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Authors: Uyioghosa Igie

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GAS TURBINE COMPRESSOR FOULING AND WASHING IN POWER AND AEROSPACE PROPULSION

Uyioghosa Igie

School of Aerospace, Transport and Manufacturing [SATM]

Cranfield University,

Bedfordshire, MK43 0AL, UK

email: u.igie@cranfield.ac.uk

tel: +44 (0) 1234 75 8382

ABSTRACT

This paper presents a well-researched subject area within academia, with a high degree of application in industry. Compressor fouling effect is one of the commonest degradations associated with gas turbine operations. The aim of this review is to broadly communicate some of the current knowledge while identifying some gaps in understanding, in an effort to present some industry/operational interest for academic research. Likewise, highlight some studies from academia that present the current state of research, with their corresponding methods (experimental, numerical, actual operations and analytical methods). The merits and limitations of the individual method and their approaches are discussed, thereby providing industry practitioners with a view to appreciating academic research outputs.

The review shows opportunities for improving compressor washing effectiveness through computational fluid dynamics. This is presented in the form of addressing the factors influencing compressor washing efficiency. Pertinent questions from academic research and operational experiences are posed, on the basis of this review.

Keywords: gas turbine, jet engine, degradation, fouling, compressor washing, maintenance

INTRODUCTION

Compressor fouling is one the commonest forms of degradation for gas turbine engines during operation. For stationary gas turbines, the operating environment can vary significantly. This could be industrial environments such as a refinery that can be around the proximity of the coast and subject to changes in seasonal conditions. Stationary gas turbines have found use in a desert climate such as a: Wintershall power plant at Nakhla site in the Libyan desert **[1]** and the 800MW Sentinel plant, Desert Hot Springs, California **[2]**. The type of environment also includes off-shore platforms and cement factories that bring about particles that are particularly problematic for the gas turbines engines that power such facility.

For jet engines that typically operate at high altitude clean sky, the exposure to airborne contaminants is relatively less. Nevertheless, at the lower altitude, the particles (especially larger) concentration is higher as shown in Alpert et al. **[3]**. For this engine application, some factors leading to the susceptibility of compressor fouling includes:

- Location of the airport (e.g. around desert or coastal)
- Number of take-offs/landings (short or long-haul)
- Atmospheric and seasonal changes
- Flight path/route

The location of the airport is important and especially for the fact that the engine will operate at the highest power setting on ground, ingesting the most amount of air compared to any given individual segment of its entire mission. For example, a jet engine with a take-off mass flow of 1300kg/s (~ 2.3 times more than cruise mass flow) with about 30 seconds of take-off roll ingests about 39,000kg of air. During take-off, it is also typical for aircraft to depart facing the prevailing wind to achieve shorter take-off roll benefitted from higher relative speed and higher lift. Landing performance is also improved by descending in the prevailing wind; however, these two phases increases the vulnerability of airborne particle contamination or compressor fouling. Unlike stationary gas turbines, and with exception of helicopter engines, jet engines have no inlet air filters to mitigate this effect. While compressor fouling can be mitigated by on-wing compressor washing, particle ingestion can lead to compressor blade erosion that is a non-recoverable damage. **Figure 1**and **Figure 2** indicates airports in potentially aggressive environments for aircraft engines (Refs **[4] [5]**).

Figure 1 Satellite view of Queen Alia International Airport [4]

Figure 2 Satellite view of Hong Kong International Airport [5]

In the desert location, the risk is sand and larger particle sizes, as well as sandstorm events which were reported at Queen Alia Airport in Amman, in 2015. The Hong Kong International airport is located on the coast, and while there is no well-documented evidence of Sodium Sulphate (Na_2SO_4) acid formation on turbine blades (caused by sodium in sea salt and Sulphur in jet fuel), the occurrence is possible and known for gas turbines operating in coastal environment as indicated in Khanna **[6]**.

Igie et al. **[7]** indicate the impact of compressor fouling for short and long-haul aircraft with integrated engine models for their respective typical missions. This study which investigates different levels of assumed deterioration shows that the penalty of compressor fouling is worse during take-off than other flight segments (climb, cruise and descent). The additional total fuel consumed due to the rise in fuel flow to achieve the required thrust is shown to be less significant when compared with the accompanying rise in Turbine Entry Temperature (TET) that will reduce the turbine blade life. Both aircraft engines in their respective mission demonstrated similar magnitude in penalty to fouling, with the exception of the worst case simulated, for which the short-haul aircraft became more penalised. This relates to the take-off segment that constitutes a more significant portion of the flight duration compared to the long-haul. Syverud et al. **[8]** demonstrate the impact of compressor fouling with a single-spool turbojet engine. The experimental test carried out for the stand-alone machine (without airframe) involved accelerated fouling using atomised saltwater. This study conducted at different corrected shaft speed shows that the front stage of the compressor is the most fouled, based on the measurements of deposits on the stator blades. The rotors were significantly less fouled based on visual inspection, as reported. In addition to this, it is stated that finer deposits were observed around the annulus, while coarse particles concentrated at the hub. The observation of predominant fouling at the front stages and less or none at the rear stages is consistent with observations in Tarabrin et al. **[9]** for an industrial gas turbine engine of the single-spool. Nevertheless, most civil aircraft engines are multiple-spool and there is currently no quantitative analysis in open-literature to support research studies when implanting degradation across the various jet engine compressor sections. Igie et al. **[7]** implemented fouling degradation only for the fan, while Giesecke et al. **[10]** and Döring et al. **[11]** have considered the booster compressor and High-Pressure Compressor (HPC) respectively.

It can be expected that the fan and Low-Pressure Compressor (LPC) or booster are likely to be more fouled than the HPC, as these compressors are in early contact with foulants and operate at relatively lower rotational speeds, lower temperatures and higher moisture content. Kurz et al. **[12]** show that particle deposition is more conducive with wetness. This supports the notion of less fouling at the HPC where the temperatures are the highest in the compressor. The referred study also indicates that amount of wetness and viscosity is also a determinant for deposition.

On-wing compressor washing is conducted with the engine still on the airframe. This typically occurs by using a starter motor to crank the engine at low rotational shaft speed. The procedure involves the use of spray nozzles on lances that are installed at the inlet of the intake as shown in **Figure 3** . The installation varies in the arrangement, depending on the design of the engine/aircraft intake and varies with the vendor. The washing process usually takes several minutes. This involves the use of detergents and then several rinses with demineralised water until the collected liquid effluent is clear. The frequency of washing is at the discretion of the airline operator. Factors that influences the decision to wash is usually based on the number of flight cycles, the TGT margin, type of environment flown, physical observation of the fan, as well as during other routine maintenance related checks. A Lockheed service publication **[13]** propose compressor water wash after the final flight of the day in a situation whereby salt water from the sea has being ingested from wave splash or wind pickup that can occur in airports around the seashore. This publication also advises washing every 15 days in such environments when the exposure is not direct.

Figure 3 Example of on-wing compressor washing

On-condition monitoring is beneficial in keeping up-to-date with engine performance and health in service, using acquired measurement sensor data and subsequently calculated parameters. Nevertheless, the full potential and level of insight gained from machine data are just ever more exploited in current times, with the availability of more powerful computers, relatively cheaper sensors and developments in cloud computing. **Figure 4** indicates some engine health monitoring sensor location and measurement information obtained from Rolls-Royce **[14]**. This source indicates these as typical parameters, also stating that the Trent engine can be installed with about 25 permanent sensors.

