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FOULING MECHANISMS IN AXIAL COMPRESSORS

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ABSTRACT

Fouling of compressor blades is an important mechanism leading to performance deterioration in gas turbines over time. Fouling is caused by the adherence of particles to airfoils and annulus surfaces. Particles that cause fouling are typically smaller than 2 to 10 microns. Smoke, oil mists, carbon, and sea salts are common examples. Fouling can be controlled by appropriate air filtration systems, and can often be reversed to some degree by detergent washing of components. The adherence of particles is impacted by oil or water mists. The result is a build-up of material that causes increased surface roughness and to some degree changes the shape of the airfoil (if the material build up forms thicker layers of deposits).

Fouling mechanisms are evaluated based on observed data, and a discussion on fouling susceptibility is provided. A particular emphasis will be on the capabilities of modern air filtration systems.

INTRODUCTION

Fouling of compressor blades is an important mechanism leading to performance deterioration in gas turbines over time. Fouling is caused by the adherence of particles to airfoils and annulus surfaces. Particles that cause fouling are typically smaller than 2 to 10 μ m. Smoke, oil mists, carbon, and sea salts are common examples. Fouling can be controlled by an appropriate air filtration system, and often reversed to some degree by detergent washing of components. The adherence is impacted by oil or water mists. The result is a build-up of material that causes increased surface roughness and to some degree changes the shape of the airfoil (if the material build up forms thicker layers of deposits).

Compressor fouling is due to the size, amount, and chemical nature of the aerosols in the inlet air flow, dust, insects, organic matter such as seeds from trees, rust or scale from the inlet ductwork, carryover from a media type evaporative cooler, deposits from dissolved solids in a water spray inlet cooling system, oil from leaky compressor bearing seals, ingestion of the stack gas or plumes from nearby cooling towers. Fouling must be distinguished from erosion, the abrasive removal of material from the flow path by hard particles impinging on flow surfaces. These particles typically have to be larger than 10µm in diameter to cause erosion by impact. Erosion is probably more a problem for aero engine applications, because state of the art filtration systems used for industrial applications will typically eliminate the bulk of the larger particles. Erosion can become a problem for engines using water droplets for inlet cooling or water washing.

The purpose of this paper is to determine which mechanisms play a role in the fouling of airfoils. One might argue that the mechanisms are well known and have been described in numerous papers. There has, however, never been made an effort to correlate the location and severity of observed deposits on compressor blades with the aerodynamic features of particle laden flow around airfoils. This study should bring deeper insight into the questions regarding the relative impact of different particle sizes and the capture efficiency of gas turbine compressor blades, in particular transonic front stages. The paper thus contains two parts: An assessment of the aerodynamic mechanisms, followed by a review of actual, contaminated blades. The mechanisms that lead to the entrainment of particles are, at least theoretically, well understood. However, the conditions under which particles on impact actually stick to the surface of the blades are less well understood. Understanding can be gained from the study of fouled blades.

The adherence of small particles to airfoils, i.e. the fouling of their surfaces, will cause a performance deterioration of these airfoils. The deterioration in this case is usually reversible, as the particles can be removed through water washing (Kurz and Brun,[1]). This distinction is important, because the economic implications of recoverable and non-recoverable degradation have different economic impacts:

Fouling can be removed by off line water washing and slowed down by online water washing. Theoretically, the engine can be kept at a very small degradation level at all times, if it is frequently washed online, and the cost (i.e lost production) of shutting the engine down for water washing (typically half a day) is carried. The decision to shut the engine down for off line washing is a balance between lost production due to the lower power versus the lost production for shutting the engine down for a certain amount of time. The reversal of nonrecoverable degradation requires the engine to be overhauled. Therefore, operators likely will allow much larger levels of non-recoverable degradation before they take action.

Although theoretical considerations (Tarabrin et al,[2]) indicate that smaller engines show more fouling than bigger engines, there is no anecdotal evidence for this to be true. If there is an impact of engine size, it is probably obscured by the fact that smaller engines usually have fewer compressor stages, and, more importantly, by the exact circumstances of site dust load and air filtration system.

Also, Meher-Homji et al [3] introduced the important distinction between susceptibility and sensitivity to fouling. Susceptibility is the amount of fouling a compressor incurs under a specified contaminant load, while sensitivity describes the effect on compressor efficiency, or, in a wider sense gas turbine power output capability and efficiency, of a certain amount of compressor fouling.

The paper does not address the other, more permanent consequence of particle ingestion, that is the potential for hot corrosion as a result of salt particles entering the engine and reacting with sulfur from fuel or combustion air. This will be another topic of research.

