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DRAMATIC REDUCTION OF GAS TURBINE FOULING WITH HEPA COMPOSITE MEMBRANE AIR INTAKE FILTERS

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ABSTRACT

Gas turbines are protected by air inlet filters that remove particulate contaminants to prevent blade fouling and erosion. The most common filters used today are medium grade filters, which are insufficient to capture submicron particles that cause fouling and performance loss. This leads to reduced productivity, profits and reliability of gas turbines. This paper presents a newly developed filter made with hydrophobic expanded-polytetrafluoroethylene (ePTFE) membrane. The filter offers high efficiency particulate arrestor (HEPA) efficiency with ability to block water and salt penetration. The multilayered media significantly improves the capture efficiency of submicron particles, without the burden of high pressure loss and short filter lifetime typically associated with high efficiency filters. A full-scale study was conducted to evaluate the performance of HEPA composite membrane filters. The new filters were installed at an oil refinery site equipped with two gas turbines from July 2008 to June 2010. The results showed that the HEPA membrane composite filters dramatically reduced fouling and resulted in no noticeable performance loss of the gas turbine over 22.5 months. Filters returned for analysis after 11 months showed only 0.2 inwg increase in pressure loss, indicating that the filters can easily achieve two years or more service in this oil refinery environment.

INTRODUCTION

Combustion turbine operators generally experience turbine fouling from airborne particles passing through their inlet air filters. Fouling is caused by the particle capture limitations of current filters. Ambient air contains a large number of small particles from submicron to a few microns in diameter. Filters used today are not sufficiently efficient to capture these small particles. Consequently, they are ingested into the gas turbine, causing fouling on the compressor blades (Figure 1). Degradation can be measured rather quickly via power output reductions caused by fouling of the compressor section (Kurz and Brun, 2009). For independent power producers, they may have to increase the firing temperature to maintain the contracted power output. An increase of hot gas temperature will increase the turbine blade temperature, which negatively affects the blade life (Jordal, et al., 2002). Additionally, poor inlet filters allow water and soluble salts to pass through, leading to costly corrosion damages. Effects of fouling were documented by various researchers (Kurz and Brun, 2009; Meher-Homji, et al., 2009).

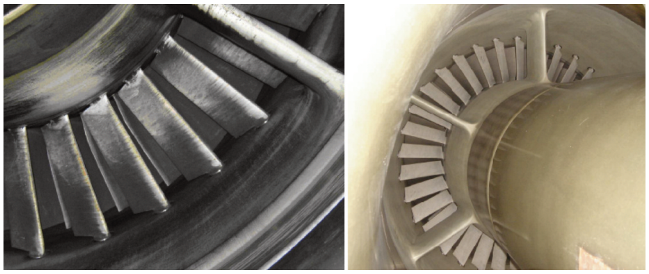

Figure 1. Fouled Compressor Blades (Left) from a 31 MW Gas Turbine in the UK Equipped with F9 Filters. The Power Output Decreased by 4 MW in 150 Days after Soak Wash. Clean Compressor Blades (Right) after Soak Wash.

Today, the operator either accepts these performance reductions or tries to minimize them via offline and online washing programs (Stalder, 2001; Meher-Homji and Bromley, 2004). Offline washing is done by completely stopping the gas turbine and spraying the compressor blades with a strong cleaning agent to remove dirt particles. The time needed to perform offline wash varies from several hours for small turbines to 24 hours for large turbines. During this time, the operators are not producing power or steam, and may have to buy power from the spot market. Starting and stopping induce thermal fatigue on materials. This may shorten the life of sensitive components. Online washing is done while the gas turbine is online above a minimum load. The frequency can range from every day, to every few days, to a few weeks and can become very expensive when antifreeze is required during low ambient temperatures. However, it generally can only partially recover the performance loss. Online washing can carry contaminants to later stages of the turbine, which are difficult to access and costly to clean (Kurz, et al., 2009). Furthermore, washing effluents are hazardous waste and must be disposed of at additional cost. For improved gas turbine performance, availability, and reliability, clearly the best solution is to prevent the airborne particles from reaching the gas turbine in the first place.