Some of the typical measurement data can be used in evaluating engine degradation. However, these data do not directly identify compressor fouling degradation. Lengthy performance analysis similar to that indicated in Igie et al. **[15]** needs to be conducted, with consistent data acquisition over a period of time.

Otherwise, is it challenging to conclude compressor fouling as the dominant cause of degradation without a physical examination of the state of the compressor. With the engines on-wing and in operation, other forms of deterioration or similar faults exist concurrently with compressor fouling effects. Changes in power settings related to the flight segment altitude, flight cycle payload and variation, engine de-rate and varied ambient conditions makes it cumbersome to incorporate gas path diagnostic approaches in definitively detecting compressor fouling. Advances in this field can see that compressor washing can be implemented only when required rather than based on counting the number of flight cycles or relying on the monitored TGT margin. Aretakis et al. **[16]** present the assessment of a turbofan engine with measurements taken for about one-year, covering 1,100 short-haul flight cycles. This study demonstrates the engine degradation with progressive flight cycles. These include an increase in exhaust gas temperature, increase in fuel flow and a decrease in the compressor exit pressure. Apart from conducting trend analysis used to investigate the health of the machine, model-based diagnostics methods (probabilistic neural network and deterioration tracking) were employed to identify the faulty component and level of deterioration respectively. This study presents an approach to identifying the main degraded component. The high-pressure turbine was identified as the most degraded component using PNN, while the fault mechanism was attributed to the active clearance control that was shown to be actually faulty in operation (mostly closed). The subsequent review highlights studies mainly related to industrial stationary gas turbines, which in parts, are relevant to the gas turbine for propulsion in sections addressing experimental and numerical investigations.

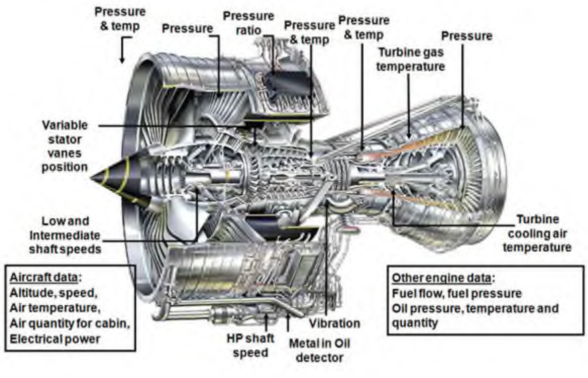

Figure 4 Engine health monitoring sensor locations and parameters [14]

STATIONARY GAS TURBINES

Unlike jet engines, stationary gas turbines are continuously predisposed to contaminants in a given fixed location. Some of the worst cases of compressor fouling are documented in this application, notwithstanding the widespread use of inlet air filters. **Figure 5** shows the fouled rotor blades of a heavy-duty industrial gas turbine engine compressor of 17 stages, with predominant fouling in the front stages.

To mitigate or eradicate the effects of fouling, compressor blade washing off-line or on-line is possible in this application. Off-line compressor washing is implemented when there is an opportunity for engine shut-down. This can often take place accompanying scheduled maintenance checks, before the return to service from an outage or shut-downs related to peak operating plants. Off-line compressor cleaning can be categorised into abrasive blasting, hand cleaning and liquid injection washing. The liquid injection cleaning with installed nozzles involves crank washing, in which the starter motor is used in rotating the blades between 10-20% of the maximum rotational speed.

Abrasive blasting can involve the ingestion of rice, nutshells, walnut shells or synthetic resin particles. Gordon **[17]** states that this method was discouraged, as the new turbine blades in the late 70s/early 80s came with a series of fine holes for cooling. The cooling air to these holes and its passages emanate from the compressor, which meant solid cleaners couldn't be used to avoid blockage. In addition to this, Boyce and Gonzalez **[18]** indicates that some of the abrasives tend to shatter and get into the bearings, seals and lubrication system. Further to this, compressor blades have become more sophisticated having fewer, thinner, larger 3-dimensional shaped airfoils with smaller clearances **[19]**. This also implies that they would be more sensitive to fouling and erosion.

For hand cleaning, this is a manual activity applicable to major maintenance or upgrades. The highest cleaning effectiveness can be obtained, due to direct contact with all set of rotor and stator blades but time-consuming. With regards to the liquid injection approach mentioned, hand cleaning can be conducted for the IGV and first stage blades with a fair amount of access. Nevertheless, this can be an additional time for washing with liquid injection approach. Relatively smaller engines of the aero-derivative sizes may take as long as 2 hours to cool down before an off-line wash is implemented **[20]**. Larger engines take longer and such considerations have to be accounted for when implementing off-line wash if there is ever a time constraint. Allowing the cooling of the hot-section component before a wash is the practice, to avoid thermal stressing in the turbine blade. This can occur when cold liquid is in contact with high-temperature metal surfaces.

Figure 5 Fouled rotor blades of heavy-duty engine compressor

On-line compressor washing involves washing the compressor blade during normal operation, at full-load or part-load. This technique typically involves the injection of atomised washing droplets into the compressor to dislodge fouled deposits on the blades. The nozzles are usually placed around the periphery of the intake. The philosophy behind on-line washing is that it is a proactive strategy to control the build-up of particles on the blades while the engine is in operation. This makes the approach particularly suited for base load continuous operation. The greatest benefits are achieved when the washing process is initiated timely, following engine commissioning, an overhaul or off-line wash. **Figure 6** from Ref **[21]** shows a compressor washing nozzle positioned at the plenum, injecting a spray of droplets into the compressor. Another type of nozzle installation, with the nozzles placed at the engine bellmouth. Other nozzle installations exist, and the location depends on the design of the gas turbine intake. The aero-derivative and smaller engines typically have the nozzles installed on the bellmouth, while the larger frame engines without a bellmouth have such installation on the plenum. One of the main considerations in any installation is to avoid excessive distortion caused by nozzle intrusion with the airflow, as well as unwanted vibration.

Figure 6 Compressor washing spray injection with nozzle at the plenum [21]

The pump pressure for wash liquid injection can range between 45 to 90 bar for the high-pressure systems and below 10 bar for the low-pressure systems. **Figure 7** shows a wash delivery system that can vary in size, depending on the size of the tank, related to the amount of liquid required for a given engine mass flow, the number of engines to be served, the size of the pump and type of application (e.g. off-shore platforms and space concerns). Wash skids or delivery systems are normally connected to the injection nozzles through a network of pipes. The pressure of the liquid in the pipe is regulated by the selected pump pressure, which should be determined based on the mass flow of engine and effective droplet sizes desired. Attention to pressure losses needs to be accounted for when considering elbows and bends for less convenient installations and when the wash system is not near to the engine. There are typically 2 tanks on the wash skid; for the surfactant liquid and demineralised water. In most cases, these tanks usually receive supplies from intermediate bulk containers, however, any mixing of liquid to desired quantities or ratios occurs in the wash system. At least one of these two tanks consist of a heating coil to maintain the temperature of the mixture before injection. These actions can be automated or performed manually at intervals of operating hours.

