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Alessio Suman[1]
Dipartimento di Ingegneria,
Università degli Studi di Ferrara,
Ferrara 44122, Italy

Mirko Morini
Dipartimento di Ingegneria Industriale,
Università degli Studi di Parma,
Parma 43124, Italy

Nicola Aldi
Dipartimento di Ingegneria,
Università degli Studi di Ferrara,
Ferrara 44122, Italy

Nicola Casari
Dipartimento di Ingegneria,
Università degli Studi di Ferrara,
Ferrara 44122, Italy

Michele Pinelli
Dipartimento di Ingegneria,
Università degli Studi di Ferrara,
Ferrara 44122, Italy

Pier Ruggero Spina
Dipartimento di Ingegneria,
Università degli Studi di Ferrara,
Ferrara 44122, Italy

A Compressor Fouling Review Based on an Historical Survey of ASME Turbo Expo Papers

Fouling afflicts gas turbine operation from first time application. Filtration systems and washing operations work against air contaminants in order to limit the particles entering the compressor inlet and remove the existing deposits. In this work, a global overview of the operational experience of the manufacturer, the filtration systems, and the particle deposition of the compressor are reported. The data reported in this review have been collected from 60 years (1956–2015) of ASME Turbo Expo proceedings. This conference is recognized as the must-attend event for turbomachinery professionals. Through the years, many issues have been resolved by the contributions of this conference. Regarding the compressor fouling phenomenon, the contributions presented at the ASME Turbo Expo mark the high level of development in this field of research, thanks to the simultaneous presence of manufacturers, government, and academia attendees. The goal of the authors is to describe the technological evolution and challenges faced by manufacturers and researchers through the years, highlighting the state of the art in the knowledge of fouling, and defining the background on which further studies will be based.

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1 Introduction

Each gas turbine manufacturer has his own tolerances and design constraints, each installation site its own peculiar climatic conditions, and each user his own operational requirements. Land-based (desert, city, rural, etc.) and offshore (marine, platform, etc.) power plant locations are characterized by different sources of contaminants due to the combination of natural/artificial sources and weather (rain, fog, wind, etc.). In each location, the gas turbine is involved in performance degradation. As reported by Diakunchak [1], types of engine performance deterioration may be listed under the following headings:

- permanent performance deterioration (aging), which is theoretically recoverable after the overhaul and refurbishment of all clearances and the replacement of damaged parts. The "as new condition" depends on the manufacturer's capability of restoring the initial condition of eccentricity, surface roughness, and distortions (of platform, struts, airfoil, etc.);
- performance deterioration, which is non-recoverable with cleaning/washing operations,
- performance deterioration which is recoverable with cleaning/washing operations.

In the light of the three aforementioned points, the three main families that cause degradation in compressor gas turbines are: (i) corrosion, (ii) erosion, and (iii) fouling. In general, corrosion and erosion are classified as nonrecoverable with cleaning/washing operations, while fouling is classified as recoverable with cleaning/washing operations. Diakunchak [1] estimated that the extent of nonrecoverable deterioration is usually less than 1% and Hepperle et al. [2] summarized the performance trend affected by the degradation and the effects of subsequent actions in order to reach the best possible performance of the gas turbine.

Fouling mechanisms involve three specific aspects: (i) the environmental conditions (airborne contaminant, salt, etc.) in which the gas turbine operates, (ii) power plant design and management (filtration system, washing operation, etc.), and (iii) compressor characteristics (pressure ratio, number of stages, etc.). Kurz and Brun [3] summarized all of these aspects, and pointed out that in order to resolve the fouling issues, specific analyses must be dedicated to each of the aforementioned aspects. These aspects work together in determining the fouling mechanism. In Fig. 1, some blade contaminations are reported [3,4]. All blade areas could be affected by the contaminants which could stick to the blade surface as a function of (i) the material of the bodies in contact, (ii) the surface conditions, (iii) the particle size, (iv) the impact velocity, and (v) the impact angle. The conditions under which these contaminants stick to blade surface are still less clear. Over the years, several contributions and analyses related to the fouling phenomenon have been proposed, and this review aims to summarize and highlight the basis upon which further studies will be carried out.

2 Manufacturer State of the Art

Starting from the field experience, manufacturers have changed their test-paradigm from in situ to in-laboratory. Empiric relationships, based on the data taken from power plants, have been created in order to relate the results obtained by testing gas turbine prototypes (or power units before shipping), by means of specific laboratory tests, and real operating conditions. Land-based and off-shore environments have been considered during the inspections and tests. Particle deposition and salt in the air represent the

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[1] Corresponding author.

