used to measure the quantity of particles both in ambient air as well as downstream of the inlet air filters, for in-situ testing of filtration efficiency.
- Water analysis, using gravimetric analysis per EPA 160.2 for measuring Total Suspended Solids (TSS). Used to analyze the quantity of particles in water wash effluent, to estimate the amount of dirt removed from the gas turbine during the soak wash process.
- Turbine performance analysis, using data collected from the site historian. Two soak wash events were tracked for each of two engines, with an average of 1,577 and 988 hours between soak washes on engines A1 and A2 respectively. The performance of the engines immediately after the wash was compared to the performance of the engines during average operation, to determine the loss of performance caused by engine degradation.

Figure 4: Lighthouse Particle Counter

Air Analysis

To classify the environment at Bright Station, ambient air analysis was performed with two goals:

- Determining the quantity of particles in outside air
- Determine the quantity of particles penetration through the air inlet system

The locations where both measurements were taken are shown in Figure 5. Note for the ambient air reading, the particle counter's built in isokinetic probe was used. However, for sampling downstream of the air inlet filters, the isokinetic sampling probes shown in Figure 6 were used. Isokinetic air sampling probes were installed at site to properly sample the incoming airflow. The goal of isokinetic air sampling is to ensure that there is no change in face velocity of the measured air sample when it flows from the sampled location – in this case the duct where the probe is installed – into the front nozzle of the isokinetic probe.

Figure 5: Locations for Particle Sampling

Figure 6: Air Sampling Probes (2x)

For the ambient air analysis, outside air results were used. For filter efficiency analysis, both ambient (upstream) and downstream air particle counts were used. Once a series of particle count readings were taken before and after the filter, the filter efficiency was then defined as:

$$Efficiency = \frac{(Particle\ Count\ Before\ Filter\ - Particle\ Count\ After\ Filter)}{Particle\ Count\ Before\ Filter} \qquad (1)$$

The particle counter used had channel sizes of 0.3, 0.5, 1.0, 2.5, 5.0 and 10.0 microns. By taking the geometric mean of the channel sizes, we can find the actual sampled particle sizes of 0.4, 0.7, 1.6, 3.5, 7.1 and 10.0 microns.

$$Particle\ Size\ Measured = \sqrt{Channel\ Size_1 \times Channel\ Size_2} \qquad (2)$$

This analysis shows that ambient dust levels are as follows:

Table 2: Average Ambient Dust Concentrations

Date	PM10 (µg/m³)	PM2.5 (µg/m³)
03-Dec-13 & 06-Jan-14	15	7

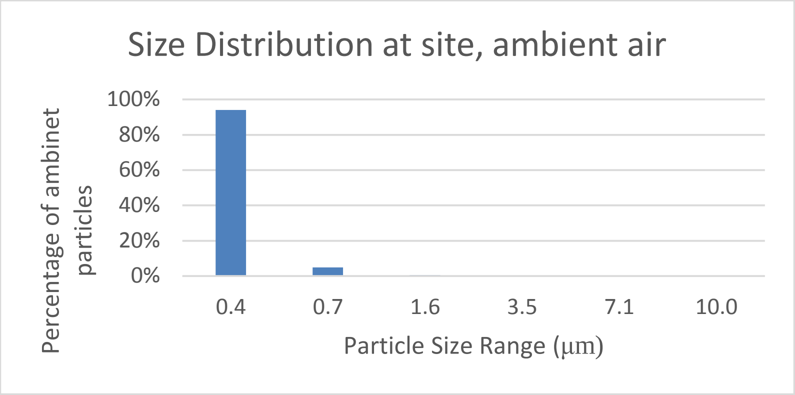


Figure 7: Particle Size Distribution

Note that while there is significant mass present in larger particle size ranges, most particles present in ambient air are submicron, with over 95% of all particles found in ambient air being 0.4μm. This distribution is relatively common, as particle counts typically rise on smaller particles.

Local readings taken at site after several months of operation match well with the expected PM2.5 concentration of 5.3-10.2 μg/m³ in this region [3]. Note upgraded filters (F9 per EN779:2012) were installed on engine A1 while standard filters were installed on engine A2 (M6 per EN779:2012).