Improving the performance of filtration media is key to changing the paradigm that fouling must be accepted and managed via washings. This paper describes a breakthrough composite membrane media that overcomes the limitations of current gas turbine filters, offering significantly higher particle capture efficiency, ability to stop water and salt, excellent filter lifetime, and resistance to wet burst pressure. The 100 percent synthetic media is a composite of three layers of filtration materials. They perform four critical functions: coarse filtration, fine filtration, hydrophobicity, and mechanical integrity. The filter is rated at E12 according to EN1822:2009 (2009). Previously, HEPA filtration upgrade requires costly inlet filter house modification due to high filter pressure loss and short lifetime. The new HEPA filters are designed to work with existing filter houses. In the following sections, this paper compares the new filtration media with other types of filtration media, and reports the field experience from an oil refinery site with two gas turbines.

FILTRATION MEDIA

There are many types of materials on the market today. The most commonly used media for gas turbine air inlet filters are cellulose, microfibers, and nanofibers. Cellulose media is the most economical, but has the lowest filtration efficiency. It is made of natural fibers (plant-based), which are coarse and nonuniform. Microfibers are made by spunbond and meltblown processes. The polymer fibers are extruded through dies. Spunbond fibers are typically 10 to 100 μm in size. The meltblown process is similar to the spunbond, but the dies have much smaller apertures and use air to "blow" the fibers to achieve smaller diameter, usually one to five microns. New technology has been developed that is capable of melt-blowing nanofibers. Furthermore, the fibers can be charged artificially to enhance electrostatic collection; therefore, offering higher efficiency at low pressure loss. However, once the charges are dissipated by loading, the efficiency of the material can degrade quickly.

Efficiency of media is related to the size of the fibers, as discussed above. Generally, the smaller the fiber, the higher the efficiency. Nano-sized fibers can be made by many means. The most common technique employed in air filtration is electrospinning. In this process, the polymer is dissolved and fed through capillary tubes under a high potential field. The resulting fibers are nanometer in size and extremely uniform. A thin layer of nanofibers can markedly increase the efficiency of the open substrate. The drawback of the technology is that the nanofibers layer is very thin, and therefore, relatively weak. It can degrade quickly in harsh and chemical environments. To achieve high filtration efficiency, a large number of nanofibers are required, but the flat morphology of the nanofibers can increase the pressure drop substantially.

Membrane media with expanded PTFE (ePTFE) have been used for many years in industrial applications such as cleanable filtration. It is made from a biaxial stretching process on PTFE tape, creating the microporous structure as shown in the picture. The fibers are connected by nodes. The three-dimensional structure of the membrane and the submicron fiber size allow it to achieve high filtration efficiency, low pressure loss, and relatively high strength. Still, in most cases, the membrane has to be bonded to support substrate in order to be made into final products. PTFE material has high hydrophobicity. Combined with microporous structure, ePTFE membrane can resist penetration of water, while allowing air to pass through.

The generic cellulose, meltblown, electrospun nanofibers are compared to the composite membrane media as shown in Figure 2. The cellulose has large irregular fiber diameter. The meltblown has open structure with fibers from 1 to 10 micrometers. The electrospun nanofibers media has a thin layer of nanofibers on the surface of the substrate. Because the layer is so thin, it is relatively open and the cellulose fibers behind are clearly visible. The ePTFE membrane has a continuous web of interconnected fibrils that are less than one micrometer. The microporous membrane is relatively thick (75 micrometer) compared to the electrospun nanofibers.

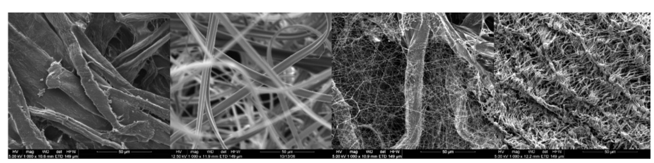

Figure 2. Common Filter Media at 1,000× Magnification. From Left to Right: Cellulose, Meltblown, Electrospun Nanofibers on Cellulose, and EPTFE Membrane.

FILTER EFFICIENCY RATINGS

Today, there is no test standard for filters specific to the gas turbine application. Currently, there is effort in the ISO TC142 Workgroup 9 to develop new test standards for gas turbine air inlet filters. As of this writing, the draft version for ISO/CD 29461-1 (Draft) is available. It is partly based on the previous EN779 test method and the new ISO/TS 21220:2009 (2009) test method.