Figure 7 Compressor washing system

Gordon **[17]** indicates that the next stage of compressor wash system development points towards systems that are linked to the gas turbine performance; by initiating washing when certain amount power is lost, rather than a scheduled wash interval. As for the amount of liquid utilised for on-line compressor washing, it is usually no more than 2% liquid-to-air ratio, with 0.2-0.4% more common. Roumeliotis and Mathioudakis **[22]** highlights the effects of water injection in an experimental study of a single-stage axial compressor at low rotational speed, thereby avoiding evaporation in the stage. The study shows no significant implications in most aerodynamic performance (pressure rise, stall margin and flow pattern) of the compressor. Further to this, however, increase in water-to-air ratio increased the power consumed by the compressor, accompanied by decreases in compressor efficiency. Mechanical losses and acceleration of water were indicated as possible causes of the dominant losses.

Some washing system OEM use the same nozzle for both off-line and on-line washing by varying the injection pressure using lower pump pressure for the former and higher for the latter. This is essentially more liquid with larger droplet and less liquid with smaller droplets respectively. Other OEMs provide separate nozzles for both washing types. Some of the factors that determine the effectiveness of compressor washing is discussed subsequently.

<u>Compressor Cleaners</u>

Commercially available washing liquid type applicable to on-line compressor washing includes demineralised water, solvent-based cleaners and aqueous-based cleaners. These are described as follows:

Demineralised water - The mechanism of washing is based on the injection of demineralised water and impact of droplets. It is non-toxic and not effective to clean oily and carbonaceous deposits especially at low temperatures. However, for some foulants, demineralised water alone is sufficient for cleaning. It is important to add that demineralised water is also used for rinsing after the use of detergents or surfactants.

Solvent-based cleaners **-** Solvent-based cleaners are generally good and contain water and some detergent **[23]**. They are effective in removing oil and grease, however, the removal of inorganic substances like salt in offshore environments is difficult. Further to this, they have low flash point making them susceptible to quick evaporation. ZOK **[23]** indicates that they have an unpleasant smell, may be harmful and hazardous to handle. They are also known to attack or harden rubber seals with the possibility of dangerously fuelling the engine **[23]**.

Aqueous-based cleaners – These solutions contain a mix of surfactant with water. Surfactants are surface-active agents that lower the surface tension of water and oils or solid dirt. They contain hydrophobic and hydrophilic groups that ensure its spreading and wetting properties. Surfactants are effective on greasy fouled blades leaving behind molecules on the surface the help mitigate redeposition. They have non-toxic and non-inflammable characteristics, and also effective on inorganic deposits.

Quick evaporation or low flash point is a collective limitation for cleaner types, given the operating temperatures in the compressor. This problem is common from operational experience and evident when the engine compressor is stripped open for overhaul or upgrade. **Figure 8** shows the effect of liquid evaporation on redeposition of foulants on the rear stages, in a study conducted by Syverud and Bakken **[24]**. In this case, the water-to-air ratio of 0.42% with 75μm droplet size was implemented. Igie et al. **[25]** address the impact of fouling on different stages individually, at a time, for the same level of input degradation. The rationale behind this is to understand the performance implications of redeposition. The findings from the simulation study shown in **Figure 9** indicate that though repositions on the latter/back stages is not favourable, the impact on the overall engine performance can be a lot less bad, the farther away the redeposition is from the first stage. This is mainly because the front stages of the compressor typically have higher loadings and pressure ratios compared to the back stages. The farther away high levels of fouling occur on a stage away from the first stage, lesser critical compression phases are adversely affected. This leads to a more dominant drop in the compressor efficiency in relation to the overall pressure ratio due to an increase in compressor discharge temperature as shown. Nevertheless, the power output reduction remains the most dominant yardstick in relation to the penalty on the machine. To address the problem of evaporation, the use of high-temperature carrier agents can be considered due to their better flash point.

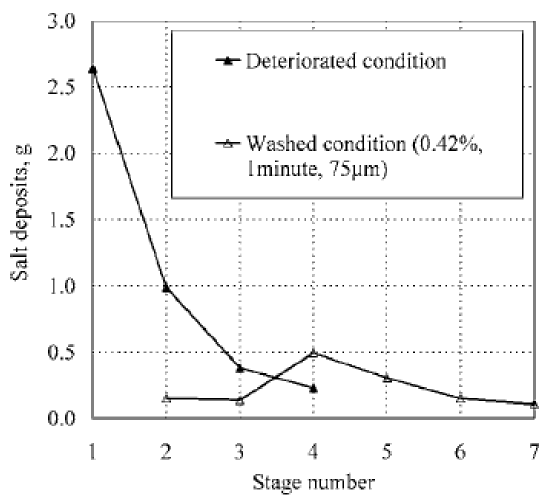

Figure 8 Foulant deposition on compressor stators – fouled and washed compressor stages [24]

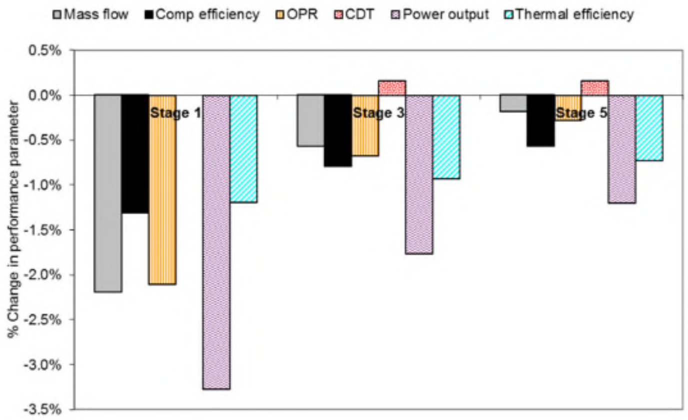

Figure 9 Effect of fouling on engine performance for various individual stage fouling [25]

Injection Spray Droplet Size

The spray droplet size emanating from the injection nozzle varies depending on the orifice diameter, its design spray angle/type, injection pressure, flow rate and liquid property (viscosity, surface tension and specific gravity). In general, if the droplet size is too large, there is a high possibility that the droplets get deflected towards the compressor casing due to centrifugal effects of the rotor blades. In addition to this, large droplets bring about the risk of blade erosion. The smaller droplets with lower inertia tend to flow along the main airflow streamline as show in Rocchi **[26]**. This is demonstrated in **Figure 10** for 50µm, 100µm and 300µm droplet sizes. Nevertheless, droplets too small possess lower kinetic energy to penetrate the blade boundary layer to the effective. This is also accompanied by the higher possibility of evaporation already mentioned.

Bromley and Meher-Homji **[27]** indicates a droplet size range between 50 to 250µm, as an industry agreement for an efficient on-line washing. **Figure 11** is a depiction of a flat fan nozzle applied for compressor washing obtained from Refs **[28]** and **[29]**. This nozzle has an elliptical orifice that forms a non-uniform spray droplet size distribution as suggested. The shape of the distribution can be varied to a positively or negatively skewed distribution by increasing or decreasing the injection pressure. This consequently changes the Sauter mean diameter as shown in Agbadede et al. **[30]**.

Other key consideration is the nozzle spray coverage area and spray distance from the nozzle tip to impact surface (compressor blade). Some knowledge of the potential droplet spray penetration distance is required in producing initial droplets that finally arrives at the compressor stages in liquid form. This is also influenced by the proximity of the nozzle tip to the compressor stages and air flow velocity in the compressor.

The latter effect makes compressor washing challenging to execute with a high level of accuracy, as most understanding of nozzle droplet characteristic is obtained from static air conditions, except through CFD analysis as shown subsequently.