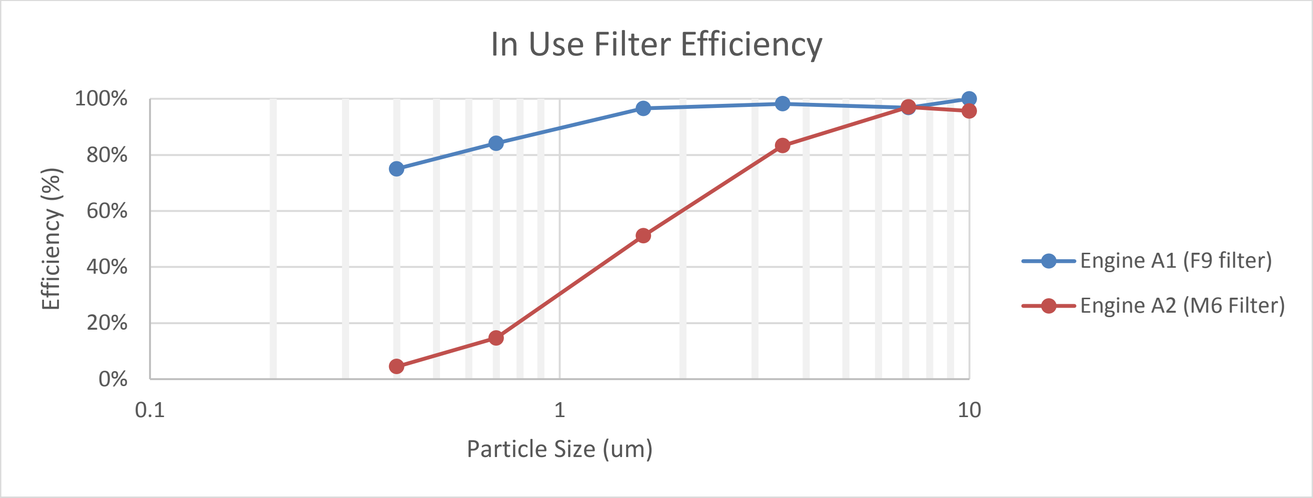


Figure 8: In-situ Efficiency Results

As expected, the particle removal efficiency for the air inlet filters installed on engine A1 was significantly higher at smaller particle sizes, showing an advantage from 7 μm and below. The increase in efficiency was significant, in particular for particles of 2.5 μm and below which are known to contribute significantly to engine fouling and performance degradation [2]. Note this is not the filtration efficiency from laboratory tests, but rather the result of in-situ testing of the performance of the inlet system as installed at Bright Station. Of importance is the large difference in efficiency at 0.4μm, which is the size range most prevalent at Bright Station.

Table 3: In-situ Filtration Efficiency

	Filtration Efficiency	
Particle Size (μm)	Engine A1	Engine A2
0.4	75%	5%
1.0	90%	30%
2.5	98%	70%
10.0	100%	96%

Soak Wash Analysis

Analysis of water wash fluid was carried out to verify the impact on engine performance due to change in filtration efficiency; see the results of soak washes of both engines in Table 4. Total Suspended Solids (TSS) was analyzed in the soak wash fluid to determine the level of contaminants present.

Note that while engine A1 was run for longer durations between soak washes, the soak wash fluid analyzed had less particles present. Normalizing the results for a standard number of fired hours between soak washes, the fluid in engine A1 contained an average of 148mg/L per 1,000 firing hours while the fluid in engine A2 contained 364 mg/L per 1,000 firing hours. This 2.4x increase in particle contamination per fired hour on engine A2 relative to engine A1 shows that the increase in filtration efficiency has caused a measurable reduction in particle buildup in the engine.

Figure 9: Soak Wash Samples for Analysis

Table 4: Soak Wash Analysis Results

Engine	Soak Wash Date	Runtime Between Washes (hours)	TSS (mg/L)	TSS per 1,000 firing hours (mg/L)
A1	07-Mar-14	1,300	230	176.9
A1	29-Jan-15	1,853	220	118.7
A2	18-Dec-13	1,000	360	360.0
A2	19-Mar-14	976	360	368.9
			A1 Average:	148 mg/L per 1,000 fired hours
			A2 Average:	364 mg/L per 1,000 fired hours

From a maintenance perspective, this suggests that engine A1 with an upgraded inlet air filtration can have a 2.4x longer interval between soak washes (2,400 hours vs 1,000 hours) while maintaining the same level of engine cleanliness as engine A2 with the standard inlet air filters.

