WHITEPAPER

GAS TURBINE HOT CORROSION:

CAUSES, EFFECTS AND PREVENTIVE MEASURES

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Abstract

Hot corrosion is a form of corrosion and a source of non-recoverable degradation on gas turbines. It is a chemical reaction between salts, sulfur and heat, where the damages from hot corrosion can reduce an engine's life by up to 75%. One of the most effective solutions to mitigate hot corrosion is to eliminate the contaminants triggering the chemical reaction with the air inlet filtration system. This paper is divided in two parts: the first part examines different causes of hot corrosion on gas turbines, including environmental challenges, sulfur content in fuels, design of the engine and other types of degradation that complement hot corrosion; the second part assesses different necessary considerations, namely filter media and filter design, in adopting a suitable filtration system.

Introduction

Technological advances in hot section materials and coating, as well as hot section blade cooling schemes have led to increased temperature in turbine hot gas path. This enabled impressive gains in turbine efficiency. However, a new challenge has also arisen. Many environments and fuel supplies contain contaminants in the form of salts, normally sodium chloride, and sulfurs or sulfides. When combined with the extreme heat of a gas turbine, these contaminants will form into sulphates, a corrosive species that can condense on metal surfaces and catalyze a rapid structural and aerodynamic degradation process. This chemical reaction is called hot corrosion. To give clarity on this subject, a discussion will be provided on impacts of both corrosion and hot corrosion.

Corrosion is, at a macro level, a form of non-recoverable engine degradation. It is not to be confused with engine wear from rotating parts, which is also a form of non-recoverable degradation. Hot Corrosion is a form of corrosion, but its effects are substantially more severe. In fact, it can reduce an engine's life by up to 75%. The reaction will lead to a rapid degradation in engine performance, and if not addressed, will lead to a structural compromise of materials, resulting in a catastrophic failure of the gas turbine. As the engine's operating temperature increases, so does the risk of hot corrosion. This phenomenon is found mainly in the engine's turbine section, but may also be found in the combustion section.

Types of hot corrosion

There are two different types of hot corrosion categorized by their temperature of occurrence. The first is called *Type I Hot Corrosion* which occurs in engines between 800°C - 950°C (1350°F - 1740°F). The main ingredients are heat, sulfur and salt (normally sodium chloride) which combine into sodium sulfate. Hot corrosion removes the 1st stage blade coatings and causes surface oxidation and inter-granular attack in the combustor liner and nozzles, and turbine section blades air foils and tips. Because higher efficiency engines burn hotter, they are potentially more susceptible to hot corrosion attack, where the melting point of sodium sulfate is 884^{o}C (1623^{o}F).

Type II Hot Corrosion is a complex three-step reaction that reduces the melting point of sodium sulfate and can trigger hot corrosion at a much lower temperature, ranging from 600°C - 800°C (1000°F - 1350°F). It affects the 2nd and 3rd turbine stage blades, and it attacks around the blade platform, to the shank and fir tree root, and leads to scaling of turbine air foil surfaces.

Environmental & application design considerations

Salt concentrations in the air can be a challenging variable. Depending on whether the application is offshore, coastal or onshore, extreme airborne concentrations have been measured throughout the world. Some of the highest salt concentrations in the air have been measured in the Middle East Deserts during their seasonal dust storms called 'Shamals'. Much of this territory consists of ancient sea-beds and can have salt concentrations in the sand up to around 20%. Moreover, salt concentrations in the offshore Persian Gulf fluctuate around 4%. Strong winds cause these high salt concentrations to become aerosolized, which would inevitably be ingested by turbines even when installed at a great distance from this origin, if not protected by an adequate air filtration system.

Gas turbine inlet elevation, orientation and location are important aspects to consider at the initial design phase. In normal conditions, salt concentrations will decrease with higher elevation. It also helps to have the inlet system facing away from the prevailing winds, as it can minimize the contaminant levels. In addition, where possible, ensure the air inlets are not being impacted by upwind mining, industrial processing, exhausts, vents or other sources of contaminants, such as oil mists, smoke, water vapors, coal piles and coal mining. Coal dust, for example, usually contains 1% to 2% sulfur and traces of salts; these chemicals are determined to be the root cause of many hot corrosion engine failures.