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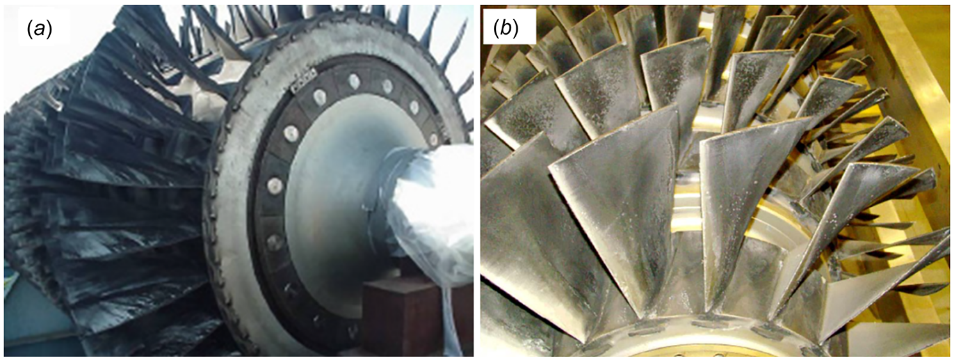

Fig. 1 Blade contamination: (*a*) oily deposits on axial compressor blades as a result of oil leakage on a large heavy duty gas turbine [4] and (*b*) salt deposits on compressor blades after 18,000 h [3]

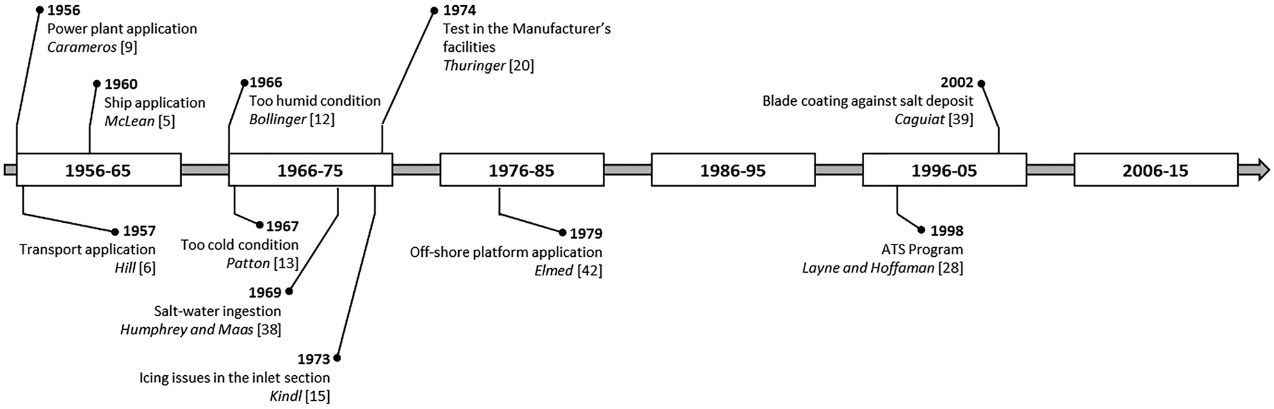

Fig. 2 Manufacturer state of the art timeline

major issues. Figure 2 shows a timeline which summarizes the principal contributions within this field.

2.1 Land-Based Applications. Since the beginning of the 1950s, gas turbines have quickly become widespread. McLean [5] reported extensive use of GE gas turbines in the middle of the 1950s. A review is made of all General Electric Company Gas Turbines installed and in operation prior to January 1, 1958. At the end of 1957, there were 134 General Electric Gas Turbines installed and in operation. These gas turbines operated in three basic applications: 80 industrial, mechanical drive; 28 transportation (27 locomotive and one marine), and 26 power generation. Electric utility applications included base load, end of line, peaking, and stand-by service. The industrial applications included natural-gas pipe-line compressor drives, refinery compressor drives, oilfield pressure maintenance, crude-oil pipe-line pumping, and chemical-process compressor drives.

In early gas turbine applications, manufacturers pushed for the testing of turbine capabilities beyond the power plants or compressor stations. Some field experiences can be found regarding the application of gas turbines for transportation. These applications are characterized by the contemporary presence of erosion and fouling phenomena [6–8].

One of the first reports on gas turbine operation in a power plant can be found in Carameros's study [9]. This is a summary of El Paso Natural Gas Company's operating experience, covering the design and operating problems encountered during the period between September 1952 and January 1956. Some discussion on operating and maintenance costs is also offered. The paper reports operating experiences with 28 gas turbines from 1952 to 1956. The power station used air washers for both cleaning and cooling the inlet air and for this reason, fouling affected the axial compressors. This type of cleaning gave the turbine additional horsepower capability, but also introduced the possibility of fouling the axial-flow compressor with water-soluble solids if any water was carried over into the compressor. Another heavy-duty application can be found in Aguet and Von Salis [10]. In this case, the heavy environmental conditions due to proximity to the furnace are reflected in the extremely high amount of deposits in the turbine sections. The build-up of deposits in the turbine took place relatively rapidly, owing to the fairly high dust content of the blast-furnace gas. These deposits caused a drop in the power output of about 15% after 6 months of operation and about 25% after a full year. This deficiency could be nullified to a certain degree if it were possible to overhaul the group in the spring. The plant would then remain relatively clean during the summer months, whereas the effect of the deposits would be largely compensated for during the following winter, owing to the lower ambient air temperature. The first gas turbine overhaul showed slight corrosion in the combustion chamber and on some blades in the first stator row of the turbine. In this case, no data were given regarding the compressor sections.

Thanks to the increase in the number of gas turbine applications, over the years some reports related to gas turbine operations in "exotic" environments have become available. Arvidsson [11] compared two operating experiences with gas turbines in arctic (Sweden and Canada) and tropical (Venezuela and Nigeria) conditions. As well as the different operating temperatures experienced by the gas turbines, a huge quantity of insects was always collected on the filters in the tropics. A similar problem could potentially arise in arctic zones, where big swarms of mosquitoes are present during summertime. For these reasons, equipment was provided for compressor washing during normal operations.