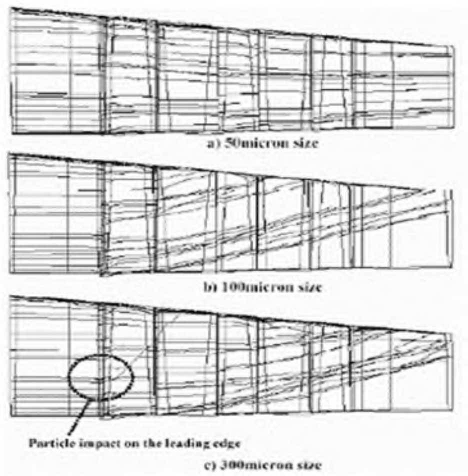

Figure 10 Influence of droplet size on streamlines [26]

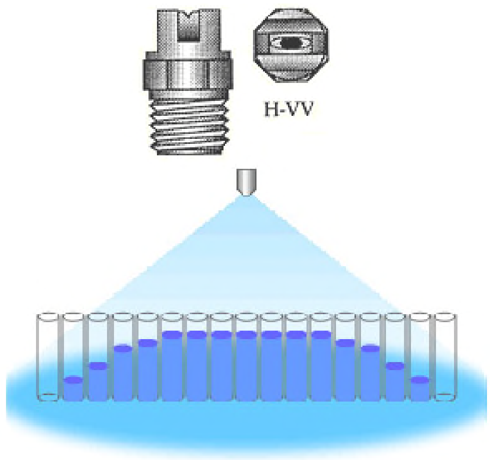

Figure 11 Depiction of flat fan nozzle - top [28] and spray - bottom [29]

<u>Nozzle Positioning</u>

The nozzle positioning around the periphery of the compressor is another key factor in the effectiveness of on-line compressor washing. Much of the liquid spray can be wasted despite meeting all the specified requirements if the nozzle is placed wrongly. The positioning and number of nozzles have to be considered with respect to the coverage areas of the nozzles, the number of compressor blades in the front stage row and their pitch. Better nozzle positioning can be achieved through CFD analysis that can provide good visualisation of the compressor flow. Fouflias **[31]** identifies a 30 degrees deviation from still air compared to that of a working engine in a CFD model. The model of an ABB GT 13 compressor consists of the intake plenum, IGV and first stage as shown in **Figure 12**. This arrangement consists of 19 nozzles on the plenum, and the analysis covers the impacts of varying droplet size and velocity, as well as nozzle placement. The comparisons made are with respect to droplet concentration (coverage area) on blades and droplet trajectories. Despite droplet-to-droplet interaction, breakup, evaporation and deformation are not accounted for in this model, the outcomes have informed practice. The greater understanding gained have been implemented in actual existing installations of similar engine intake design.

Other challenges experienced during washing includes clogging of nozzle orifice, especially for the smaller nozzles used for high-pressure systems to create higher velocity/penetration/spray distance. For the lower pressure system, there is the risk of liquid streaking. To avoid icing in cold conditions, vendors provide pre-mix of washing liquid with antifreeze.

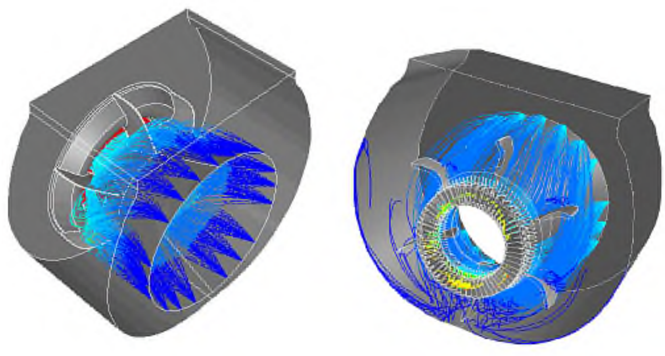

Figure 12 CFD model of on-line washing [31]

RESEARCH METHODS AND THEIR APPROACHES

The previous review focuses on the technology of compressor washing in improving its effectiveness. The emphasis here is on existing research methods and their approaches in investigating fouling degradation and evaluating washing. This also includes a discussion of the individual merit and drawback of the methods/approaches.

Experimental Methods

Experimental methods are useful in the understanding of compressor fouling and on-line washing. These types of investigations are often laboratory accelerated fouling, requiring deliberate human intervention to foul the compressor blades. It is common for the experimental setup to be a compressor cascade wind tunnel consisting of stationary airfoil blades**[11][12][25][32]**. Presently, Syverud et al. **[8]** and Syverud and Bakken **[24]** are the only studies in the open literature for which a full-scale engine has been used for experimental studies. Other experimental setup and investigations include a NASA transonic rotor case described in Suder et al. **[33]** and a single-stage low-speed compressor presented in Gbadebo et al. **[34]**.

Studies show different approaches at initiating fouling effects. Partial blade fouling (surface roughening/coating) on specific parts of the stator blade is shown in Gbadebo et al. **[34]**, to identify the most sensitive part to roughness. The study shows three-dimensional separation on the stator blades, using a roughness strip of ASTM 150 emery paper. This abrasive strip was stuck to a double-sided sticky tape placed on the stator blade, thereby increasing the blade thickness by 0.3mm. The study demonstrates that the leading edge to peak-suction is the most sensitive part especially at flow coefficients close to its design point (ϕ = 0.51). Focus on the impact of an increased roughness and thickness on a low-aspect-ratio compressor rotor is the main focus of Suder et al. **[33]**. The work indicates that a coating of 0.025mm was applied on the suction and pressure side of the rotor blades, which led to 10% increase in thickness of the leading edge and hub, and 20% at the tip (operating close to design point). For the case of rough coating, this amounted to 9% decrease in pressure ratio and 6 points loss in efficiency. Further investigation aimed at separating the effects of coating roughness and thickness, by applying a similar thickness with a smooth coating. This proved that the roughness played a bigger role in deterioration, as the latter case amounted to 4% reduction in pressure ratio.

Fouflias et al. **[35]** adopted an entire blade fouling/coating on a low-speed wind tunnel compressor cascade. The two-dimensional linear analysis with stator blades involved the use of a double-sided sticky tape and carborundum particle ranging from 63µm to 254µm to roughen the blade surface. This study highlights the effect of increasing blade surface roughness on an equivalent stage performance, by subsequently applying Howell’s method. The study also demonstrates reductions in stage flow coefficient and efficiency with increase in roughness. The aerodynamic performance of the blade indicates that total pressure loss coefficient increases with roughness, while the static pressure reduces. The advantage of entire blade fouling and increased levels of roughness employed in the study is that it allows for investigating and gaining insight on worst possible case scenarios.