Filters for gas turbine intake are typically rated according to ventilation filter test standards. The most common of which are ASHRAE 52.2-1999 (1999), EN779:2002 (2002), and EN1822:2009 (2009). The filter ratings from these test standards are summarized in Tables 1 and 2.

Table 1. Filter Ratings According to EN779:2002 (2002).

FILTER CLASS	AVERAGE EFFICIENCY 0.4 μm	EN 779	ASHRAE 52.2	Efficiency 0.3 - 1.0 μm	Efficiency 1.0 - 3.0 μm	Efficiency 3.0 - 10 μm
Fine Filters	40% < E < 60%	F5	MERV 9	-	> 50%	> 85%
			MERV 10	-	50 - 65%	> 85%
	60% < E < 80%	F6	MERV 11	-	65 - 80%	> 90%
			MERV 12	-	> 80%	> 90%
	80% < E < 90%	F7	MERV 13	> 75%	> 90%	> 90%
	90% < E < 95%	F8	MERV 14	75 - 85%	> 90%	> 90%
	95% < E	F9	MERV 15	85 - 95%	> 90%	> 90%
			MERV 16	> 95%	> 95%	> 95%

Table 2. Filter Ratings According to EN1822:2009 (2009).

FILTER CLASS	EFFICIENCY @ MPPS		EN 1822 (2009)
	Overall	Local	
HEPA	>85%	-	E10
Filters	>95%	-	E11
MPPS	>99,5%	-	E12
	>99,95%	>99,75%	H13
	>99,995%	>99,975%	H14

Many inlet systems employ a single stage of round filters in F7 to F9 classes according to Table 1. Filters are classified according to the average efficiency of filters loaded with artificial dust. The filtration efficiency is highly dependent on the particle size due to the effects of particle diffusion, interception, impaction, and electrostatic charge. Figure 3 depicts the typical filtration efficiency of a different class of filters when they are clean. A significant portion of the ambient air particles, particularly in the submicron size range, bypasses the F-class filters and causes fouling. It is estimated that a 25 MW gas turbine will ingest 13 kg of dust annually with F9 filters, versus 0.04 kg for E12 filters (Figure 4).

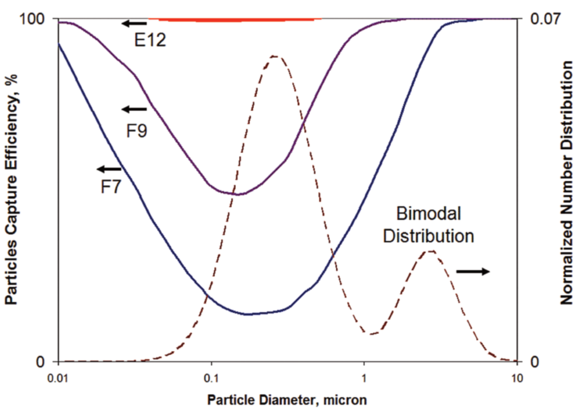

Figure 3. Initial Efficiency of F7, F9 and E12 Filters Compared to the Number Size Distribution of Ambient Air Particles.

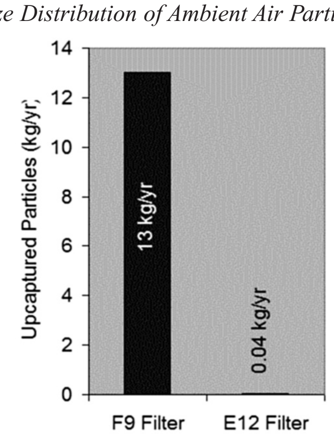

Figure 4. Theoretical Calculation of Dust Not Captured by Filters for a 25 MW Gas Turbine in Typical Ambient Environment.

COMPOSITE MEMBRANE FILTERS

To address the needs of better performance for gas turbine inlet filtration, a new filtration technology was developed based on composite membrane. The key to the invention is a multilayer media that combines microporous membrane (Figure 2) with a prefiltration layer in a proprietary bonding process. The hydrophobic PTFE membrane is air permeable, but highly resistance to liquid water. The media is pleated to form a cartridge filter that can withstand extreme environmental conditions in the field and the potential burst pressure due to gas turbine upset. An expanded view of the filter construction is shown in Figure 5.