NOMENCLATURE

c	chord
cp	heat capacity
d	Diameter
D	Diffusion Coefficient
E	Capture rate
Ι	Particle Flux
k	roughness
L	Length
N	Number
Р	Power
r	Radius
Re	Reynolds Number
St	Stokes Number
Т	Temperature
U	Velocity
W	Work
β	Direction of relative flow
ρ	Density
μ	Viscosity
ν	Viscosity
η	Efficiency
Subsripts	

-		
c	compressor	
f	fluid	
1	laminar	
out	Output	
р	particle	
t	turbulent	
t	Turbine	
0	initial	

INLET FILTRATION SYSTEMS

Industrial gas turbines can afford very effective inlet filtration systems. Modern systems can virtually eliminate the ingestion of particles into the engine compressor that can cause erosion (Figure 1). The trade-off for filtration systems lies in size, weight and cost on one side versus filtration efficiency versus low pressure loss [4].



Figure 1: Comparison of fractional efficiency for filter elements from different suppliers and different face velocities in new and dirty conditions [5].

Schroth et al [6] report on a comparison of GT power loss for two different air filtration systems used on 165MW gas turbines. The filtration systems are either a 2 stage or a 3stage system. The 3 stage system causes a significant reduction in finer particles entering the engine. Power loss after 3000 hours of operation was 4% with the 2 stage system and 2% with the 3 stage system.

If an engine ingests 100kg/year of contaminants if there were no filtration system in a typical off shore application, an $F5^1$ filter would reduce this to about 21kg/year, an $F6^1$ filter to 6kg/year, a $F7/H10^1$ filter system to 0.2kg/year and a $F7/F9/H10^1$ system to as little as 0.05 kg/year.

This indicates two conclusions: While large particles have a significant impact on fouling degradation, a significant amount is due to the finer particles. The overall contaminant ingestion can be influenced by several orders of magnitude by using an appropriate air filtration system. Also, with filtration systems of this type, there are virtually no particles larger than a few microns entering the engine.

OBSERVED DATA

To assess the fouling mechanisms, observed fouling patterns must be analyzed. We will discuss both findings in the literature as well as own observations. Vigueras Zuniga [7] reports deposits on the gas turbine compressor rotor and vanes. (Fig.2) indicate deposits both on suction and pressure surface. There is evidence of increased deposits in the leading edge region of the rotor blade suction side.

Figure 3 shows salt deposits on the compressors of several different gas turbines in offshore service. The deposits are fairly uniform, and exist on both suction and pressure side of the rotor blades.

Figure 4 shows another example of a gas turbine compressor rotor from an offshore application. In this example, the salt deposits on the suction side are missing immediately downstream of the leading edge.

¹ Per EN 779



a)







c)

Figure 2: Fouling on the compressor blades of a gas turbine in a power plant in the UK after 8000hrs. a) Compressor rotor b)inlet guide vane, suction side, c) inlet guide vane , pressure side [7].





Figure 3 : Salt deposits on Compressor blades, 18000 hrs, 5000 hrs and 12000 hrs of operation, respectively. View on suction side.



Figure 4: Salt deposits on a Compressor Rotor [3]. Fewer deposits near leading edge and in the hub region.



Figure 5: Fouling Deposition Rates on Axial Compressor Airfoil (solid..experiment, dotted..prediction) Particle mass median diameter (Top) 0.13 µm, (bottom) 0.19 µm. [8]

Parker and Lee [8] studied fouling patterns on rotating blades for very fine (0.13 to 0.19 μ m) particles. Sample results of the estimated deposition rates for different regions of the blade surface are shown in Figure 5. Results show high deposition rates at the blade leading edge, relatively low deposition on the pressure side, and a higher deposition rate on the suction side toward the trailing edge. The deposition rates on the suction surface near the trailing edge are where the boundary layer is thick and turbulent.

On the other hand, Syverud et al [9] detected in a gas turbine subjected to salt water spray deposits mainly on the blade pressure side and the blade leading edges, causing a significant increase in surface roughness. They also found, like other researchers, that the majority of the deposits occurred on the early stages of the compressor. It must be noted that the salt water spray in these experiments formed larger size and wet droplets (23 μ m median volume diameter). Obviously, the relative humidity (and with it the salt particle size) drops in the latter compressor stages due to the temperature increase. Typical particle sizes after air filters in industrial gas turbines will be much lower.

Due to the acceleration of the inlet air when it enters the compressor through a bellmouth and inlet guide vanes, the relative humidity of the air will increase. An ambient relative humidity of 50% can therefore lead to condensation at the inlet guide vanes. The droplets that can form due to this effect may scrub entrained solids, such as salts, as well as some gases like CO_2 or SO_x . Since they form downstream of the filter, their droplet size can be larger than the particle sizes normally prevented from passing through the air filter. They also will create an acid atmosphere within the compressor, thus causing corrosion pitting on the blades².