Particle ingestion into the wind tunnel to foul the cascade blades have been implemented by Balan and Tabakoff **[36]**, Vigueras-Zuniga **[37]** and Igie et al. **[25]**. Balan and Tabakoff **[36]** indicates a 50% rise in the total pressure loss coefficient due to fouling. However, this was likely due to the erosion of the blade's leading edge using large sand particles. This investigation also involved particle ingestion on three separate airfoil cascades with different air inlet angle (0°, 35° and 45°) and stagger angle (-20°, +15° and 25°) but the same incidence, camber and pitch-to-chord ratio. The case with the negative stagger showed the least erosion while the highly positive stagger had the most effect. In all cases, the leading edge and pressure side were the most affected parts of the blade. Vigueras-Zuniga **[37]** improvised a technique to ingest particles into a compressor cascade tunnel. The ingestion system included a vertically placed cylinder connected to a hose feed that sprays out particles towards the inlet of the wind tunnel. The design was based on sand-clock function aided by suction and gravitational effect for the dispersion of particles. The difficulty in trying to capture a substantial fouling case is highlighted in the study, as the flour particle deposition alone led to very little deposition due to lack of a sticking agent. Further efforts were made to apply glue liquid oil (WD40) on the blades thinly and thereafter inject the particles. This procedure proved successful and became the final fouling procedure. The use of a more viscous agent during the trials on the blade proved ineffective as the particles got absorbed in the layer of grease, which appeared to be too thick. Similarly, Igie et al. **[25]** indicate the difficulty in fouling the compressor cascade blades in the wind tunnel show in **Figure 13**. This was eventually achieved at lower inlet Mach number, using an adhering agent containing acrylate copolymer and flour (with measurement probes removed during this process). More deposition on the pressure side of the blades, as well as changes in aerodynamic performance, was accounted. A notable observation is an increase in exit flow angle due to fouling and reduction in the effective blade-to-blade pitch. It also shows an increase in the passage velocity due to boundary layer increase. A decrease in the trailing wake velocity is observed, that is influenced by increased frictional effects. The referred study also includes an investigation of on-line compressor washing with demineralised water applied for 10 minutes at 0.2% water- to-air ratio. From visual observation, there was little or no further removal of particles beyond the first 5 minutes. Measurements taken showed improvements in the aerodynamic performance of the blades after washing. This includes better total pressure loss coefficient and lower exit flow angles. The question about the effectiveness of on-line compressor washing for different wash liquid (2 commercial fluids and 3 grades of water) is addressed in Brun et al. **[32]** for the wind tunnel study involving different flow velocities and incident angles. Paint was used as the foulant, initiated by a spray gun, and the level of fouling was estimated using an image processing software. The outcome of the washing test concluded that all liquid cleaned the blades and that washing mechanism is predominantly a mechanical effect. Igie et al. **[38]** compare the effectiveness of two experimental wash liquids containing different blends of surfactant. With the same level of fouling coating (crude oil and carborundum applied), the case of one liquid regarded as Fluid B produced slightly better washing effect as shown in **Figure 14.** Fluid B washing amounted to marginally improved average total pressure loss coefficient compared to Fluid A. The open question from this study remains to be whether the accumulative effects of compressor washing using Fluid B markedly outperform Fluid A for an extended period of time in operation. This is especially for the fact that the natural build-up of foulants and the interaction of washing agents in the accretion process is not accounted for in this accelerated fouling study.

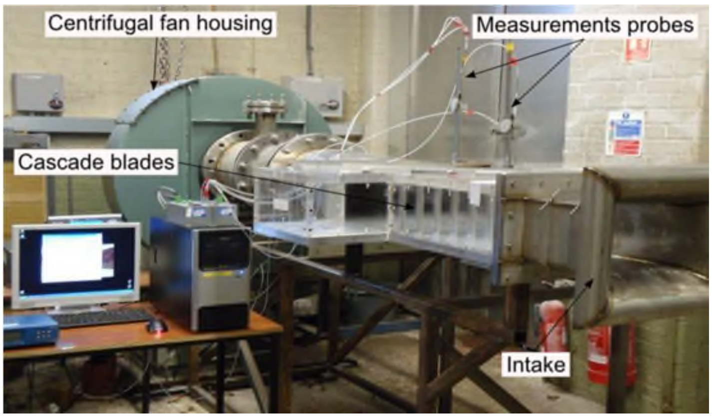

Figure 13 Wind tunnel compressor cascade rig [25]

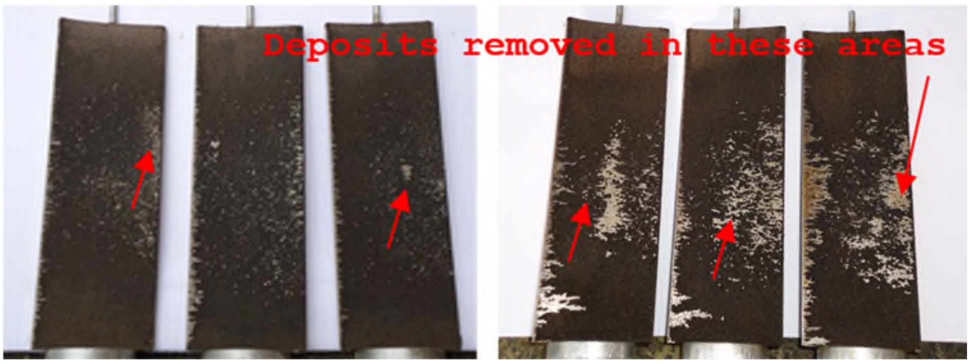

Figure 14 Blade pressure side using Fluid A and B respectively [38]

The ingestion of atomised salt water to accelerate the fouling indicated in **Figure 8** for an engine with 8 compressor stages is presented in Syverud and Bakken **[24]**. The experimental work shows the distribution of salt deposits across the compressor stator blades as indicated in the figure. Reduction in the intake depression and compressor isentropic efficiency is shown to be an effect of fouling in this study. The paper shows the use of demineralised water with water-to-air ratios by mass flow ranging from 0.4% to 3%. The influence of liquid quantity, droplet size and duration on the effectiveness of washing is shown in this study. This includes evidence that more water at 1.7% water-to-air ratio was more effective than at 0.4%, and for the later, washing for 4 minutes did not lead to any significant performance benefit compared to 1 minute. Increasing the droplet size from 25μm to 75μm led to an increase in performance of the compressor but not the case when increased to 200μm.

Experimental studies using actual machines are the closest forms of replicating actual fouling conditions. Nevertheless, the degrading nature of the fouling problem, especially with particle ingestion has meant that majority of the studies are wind tunnel cascade analysis. Most experimental studies conducted have provided typically insights on the aerodynamic performance due to fouling and compressor washing.

Numerical Methods

Numerical analysis using CFD is useful in obtaining approximate solutions to real problems. It also allows for investigation of existing design or processes where experimental measurement is impossible. For compressor fouling and washing, CFD is very useful in predicting particle/droplet trajectories within a compressor as well as improving the understanding of particle deposition. Recent studies in this area on fouling are presented in Suman et al. **[39]**, Saxena et al. **[40]** and Casari et al. **[41]**.

Unlike experimental and actual engine operation, there is currently no numerical study that predicts the removal of fouling particles on compressor blades due to washing. This is a difficult and complex phenomenon to stimulate with a number limit factors arising from the fouling problem, even before the washing is investigated, as subsequently discussed. Studies on compressor washing currently focus on droplet particle tracking and coverage areas as discussed in Refs **[26][31]**. There are a number of existing ways to account for fouling in compressors using CFD tools. This currently includes:

- manually assigning/imposing surface roughness partially or entirely on the blades (without particle ingestion) **[31] [34] [42]**. And added thickness **[43]**
- applying roughness and thickness (change in blade geometry) based on particle ingestion **[33]**. Other studies **[44][45][46][47]** in this category focus only on particle tracking and deposition (no change in geometry). Furthermore, Suman et al. **[39][48]** have investigated these depositions for subsonic and transonic axial compressors respectively.