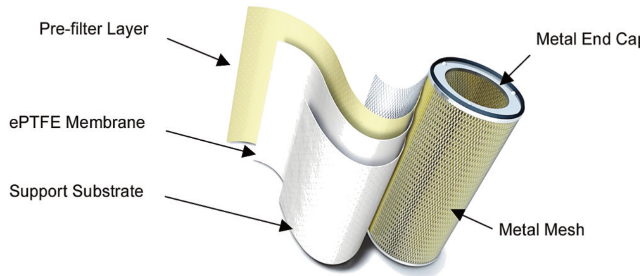

Figure 5. Expanded View of E12 Pleated Filter with Composite Membrane Media.

The filtration efficiency of a cylindrical filter (323 mm OD 660 mm L) and a conical filter (323/430 mm OD, 660 mm L) in stack were measured according to EN1822:2009 (2009). The result is shown in Figure 6. The minimum efficiency of the clean filter was 99.6 percent at 2500 m^3/h. The MPPS was 0.09 μm diameter. This filter set is classified as E12.

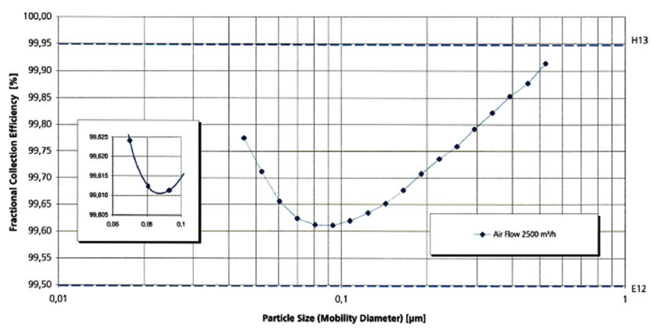

Figure 6. Efficiency of Cylindrical and Conical Filters Stack According to EN1822:2009 (2009).

WATER AND SALT PROTECTION

Most of today's filters do not stop water from passing through the filters. Filters can become wet due to high humidity, heavy rain, or mist from nearby cooling towers. When this occurs, the soluble particles collected on filters can dissolve in water and migrate downstream. Over time, enough salt crystals can build up and then shed off from the filter. Salt can contribute to hot corrosion in gas turbines and cause long-term reliability issues.

The hydrophobicity and microporous structure of ePTFE provides a natural barrier to liquid water and dissolved salts. To evaluate the resistance to deliquescent salt penetration, the composite membrane media and a F9 grade 80/20 blend media with nanofibers were set to filter a salt mist atomized from a 5 percent concentration solution. The samples were exposed to the fine salt mist for 72 hours and then dried for 24 hours. The clean side of the samples is shown in Figure 7. The picture on the left showed the surface view of the support substrate. No salt crystals were visible. On the other hand, the F9 filter media showed numerous salt crystals on the back side of the filter.

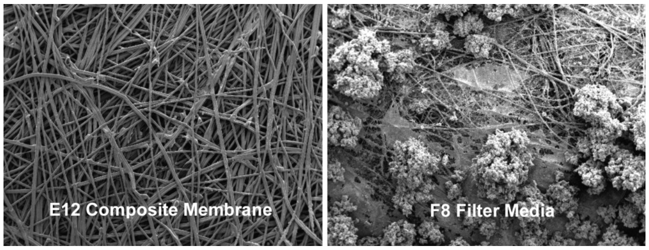

Figure 7. Clean Side of Composite Membrane Media and F9 Media after 72 Hours Exposure to Salt Mist. 50× Magnification.

FIELD EXPERIENCE

Installations of HEPA membrane filters began in 2004. Table 3 is a partial list of applications that had installed HEPA membrane filters. The operators reported no major issues installing the filters and operating the gas turbine. Fouling was dramatically reduced. Some operators reported they completely eliminated washing; some extended washing intervals to scheduled downtime during outage. In all cases, the performance losses due to fouling were dramatically reduced compared to filters previously used.