Another area that is affected by fouling is the compressor shroud or casing. Elrod and Bettner [10] compared the performance of the axial compressor of a gas turbine for different shroud roughness levels. Comparing the results for design roughness ($1.8\mu m$) with a rough ($13\mu m$) shroud, the compressor loses about 1% in flow capacity and about 1% in peak efficiency. The added wall roughness increases the wall boundary layer displacement thickness.

The type of foulants entering the compressor vary widely from site to site. Deposits of oil and grease are commonly found in industrial locations as a result of local emissions from refineries and petrochemical plants, or from internal lube oil leaks [3]. These type deposits act as "glue" and entrap other materials entering the compressor. Lube oil ingested into the flow path is spread by centrifugal and aerodynamic forces and generates a film on ten blades that allows even larger particles to stick to the surface (Figure 6).

Coastal locations usually involve the ingestion of sea salt, desert regions attract dry sand and dust particles, and a variety of fertilizer chemicals may be ingested in agricultural areas.



Figure 6:Oily deposits on axial compressor blades from bearing oil leakage on a large heavy duty gas turbine [3]. Oil steaks originate at hub region and are distributed over the airfoil be centrifugal forces and blade boundary layer shear stresses.

² Corrosion pitting can be prevented by appropriate coatings.

MECHANISMS

The discussion about fouling mechanisms has to address three issues:

- Entrainment Mechanisms: How do particles of various sizes reach blade and wall surfaces?
- Sticking Mechanisms: When do particles that reach the surface actually stick to it?
- What is the impact of particles on the blade surface or the walls on the compressor performance?

Related to these questions is the susceptibility of compressors to fouling.

ENTRAINMENT MECHANISMS

In the previous paragraph, we have shown typical patterns of deposition. The next question is, how the contaminants find their way to the compressor surfaces. Particles can reach the surfaces by one of the following mechanisms [11], which are well researched in the context of inlet air filtration [4,12]:

-Settling

- -Inertial impaction
- -Interception
- -Diffusion

-Electrostatic Forces



Figure 7: Filtration Mechanisms

Figure 7 shows the collection efficiency for the different mechanisms as a function of particle size. For the particle sizes responsible for fouling, impaction, interception and diffusion mechanisms have to be considered. In particular, diffusion mechanisms are very important for sub-micron particles. Electrostatic forces, while important for inlet air filtration, play no role in compressor fouling. A widely used correlation to describe susceptibility to fouling was presented by Tarabrin et al [2], and expanded by Song et al [13,14]. They use an inertial impaction mechanism described by Fuchs [11]: In accelerated flows, particles will not follow the gas flow precisely. The deviation between gas path and particle path is a function of acceleration of the gas, and the size and density of the particle. The particle behavior is captured by the Stokes number St

$$St = \frac{\rho_p d_p^2 U}{18\mu \cdot 2L} \qquad \qquad L = s \sin(\beta_b - \beta_1) \tag{1}$$

This means in particular, that the flow deflection in a compressor blade will cause the particles to deviate from the flow path. Larger particles, with a larger Stokes number, will show greater deviations from the gas flow path, and will therefore impact more frequently on the pressure side of the blade. The capture rate E therefore increases with Stokes number [2]:

$$E = 0.08855 \cdot St - 0.0055 \tag{2}$$

It should be noted that the suction side of the leading edge can also be impacted by particles, but this is not taken into account in the analyses in [2],[13], and[14]. The derivation can explain how particles reach the pressure side (and the compressor casing), and the area on the suction side immediately downstream of the leading edge, but it can not explain the presence of particles on the blade suction side. Evidence suggests that fouling rates are driven by very small (sub micron) particles. The mechanism for particle deposition for these small particles is not so much inertia and interception (as is the case for larger particles), but rather diffusion in proportion to the original concentration and in accord with random Brownian motion [15]. Transport of particles to the surface is enhanced by turbulent mixing and diffusion.

Siegel [16] researched the fouling of heat exchanger tubes, which follows similar mechanisms as airfoils. His findings are directly applicable to this discussion:

- Deposition rates are sensitive to the level of turbulence in the flow.
- Impaction of particles is an important factor at the leading edges.
- Brownian motion does not significantly contribute to deposition rates due to the very short residence times, i.e the flow velocity is very large compared to the particle movement.
- Particle interception does not significantly add to particle deposition
- The motion of particles due to a shear force gradient (i.e boundary layer) does not yield significant deposits except for very large particles.
- While wet particles and droplets have a very high rate of adhesion to the surface, dry particles will bounce at significant rates.

The particle size most responsible for fouling is 1 to 5 μ m, although higher velocities seem to shift this to smaller particle sizes.

Sample results of the estimated deposition rates for different regions of the blade surface are shown in Figure 6. Relatively low deposition rates are found for the leading edge region. The highest deposition rates are on the suction surface near the trailing edge where the boundary layer is thick and turbulent.