The average interval between washings in the tropics was 1000–2000 h in installations with air filters, whereas 500 h was achieved without filters in the arctic. During icy conditions, the air filter had to be removed, and thus, the inlet fairing, bellmouth, inlet guide vanes, and nosecone had an anti-icing system using compressor bleed air. No problems with ice formation were experienced on these parts. On the other hand, the specific problems associated with the gas turbine operation in the tropics are mainly due to torrential rain, high temperature, and high humidity levels, as also reported by Bolliger [12].

Regarding arctic conditions, experience and reports from customers indicate four principal problem areas in extremely cold weather operations [13]: (i) air-handling combustion and ventilation, (ii) lubricating oil systems, (iii) fuel-handling systems, and (iv) materials and construction. Patton [13] and Dickson [14] provided a description of some issues due to the gas turbine operation in cold conditions. Related to air handling, Kindl [15] reported the correlation between the drop in air temperature and air velocity, highlighting that the droplets in the vapor phase that enter the air filtration inlet could freeze and produce entrained ice particles. This correlation is reported in Fig. 3. In the same context, Bagshaw [16] provided the results of experimental tests conducted in order to investigate the effect of ice ingestion. A purpose-built test rig was used to discover the effects of ice ingestion. Field service evaluation and laboratory testing were combined to determine the standard design criteria regarding future intake and plenum, which will go a long way toward reducing, if not eliminating ice ingestion. Cleveland and Humphries [17] reported a complete overview of the application of an arctic gas turbine. The issues reported include: (i) environment, (ii) accessibility and transport, (iii) seismic risk, (iv) site selection, (v) foundation design, and (vi) maintenance and cost. Ice problems were also encountered by Maas and McCown [18] and Ojo et al. [19].

In the 1970s, some companies moved experimental tests from the field to laboratories. To ensure success on the field, in some cases a special test facility was constructed in order to test the power unit-simulated field condition. One of the first was Thueringer [20], who reported an extensive factory full-load test program before the shipment of two gas turbines. Subsequently, in Refs. [21–27], the authors highlighted the importance of preliminary testing during power unit design. Full load and transient testing with and without instrumented rotors can, and did, minimize the risk of both the manufacturer and the customer in installing a prototype machine in a critical process application. In the light of this consideration, in the latter part of the 1990s, the program named Advance Turbine System (ATS) pushed the manufacturer to increase the efficiency and overall service of the gas turbine. In the light of these measures, some contributions can be found in the literature. Layne and Hoffman [28] and Layne [29] described the ATS program, while the authors in Refs. [30–34] reported the updates of Westinghouse's gas turbine and power plant.

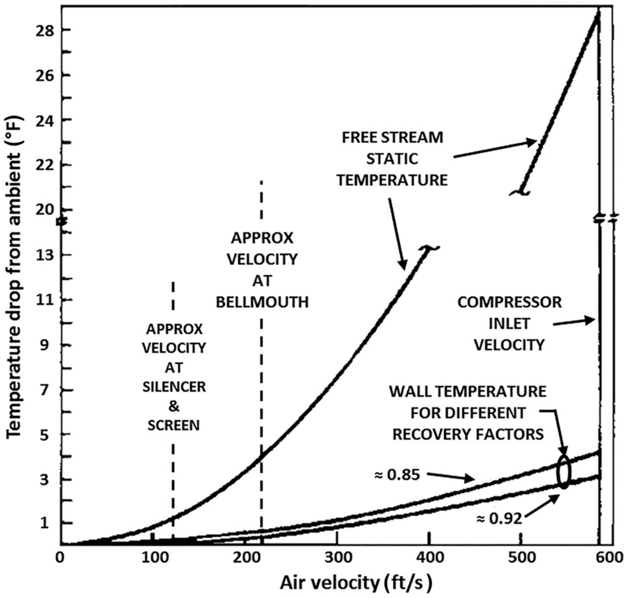

Fig. 3 Inlet system temperature drop as a function of the air acceleration. The higher inlet velocity results in a reduction of the free stream air temperature. This may determine water condensation or ice. The air in the boundary layer immediately adjacent to any stationary surface has slowed to almost zero velocity and is restored to almost its initial static temperature (recovery factor lines) [15].

2.2 Near Shore and Off-Shore Applications. Salt deposits determine blade shape variation and could determine the issue of corrosion. In this case, the operational experience is strongly correlated with the washing operation reported in the following paragraph. Hill [35] focused his analysis on salt particles carried by the air as a function of wind speed, highlighting the results reported in Table 1.

The first evaluation of the operational experience of this compressor is reported by McLean et al. [36], who made a detailed report based on the inspection of gas-turbine parts housed on a Liberty ship. The authors pointed out that it was a routine to clean the compressor and turbines through water washing after each long sea passage (10 days' duration). Other attempts to use gas turbines in different applications can be found in Ref. [37]. The authors report the evolution of the "Auris project," whose objective was the development of gas-turbine propelling machinery for medium-sized tankers and other types of merchant ships. When adverse weather caused sea-water spray to enter the intake, efficiency levels fell and could only be restored by shutting down and injecting water and a detergent into the intake, with the machine rotating at about 400 rpm.