Turbine Performance Analysis

The main performance parameters used for engine performance are the compressor efficiency and the fuel consumption. Compressor efficiency degradation due to dirt entering the engine would lower the power output. This will help isolate other factors related to engine performance that can reduce the power output independent of incoming air quality. Heat rate was chosen to measure fuel consumption, as this term measures the overall efficiency of the engine, relating the engine output to the amount of fuel used.

- Compressor Efficiency,
- Heat Rate, to measure the change in fuel consumption at operating loads due to performance degradation

Compressor efficiency, in percent, can be calculated from turbine performance data as:

$$Compressor\ Efficiency = \left(\frac{Temp\ Compressor\ Inlet}{Temp\ Compressor\ Outlet - Temp\ Compressor\ Inlet}\right) \times \left[\left(\frac{Pressure\ Compressor\ Outlet}{Pressure\ Compressor\ Inlet}\right)^{\frac{0.4}{1.4}} - 1\right] \tag{3}$$

Engine heat rate can be calculated as:

$$Heat\ Rate = \frac{Fuel\ Input}{Engine\ Output} \tag{4}$$

Finally, the effects of changing loads can be considered by measuring the shaft speed corrected back to ISO conditions of the engine. This is calculated as:

$$Corrected\ Shaft\ Speed = Shaft\ Speed\ (RPM) \times \left(\frac{\sqrt{273.15 + 15}}{\sqrt{273.15 + Temp\ (°C)}}\right) \tag{5}$$

As the engines at this site are only run sporadically, the “clean” engine state was taken to be the condition of the engine immediately following a soak wash. The compressor efficiency and heat rate at each load was then measured versus the expected value for the clean engine at that load, with the number of measured hours at each load being used to generate a weighed degradation rate.

$$Degradation\ Rate = \frac{(Degraded\ Performance - Clean\ Performance)}{Clean\ Performance} \tag{6}$$

Table 5: Heat Rate Degradation

Corrected Shaft Speed	*A1 Heat Rate Degradation Rate*	*A2 Heat Rate Degradation Rate*
5,770	-0.3%	-0.9%
5,860	-0.3%	-2.0%
5,940	-0.4%	-2.8%
6,030	-0.5%	-3.3%
6,110	-0.5%	-3.5%
6,200	-0.4%	-3.3%
6,280	-0.4%	-3.0%
6,370	-0.3%	-2.5%
6,450	-0.2%	-1.8%
6,540	0.0%	-1.2%
6,620	0.2%	-0.6%
6,710	0.4%	-0.1%
Weighed Total	***-0.3%***	***-2.2%***

Table *5* shows the degradation in heat rate impact, for both engine A1 and A2. Note that at partial load, the heat rate degradation due over time was more pronounced than at full load. Note the sign of this degradation is negative, as the heat rate increases as it degrades.

Table 6: Compressor Efficiency Degradation

Corrected Shaft Speed	*A1 Comp Eff Degradation Rate*	*A2 Comp Eff Degradation Rate*
5,770	0.2%	0.9%
5,860	0.1%	0.9%
5,940	0.1%	0.9%
6,030	0.1%	1.0%
6,110	0.2%	1.1%
6,200	0.2%	1.2%
6,280	0.2%	1.4%
6,370	0.3%	1.6%
6,450	0.4%	1.9%
6,540	0.5%	2.3%
6,620	0.6%	2.6%
6,710	0.7%	3.1%
Average:	***0.2%***	***1.2%***

Table 6 shows the same compressor efficiency degradation, but here the compressor efficiency degrades quicker at full load. Note the sign is positive as the compressor efficiency decreases as it degrades.

The total effects of engine performance degradation between water washes can then be seen in Table 7. Engine A1 with an upgraded level of air filtration saw 6x less compressor efficiency degradation and 7x less heat rate degradation compared to engine A2 with a standard level of filtration.

Table 7: Average Effects of Engine Degradation

	A1	A2	Delta
Compressor Efficiency	0.2%	1.2%	1.0%
Heat Rate	-0.3%	-2.2%	1.9%

Taken together, we can show that an increase in air filtration efficiency from M6 to F9 per EN779:2012 leads to an increase in filtration efficiency, a decrease in particles found downstream of the air inlet filters, a 2.4x reduction in particles ingested in the gas turbine and removable through soak washing, and a 6x to 7x reduction in performance degradation. This performance degradation, if allowed to occur unchecked, would have led to a decrease in compressor efficiency and an increase in fuel consumption and engine heat rate.