It must be noted that, in general, particle deposition by diffusion mechanisms is typically related to low flow velocities, significantly lower than the free stream velocities in a compressor cascade (Fuchs [11]). However, the blade boundary layer sees significantly lower velocities (actually no velocity at all at the blade surface) than the free stream velocity, that may allow for a sufficient amount of deposition by diffusion.

The diffusion of particles in laminar flow in a tube of radius R $\,$ can be described by

$$n/n_{0} = 1 - 2.56 \cdot \left(\frac{Dx}{R^{2}U}\right)^{2/3} + 1.2 \cdot \left(\frac{Dx}{R^{2}U}\right) + .0177 \left(\frac{Dx}{R^{2}U}\right)^{2}$$

where n is the number of particles out of initial n_0 particles that is not captured by the tube walls after traveling the distance x along the tube (Fuchs [11]). Similar equations describe the diffusion for flows in channels with parallel walls. In this equation , D is the Diffusion coefficient, which depends (among other things) on the particle size and flow velocity. It is known that diffusion in a turbulent flow is orders of magnitude larger than in laminar flow. Since turbulent flow can be thought of as a combination of eddies of various sizes [21], and the eddy size follows a power law distribution (i.e there are more small eddies than large eddies), the diffusion rate of small particles will also be much larger than for larger particles. Particle diffusion as a transport mechanism follows similar relationships as other transport mechanisms, for example heat transfer. It is not surprising that the particle distribution on the surface of the blade (Figure 5) resembles



Figure 8: Blade heat transfer [17].

very much a typical distribution of heat transfer on a blade (Fig. 8)and probably for the same reason: The turbulent boundary layer that leads to high heat transfer also promotes the diffusion of particles. Particles less than 1 micron in diameter are found to diffuse to the surface in proportion to their original concentration and in accord with random Brownian motion [15]. Transport of larger particles to the surface is enhanced by turbulent mixing and diffusion.

Fuchs [11] presents experimental data for air flow in a tube, indicating that the particle flux I (i.e the flow of particles per surface area and time) to the tube walls is

$$\frac{I}{N_0} = \frac{D^{\frac{3}{4}} \operatorname{Re}_f^{\frac{7}{8}} \upsilon^{\frac{1}{4}}}{90 \cdot r_{particle}} = \frac{D^{\frac{3}{4}} U_f^{\frac{7}{8}} \upsilon^{-\frac{5}{8}}}{90 \cdot (r_{particle} / L^{\frac{7}{8}})}$$
(4)

This actually means that for a constant amount N_0 of particles in the air, increasing flow velocity and reducing relative particle size both lead to increased deposition rates. This means in particular that the 4/3 larger the blade dimension L for a given particle size, the higher the deposition rate. This means, that a larger compressor has a higher particle accumulation for a given particle size distribution than a smaller compressor. The data also indicates that only in a turbulent boundary layer is the diffusion coefficient $D=D_l+D_t$ large enough to cause appreciable particle deposition.

The fouling of casings is due to the centrifuge action of the swirling airflow through the compressor. This means in particular, that larger particles hit the walls at earlier stages and more frequently, while smaller particles will come into contact with the walls further downstream in the compressor. The study by Tabakoff et al [18] clearly indicates this: A very small percentage of particles 2.5 μ m and smaller come into contact with the end walls, while a large portion of particles 15 μ m will come into contact with the walls. It must also be noted that foulants can be removed from the airfoil due to natural causes, for example water droplets generated during high humidity. The capability of these droplets (or droplets from on-line water wash systems) to reach the blade surface follows the same limitations mentioned above for particles of different sizes.

CONSIDERATION OF BLADE AERODYNAMICS

Particle entrainment is determined by the compressor aerodynamics. We need to consider both the two dimensional flow across the compressor blades and the three dimensional flow in compressor stages.

Front stages in modern gas turbine compressors usually experience transonic flow, while the later stages are subsonic. In either case, the incidence angle of the air flowing into the blade depends on the operating point. For transonic blades in the choke region, there is a 'unique incidence', i.e. the incidence angle does not change and the shock is attached to the leading edge. For lower throughput at a given speed, the flow tends to enter the blade row at increasing incidence, and the shock is detached from the leading edge. In subsonic compressor blades the incidence angle increases for low flows and decreases for high flows [19].

Regarding the particle behavior, there will be a dominant impact of particles on the pressure side of the blade at low flows, and a increased impact on the suction side near the leading edge at higher flows. In transonic blades, where a oblique shock exists at or upstream of the leading edge, particles will not be able to follow the air flow through the shock without slip. This can cause particles to impact on the blade suction side near the leading edge. It should be noted that the particles, when passing through the shock, develop high velocity differences with the surrounding air, which require adjustments of the equations governing particle drag [21].