Table 3. Test Sites with HEPA Composite Membrane Filters.

Industry/ Location	Country	Gas Turbine and Output Rating	Offline Wash Cycles Before & After Installing HEPA Filters	
			Before	After
Plastics Mfg Coastal	UK	Rolls Royce 501 KB7, 5 MW	12/yr	0
Brewery Coastal	Netherlands	Rolls Royce 501 KB5, 3.7 MW	17/yr	0
Food Suburban	Germany	Rolls Royce 501 KB7, 5 MW	26/yr	0
PowerGen Highway	Germany	Rolls Royce 501 KH5, 3.7 MW	6/yr	0
Ceramics Mfg Industrial	Italy	Rolls Royce 501 KB7, 3.7 MW	52/yr	0
PowerGen Coastal	Europe	Rolls Royce RB211, 31 MW	3/yr	0
Oil Refinery Coastal	Canada	GE LM6000PD, 44 MW	10/yr	N/A*
Oil Refinery Coastal	United States	GE 6B, 39 MW	0/yr †	0
Oil Refinery Coastal	Singapore	GE 6FA, 75 MW	2/yr	0

* Operator saw insignificant fouling and power loss, but continued to soak wash due to scheduled maintenance.
† The gas turbine is used for critical steam supply for chemical processes. The operator only performs online wash and there is significant performance loss of the gas turbine over time.

In the next section, a demonstration site with two gas turbines side-by-side compared the performance of HEPA composite membrane filters with F9 filters in an oil refinery environment.

A study was conducted at an oil refinery site in Canada, equipped with two identical gas turbines running in cogeneration mode. The goal was to evaluate the impacts of the HEPA membrane filters on gas turbine performance. The site is located at sea level. Climate conditions at the site vary from cool summers (21°C) to arctic winters (−10°C). The gas turbines are operated in baseload mode. Unit #2 was installed with newly developed HEPA membrane filters. Unit #1 was installed with F9-class filters with nanofibers media.

The airflow paths of the system are shown in Figure 8. The inlet air passes first through a wire mesh screen that removes trash, paper, and other loose objects. Then it passes through coarse panel prefilters (2 ft × 2 ft), heating coils, and drift eliminators. The air was then filtered by 112 cartridge filters (Figure 9) for the gas turbine.

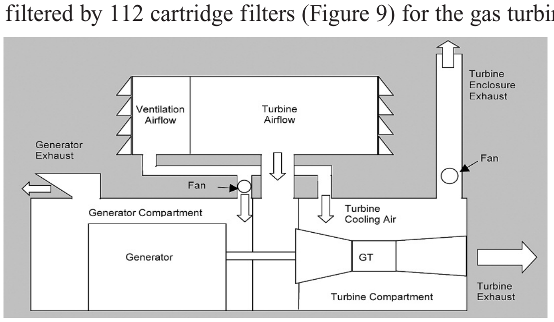

Figure 8. Schematic of the Inlet Air System for Gas Turbine.

Figure 9. Cartridge Filter with HEPA Composite Membrane Media.

Later in the study, the same HEPA composite membrane filters were installed for ventilation air also. 40 filters provided clean ventilation air for the generator and turbine compartments. The cleanliness of the compartments and the generator condition were evaluated after the installation of HEPA membrane filters. The airflows are listed in Table 4.

Table 4. Gas Turbine Airflows.

Total Airflow :	9175scmm (335,000scfm).
Turbine Intake :	6513scmm (230,000scfm).
Ventilation (total) :	2662scmm (105,000scfm).
Gen. Compartment. :	1274scmm (45,000scfm) each fan.
Turb. Compartment. :	1699scmm (60,000scfm) each fan.

The filters were mounted horizontally as shown in Figure 10. The airflow enters the inside diameter of the filter and exits through the outside diameter. The filter design is noncleanable; that is, there is no pulse cleaning equipment. The inside-out design allows for a pleated prefilter insert to be placed inside the filter. It is made of pleated microfiberglass media with efficiency in the F5 range (EN779:2002, 2002). The prefilter insert reduces the loading on the final filters and extends their lifetime.

