

Gain a competitive edge with a better understanding of GT compressor fouling, washing

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The competitive merchant power market and high price of natural gas have created a strong incentive for gas-turbine (GT) operators to both minimize and control performance deterioration. The most significant deterioration problem faced at GT-based powerplants is compressor fouling (Fig 1). Negative impacts of fouling include reduced compressor air-flow, pressure ratio, and efficiency, which cause a “rematching” of the turbine and compressor and a drop in power output and thermal efficiency.

Some experts estimate that fouling is responsible for 70 to 85% of all GT performance losses accumulated during operation, and that output losses of between 2% (under favorable conditions) and 15 to 20% (under adverse conditions) have been experienced.

It doesn't take more than a few parts per million (ppm) of airborne impurities to create a great deal of fouling. Reason is the huge volume of air that flows through the typical GT used for bulk power production. To help visualize the air-flow, assume that the volume of air consumed is represented by an imaginary column that extends for miles above a traditional football field (360 × 160 ft). The popular GE Energy Model 7FA, for example, which requires 971 lb/sec of air (ISO conditions) at full load, would consume in one year a column of air that is 1325 miles high. Also, if the inlet air contains a modest 10 ppm of impurities, 153 tons of impurities would be ingested annually.

Impacts of fouling. In round numbers, 50 to 60% of the total work produced in the turbine is consumed by its axial compressor. Large frame machines typically are at the lower end of this range, small aeroderivative engines



1. Don't let this happen at your plant. Severely fouled bellmouth and blading on a 35-MW engine operated in an industrial environment dramatically reduced GT performance

at the upper end. To illustrate: For a Model 7FA, the total turbine work is 340.7 MW and the compressor work 164.4 MW (48%). Machine electrical output is 172.8 MW—that is, turbine work less compressor work and parasitic and mechanical losses.

Thus deposits on compressor rotating and stationary blades that change the aerodynamic profile and reduce compressor mass flow have a significant adverse impact on efficiency and power output. In addition to fouling, contaminated air can cause erosion and corrosion, and, in some cases, plugging of hot-section cooling passages. There is a close relationship between mechanical reliability and fouling deterioration with its consequent damaging effects on the integrity of compressor blades.

Fouling also contributes to a higher turbine inlet temperature for a given power level, and this can lead to increased emissions. If the turbine is temperature-limited, there will be a loss of power.

To dig deeper . . .

. . . into the science of axial compressor fouling and associated washing technology, consult the source of the information for this article, “Gas Turbine Axial Compressor Fouling and Washing,” published as part of the Proceedings of the Thirty-Third Symposium, Turbomachinery Laboratory (<http://turbolab.tamu.edu>), Texas A&M University, College Station, Tex, pages 163-191, Copyright 2004.

A valuable part of the tutorial paper (TMS33) presented by Cyrus B Meher-Homji and Andrew F Bromley before the Texas A&M symposium is a detailed bibliography which includes references of associated work by Jean-Pierre Stalder, Turbotect Ltd, and Meher-Homji, both of whom have made significant contributions to this field.

1. Sources of fouling include the following:

- Industrial and urban pollution—including hydrocarbons, flyash, smog, exhaust from mobile sources.
- Airborne salt.
- Ingestion of GT exhaust and/or vapors from the lube-oil tank.
- Mineral deposits, such as limestone, coal dust, cement dust.
- Typical airborne materials—including soil, dust, sand, chemical fertilizers, insecticides, plant matter.
- Insects, which can be a serious problem in tropical environments.
- GT bearing oil leakage. Leakage from the compressor front bearing is common. Oil leaks, combined with dirt ingestion, cause heavy fouling.
- Carryover from evaporative coolers.
- Vapor plumes from adjacent cooling towers.

2. Off-line washing

The objectives of off-line washing are twofold: Clean a dirty compressor and restore power and efficiency to virtually “new and clean” values.

- Characteristics of off-line washing are these:
- Reaches all compressor stages.
- Achieves virtually full power recovery (approaches “new and clean” values).
- Involves a shutdown/cool-down period of from 12 to 36 hours.
- Revenue is lost during shutdown.
- Optimum time for cleaning may not be convenient, especially for base-load plants.
- Requires disposal of effluent water.