In the light of these initial applications, during the years, other contributions have been made regarding gas turbine marine applications. Reports and design criteria can be found in Humphrey and Maas [38], who provided a highly detailed report on an experimental test related to salt-water ingestion, and the authors in Refs. [39–41], who dealt with the development of a particular compressor blade coating which reduces the blade surface contamination caused by the saltwater. The experimental results demonstrated that the modification of the surface roughness determines the modification of the deposition rate and in this case, its reduction.

Until now, the description of off-shore applications has been related to gas turbines installed in coastal locations and used for ship propulsion. There is, however, another gas turbine application within the marine environment which is related to off-shore platform installation. Elmed et al. [42] reported some considerations regarding this type of application. In particular, the operation

Table 1 Salt particles (parts per million by weight) as a function of the wind dispersion and particle diameter. The data shown are taken from several samples [35].

	Wind velocity (kn)		
Particle size range (μm)	20	30	40
2	0.0038	0.0038	0.0038
2–4	0.0122	0.0212	0.0377
4–6	0.0286	0.01404	0.5585
6–8	0.0364	0.3060	1.9000
8–10	0.0364	0.4320	3.5000
10–13	0.0416	0.6480	8.0000
13	0.1040	2.0486	36.0000
Total	0.2630	3.6000	50.0000

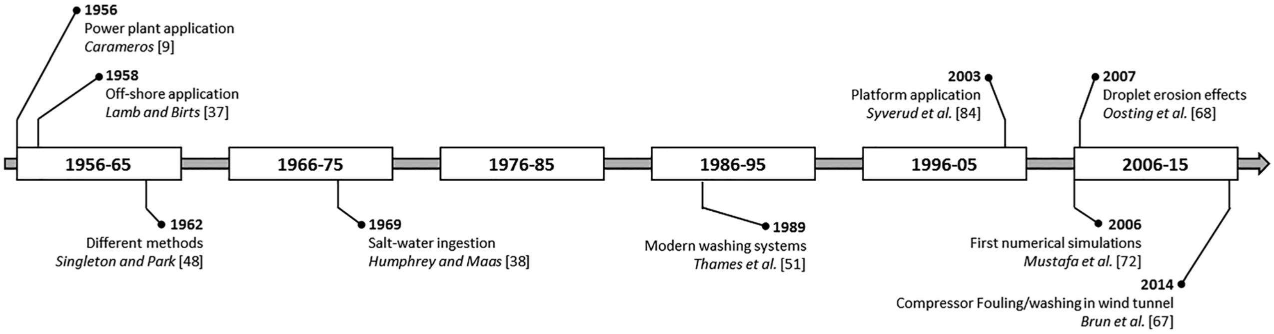

Fig. 4 Washing operations timeline

duty is long and continuous and requires long periods of activity between overhauls. The development has to be provided for the gas turbine itself and the installation lay-out, including air intake filter designs, operational mode, and service. Other off-shore platform operational experiences can be found in Refs. [43,44]. The authors in Refs. [45–47] summarized the field experience of gas turbines used in platforms, starting from the environment, layout, maintenance, compressor station, and future improvements.

3 Washing Operations

Washing operations are still present in the early gas turbine operation reports. Different methods have been discovered over the years, but only through the use of specific tests has it been possible to determine the influence of: (i) water droplet size, (ii) effectiveness of cleaning fluids, and (iii) the influence of washing operation on compressor blade erosion. Washing operations must be carried out periodically for all of the off-shore (and near shore) applications, from ship equipment to platform installations. Figure 4 reports the timeline that summarizes the principal contributions to this field.

This work does not deal with the compressor washing techniques even though it is one of the operational techniques used in order to contrast the issue of fouling. There have been numerous contributions related to washing operations over the years and in order to provide a complete review of this issue, a brief description is outlined in this paragraph. In Ref. [8] in fact, washing operations were performed. The author described his experience in detail, pointing out in particular that washing operations take place only when the relative humidity is below 50%, and the ambient temperature is above 10 °C (50 °F). This method of operation calls for cleaning the axial-flow compressor every 10,000–15,000 h, depend mostly upon the dust conditions. Singleton and Park [48] showed a comparison between the fouling susceptibility of single-shaft and two-shaft gas turbines. The authors reported a comparison between a single-shaft gas turbine and a two-shaft turbine as a prime mover for natural gas pipeline operations. The authors injected about 2.5 kg (6 lb) of spent catalyst into the air intake every 30 days. This is a very fine abrasive material which eliminated part of the build-up on the blading. After several months of operation, the units still needed cleaning by some other method. The units were steam cleaned twice a year and using this method on the single-shaft unit proved to be highly effective. The percentage gain in compressor efficiency and power output of the two-shaft turbine was about the same as that of the single-shaft unit immediately after cleaning. However, the two-shaft unit lost part of this gain within a few days. In cleaner environmental conditions, such as a Swedish island, compressor fouling, and washing systems were adopted in the earliest power plants. Schnittger [49] reported a general description thereof and a discussion on the initial operational experience of a 40 MW gas turbine installation on the Swedish East coast. In this case, compressors were equipped with a purpose-built detergent-spraying system. Some tests were performed in order to evaluate the washing capabilities in restoring gas turbine performance. The results are reported in Fig. 5. It is interesting to note that the involuntary shutdown resulted in certain recovery, although no positive cleaning measure was effected. Turbine washing apparently led to an almost complete recovery of output.