One last but critical item is to evaluate local conditions. For example, wind vortexes which can be observed on the leeward side of vessel such as on ships, FPSOs, FSOs,...etc., have been measured to subject an inlet system to up to 2.5 times the salt concentrations from what was measured in the ambient air.

Difference between liquid and gas fuel relative to sulfur content and hot corrosion potential

A gas turbine's operational life has quite a few complex considerations, where the engine and its system designs, environment, and operational and maintenance practices all come into play. So, designing a fuel system to burn liquid fuel is very challenging because of the emission requirements, flame stability impacted by fouling, and the high-level of maintenance required. Diesel fuel is heavier, denser, less flammable, and is less volatile than gas fuel.

When an engine's injectors start to foul due to high levels of contaminants in the fuel, flame instabilities can start, and hot spots in the combustor can then occur. Ash fouling is another challenge where blade cooling ports get plugged and causes the blades to overheat. In general, operating on liquid fuel is substantially harder on an engine than burning gas fuel.

Be it gas fuel or liquid fuel, the flame instability creates oscillations that will shorten the life of the combustor, blades and nozzles. The hot spots can also directly impact these same engine components. When sulfur and salts are added to the already high challenges posed by using liquid fuels, a very aggressive corrosive reaction can occur much quicker than when using just gas fuel.

Extended gas turbine part life

The impact of clean air on a gas turbine's part life can be substantial, especially when one considers the operational requirements and the environments these engines must perform in. There are three major sections of a gas turbine that can be positively or negatively impacted if the air being ingested is clean or contaminated. These engine sections include the: *Air Compressor Section* (susceptible to fouling, erosion and corrosion), *Combustion Section* (susceptible to corrosion and hot corrosion) and *Power Turbine section* (susceptible to corrosion, plugging of the cooling channels and hot corrosion). So, the selection of a proper filtration and the implementation of proper maintenance of the filtration system will extend the GT Part Life in each of these three engine sections. When Hot Corrosion is part of the equation, engine part life can be severely impacted. The Issues and opportunities can vary, and are listed below:

Compressor Section – Compressor degradation such as fouling, and erosion increase the risks and the negative impacts of corrosion. The engine's compressor section requires a filtration system which is rated at a high efficiency, and in most instances, hydrophobic to minimize the following engine life limiting factors:

1. Compressor Blade Fouling can cause 'recoverable engine performance degradation'. The leading short-term indicator to this event is when an engine detergent / water wash is performed and the performance recovers to within the range of the previous water wash. The root cause is mainly from dirt, hydrocarbons and salt deposits on the compressor blade surfaces, casing walls, and other flow path components. Compressor fouling increases the temperature in the hot section that could in turn reduce engine part life.

2. Compressor Blade Fouling can also cause 'non-recoverable engine performance degradation'. The leading indicator is when detergent water washing is performed, and the recovery efficiency is less than what was seen on the water wash before. The actual compromised parts can be found in both the cooler and hotter sections of the compressor. This is due to blade surface deformation, and blade tip erosion and corrosion. The main causes are dirt, hydrocarbons and salts.
   - **a.** Dirt, if left on the blade, can bake and adhere to the higher pressure / temperature compressor stage blades. In many cases, when this type of failure occurs, the compromised part cleaning must be done away from site.
   - **b.** Hydrocarbons, when combined with dirt and/or carbon deposits, can also bake and adhere to compressor blades
   - **c.** Salts and other chlorides when combined with moisture can cause compressor blade airfoil surface pitting and cracking. They can also increase blade tip clearances which adversely impacts the engine's performance.

3. Erosion and Pitting Corrosion can occur on the compressor blade's leading edges, tips and surfaces. Erosion is caused by solids and liquids impacting the blades, whereas pitting corrosion is caused by aggressive chemical species such as sodium chloride attacking the material's passive film / oxide surface, allowing pitting to initiate at the oxide breaks. Pitting can develop into cracks, and ultimately compromise the part, or even worse, compromise downstream components of the engine.

These issues change the aerodynamic flow of the air across the blades, which forces the engine to work harder and less efficiently. The major issue in items 2 and 3 above is that water washing will not help recover the engine performance. High efficiency air filtration, however, will reduce blade surface deformation and blade tip erosion. While efficiency filtration cannot remedy the situation if erosion has occured; it can, however, prevent the issue from occuring initially.