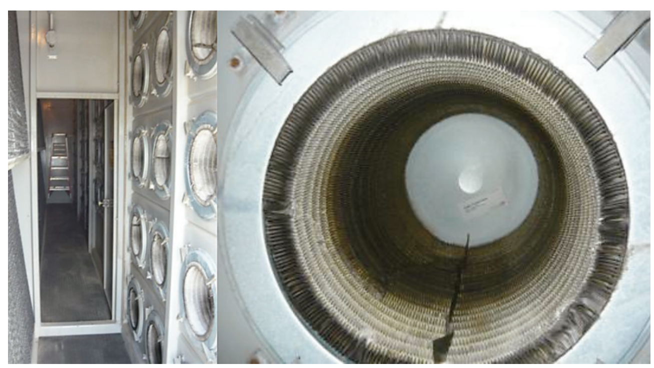

Figure 10. Filter Inlet House (Left); Prefilter Insert and Cartridge Filter (Right).

The gas turbine Unit #2 installed with HEPA membrane filters operated at full load during the test period, from July 2008 to present. Offline soak wash was performed every four months, but only because the engine was scheduled off for other reasons. Prior to washing the operator was not seeing a performance loss, and did not see a performance gain after washing, indicating the engine was clean to begin with. Based on the observation, the operator was very confident that offline washing can be pushed out even further to 6, 9, or 12 months.

The inlet housing pressure loss is shown in Figure 11. The initial pressure loss, including the coarse prefilters, heating coils, drift eliminators, cartridge filters, and pleated inserts, was 1.5 inches of water. The pressure drop increased to 2.2 inch after 22.5 months. The HEPA composite membrane filters were inspected periodically and found to be in good condition.

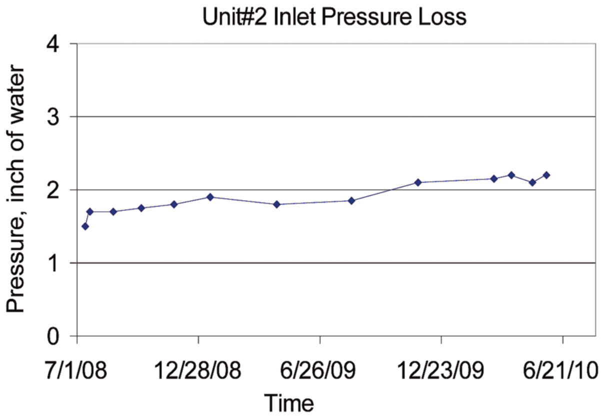

Figure 11. Inlet Pressure Loss of Unit #2 over 22.5 Months.

Unit #1 encountered problems during the test period due to prematurely reaching its NOx emission limit. As a result, the gas turbine was operated at less than full power output, with a lower inlet airflow than the one corresponding to full load. The airflow through the F9 filters with nanofibers was thus lower than the airflow experienced by the HEPA membrane filters. Comparison of Unit #1 and Unit #2 inlet air system pressure drop readings was, therefore, meaningless. The load restriction of Unit #1 also made it impossible to continuously monitor the performance of the two units via operating data reduction to a common denominator, as had originally been planned.

The after-wash effluents from offline washings are pictured in Figure 12. The effluent from Unit #2 installed with HEPA composite membrane filters was virtually clean, indicating very few particulates were washed from the blades. On the other hand, the effluent from Unit #1 installed with F9 filters was dark black, showing significant collection of dirt particles on the blades. Although the effluents were not analyzed, the blackish color of the effluent with F9 filters was strong evidence of submicron soot particles in the air; not surprising in an oil refinery environment.

Figure 12. Used Washing Effluents. Unit #1 with 1,450 Firing Hours with F9 Filters Installed. Unit #2 with 2,500 Firing Hours with HEPA Membrane Composite Filters Installed.

The boroscope picture of the compressor section of Unit #2 after 10,600 hours is shown in Figure 13. The plant manager commented that after 10,600 hours, the engine was still clean. There was insignificant power loss or heat rate increase.