The economic impact of not cleaning the compressor on a regular basis—to restore the machine to its “as-new” condition, to the extent possible—can have serious economic consequences, and power losses attributable to compressor fouling can easily amount to millions of dollars annually.

A revenue shortfall can be avoided for a relatively small cost. The amount of improvement at a given site depends on the type of cleaning program adopted and the thoroughness of its implementation. All elements of the program are important—including system design, choice and use of detergents, frequency of cleaning, and the washing procedure used.

Important to remember is that an axial compressor is a machine where the aerodynamic performance of each stage depends on that of the earlier stages. Thus fouling on the inlet guide vanes (IGVs) and blades in the first few stages can con-

tribute to a dramatic drop in overall compressor performance.

This often occurs when oil and industrial smog, or other pollutants, are present in the inlet air and form adherent deposits on compressor blades. The first few stages usually are fouled the worst. If the rear stages foul, the impact on performance is less; however, the higher temperatures can bake-on deposits and make them difficult to remove. Baking is more severe in the high-pressure-ratio compressors associated with aero units than it is in large frame machines with their typically lower pressure ratios.

The type of impurities entering the compressor varies widely from site to site (refer to Sidebar 1 for a list of fouling sources), and ambient air can be contaminated by solids, liquids, and gases in various concentrations depending on the local environment. In general, particles in sizes up to 10 microns cause fouling, but not erosion; particles above 10 to 20 microns cause erosion.

Impurities often are classified as oil soluble, water soluble, or water wettable, but typically they are a combination of these. To illustrate: Sea salt essentially is water soluble, but its retention within the compressor can be influenced significantly by trace quantities of oil and grease.

Plant operations. GT manufacturers and plant personnel generally develop guidelines based on load and exhaust temperature to define when fouling deterioration suggests corrective action. Users also monitor compressor discharge pressure and compressor efficiency. An important requirement is to select a method that detects fouling in time to prevent a significant power drop and before a substantial fuel penalty is incurred.

Fouling is best controlled by a combination of two methods. Your first line of defense is a high-quality inlet air filtration system (refer to COMBINED CYCLE Journal, Spring 2004, available at www.psimedia.info/ccjarchives.htm). But since fouling inevitably occurs, compressor washing should also be used to control its impact.

This is an area in which strong and divergent opinions exist. Washing efficacy is so site specific that approaches suitable for one location may not be appropriate for another. Controversy often is caused by polarized opinions relating to wash procedures, wash media, and techniques.

Operators must determine the best approach for their gas turbines at a particular site in terms of optimum wash technique, use of online washing, cleaning formulations to use, and washing frequency. For example, base-load merchant plants that cannot shut down for crank washes may need to be more aggressive in controlling fouling by online washing than cycling units.

Several different methods for cleaning GT compressors have been applied over the years, but wet cleaning is by far the most effective and economic technique. However, today’s sophisticated large industrial engines and blade coatings require appropriately designed cleaning systems to ensure operational safety, reliability, and optimum efficiency.



EXPERTS IN PROBLEM SOLVING



On-line compressor washing for large gas turbines



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Wash off-line, online, or both ways?

Two different wet cleaning techniques are generally applied—off-line (crank wash) and online cleaning. Under extreme fouling conditions, hand washing of the IGVs may need to be conducted if time permits. During overhauls, hand cleaning of

the full axial compressor is recommended. Optimal compressor cleaning normally can be achieved by adopting a combined program of regular online washing, plus periodic off-line washing during planned outages.

Off-line washing almost always is conducted with the aid of a detergent and is extremely effec-

3. Crank-wash checklist

Preparing for a successful off-line wash is relatively simple provided you follow the OEM's recommendations. Typical items of importance include these:

- Ensure that wheel space temperature criteria are satisfied.
- Close off seal and atomizing air pipes to prevent water entry.
- Open IGVs (if applicable) to the maximum-air-flow position.
- Open all drains.
- Close flame-detector valves.
- Ensure that any special precautions for regenerators (if installed) are followed.
- Hand-wash the plenum to prevent dirt from being washed into the compressor.
- Follow instructions regarding duration and amount of fluid injection.
- Use an approved anti-icing agent if cleaning is performed when the ambient temperature is near or below freezing (Sidebar 5).

4. Online washing

The objectives of online washing are to (1) maintain the cleanliness of a compressor (not to clean a dirty compressor), (2) extend the period between shutdowns required for off-line cleaning, and (3) maintain power and efficiency and minimize ongoing losses.