Combustion Section – The engine's combustor section requires high efficiency, and in most instances, hydrophobic air filtration to minimize the following engine life limiting factors:

1. Combustion Section Corrosion can develop if the gas turbine ingests air contaminated with salts, and/or other corrosive materials.

2. Combustion Section Hot Corrosion can develop if the gas turbine ingests air contaminated with salts and/or hydrogen

sulfide, and the fuel contains excessive amounts of sulfur and possibly salts. Hot corrosion will attack the injectors and combustor coatings and combustor liner material, and/or create combustor oscillations, high cycle fatigue, resulting in a reduction of engine life.

Turbine Section – The engine's turbine Section is very dependent upon the cooling system to allow clean and dry air to freely flow inside the turbine blades, vanes, shrouds and other components; therefore, it requires high efficiency, and in most instances, hydrophobic air filtration to reduce oxidation and corrosion, thus maximizing the engine life. The main engine life limiting factor is turbine blade fouling which can occur when low melting point contaminants are deposited onto its surfaces. The aerodynamic performance can be affected along with clogging or plugging of the blades cooling passages and vents. Once this occurs, the expected life of these components will be substantially reduced. If the gas turbine ingests air contaminated with salts, and the fuel contains excessive amounts of sulfur, hot corrosion will occur and attack the blade coatings and blade material.

The combination of improved air filtration, advanced air cooling, improved compressor, combustor and turbine section efficiencies, increases in blade alloy temperature capabilities and advances in blade coatings in gas turbines has allowed the industry to design higher firing engines. These improvements have also helped enable increases in overall engine efficiency and most importantly, extend engine life. A critical aspect of these advances is the filtration systems capability to reduce the rate of blade fouling, erosion, corrosion and cooling passage plugging.

Action items

To help ensure the operational life of an engine is met, several factors must be considered.

1. The OEM needs to ensure the engine materials are designed for the application. This is especially so when sour fuel will be used in the engine.

2. The EPC contractor needs to design to meet the environment and application. This includes working with the OEM and the end user, in order to ensure proper engine materials and inlet systems are specified. The EPC also needs to ensure the design is robust so that it provides an optimized Life Cycle Cost.

3. The owner / operator needs to adhere to good design, operational and maintenance practices, in order to ensure that the capital expenditures support optimized Life Cycle cost targets. Operational considerations may include minimizing the threat of sodium contamination in the fuel by proper transportation, storage and treatment techniques. Also, a sometimes-overlooked item in harsh environments is to on-crank water wash the compressor section once a year versus online water washing. The on-crank wash limits contaminants from being washed into the hot section, thus reducing the possibility for cooling passage plugging and hot corrosion.

4. The sulfur, salt and heat reaction must be broken. This can most effectively be achieved by removing salt from the equation, with a quality air filtration system / solution designed for the application.

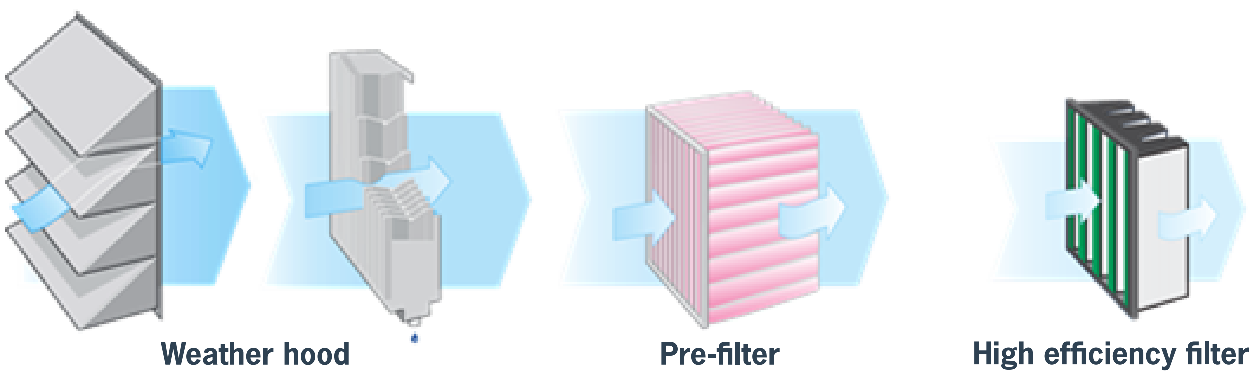
Mitigate corrosion with proper inlet filtration

As stated above, the most effective way to mitigate turbine corrosion is to improve the quality of the inlet air. Specifically, a proper inlet filtration system is required to remove salts and water in the air. This section will discuss some requirements for filtration systems that aim to eliminate corrosion problems, under different challenging environmental conditions.