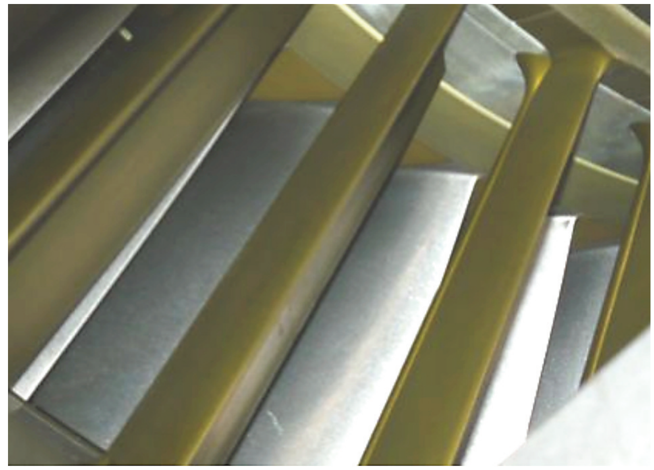

Figure 13. Unit #2 Compressor Section after 10,600 Operating Hours with HEPA Composite Membrane Filter.

The generator compartment is cooled by ambient air in this gas turbine package. A wall in the inlet filter house separates the ventilation air from the turbine inlet air. The ventilation filters remove dirt particles that can contaminate the electrical windings of the generator. After the first nine months of operation with HEPA filters, the generator windings were visually inspected by the operator noting no further increase of residue on the windings. Accumulation of the residue on the windings happened during the first five years of operation with F8 and F9 filters (Figure 14).

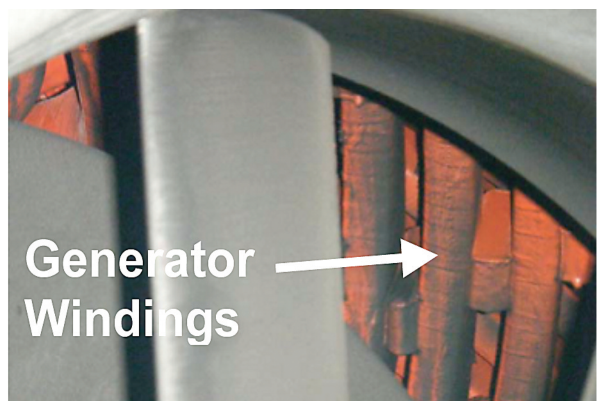

Figure 14. Residues on Generator Winding. F8 and F9 Filters Were Used for Ventilation Air to the Generator Compartment.

A set of HEPA composite membrane filters with prefilter insert was returned on May 29, 2009, for evaluation. The filters were in service for 7,425 hours over an 11 month period. The pressure drops of the final and insert prefilter were measured. The initial pressure loss of this set was not available, so the data were compared to typical new filters.

As shown in Figure 15, the 11-month filters' pressure loss measured 1.76 inch of water at 2,000 CFM. In Figure 11, the inlet pressure loss was 1.8 inch of water during this period. The pressure loss of the final and prefilter insert is expected to be 0.2 inch lower due to coarse filters. This implies that the pressure loss of the cartridge filter and prefilter insert was 1.6 inch. The lab measurement and field data are, therefore, within 0.2 inch. Given the uncertainties of reading error with a 10 inch of water pressure gauge in the field, and other unknown differences in the two systems, the close agreement is considered excellent. Also, the total pressure loss measurement at site is inclusive of the heating coils and drift eliminators.

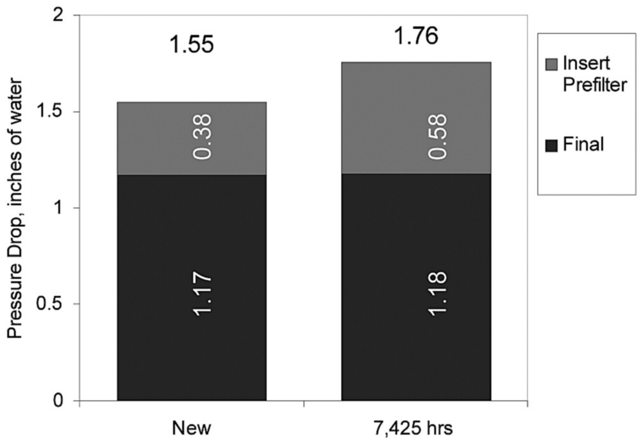

Figure 15. Pressure Drop of Prefilter and Final Filters after 11 Months, Compared to New Filters.