Fouflias **[31]** employs the first method, applying a uniform equivalent sand roughness ranging from 63µm to 254µm, in accordance with a corresponding experimental case **[35]**. The clean blade was considered using enhanced wall function treatment. To implement this roughness effect computationally, the referred study made adjustments on the first grid around the clean blade airfoil. The centroid of the cell around the wall was made greater than the roughness height (diameter) imposed. Using a K-epsilon turbulence model, the study demonstrates the impact of increasing surface roughness on the total pressure loss coefficient, blade passage velocity and exit flow angles. The work shows a 2º increase in the exit flow angle for the first 102µm surface roughening, but 1º increase in the exit flow angle for an additional 152µm (to become 254µm). This non-linear increase is attributed to a possible blockage because of increased wake size that is characterised by lower downstream velocity arising from wall friction. The numerical aspect of Gbadebo et al. **[34]** is validated with experimental studies that show qualitative agreement between both approaches, for the same flow coefficient. Roughness is accounted for considering skin friction and turbulent mixing, as a shift in wall functions y^+ and u^+. This aspect, like the larger part based on experiment, considered stator only blade roughening in the stage. Morini et al. **[42]** consider roughness on the rotor blades only, stator blades only and a combination of both using a NASA stage 37 geometry. The study shows the biggest penalty of roughness for the case of combined rotor and stator roughness that is signified by a lower pressure ratio as shown in **Figure 15**. The performance penalty is comparable to the case of rotor only roughness case as shown, while that of the roughness on the stator only is similar to the smooth/clean stage. The dominant penalty for the rotor case is due to the main contribution to total pressure rise in the stage. This study extends to identifying the effects of roughness on the suction and pressure side of the rotor respectively. The outcome shows more significant deterioration in performance for the suction side roughness between both cases and worsened when both surfaces are roughened.

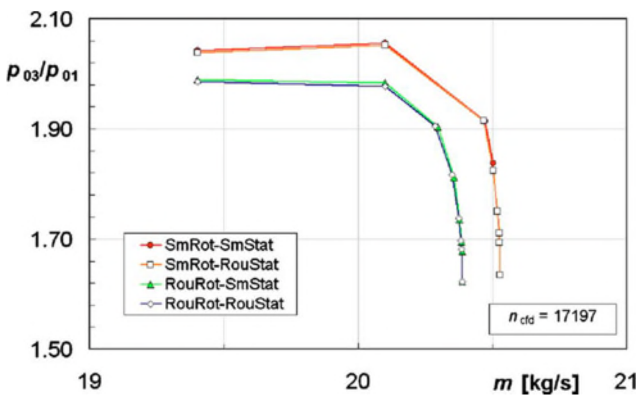

Figure 15 Pressure ratio versus mass flow (smooth stage, rough stator, rough rotor and rough stage)[42]

Particle ingestion in a Rolls-Royce HP9 single-stage research compressor model is the focus of Sauniere **[45]** that implements a Discrete Phase Model (DPM). The DPM solves the individual particle dispersion/trajectories using Ordinary Differential Equations (ODE). Unlike the converged continuous air flow that was simulated using the Eulerian frame of reference, the method applied here is the Lagrangian approach that considers each particle as a point without finite dimensions. The outcome of the particle ingestion study shows that particles of larger sizes generally have higher collection efficiencies. The rotor is seen to have higher collection efficiency than the stator due to its position in front of the stator. However, with respect to the number of particles at the stator inlet, the stator is relatively more fouled than the rotor. It is important to state that these findings are based on a trap model and do not include the effect of particles detachment. In an earlier study by Bouris et al. **[44]** that focuses on rotor and stator blade deposition rates, the leading edge is shown to have the highest deposition rate. The stator pressure side was found to be more susceptible to larger and heavier particles due to inertial impaction mechanism. As such, the authors suggest that the stator pressure side will also be more vulnerable to erosion, as the larger particles deviate from the flow streamlines leading to more impact. The deposition rate model implemented in this work takes into account the particle and blade surface material, as well as the energy balance at the impact point. Suman et al. **[39] [48]** used actual particle concentration and their size distribution and effects of filtration efficiency for a subsonic and transonic compressor to establish fouling location and quantity. These studies also agree with the high susceptibility to fouling on the pressure side of the blade for different environment and seasons. The impact of rotor and stator interaction in the prevailing levels of deposition on the blades is the focus of Aldi et al. **[47]**. This study shows the build-up of particles for isolated rotor and stator cases, also indicating a dominance in particle deposition on the pressure side for both rotor and stator respectively. This is dominant for the larger particles (1.5µm) for which the hit impact efficiency is the highest. For the smallest particle size (0.15µm) investigated, there is a more even concentration of particles on both sides of the blade, for isolated rotor and stator as shown in **Figure 16**. In another Eulerian-Lagrangian model, the emphasis is on a multi-stage high-pressure compressor particle tracking [39]. This study shows the role of particle size, shape factors and bleed position on the trajectories of these particles. The paper shows particles centrifuged towards the casing but a more distributed radial profile for 40µm and 60µm particle sizes compared to 20µm. The first bleed is shown to extract more particles than the second bleed, with the smallest particle size of 20µm as the most extracted for spherical particles. In addition, a greater amount of particle extraction is observed for non-spherical particles at the first bleed.

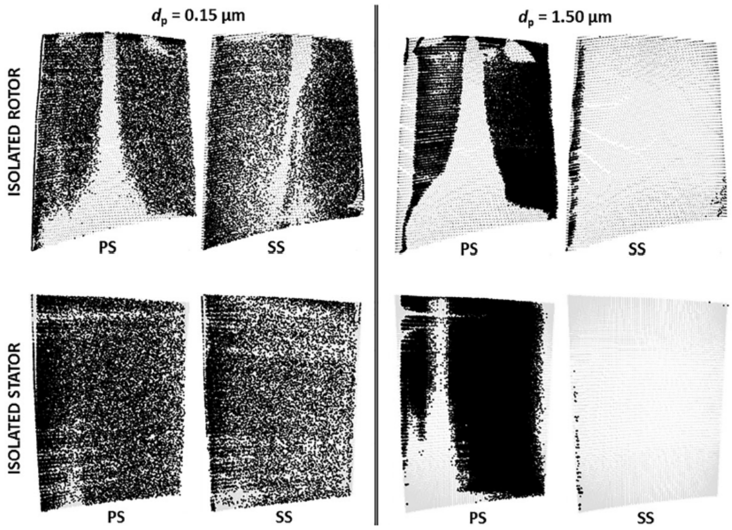

Figure 16 Isolated rotor and stator – pressure and suction side particle depositions [47]

In a related study, on turbine blade particle deposition, El-Batsh **[49]** highlights the difficulty in attempting to account for the change in the geometrical shape of the blade applying user defined subroutines. **Figure 17** (left) shows a modified mesh around the blade wall. The modification of the cell wall was determined and implemented when the deposited particle volume is greater than the fluid cell volume. Nevertheless, it is reported that obtaining convergence proved difficult due to the non-uniform surface of the blade. This also caused a change in the y^+ value that did not necessarily satisfy the criteria for near-wall modelling. Further to this, a converged solution was achieved by using the known deposited mass of particle and locations to create an added thickness of the blade (as shown on the right). This ensured that near wall modelling requirement was satisfied. The lengthy procedure in achieving a change in the geometry of the blade and consequently changes in downstream flow based on the related deposition demonstrated the first of its kind. For a compressor stage, Morini et al. **[43]** demonstrate the implications of added thickness further from the work of Suder et al. **[33]**.

The studies discussed have provided a lot of understanding of fouling phenomenon from an aerodynamic performance viewpoint, with wider implications for the gas turbine engine system. From the review of some of the main studies indicated, it is clear that a lot fewer studies have investigated compressor washing. Some recommendations are provided later in this review.