Salts

From a filtration perspective, sodium chloride is an interesting particulate contaminant. It has a wide range in particle size, from submicron to millimeters. In its aerosol (small size) form, salts have a unique characteristic, where the salt particle will grow and change its state – from solid to liquid, as the relative

Figure 1: Different stages of filtration system



humidity increases. A process known as deliquesce. As rain / spray water droplets, larger in size, are also likely salt carriers, a proper filter must be capable to not only mitigate 'dry' salt particles, but also saline deliquesce droplets and water carry-over (rain/spray). It is important to note there are many types of filters that are highly efficient at mitigating small dry salt but not droplets. Thus, these filters are inferior to hydrophobic filters, in preventing corrosion.

In corrosion-prone environments, i.e. coastal and offshore, a multistage barrier filter system is recommended. The first stage deals with the bulk water, rain, and spray. This stage is either a weather hood, or an inertial vane droplet separator, and in a few aggressive locations both. An inertial vane droplet separator will have better water separation, but, on the downside, it will also have a higher pressure drop. Behind the weather treatment stage, there are two or three filter stages, depending on the site conditions. The first filter stage – the pre-filter, collects bigger particles, extending the service life of the final filter. It should be mentioned that in coastal environments, a prefilter should have coalescing properties. The final filter needs a combination properties of high-water prevention and efficiency. To successfully address the requirements of high efficiency and droplet resistances, two factors are considered: the filter media and the design of the filter. (fig. 1)

Final filter media

The First requirement is high particle efficiency. The definition of 'high efficiency' is not clear. There are differing recommendations regarding the allowable amount of salts that can be ingested by an engine. Technical publications and GT manufacturers generally state the allowable amount in terms of ppm(w). Some specify just the type of salt to be Na, but others NaCl. A brief review of some of these publications and specifications found values varied greatly: ppm(w) values vary greatly: from 0.003 to 0.008 for Na, and 0.001 to 0.01 for NaCl. And from a filtration view these values are difficult to interpret. The required filtration efficiency to meet a given ppm(w) is a function of ambient conditions – how much salt is in the air. For example: one efficiency level would be adequate in one location, while not acceptable in a higher salt environment. To make the matter more difficult, ambient salt concentrations are rarely known. Therefore, industry consensus defines a 'high efficiency' filter as one that is rated as minimum E10 up to E12, per filtration test standards[1].

Figure 2 shows the impact of filtration on gas turbine (dry) salt ingestion. This theoretical calculation is based on an inlet airflow typical of a 35 MW GT and an ambient NaCl concentration of 0.75 ppm. The 15 grams ingested by the multistage stage F7/E12 system of this example equates to 0.00022 ppm(w).

The second requirement is its resistance to water / droplet penetration – hydrophobicity. A common measurement of this media property is its hydrostatic head test (HHT). Simply, this is a measurement of the height of a water column on a media flat sheet, before water droplets penetrate through the media. To provide good corrosion resistance, a media should have a HHT of 400 mm of water (4000 Pa / 15" w.g.).