Cost – Benefit Analysis

Benefits

The main benefits seen by enhanced *air filtration* are:

- Decreased heat rate and corresponding decrease in fuel consumption
- Reduction in maintenance needs for engine soak washes
- If the shelf life is reached and still they are performing well, then air filter change out could be deferred. This could also be ratified by sending out a sample back to the vendor or third party to check the integrity of the air filter.

Fuel Consumption

Fuel consumption across the pipeline is significant. As we have seen in Table 7, the heat rate degradation on engine A1 with upgraded air inlet filters was 1.9% lower than on engine A2 on average. The potential cost savings from performing a similar upgrade on engine A2 are then a 1.9% savings on fuel costs. Over 1,219 hours of runtime analyzed for engine A2 in this study, total fuel savings would potentially be 19,500 CAD. Over a typical 20,000-hour filter lifetime, a total of 320,000 CAD would be saved, based on a typical fuel cost of 159.5 CAD per 1,000 m³/fuel and average fuel consumption per engine of 5,400 m³ fuel/hour.

$$\begin{aligned} Fuel\ Savings(CAD) \\ &= Fuel\ Consumption\left(\frac{m^3}{hr}\right) \times Fuel\ Cost\left(\frac{CAD}{m^3}\right) \times Runtime(hours) \\ &\quad \times Degradation\ Improvement(\%) \end{aligned} \tag{7}$$

$$= 5{,}400\,\frac{m^3\ fuel}{hr} \times \frac{159.5\ CAD}{1000\ m^3\ fuel} \times 20{,}000\ hours \times 1.9\% = 320{,}000\ CAD$$

Soak Washes

Soak washes are recommended by OEMs on operating hours (usually 1,000 hours) irrespective of operating conditions and environment. A machine running at full load versus partial load during 1,000 hours would have higher airflow rates leading to higher particle ingesting, causing an increase in fouling on the compressor blades. Note as well that different environments will cause fouling of the blades at different rates, so a static recommendation on water wash may not be suitable for all sites. The units in UGL system run at many different speeds due to a high volatility of loads, and operate in quite different locations – some close to cities and other nearby farms.

If soak washes could be scheduled due to monitoring of turbine performance on a site-by-site level, combined with an increase in the level of air filtration to reduce the need for soak washes, the maintenance level across the pipeline could be reduced substantially. A typical soak wash cost for smaller units 0.745 MW (1,000 HP) could be $2,000 and for bigger units 33 MW (44,500 HP) are in the range of $5,000.

As we have seen in Table 4, the quantity of dirt entering the engine can be reduced by 2.4x between washes by upgrading the filters used. If the soak wash schedule was reduced by a conservative 2x, then the quantity of soak washes needed could be cut in half. Over a typical 20,000-hour filter lifetime on a 33 MW unit, 10 soak washes would be eliminated resulting in 50,000 CAD in reduced maintenance costs.

The main ingredients for this cost are:

1. Manpower hours
2. Fuel consumption during dry runs
3. Opportunity cost; downtime of one day in winter season or not carrying out the wash in winter season due to loads in this system thereby in turn causing efficiency loss.

However, soak wash timing does not need to be scheduled based on past analysis – it can be scheduled based on actual air compressor efficiency and heat rate degradation over time.

Cost

The above benefits must be balanced against the increased costs:

- Increased cost of air inlet filter elements
- Potentially increased filter pressure drop and corresponding reduction in engine efficiency
- Potentially reduced service life of air inlet filter elements

Air Filters

A typical air filter change out could cost from $14,000 to $36,000 per unit depending upon the brand and type and number of elements. Like soak washes, air filter change out can be made subject to filter delta P. However, it has been observed that delta P does not change significantly over the life cycle of the filter elements mostly because running hours are much less than what is expected over its life cycle period. As such, filter elements are typically replaced after either 20,000 operating hours or once 5 years have passed. Upgrading to the higher efficiency filters used on engine A1 costs an additional 12,500 CAD.

Another interesting observation is that we have different types of air filters for the same models of units at the same location. The most plausible reason for this variance is that these units when installed came with different types of air filters and the company continued to replace air filters on these units with the same brand as recommended by OEM. Consistency in air filters would help reduce cost such as both maintenance and inventory costs.