Hondius and Meyer [50] reported the ten years of gas turbine operation in compressor stations. The power units were equipped with inertia-type dust filters in the air inlets. The filters worked satisfactorily, capturing 90% of the dust of 10 μm and larger. The deposits in the compressor consisted of an oily layer with very fine dust, necessitating water washing every 200 h, and subsequently, a soak wash and unfired rinse using the starter motor. This system kept the compressor in reasonable shape, but in the second year corrosion became evident on the surface of the compressor blades.

In the 1980s, experiences related to compressor washing gained interest, and some useful reports were provided [51]. Mezheritsky and Sudarev [52] described a washing operation and the effects of corrosive materials used as a washing agent on the compressor sections. Some field experiences can be found in Refs. [53–63].

The improvement and diversification of washing systems can be found in Ref. [64], while Mund and Pilidis [65] reported a review of gas turbine online washing systems. Roupa et al. [66] and Brun et al. [67] reported a study regarding the effectiveness of cleaning fluids. Oosting et al. [68] proposed some improvements to on-line washing techniques in order to diminish the blade erosion. Blade erosion, especially the leading edge erosion is involved in compressor washing, as also reported by

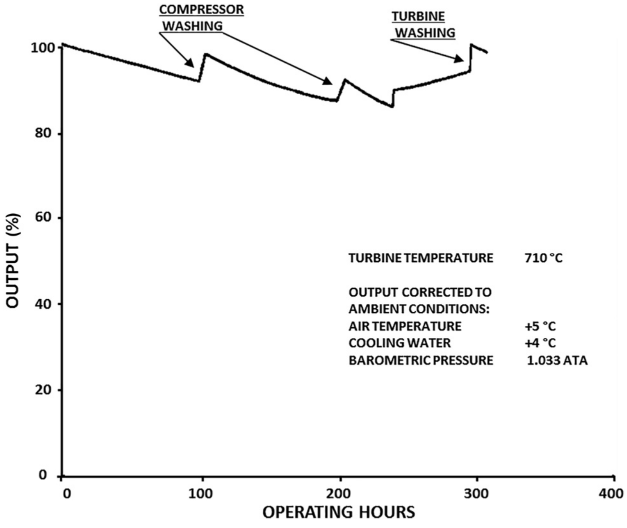

Fig. 5 Normalized output versus operating hours using heavy oil. This test was conducted for approximately 1 month (February) with periodic compressor washing and single turbine washing [49].

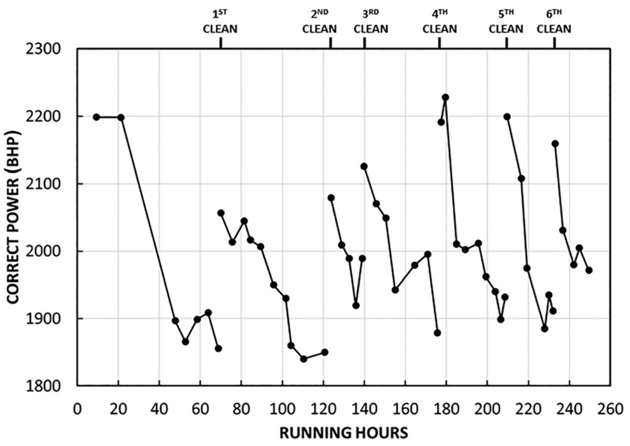

Fig. 6 Gas turbine power output (measured at the propeller shaft by a torque meter) over a long period of sea trials, showing the effect of occasional water-spray cleaning [76]

Kurz et al. [69]. Behavior of droplet that impacts on the leading edge (i.e., splashing) is reported by Eisfeld and Joos [70]. Shorter periods of on-line washing and redesign of the spray and washing systems in order to avoid overspray conditions could reduce or eliminate this type of erosion [67]. Recently, Botros et al. [71] showed the performance degradation of five compressor stations associated with different environmental characteristics and different washing periods. Numerical simulations related to washing operations can be found in Refs. [72,73] (investigation of the detrimental effect of water ingestion on gas turbine operation, especially due to the torque increase) and in Refs. [74,75].

Washing operations are also fundamental in off-shore and near-shore applications. The authors in Refs. [36,37,76] represented the first contributions to this field. In the study of McLean et al. [36], the washing of the compressor and turbines was a simple operation taking less than 3 h to complete. The compressor was washed (while being cranked at 1400 rpm) through spray heads permanently fitted in the inlet ducting. Washing the compressor always removed the dirt and salt deposits from it and restored it to the design efficiency.

Lamb and Birts [37] and Harris [76] removed the salt deposits in the compressor sections by washing operations (spray cleaning) performed at about 93% of the full speed. The effects on the gas turbine power are reported in Fig. 6. The authors remarked that the washing operations used for restoring full power are completely successful only when the deposit on the compressor blades is water-soluble, such as the salt deposited after operations in clean sea air. Distilled or demineralized water (sometimes in conjunction with kerosene) was also used in systematic washing operations [77,78]. Other field experiences on washing operations in Navy applications are reported in Refs. [79–83], while the field experiences on washing operations in off-shore platform applications are reported in Refs. [84–86].