Further, the boundary layer that forms between free stream and blade surface needs to be considered. The boundary layer will initially be laminar, and transition to a turbulent boundary layer downstream. In a laminar boundary layer, particle transport perpendicular to the streamlines is possible by means of diffusion. At flow velocities typical in turbomachines, diffusion processes are negligible, although in a laminar boundary layer, where flow velocities are much lower, diffusion processes can have some impact. Turbulent flow, on the other hand, can be thought of as a large number of eddies of various sizes [22]. Particle transport perpendicular to the stream lines is therefore greatly increased. This is therefore a possible mechanism to transport very small particles to the surface of the blades.

Another feature of the boundary layer also has to be considered [21]: Depending on the state of the boundary layer, the shear stresses (and the friction factor) between the air and the blade surface vary significantly (Figure 9)



Figure 9: Friction factor on the suction side of a compressor blade.

This means in particular that particles that reach areas of high shear stresses have a high chance of being swept downstream. Figures 2, 3, and 4 show fewer deposits downstream of the suction side leading edge, which are also areas with a high friction factor (Figure 9). The distribution of the friction factor c_f shown, while in detail very specific to the velocity distribution, is fairly typical for compressor airfoils.

The considerations above are based on two dimensional flow situations. In a three dimensional flow field, secondary flows, driven by the flow through tip clearances and the imbalance between the pressure field and the kinetic energy of the air in the boundary layer, have to be considered (Figure 10). This means in particular, that particles can be deposited in places that would not be reachable for particles in two dimensional flow.

Channel vortices can deposit particles both on the suction and discharge side of the blades. If this is the case, characteristic deposit patterns should be visible on the blade surfaces

Beacher et al [28] describe a potential mechanism how even larger particles can reach the blade suction side, at least the part close to the leading edge: Particles bouncing off the surface of the previous blades will show a large discrepancy of velocity and flow direction relative to the main flow, and thus can reach at least the front part of the airfoils' suction side. However, for compressor blades, with their smaller curvature, particles might actually even reach the rear parts of the suction surface. It obviously would depend on the consistency of the particles whether they actually stick to the blade: They cannot be too sticky, otherwise they cannot bounce off the previous blade.



Figure 10: Secondary Flow Regions in rotor and stator of an axial flow compressor [20].

STATOR



Figure 11: Particle trajectories

By extension, liquid droplets hitting the leading edge of the blade can be transported along the blade surface both on the suction and discharge side due to the shear stress in the boundary layers. If these liquids contain solid contaminants (such as salt, for example), and the liquids evaporate, the contaminants will be left on the blade surface. For this mechanism, droplet size is not very important, because even bigger particles will hit the blade leading edges.

It is often assumed that particles enter the rotor with homogeneously distributed particle sizes. This is generally not the case: Large particles may be collected on the pressure side of the previous blades without sticking to them, entering the air stream with lower momentum. The centrifuge effect of rotors, and probably the turbine inlet system will lead to a separation, bringing the larger particles to a higher concentration at the blade tip, and a lower concentration at the hub.

	Possible Deposition Mechanism for Particle Size (µm)	Reachable Surface	Generate Surface Rough- ness	Chanc e to Stick
Impact [2]	> 5	Leading Edge and Pressure Side	х	-
Diffusion [11]	<0.1	All	-	х
Turbulent Diffusion [11]	<0.5	All	(x)	X
Bouncing Particles [28]	> 5	Leading edge, PressureSide,(Su ction Side near leading edge)	X	-

Table 1: Fouling Mechanisms, i.e. mechanisms that bring particles in contact with blade surfaces

This may favor larger tip-to-hub ratios, as a smaller portion of the blade is subjected to the large particles.

In cases where bearing oil is introduced at the rotor hub, essentially entering the air stream in the hub boundary layer, the movement of these particulates can only be described by three dimensional

considerations, as the transport is along the secondary flow of the blade rows.

STICKING MECHANISMS

Whether particles that come into contact with the blade surface attach themselves depends in two factors: The 'stickiness' of the surface relative to the particle and the shear forces in the boundary layer [21]. The 'stickiness' of the surface is increased if the surface is wet (from water or oil), but it also depends on particle size (particles above about $10\mu m$ in diameter tend not to stick), and the angle of impact on the surface.

The shear forces in the boundary layer are low in areas of laminar flow, and particularly low in areas where the flow separates or transitions from laminar to turbulent flow. The state of the boundary layer is highly sensitive to the operating pint of the compressor blade. The sticking forces of very small particles are very high even without the presence of oils or other liquids on the blade surface. Presence of oil or liquid films on the blades will however increase the particle size that still can stick to blades even in the presence of high shear or centrifugal forces.

Fine particles adhere to rotating blades due to their stickiness that is sufficient to hold the particles even on the rotating blades where the centrifugal forces are high [15]. It is further known from experiments with cyclone separators (Fuchs,[11]), that wet walls increase the entrainment efficiency significantly.