Characteristics of online washing are these:

- Extends operating time between shutdowns for off-line cleaning, thereby maximizing power production.
- With a frequent online cleaning program, each wash typically can recover about 1% of a unit's generating capability which otherwise would be lost.
- Primarily cleans IGVs (no cleaning is accomplished after the water evaporates).
- Revenue is not lost because the unit continues to operate during the cleaning process.
- Optimum wash frequency is site specific.
- No effluent water to dispose of.
- Maintains safe margin to surge line.
- Reduces risk of blade corrosion.

COMPRESSOR WASHING



2. Heavy black deposits on the tips of IGVs illustrate the severity of fouling that would have occurred over the entire vane length had regular online cleaning (detergent wash every fourth day) not been performed (left)

3. Typical online manifold is installed on a frame GT. A second, similar manifold is located downstream around the bellmouth (right)



tive in recovering lost power (Sidebar 2). However, it is important to follow the OEM's (original equipment manufacturer's) recommendations with respect to water quality, detergent/water ratio, and operating procedures. Typically, wheel space temperatures must be below 200F to avoid thermal shock (Sidebar 3).

The downtime for a crank wash depends mainly on the time it takes for the engine to cool. Large heavy-duty machines can require from eight to 10 hours to cool, whereas aerospines may only need one and a half to three hours because of the low metal mass. After cool-down, the compressor is rotated at crank-speed while a cleaning fluid is injected via nozzles or jet lances.

Hand-held jet lances were widely used in the past and are still fairly popular with some operators. Today, permanently mounted off-line nozzle systems installed in the air intake plenum are preferred, and generally are a standard offering from most major turbine manufacturers. Nozzle design, system operating pressure and total mass flow parameters vary widely, however, among manufacturers.

Off-line cleaning is most effective when carried out in several steps that involve the application of a cleaning solution, followed by several rinse cycles using water alone. Each rinse cycle typically involves acceleration of the machine to approximately 50% of the starting speed, after which the machine is allowed to coast to a stop.

A soaking period between each wash and rinse cycle is very important, and allows the soapy cleaning fluid to penetrate the deposits, dissolving salts and emulsifying oil and grease components. A useful method for determining the effectiveness of the off-line wash, and perhaps the need for additional wash or rinse cycles, is to collect samples of the effluent water from all available drain ports. The samples can be checked visually for color and clarity (which should improve as dirt is removed), or by a simple conductivity meter to monitor the removal of salts.

Of prime importance is the design of an effluent water collection system that handles appropri-

ately the dirty wash water. Care must be taken to prevent runoff water from penetrating sensitive areas, such as sealing and cooling air systems as well as instrument air systems. The preferred location of bleed air taps is in the upper half of the compressor casing. Drains in the inlet air housing, compressor casing, combustion chamber, and exhaust casing should be at the lowest point. Size the drain diameters to facilitate runoff and take appropriate steps to ensure that they do not become plugged with dirt.

Online washing is popular for controlling fouling by preventing its buildup (Sidebar 3). If performed on a frequent and regular basis, it will extend the operating period between shutdowns needed for off-line cleaning. Online washing is per-

5. Anti-icing agents

An anti-icing agent must be used if online or off-line compressor washing is performed when the ambient temperature is near or below freezing. Here are some of the things you should know about the various types of agents:

- Alcohols (methanol, ethanol, isopropanol). Main problems are safety-related—that is, low flash point, high volatility, etc. Explosion-proof equipment and area rating are required.
- Ketones (acetone, methyl ethyl ketone). Pose a greater safety risk than alcohols because of their low flash points.
- Ethylene glycol. Does not pose a flash-point problem, but it forms sticky deposits on compressor blades.
- Propylene glycol. Generally recognized as the most suitable anti-icing agent for GT applications. It has a high flash point, is nontoxic and biodegradable, does not form sticky deposits during the cleaning process, and can be mixed with most cleaning agents to form the wash fluid or used as-delivered for compressor rinsing. Freeze points in this family of anti-icing agents extend to -18F.

formed with the unit in full operation and involves the injection of wash fluid via atomizing spray nozzles positioned around the air intake plenum. The latest techniques and wash systems have evolved to a point where this can be done effectively and safely. Designers strive to obtain the highest possible cleaning efficiency with the lowest injection mass flow rate.