4 Filtration Systems

Multistage filtration systems allow the reduction of particles entering the gas turbine. A correct combination of inertial separators, wet barriers, self-cleaning filters, and coalesces has to be defined for each environmental condition. Salt particles represent the principal issue for marine, off-shore, and near shore applications. Compressor salt ingestion is due, in particular, to the action of wind and wave splashing. Starting from rudimental vestibules, filtration systems were developed in conjunction with the gas turbine air intake position.

Filtration system performance cannot be described by using an absolute value but should instead be compared with the contamination of the surrounding environment and contaminant typology. Therefore, each rule of thumb refers to the paradigm of a proper filtration system for each gas turbine application. Standard methods for the evaluation of filtration efficiency represent the basis for proper gas turbine management. Unfortunately, manufacturers and government organizations have only provided tests for the quantification of filtration efficiency since the last decade.

Pressure drop and filtration system maintenance represent the greatest side effects. Filtration methods and the design of the filtration chambers could be adjusted according to the life cycle cost management related to the entire maintenance program of the gas turbine power plant. Figure 7 reports the timeline that summarizes the principal contributions in this field.

Inlet air can have a significant impact on the operation, performance, and life of the gas turbine. An inlet air barrier for gas turbines is required for several reasons: (i) to prevent the erosion and fouling of axial compressor blades, (ii) to reduce corrosion of the compressor air path and blading, (iii) to reduce corrosion in the hot gas area, (iv) for weather protection, (v) for cooling, and (vi) for sound attenuation [35].

Compressor blade fouling is normally due to one of the two elements. The first is solid particulate mineral and/or plant matter, and the other is carbon smoke and/or hydrocarbon fumes, which create a sticky "fly paper" substance when deposited on the turbine blades. One contributory source of carbon smoke and hydrocarbon fumes is the gas turbine itself, with its exhaust combustion gases and lube-oil tank vent vapors. Fouling of the compressor blading is predominantly caused by the fraction of normal atmospheric dust which has the greatest surface area. Brake [87] explained the issue related to contaminant transportation in detail. A 20 μm particle will fall at around 350 m/h. If the particle has been lifted to 2100 m, it would take 6 h to fall back to earth. A wind speed of 20 km/h would give this particle a range of 120 km. However, in the same situation, a 5 μm particle would settle at around 35 m/h, meaning it would take 60 h to fall back to earth, giving it a range of 1200 km under the same circumstances. This means that even if the contaminant sources are recognized and characterized in the proximity of the gas turbine installation, the

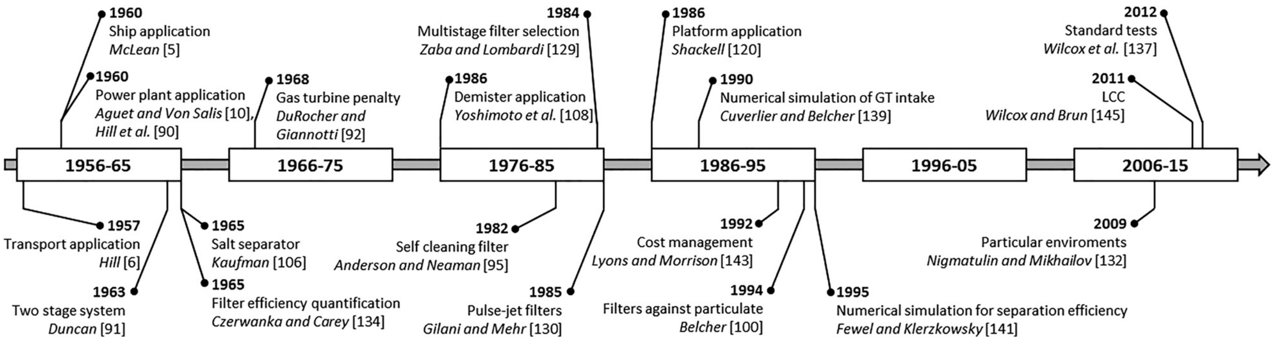

Fig. 7 Filtration systems timeline

contaminant transportation provided by the wind could determine a strong variation in the contaminant composition. Salt particles and soot transportation are recognized as the major issues.

The positive effects of the air filtration systems are well known, but the authors also highlight the undesirable associated properties of an air cleaner, summarized as: (i) pressure losses in the induction system, (ii) the space required to install the air cleaner with its accessories, (iii) the weight the air cleaner adds to an installation, (iv) additional labor and parts required to maintain the air cleaner, (v) the initial cash outlay for the air cleaner, and (vi) other structural and environmental properties [88].

In light of these preliminary considerations, this chapter is developed according to the following points:

- evaluation of different filtration systems and filtration evolution over the years in the case of land-based applications;
- evaluation of different filtration systems and filtration evolution over the years in the case of offshore applications;
- the relationship between the filter type and environmental conditions and, as a consequence, the selection of filter;
- evolution of the experimental tests and setting a standard in order to define a unique filtration efficiency;
- evaluation of the side effects of the filtration systems, such as pressure drops, costs of maintenance, management of the power unit, and degradation of the power unit performance and its production capabilities.

4.1 Land-Based Filtration Systems. The first reports on the use of filtration systems for a gas turbine can be found for transportation uses. In this application, both environmental conditions and space requirements could be highly detrimental for the compressor, which experiences erosion issues [6,8,89].