Data suggests [11] that is virtually impossible to blow particles with a diameter of 1 to 2 μ m from deposits on clean plates, even at high

velocities (200m/s). The particles seem to lodge into surface pits and crevices, and thus require far higher flow velocities, or some form of vibration to dislodge. Adhesion of solid particles with diameters $2 - 10\mu$ m can only be secured if some adhesive film (grease, oil) is present. The layer thickness and its viscosity impact the probability of a particle sticking to the surface. A layer thickness of 0.5 to 1 μ m seems to be most effective, thinner layers usually will not retain larger (diameters $2 - 10\mu$ m) particles.

The effects for liquid particles are different from solids. In particular, the higher the impact velocity of the droplet, the higher the changes are that the liquid remains on the surface. Hydrophobic surfaces (e.g. oil covered) increase the chances of particles to bounce off the surface after initial contact. The chance that a particle sticks to a surface is well evaluated for fly ash in boilers and gas turbine hot sections [23]. In general, the mechanisms include van der Waals , capillary, and electrostatic forces, and re-entrainment. The forces get more dominant for smaller particles. If there is wetness, capillary forces tend to dominate. The probability of a particle sticking to a surface increases the lower the viscosity of the particle becomes. This leads to the following:

-Dry particles have to be very small to stick -wet surface and/or wet particles allow bigger particles to stick.

It must be noted that wet particles (for example water droplets) will dry out as they pass though the compressor, and therefore have reduced 'stickiness' when the pass trough the rear compressor stages. Of importance is, that the design of a gas turbine compressor has very little impact on the capability of particles to stick to surfaces once they reach them.

IMPACT ON THE COMPRESSOR PERFORMANCE

The main effect of fouling on compressor blades is an increase in surface roughness, which effects the formation of the blade boundary layer. Because the boundary layer on the blade suction side is affected by an adverse pressure gradient, the impact of added roughness is larger here, than on the blade pressure side.

Morini et al [24] analyzed the performance of a compressor stage with increased surface roughness, compared to a smooth stage. They found a significant deterioration when they used a surface roughness equivalent to about $k_s/c=0.714 \cdot 10^{-3}$ (ks=40µm). The degradation is almost entirely determined by the roughness on the suction side. For a typical compressor blade in an industrial gas turbine, with 100mm chord length, this is equivalent to a surface roughness of 71µm.

If the contamination mechanism is due to impact (i.e the particle can't follow the streamline), then most, if not all contamination would be on the pressure side. If the blades or the particle are wet, then larger particles would stick, and they would cover the pressure side more or less uniformly. Otherwise, for dry particles, mostly small particles would stick, and, since the can follow the streamlines with less lag, they would be found mostly towards the trailing edge. The exception would be particles entrained in the blade passage vortex, that could end up on the suction side, but only very localized where the passage vortex hits the suction surface. The impact of pressure side contamination mechanism is due to diffusion, then we would find small particles on the suction side and the pressure side. They would be expected to have higher changes in high turbulence areas. One also

would expect to be able to identify the areas of boundary layer transition (either natural or through a separation bubble) and flow separation from the contamination patterns. In other words, one would expect a pattern similar to observations in [8]. However, the diffusion mechanism works only for very small particles, so the question becomes how the necessary additional surface roughness (eg ks=40 μ m in Pinellis study) can be generated by particles in the submicron size range.

Syverud et al [9] found indeed that the surface roughness on the suction side was significantly lower than on the pressure side of the compressor blades after spraying atomized salt water into the engine inlet, with $k_s/c=0.06 \cdot 10^{-3}$ on the suction side and up to $k_s/c=1.1 \cdot 10^{-3}$ on the pressure side. The two values would correspond to 6 μ m and 110 μ m, for an industrial gas turbine, respectively.

The question about the roughness necessary to create additional losses can be answered using data found by Milsch [25]. He performed systematic tests with subsonic NACA compressor profiles of increased roughness: The sand roughness had to be larger than about $k_s/c=0.4 \cdot 10^{-3}$ to show increased profile losses (Fig 26-28) and larger than about $k_s/c=0.2 \cdot 10^{-3}$ to show a reduction in turning (Fig 29). Bammert and Woelk [26] conducted experimental tests on a threestage compressor with an increasing blade surface roughness ($k_s/c =$ 1.5·10-3, 2.5·10-3 and 4.5·10-3).