Depending on the nature of the fouling material, online washing is sometimes performed with water alone. In most cases, however, use of an approved cleaning agent (detergent) will improve the effectiveness of the washing operation (Fig 2). This is particularly true if the fouling material contains any quantity of oil or grease. Demineralized water quality almost always is specified by the OEMs for online washing—to avoid the possibility of introducing harmful trace metal contaminants (such as sodium and potassium) into the hot gas path.

Clean compressor first. An online washing program should always be started on a clean engine—after an overhaul or crank wash. Avoid online washing on a heavily fouled engine because large quantities of dirt removed from the front stages would instantaneously pass through the compressor. After initiating an online wash program, the time intervals between subsequent washings should be kept short—such as every third day to weekly, depending on site conditions.

Also, depending on the deposit composition (specifically, how much of the deposit is water-insoluble), detergent cleaners may be used for every online wash, or for every second or third wash, but not less frequently than weekly. Note that the longer the interval between detergent washings the greater is the risk of downstream contamination caused by large portions of insoluble compounds suddenly being released when the next detergent wash is performed.

The duration of each online wash should reflect the degree of fouling, engine size, plant experience, etc. A typical online cleaning cycle is 10 to 20 minutes, and if detergent is employed, it should be followed by a rinse cycle (using only demineralized water) of about the same duration.

Detergents. Two main types of cleaning agents are available for compressor washing—water-based and solvent-based products. The latest products normally contain surfactants, wetting agents, and emulsifiers, and are specially formulated for these applications. Typically, they are supplied as concentrates and diluted onsite with water (usually one part cleaner, four parts water) to produce the cleaning fluid. Solvent-based cleaners traditionally have been recognized for being more effective in removing oil and grease deposits, but some of the new-generation water-based cleaners are formulated for equal effectiveness. Most water-based products also have the advantage of being biodegradable, which is an increasingly important requirement within this industry.

Nozzle location. Correct positioning and location of online injection nozzles is of prime impor-

tance for achieving uniform wetting and efficient blade cleaning (Fig 3). Nozzles should be designed to inject a small quantity of finely atomized cleaning solution into the airstream, where it will be mixed thoroughly and carried uniformly into the compressor bellmouth to wet the IGVs. Use of a relatively large number of online nozzles in the air inlet casing—both upstream and downstream of the bellmouth—assures optimum distribution of the cleaning solution in the airstream. Designers are keenly aware that poor atomization and/or non-uniform injection flow can cause blade erosion and vibration.

The design and configuration of inlet air systems varies with the GT model and is an important consideration in selecting appropriate nozzle locations. For example, some inlet systems direct the entire incoming air stream from the top of the plenum, down toward the bellmouth. This creates a higher air velocity within the plenum, and correct positioning of the on-line nozzles is challenging. Other systems split the airstream so that it enters the plenum equally from the right- and left-hand sides. This design lowers the air velocity and creates fewer disturbances to the airflow pattern. Hence, positioning of the online nozzles is somewhat easier.

Nozzles are atomizing devices designed to create droplets in a certain size range and with a specific spray profile. However, in order to achieve the design droplet size and spray pattern, the nozzle must be operated at its design flow rate and operating pressure. Changing the operating conditions for a particular nozzle will affect its spray characteristics. For example, droplet size usually will increase if the operating pressure is below the design point.

Online injection nozzles of many different types and designs are available commercially in a wide range of mass flow rates, operating pressures, spray patterns, droplet size ranges, and performance characteristics. About the only parameter for which there is fairly common agreement within the industry is that droplet size should be within the range 50 to 250 microns for safe and effective online washing. If droplets are too small, they are easily deflected by the airstream, and may not survive to wet the IGVs. If droplets are too large, gravity drags them toward the lower surfaces of the inlet plenum. Large droplets also are more likely to cause erosion problems.

Large, modern GTs also present new design challenges for online wash systems because of significantly increased airflow, air velocity, blade length, and inlet plenum dimensions. This can cause premature deflection of droplet trajectories, resulting in less effective wetting/cleaning of the IGVs. Premature droplet deflection also can increase the risk of blade erosion by creating a buildup of water at the IGV root area. To overcome these problems, some of the new online nozzle designs utilize a protective air curtain to enable greater droplet penetration into and across the inlet airstream. CCJ