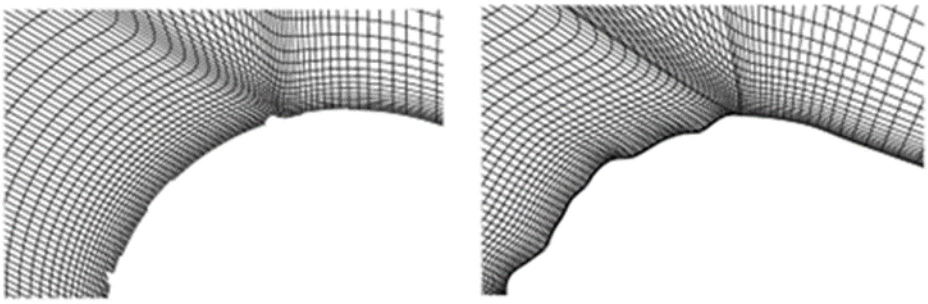

Figure 17 Modified meshes to account for fouling change in geometry [49]

Actual Engine Operations

Actual engine experience operating fouled and washed conditions has been presented in a number of publications. The main difference between these studies and experimental investigation is that the fouling here is a non-controlled process. These types of studies do not present the local aerodynamic changes that occur in the blades or stages during fouling and after washing, as a result of the intrusive nature of in taking measurements within the compressor stages. Data acquisition systems connected to probes or sensors on the machine typically measure compressor inlet and outlet conditions (pressure and temperature), guide vane opening, fuel flow, exhaust gas temperature, rotational shaft speed, torque (hence power output) and additional information of fuel heating value. These parameters are sufficient in evaluating the compressor pressure ratio, its isentropic efficiency and thermal efficiency as a function of time.

Unlike the experimental and numerical methods, there is added uncertainty in quantifying compressor fouling and washing effects from actual practice, due to the extent at which other known and unknown factors influences degradation. These factors can include: change in ambient conditions, inlet air filter pressure losses, change in fuel composition, change in power setting, possible blade erosion, turbine back pressure and ageing/natural wear and tear.

Known influencing factors such as inlet conditions (compressor inlet temperature, pressure and relative humidity), and power setting/load changes have to be accounted for in such investigations. Igie et al. **[15]** demonstrate this, showing the changes from the original data to corrected/normalised version. To investigate degradation in 4 engine units for 3.5 years, a given selected corrected fuel flow was chosen to observe the variation of the corresponding corrected power output with time. This resulted in negative slope trend lines, indicating degradation, shown in **Figure 18**. In this study, the proof of compressor fouling as a cause of deterioration was established by the analysis of the washing cases. All 51 occasions of offline washing showed improvement in the corrected power after washing with the highest recorded 5% increase. The on-line washing studies also supported this, showing a lesser average rate of degradation when the engine was washed (compared to no washing). Small benefits were obtained with a small increase in the frequency of wash and more concentrated wash solution.

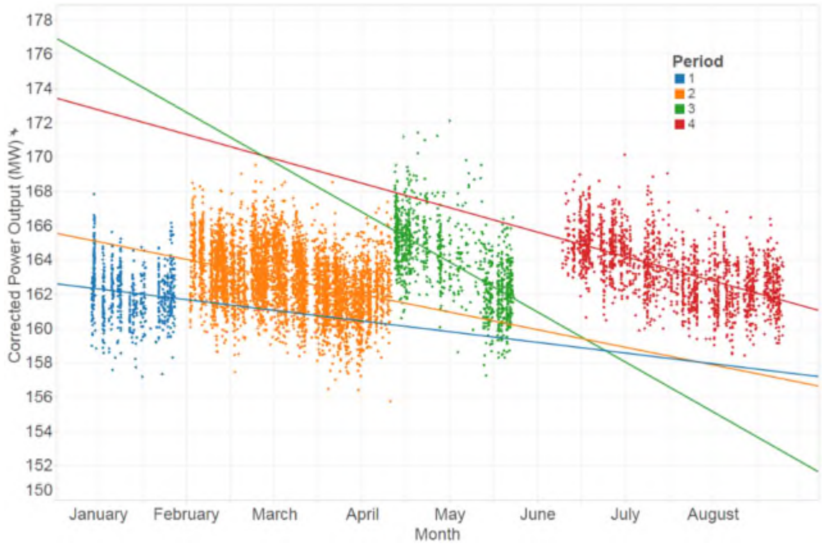

Figure 18 Engine degradation with time [15]

Schneider et al. **[50]** present a study involving on-line and off-line practices to control fouling in 6 engine units (3 single and 3 multi-shaft engines) operated at two different plants. For the single-shaft machines located in a moderate climate, the relative corrected power output trends for the engine without washing showed sign of degradation after 6 weeks, that of the engine washed weekly showed this signs after 9 weeks. For the third engine in this plant washed daily, the signs of degradation were observed after 12 weeks. This amounted to a power reduction of 3.6%, 3.4% and 2% respectively, at the end of 9 months. The multi-shaft engines located in a tropical environment generally showed slightly higher reductions. This is 4% reduction in power for the unwashed engine in the 6th week, which was similar to the magnitude of power loss with another neighbouring engine washed with detergent for the same period. The most optimistic case was the third engine washed daily with demineralised water that indicated 1.5% reduction in 11 weeks. The authors suggest that a daily wash with detergents may provide better results. Boyce and Gonzalez **[18]** also shows the results of tests comparing solvents and varied water wash frequencies.

A credible approach to identifying and quantifying fouling effects during operation (apart from complete engine decommission) is by:

- comparing neighbouring engines in the same location (engine with and without washing, for similar corrected power setting)
- comparing washed and unwashed periods for a given engine, for similar corrected power setting
- comparing effects of varied washing schemes: wash frequencies or liquid types for similar corrected power setting

The last point is particularly applicable to operations for which all the engines are washed online. In this situation, it can be difficult to ascertain whether the washing is having an impact, as the engine still degrades (as online washing only decelerates the rate of degradation **[15]**) and the consequence of not washing is not known. Other related study showing the benefits of compressor washing from operational performance data includes Leusden et al. **[51]**.

Analytical Methods

Analytical methods predominantly focusing on compressor fouling is wide ranging. This covers areas such as simulations of compressor fouling on engine thermodynamic performance using models, investigations of sensitivity and susceptibility of different engines to fouling, as wells as combining fouling effects to other off-design scenarios (e.g. power setting and ambient conditions).The input degradations are based arbitrary factors, experimental or operational experience. Some cases are presented in Kurz and Brun **[52]**, Mohammadi and Montazeri-Gh **[53]** and Igie at al. **[25]**.

The susceptibility of axial compressors to fouling is investigated in Seddigh and Saravanamuttoo **[54]**, which propose a fouling susceptibility index as a measure for comparing different engines. This index is defined as the machine power output divided by the stage work, where the stage temperature rise is obtained from stage stacking technique. As such, the study indicates that larger engines have higher susceptibility index and therefore more vulnerable to fouling than smaller engines. With regards to sensitivity to fouling, Tarabrin et al. **[55]** propose a sensitivity index that includes the work done per stage, the hub-to-tip ratio of the first stage and tip diameter. The outcome of this is that engines with compressor stage of higher temperature rise or stage loading per stage are more sensitive. As such, fouling is found to be more detrimental for smaller engines as highlighted in the study. Meher-Homji et al. **[56]** address both susceptibility and sensitivity based on these previous works, in the study that involves the simulation of 92 engine models (heavy-duty and aero-derivative), all running at similar conditions for base load application (using TET control model).The simulation was conducted using GTPRO software with an implanted degradation of 5% reduction in mass flow and 2.5% reduction in compressor component efficiency. This study shows that when applied to a wider variety of engines, the susceptibility index is more indicative of sensitivity and recommends that the net work ratio between the turbine and compressor is a yardstick for the susceptibility and sensitivity.