Three different regimes have to be considered [27] as a function of k+: (i) hydraulically smooth regime $(0 \le k + \le 5)$, the friction factor depends only on Reynolds number since the size of roughness is so small that all the protrusions are contained within the laminar sublayer; (ii) transition regime ($5 \le k + \le 70$), the friction factor depends on Reynolds number and on the ratio ks/R since the protrusions extend partly outside the laminar sublayer and the additional resistance is mainly due to the form drag experienced by the protrusions in the boundary layer; (iii) completely rough regime (k+ > 70), the friction factor only depends on the ratio ks/R since all the protrusions reach outside the laminar sub-layer and by far the largest part of resistance to flow is due to the form drag which acts on them. Thus, a key question is as follows: If the particles that stick to the blades are in the sub-micron range, then how can they increase the surface roughness to the point where it impacts the boundary layer development. Blade roughness for compressor blade may be in the range of 0.3 to 1 µm [7].

SUSCEPTIBILITY CORRELATIONS

A number of authors [2,3,13,14,29] have developed correlations that derive the susceptibility and sensitivity of a specific gas turbine model from readily available parameters. Neither correlation distinguishes clearly between susceptibility and sensitivity, but rather combines the two. The way these parameters are intended to be used is as a relative indicator for performance deterioration due to fouling. If two different engine models are compared, where one has a higher index than the other, then the engine with the higher index should show a faster performance deterioration under a given contaminant load.

Tarabrin et al [2] postulate, that a relationship for fouling exists that combines the geometric and aero-thermal characteristics of the engine compressor (ISF). It is derived based on considerations of the entrainment efficiency of a cylinder due to inertial deposition corrected to the entrainment efficiency of a row of airfoils due to inertial deposition:

$$ISF = \frac{Wc_p \Delta T_{stage}}{(1 - r_h^2)D_c^3} \cdot 10^{-6}$$
⁽⁵⁾

The susceptibility of a given engine to particles of a certain size is then:

$$\lambda = ISF \cdot \frac{\rho_p \cdot d_p^2}{\eta_f} \tag{6}$$

which leads to the unsurprising result that larger, heavier particles have a higher chance than small particles to collide with the blade surface and essentially the model predicts a higher susceptibility of smaller gas turbines to fouling, with some impact of higher stage loading. It also seems that the degradation rates referenced by Tarabrin [2] are much steeper than observed in modern industrial gas turbines. Normal operational practice also seems to suggest that engines are typically on crank washed before they get into the state were the degradation curves flattens out.

Song et al [13,14] extend the basic idea of Tarabrin [2], but still base their models on inertial impaction effects. Some important conclusions based on [13,14] include:

• Fouling is closely related to the geometric and flow characteristics of the axial compressor stage. Adhesion of particles to blades (defined as the cascade collection efficiency) is increased with a decrease of chord length and an increase of solidity. Furthermore, fouling is increased with reduced flow rates, which are closely related to the incoming air velocities.

• Large particles increase the cascade collection efficiency.

Deposition of large particles in front stages makes fouling dominant in front stages. Small particles, however, pass through the front stages and influence downstream compressor stages.

• Particle size distribution is an important parameter that influences the extent of fouling.

It is important to note that neither model addresses the question of particle retention on the blade surface. This raises the following questions: If the contamination mechanism is due to inertial impact (i.e the particle can't follow the streamline), then most, if not all contamination would be on the pressure side. If the blades or the particle are wet, then larger particles would stick, and they would cover the pressure side more or less uniformly. Otherwise, for dry particles, mostly small particles would stick, and, since the can follow the streamlines with less lag, they would be found mostly towards the trailing edge. The exception would be particles entrained in the blade passage vortex, that could end up on the suction side, but only very localized where the passage vortex hits the suction surface. The impact of pressure side contamination on loss generation would be relatively small.

It seems that from the perspective of particle behavior, there inertial impaction does not provide a mechanism that would transport particles to the suction side of the blade. In the other hand, the surface shear stresses on the pressure side are generally consistent and high, thus preventing a significant build up of dust beyond a certain thickness. It could well be argued that the maximum build up for virtually any geometry is reached after a very short time – which leaves the question why degradation builds up slowly. In other words: Is the

correct mechanism used to correlate the fouling susceptibility of compressors to compressor geometry and design parameters?

If the contamination mechanism is due to diffusion, then we would find small particles on the suction side and the pressure side. They would be expected to have higher changes in high turbulence areas. One also would expect to be able to identify the areas of boundary layer transition (either natural or through a separation bubble) and flow separation from the contamination patterns. In other words, one would expect a pattern similar to observations in [8]. However, the diffusion mechanism works only for very small particles, so the question becomes how the necessary additional surface roughness can be generated by particles in the submicron size range.