The first applications of a filter system to a heavy-duty gas turbine can be found in Refs. [10,90]. The authors reported the desert heavy-duty application and some issues due to the environmental conditions. Precipitators and a viscous-impingement-type inlet air filter were the proposed filtration technology.

Mund and Murphy [88] reported an extensive review of the actual gas turbine operation issue (erosion and fouling), while Duncan [91] proposed an evaluation of the gas turbine filtration system, starting from the air cleaners used in a piston engine. The author pointed out that the best heavy-duty air cleaners combine an inertial separator-type first stage with a dry-paper second stage. The first stage may or may not be self-scavenging. These two-stage designs are able to handle heavy dust concentrations because the first stage does not store the separated dirt in the filtering device and allows only a fraction of the ambient dust to pass on to the second stage, where removal is accomplished by storing the dirt in the filter material. Cleaning or replacing the second-stage filter is a necessary maintenance feature of this type of air cleaner. In general, the efficiency of the inertial separators decreases with particle size. Small-diameter cyclone types and close spacing of the louver types are required to separate the smaller particles.

The operating principles of the inertial separator are simple. The dirty air enters through the open end of the V-element. As the air passes through this element, its flow direction is reversed, and dust separation occurs because of the inertial forces on the dust particles. The primary or clean air then leaves the element in a direction almost 180 deg opposite to the dirty air entering the element. The dust particles, being heavier than air, tend to continue on their original path. To assist the separated dust particles in following their original direction toward the apex of the V for subsequent removal through the secondary air outlet, a separate secondary dirt air circuit is used [8]. The design of the inertial separators must fulfil these points: (i) space requirements, (ii) pressure drop, (iii) efficiency requirements, and (iv) acoustic performance. The inertial-separation concept has extreme flexibility and can therefore be constructed in many shapes and sizes. DuRocher and Giannotti [92] reported on innovative ballistic separators able to collect particles equal to 5 μm.

Regarding the second stage of filtration, dry or oil-wetted filters work in a similar manner, and it is difficult to say which is superior. The wet type has better economy in severe dust conditions, whereas the dry type is preferred in clean areas and when operation times are short [11]. There is always a risk with oil-wetted filters that small droplets of filter oil will be drawn into the compressor intake, or that the filter oil will adhere to fine dust particles, which subsequently causes compressor fouling. Tests carried out on oil-wetted filters show that these problems can be severe if the flow velocity at any point of the filter exceeds 3 m/s. These problems can of course be avoided if a dry filter is installed downstream of the wet filter, but this is a rather expensive solution. The oil-wetted solution works better in the presence of insects, which are automatically washed away. Kevil and Drost [93] also reported on the filtration performance of the rollomatic grease cleaner compared to the classic electrostatic dry cleaner. They found that the equipment of the gas turbine on the dry air filter media was in a much better condition than that on the grease side.

During the decade when filtration systems first gained attention, information about their operational experience was not widespread. This information became available in the 1980s, with Pulimood [94], for example, who outlined the field experience gained from the modular retrofitting of four gas turbine inlet systems with a second-stage high efficiency media filter to reduce gas turbine fouling conditions. The original gas turbine inlet systems were furnished with inertial filters. Field inspection revealed excessive fouling of the gas generator axial compressor sections, and crusty dust particles built up within the gas turbine internals and thermocouples. A second-stage high efficiency media filter was retrofitted to capture the fine dust particles that passed through the inertial filters. The different capabilities of particle collection are reported in Fig. 8.

In the 1980s, a new type of filter was introduced. Anderson and Neaman [95] reported on the application of self-cleaning filters in the desert. They discussed the results of two years' continuous operation of automatic self-cleaning air filtration systems designed to provide the gas turbine protection in a desert environment subject to high ambient concentrations of sand, dust, and salt. The cleaning system consists of pressurized air which, unlike processed air, pushes the dust far from the filter and cleans the filter surface. Filter cleaning is also reported by Reinauer [96], although in this case water action was used instead of pressurized air. Water was also used by Donle et al. [97], who employed

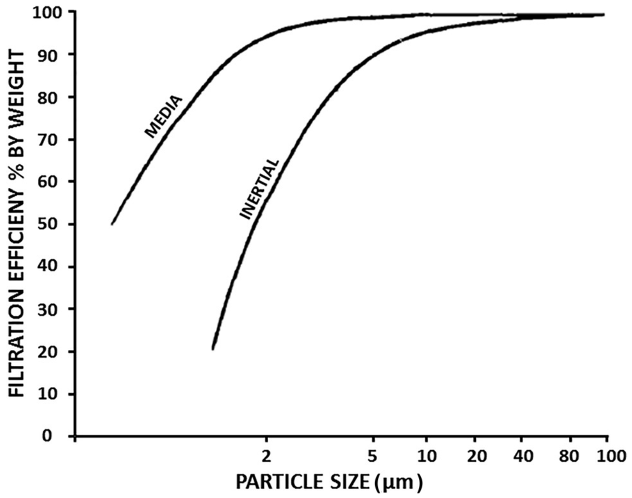

Fig. 8 Comparison between inertial and media filter efficiencies according to particle dimension. Media filters were added to the existing inertial separators [94].

artificial and natural fog to reduce the air contaminant at the compressor inlet. Operational experiences in air filtration systems are reported in Goulding et al. [98]. The authors summarized the filtration efficiency as a function of the particle diameter and type of filter. Some field data are reported for a specific filter manufacturer.