The overall increase of pressure drop was relatively small for 11 months of operation. At the writing of this paper, the filters have lasted 22.5 months and are still in good condition. Since the alarm trigger is 5 inches of water, the plant manager is confident that the filters will last two years or more.

It should be pointed out that the final filter pressure drop change was negligible, even though loading was clearly observed on the media. The reason is that the composite membrane media is integrated with a prefiltration layer. This layer significantly increases the dust holding capacity, causing less pressure drop increase with the same amount of dirt. Secondly, the prefilter insert captures the coarse particles and some fine particles, reducing the loading on the final filter. The prefilter insert pressure drop was 0.58 inch of water, up from 0.38 inch typically for new.

CONCLUSIONS

Fouling in gas turbines due to small submicron particles is a common problem. In industrial environments with higher pollution levels, such as oil refineries and chemical production, this can lead to significant loss in productivity and profits.

New HEPA filters based on composite membrane technology have been tested globally in the last five years. The filters offer H12 or E12 class filtration efficiency based on EN1822:2009 (2009). The membrane resists the penetration of water and soluble salt. The composite construction provides high dust holding capacity.

The success is demonstrated at an oil refinery running two machines. The new HEPA composite membrane filters dramatically reduced fouling on the compressor. As evidence, the effluent from the wash was practically clean, and the operator saw insignificant performance loss after 10,600 hours of operating the gas turbine at full power output. The same filters were also installed for the cooling section for the generator. After nine months, visual inspection showed no change in the condition of the windings, substantially better than experience in the past with F9 filters. The cost savings from a potential generator rewind is very significant.

As a result of all positive results—substantial decrease in fouling, no noticeable power loss, slow increase in filter pressure loss—the operator decided to install HEPA membrane filters on Unit #1 in October, 2009. Unit #2 is still operated with an original set of filters, with 22.5 months accumulated runtime to present.

This new HEPA filtration technology can be applied to other ambient intake-air applications, especially large integral geared centrifugal compressors in process air applications to prevent fouling from small submicron particulates and corrosive salts.

REFERENCES

ASHRAE 52.2-1999, 1999, “Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size,” American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, Georgia.

EN779:2002, 2002, “Particulate Air Filters for General Ventilation. Determination of the Filtration Performance,” European Standard.

EN1822:2009, 2009, “High Efficiency Air Filters—Part 1: Classification, Performance Testing, Marking,” European Standard.

ISO/CD 29461-1, (Draft), “Air Intake Filter Systems for Rotary Machinery—Part 1: Test Methods and Classification for Static Filter Elements,” International Organization for Standardization, Geneva, Switzerland.

ISO/TS 21220:2009, 2009, “Particulate Air Filters for General Ventilation—Determination of Filtration Performance,” International Organization for Standardization, Geneva, Switzerland.

Jordal, K., Assadi, M., and Genrup, M., 2002, “Variations in Gas-Turbine Blade Life and Cost Due to Compressor Fouling—A Thermoeconomic Approach,” *International Journal Applied Thermodynamics*, *5*, (1), pp. 37-47.

Kurz, R. and Brun, K., 2009, “Degradation of Gas Turbine Performance in Natural Gas Service,” *Journal of Natural Gas Science and Engineering*.

Kurz, R., Brun, K., and Wollie. M., 2009, “Degradation Effects on Industrial Gas Turbines,” *Journal of Engineering for Gas Turbines and Power*, *131*.

Meher-Homji, C., Chaker, M., and Bromley, A., 2009, “The Fouling of Axial Flow Compressors—Cause, Effect, Susceptibility and Sensitivity,” Proceedings of ASME Turbo Expo 2009: Power for Land, Sea and Air, GT 2009, Orlando, Florida.

Meher-Homji, C. B. and Bromley, A., 2004, “Gas Turbine Axial Compressor Fouling and Washing,” *Proceedings of the Thirty-Third Turbomachinery Symposium*, Turbomachinery Laboratory, Texas A&M University, College Station, Texas, pp. 163-192.

Stalder, J. P., 2001, “Gas Turbine Compressor Washing State of the Art: Field Experiences,” *Journal Engineering for Gas Turbines and Power*, *123*, pp. 363-370.