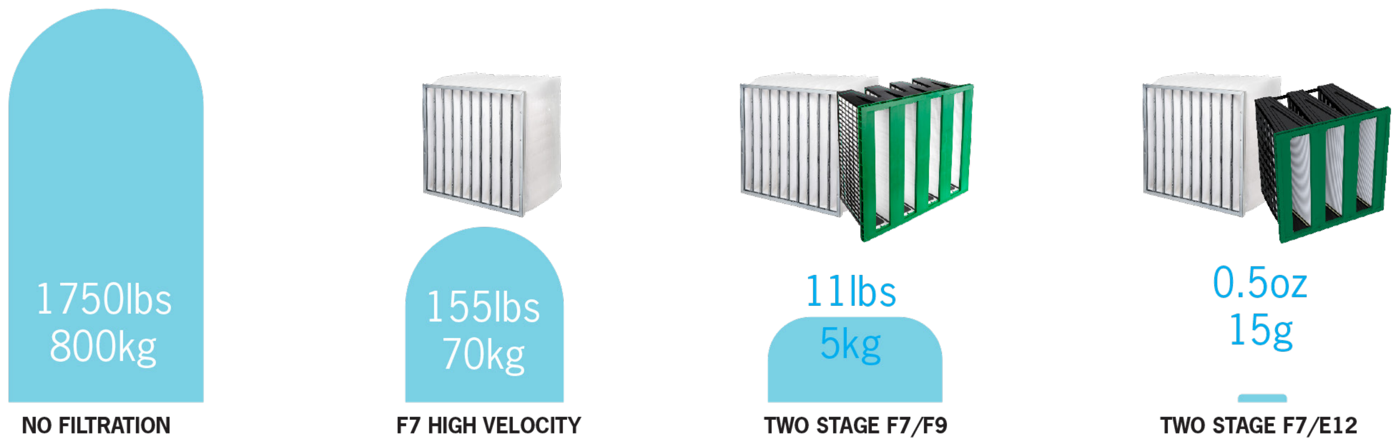
In addition to the above requirements, the media must also perform well on the parameters of pressure drop and service life. There is a class of media, which are highly surface loading, that have good efficiency and hydrophobic properties, but poor pressure drop and service life, especially in environments where hydrocarbon particles are present. To conclude, all performance factors must be considered when designing and selecting a filter media for corrosive environments.

Filter design considerations

It is not enough to have a filter media that meets the needed efficiency and hydrophobic requirements. The media must be integrated with a proper filter design. Specifically, it must manage any water that the filter media prevents from being ingested by the turbine.

The first key feature needed is the vertical orientation of the filter media pleats. If horizontal, any water (saline droplets) prevented by the media will pool on the media and increase pressure drop. It is common for these types of filters, that the pleats are separated by a polymer bead to maintain pleat separation for best

Figure 2: Impact of filtration on salt ingestion per year



1 *Efficiency of an E10 filter is a minimum of 85% for what is termed, the filters most penetrating particle size - MPPS. For an E10 filter MPPS is on the order of 0.1 microns. (If unfamiliar with GT air filter ratings, there are many resources available. Including from the author(s))*

airflow. For water / moisture management, it is important that these beads are not continuous. That is, there is a path for any separated water to drain to the bottom of the filter. If the beads are continuous, the collected water is 'trapped' and it's a similar condition to horizontal pleats, and pressure drop will increase due to water blocking airflow through the media. Another key feature of the filter element design is the ability to manage any water that has been channeled to the bottom of the filter. A drain within the filter which allows collected water to exit, is preventing pressure drop due to pooling. Water spray testing at a rate of 1 l/min., with airflow, has shown a proper drain feature will channel water from the filter.

Additional filter design considerations are its pressure drop and strength. Filter pressure drop is not solely a function of its media. Design of the filter is equally important. The filter geometry should direct the airflow to reduce airflow restriction to the media packs and through the pleats. Filters in corrosive environments, must be designed to have high strength. A common requirement is that a wet and dust loaded air filter withstand a differential pressure of 6250 Pa (25" w.g.).

Lastly, if the application allows, users would benefit from filters with extended lengths, 440 or 600 mm. A filter longer than the typical 300 mm model, will have lower pressure drop, and longer service life due to lower media velocities. Also, a lower media velocity will have additional performance benefits, albeit likely small, with respect to filter efficiency, hydrophobic resistances, and water management of the filter.

In summary, hot corrosion is one of the biggest enemies of gas turbines, as it causes non-recoverable performance degradation due to the structural and aerodynamic damages to the hot section components. Fortunately, you can protect your gas turbine with good maintenance practices, including a high-quality air filtration solution with high efficiency (EPA) and hydrophobic properties. Keep in mind that hydrophobicity should not only be evaluated on the media but on the entire filter assembly. Ideally, the filtration system should have a low and stable pressure drop, to further optimize the gas turbine's performance and efficiency.

Learn more about applicable filter products designed to meet the requirements of corrosive environments at www.camfil.com/TurboBoost

For more information on how hot corrosion damages your gas turbine, please contact your nearest local Camfil representative.

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