Pressure Drop

An additional cost related to inlet air filters is the pressure drop of the elements and the effect that has on engine performance. Every 4” wg air inlet pressure drop normally causes a 0.45% increase in heat rate across a gas turbine [5]. The average pressure drop on engine A1 has been marginally higher than on engine A2 during this test, increasing from 0.23 inch wg to 0.26 inch wg for a total increase of 0.03 inch wg. This leads to an increased fuel consumption over 20,000 hours of:

$$\begin{aligned} &Additional\ Fuel\ Consumption(CAD) \\ &\quad = Fuel\ Consumption\ \left(\frac{m^3}{hr}\right) \times Fuel\ Cost\left(\frac{CAD}{m^3}\right) \times Runtime(hours) \\ &\quad \times Pressure\ Drop\ increase\ ("\ wg)\ \times dP\ impact\ on\ fuel\left(\frac{\%}{inch\ wg}\right) \end{aligned} \tag{7}$$

$$= 5{,}400\frac{m^3\ fuel}{hr} \times \frac{159.5\ CAD}{1000\ m^3\ fuel} \times 20{,}000\ hours \times 0.03"wg \times 0.45\frac{\%}{inch\ wg} = 2{,}400\ CAD$$

Total Cost-Benefit Analysis

By upgrading to the F9-rated filters on engine A1 versus the lower M6-rated filters on engine A2 at Bright station, the potential cost-benefit over a 20,000-hour operating period would be:

- -12,500 CAD in additional spending on air inlet filters
- -2,400 CAD in increased fuel consumption due to inlet pressure drop
- +320,000 CAD in fuel savings due to reduced engine degradation
- +50,000 CAD in maintenance cost savings due to reduced demand for soak washes

Total impact across 20,000 hours of operation is then $355,100 CAD in savings generated, mainly through changes in fuel consumption and maintenance requirements.

Selection Process

One of the outcomes of this study was to review the selection process of air filters.

1. Confirm the concentration of particle size of the surrounding environment. Check for the availability of any public information on particle size [2] for that area or region. If reports were unavailable, make arrangements with the vendor to measure the particle size at site over a certain period. Typical cost to do this is roughly $5,000.
2. Once the particle size is determined then review the air filters the best fit for that particle size.
3. Look for delta P, air flow, life cycle and durability, cost and efficiency for the particular particle size and warranties.

Maintenance Process

To move to predictive maintenance from fixed interval maintenance, data gathering and analysis set up is required. Control systems of any rotating machine is already set up for gathering, trending and analysis of data using industry or in house software; however, data gathering and analysis in excel format is the most convenient way. RSLinx is the communication protocol that takes the data from the control system and stream it live into excel, where all the analysis can be done. The parameters required for predictive maintenance would be:

1. Air compressor efficiency
2. Heat rate
3. Compressor Discharge Pressure (CDP)
4. Thermal efficiency

At the same time, soak wash samples can be tested to verify if the predictive maintenance is working properly.

Conclusion

Air filtration systems play a key role in the performance of the engine. Developing a strategy of selecting and replacing filters based on factors such as environment and predictive maintenance would lead to substantial savings and improvement of engine performance. Environment assessment for particle size and concentration is a key to the selection of air filters. Usage of efficient air filters, reduced soak washes and low fuel consumption for the same power output would lead to cost savings. Heat rates and efficiencies can be easily determined if the data collection and analysis are properly set up in the system. *RSlinx* is a tool that communicates with control system of the machine and transfers the data in excel format for online or offline analysis.

References

[1] U. Schirmeister and F. Mohr, "Impact of Enhanced GT Air Filtration on Power Output and Compressor Efficiency Degradation," ASME Turbo Expo 2016, Seoul, 2016.

[2] R. Kurz, C. Meher-Homji and K. Brun, "Gas Turbine Degradation," Pump & Turbo 2014, Houston, 2014.

[3] Ontario Ministry of the Environment and Climate Change, "Air Quality in Ontario," 2015.

[4] GE Power Systems, "GE Gas Turbine Performance Characteristics (GER-3567H)".

[5] M. P. Boyce, Gas Turbine Engineering Handbook, Butterworth-Heinemann, 2012.

Copyright