Because interception mechanisms are not sufficient to explain the observed particle deposition on the suction side of the blade, we need to look into diffusion mechanisms [11]. The collection efficiency is inversely affected by particle size and flow velocity, i.e the smaller the particle and the slower the airflow, the higher the deposition rate becomes. For an airfoil of chord length L, the collection efficiency for the diffusion process becomes

$$\lambda = 3 \frac{\left(\frac{8hDR}{3\overline{U}}\right)^{2/3}}{2h^2} = 2.884 \frac{\left(\frac{DR}{\overline{U}}\right)^{2/3}}{h^{4/3}}$$
(7)

with \overline{U} the free stream flow velocity, D the diffusion coefficient, R the maximum thickness of the blade and h the blade to blade distance. Immediately, the impact of wider spaced blades (lower collection efficiency) and higher flow velocity (lower collection efficiency) becomes apparent. It further needs to be determined which factors affect the diffusion coefficient D. If the majority of diffusion is turbulent diffusion, and driven by turbulent eddies), it can be assumed that the diffusion rate is determined by the turbulence rate in the flow.

Seddigh and Saravanamuttoo $\left[29\right]$ propose a relationship for the fouling index FI

$$FI = \frac{P_{GT}}{Wc_{p}\Delta T} \approx \frac{P_{GT}}{P_{compr}}$$
(8)

essentially saying that the higher the compressor efficiency, the higher the susceptibility to fouling.

A wide range of 92 gas turbines has been studied to evaluate their sensitivity to an imposed level of fouling (Mejer-Homji et al,[3]). Key results indicate that the *net work ratio(* NWR = Net work ratio = output/ Wt) is a good predictor of both the gas turbine's susceptibility to foul and its sensitivity to fouling. Low net work ratio engines where a higher portion of the total turbine work is consumed in the compressor tend to be both more susceptible *and* sensitive to axial compressor fouling ([3]). This is basically due to the fact for a given loss of compressor efficiency (η'_c/η_c) , the impact on power output is larger for a low NWR engine (W',W'_c and η'_c are the work and compressor efficiency for the fouled engine):

$$\frac{W_{out}^{'}}{W_{out}} = \frac{W_{t} - W_{c}^{'}}{W_{t} - W_{c}} = \frac{W_{t} - \frac{\eta_{c}^{'}}{\eta_{c}}W_{c}}{W_{t} - W_{c}} = \frac{\frac{W_{out}}{NWR} - \frac{\eta_{c}^{'}}{\eta_{c}^{'}}W_{out}(\frac{1}{NWR} - 1)}{W_{out}} = \frac{1}{NWR} - \frac{\eta_{c}}{\eta_{c}^{'}}\left(\frac{1}{NWR} - 1\right)$$
(9)

In order to assess the nature of the problem, a number of experimental data sets were evaluated, Some of them are from literature references [30-32], some are from own tests (Figure 12). The analysis shows the degradation rate of engines between on-crank washes, which is mostly due to fouling. The important finding is, that neither engine size nor type have a real influence on degradation rate. In particular, the two shaft engine (two shaft engines show a higher sensitivity to fouling according to [1]) did not behave any worse than the single shaft engines.



Figure 12: Fouling Rates (Power Degradation) for different gas turbines. Engines 2 (Haub [30]), 3 (Veer [31]), and 4 (ref Schneider [32]) are all larger than Engine 1 and 5 (present data). Engines 1, 2, 4 and 5 are a single shaft engines, engine 3 is a two shaft engine.

CONCLUSIONS

Based on theoretical considerations, as well as observed engine fouling behavior, a few items can be claimed regarding engine fouling. It needs to be emphasized that this only pertains to engine fouling. Engine degradation due to erosion and corrosion is subject to other mechanisms, either separate or in conjunction with fouling mechanisms.

- Fouling is caused by particle sizes of 10µm and below. Air filtration systems for industrial gas turbines are very effective for particle sizes about 5µm and above, but, depending on the types of filter systems, allow ingestion of particles below that size. In typical operating environments, particles of various sizes, including sub-micron sized particles, are present.
- The capability of particles to stay at a surface is dependent on particle size, and the wetness of particle or surface. In particular larger particles will likely not stay attached to a surface, unless the particle or the surface are wet.
- Particles that reach the surface through inertial impact will not reach the suction surface of a blade, except for the region next to the leading edge. They will reach the pressure surface, as well as the shroud side walls.
- Mechanisms that can bring particles to the suction side of blades require very small (i.e. sub micron particles).
- To achieve a noticeable impact on the blade (or wall) boundary layer, the blade surface roughness has to be increased by the contaminants.

As far as the susceptibility of engines to fouling, a few additional observations are to be made:

- The quality of the air filtration system is probably the dominant factor in engine fouling, as it determines particle size, particle count, and presence of wet particles.

- Ambient conditions (especially the presence of high humidity conditions or the presence of wet contaminants) are the other dominant factor, since this determines the chance of particles sticking to the blades.

This means in particular, that simple factors that rate the fouling susceptibility of engines, and that are based on the chance of particles to impact the blade surface, do not take some of the most important influence factors into account. In other words, ambient conditions and the quality of air filtration systems have a far greater impact on fouling rates than engine specific fouling susceptibility factors.

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