Further considerations on the impact of fouling on engines include how the engine is controlled/constrained; approximately constant TET or shaft power. For the case of maintaining constant TET and rotational speeds for single and multi-shaft engines, Tarabrin et al. **[9]** shows that multi-shaft engines are more sensitive than single-shaft. The effect of stage location and fouling is also presented in the early work of Zaba **[57]**. The study shows that the percentage reduction in mass flow and compressor efficiency due to fouling is dependent on the location of fouling in the compressor. A fouling influence coefficient that relates to the percentage change in mass flow divided by the percentage change in compressor efficiency is proposed. This study indicates that an influence coefficient greater than one relates to a heavily fouled front stage fouling. A coefficient less than one is an indication of rear stage fouling, while one is a uniformly fouled stage. As the mass flow is not an operational data, the compressor overall pressure ratio and compressor efficiency can be an alternative as can be inferred from **Figure 9**. The bar chart would infer an influence coefficient less than one from the third stage fouling, using mass flow or pressure ratio with compressor efficiency. The absence of change in compressor discharge temperature (CDT) in this figure is also reported in Aker and Saravanmuttoo **[58]**. The referred study indicates no changes in CDT when only up to 20% of the compressor stage is fouled.

Further inference from these types of studies indicates added complexity for some engine fault diagnostic methodologies at adequately detecting fouling in actual practice, as an unseen data of rear stage fouling operation not used in training may not lead to fault detection/prediction with high confidence. The fact that the fault signatures differ for different load settings **[53]** also requires a wider range of power settings during training, when considering diagnostics for actual operations. Li **[59]** and Marinai et al. **[60]** presents reviews of different diagnostic approaches, indicating their respective advantages and disadvantages.

Igie et al. **[25]** include simulations of fouling in the first three stages of a 10-stage compressor model, using an in-house gas turbine performance code: TURBOMATCH. The implanted degradations are based on compressor cascade experimental test for the first stage and relative levels of fouling for the second and third, based on open literature. This work shows the unloading of the front stages and loading of the back stages (that only suffer the penalty of reduced mass flow) as shown in **Figure 19**. The rise in pressure ratio in the back stages attests to the possibility of flow reversal and surge in extreme situations. It is important to state that the overall pressure ratio or CDP here is still lower than the clean condition. This study also investigates the impact of fouling in part-load operations at the constant shaft rotational speed operation and constant lower TET. Mohammadi and Montazeri-Gh **[53]** also shows the implications for a two-shaft engine (variable generator speed and variable TET). Kurz et al. **[61]** highlight the implications, alongside changes in ambient conditions, applicable to single and two-shaft configurations.

Other analytical studies using engine models includes Zwebek and Pilidis **[62] [63][64]** that presents simulations of fouling (and others degradations) on combined cycle gas turbine power plant performance. The marginal increase in exhaust gas temperature experienced during fouling in the gas turbine engine does not yield added overall advantage to the power plant efficiency, mainly due to flow capacity reduction. The overall thermal efficiency of the plant is seen to be reduced as the mass flow reduction in the gas turbine also amounts to less steam generated in an unfired HRSG.

Analytical methods have brought about a better understanding of compressor fouling fault, using approaches that are often less computationally intensive compared to numerical methods. Combining different faults and conditions is more convenient, leading to further understanding of engine off-design behaviour when working with operational data and creating models for diagnostic tools.

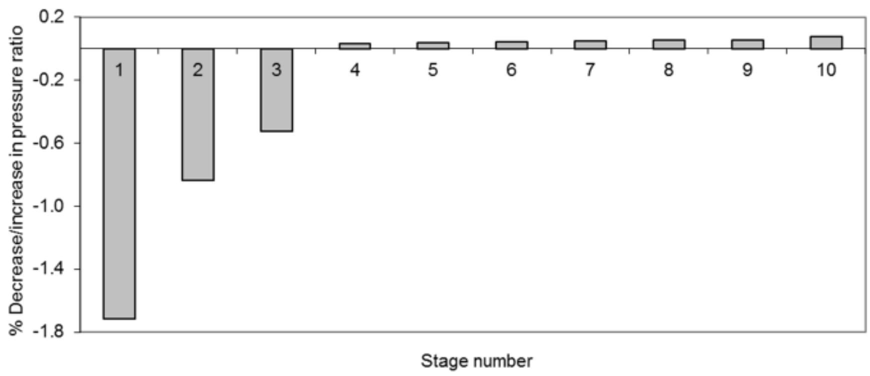

Figure 19 Changes in pressure ratio of compressor stages due to front stage fouling [25]

AREAS FOR RESEARCH EXPLORATION

This review has taken a perspective of focusing on the main areas that have furthered the understanding of compressor fouling and compressor washing, applicable to energy and aerospace applications of gas turbines. This has covered experimental, numerical, actual engine operations and analytical methods, citing their respective merits and limitations, and areas for development in some cases.

Given that the design of compressor blades is unlikely to change fundamentally to suit a conceivable novel configuration leading to reduced fouling, and that some level of fouling will occur in many operational circumstances even with high-efficiency air filters, finding effective ways of mitigating fouling when particles get past air filters, is important. From the review, some of the identified areas that also appear to consist of relatively few research contributions are as follows:

1. Compressor Washing using Numerical Methods – the use of numerical methods will enhance the knowledge and the prospects of improving washing effectiveness with regards to coverage areas of sprays. Investigations into varied nozzle positions, droplet sizes and injection velocities can be studied with respect to known vulnerable areas of deposition based on particle ingestion and deposition studies. The challenge of such proposed studies is the availability of geometries/dimensions of actual compressors and intakes, to ensure that simulated conditions and injection nozzle locations are indicative or applicable to real operations. An example of a related study is Fouflias **[31]** that considers this, however, the washing droplet investigation is not in relation to fouling studies.
2. Use of Diagnostics Tools – though this review does not cover this aspect comprehensively, collectively, limited work has been conducted in using diagnostic tools for predictions based on actual machine operational data (or realistic situations). The use of operational data is pertinent, given the widely diverse off-design engine behaviour inherent in such operations that is not embodied in simulation model based data. The level of accuracy in fouling degradation prediction and practicality of machine learning methods needs further investigation, given the influences on fault signatures as a result of changes in dominant fouled stage location and changes in power setting. Apart from the benefits of fault identification and quantification, that can inform maintenance practice, significant cost savings on washing frequency can be made with an on-condition based approach as opposed to washing at given intervals of time.

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NOMENCLATURE

CDP	Compressor discharge pressure
CDT	Compressor discharge temperature
CFD	Computational fluid dynamics
DPM	Discrete phase model
HPC	High pressure compressor
HRSG	Heat recovery steam generator
IGV	Inlet guide vanes
LPC	Low pressure compressor
MW	Mega Watt
y^+	Wall dimensionless distance
u^+	dimensionless velocity

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Igie, Uyioghosa

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