In the 1990s, particulate concentration became the major issue for gas turbine operators and, consequently, for the manufacturer of the filtration systems. The first data related to particulate concentration date back to 1974 [99]. As reported by the authors, the particulate concentration is localized in the neighborhood of the power plant and industrial areas. For this reason, an appropriate filtration system that removes particulate matter from the airflow stream has gained increasing attention through the years. Belcher [100] dedicated his tests to improving filter capability and its duration against very small particulate particles (sub-micron size). Issues related to particulate concentration were also reported by Johnson and Thomas [101]. They pointed out that heavy particulate loading due to the gas turbine surrounding gypsum environment was identified as the root cause of the problems affecting the first and second filtration stages and the evaporative cooling stage of the engine inlet air systems. A number of modifications and upgrades were studied to improve the performance of the inlet air treatment. A bag filter system for first-stage filtration was implemented in the power plant. The performance of this solution showed an increment in separation capability and a reduction in gas turbine failure.

As stated above, modern filtration systems are comprised of multiple filtration stages. Each stage is selected based on the local operating environment and the performance goals for the gas turbine. In a three-stage arrangement, a prefilter or weather louver can be used first to remove erosive particles, rain, and snow. The second may be a low to medium-performance filter selected for the type of finer-sized particles present or a coalescer to remove liquids. The third filter is usually a high-performance filter to remove smaller particles less than 2 μm in size from the air (particulate). In Table 2, a comparison in terms of the number of particles at the compressor inlet is reported for two-stage and three-stage filtration systems [102].

Recently, Ingistov et al. [103] have reported the evolution of inlet air filter systems utilized in a cogeneration plant since 1987. The data, collected over 25 years of operation and summarized in Table 3, show that the implementation of the high efficiency particulate air filter system provides a reduced number of crank washes, gas turbine performance improvement, and significant economic benefits compared to the traditional synthetic media type filters. Starting from this configuration of intake filtration systems, Ingistov [104] compared the use of long or short filter cylindrical elements in terms of gas turbine performance. A longer cylinder allows the reduction of the pressure drop with a life time longer than 3 years. The author underlines the importance of knowing the ambient conditions (size of contaminant and its nature) during the filter selection process.

Regarding the analysis of different filtration technology, Perullo et al. [105] reported the effects of different filters (F8, F9, E10, E11, E12 filter types, according to EN779:2002 and EN1822:2009 filter classification) on the performance of the GE7FA gas turbine. The authors reported the long-term trends of power output and heat rate corrected to a standard day for one of the units. Large recoveries in gas turbine performance after washing indicate that the filtration system is not doing a good job at preventing compressor fouling. Small or minimal changes in performance after

Table 2 Comparison of the filter collection efficiencies of two-stage and three-stage filter systems as a function of particle dimension. The number of particles per unit of volume is proposed before and after the filtration barrier [102].

#-Stage filtration	Particle size (μm)	Particle in the atmosphere (#/m^3)	Initial efficiency filtration (%)	Particle penetration (#/m^3)
Two-stage	0.3–0.5	20,000,000	64	7,200,000
	0.5–1.0	4,000,000	80	800,000
	1.0–2.0	300,000	95	15,000
Three-stage	0.3–0.5	20,000,000	98.9	220,000
	0.5–1.0	4,000,000	99.9	4,000
	1.0–2.0	300,000	99.999	3

Table 3 Report of inlet air filters and key characteristics in relation to maintenance and power unit management (frequency of compressor washing) [103]

Period	Filter Type	Comments
Start (Nov. 1987–1995)	Cellulose media cylindrical element Tenkey design (324 mm dia. × 680 mm long)	• Originally supplied and designed to operate in self-cleaning mode • Crank-wash once a month • Replacement of filter elements every 18 months
1995–2002	Cellulose media, long cylindrical Tenkey design (324 mm dia. × 1016 mm long)	• Modified to operate without self-cleaning mode (Modification #1) • Crank-wash once a month • Replacement of filter elements every 18 months
2002–2011	Synthetic media, long cylindrical Tenkey design (324 mm dia. × 1016 mm long)	• Changed filter element media to synthetic (Modification #2) • Crank-wash every 2 months • Changed every 24 months
Oct 2011–2014	HEPA Class 12, long cylindrical design (324 mm dia. × 1016 mm long)	• Major filter type change (Modification #3) • No crank-wash required in more than 2-years of operation • Currently operating on one GT unit (Unit #2), and the plan is in progress to install on remaining three GT units

Table 4 Average data values for F8 and E10, isolated data points for F9, E11, and E12 filters according to EN EN779:2002 and EN1822:2009 classification. The data reports the compressor efficiency recovery values and the power output recovery values obtained after washing operations as a function of the filter type installed on power units [105].

Filter Rating	Compressor Efficiency Recovery per MMWh(%)	Power Output Recovery per MMWh(%)
F8	2.0 (Average across all sites)	5.0 (Average across all sites)
F9	1.5 (Single data point)	2.2 (Single data point)
E10	0.33 (Average across all sites)	1.5 (Average across all sites)
E11	Not available	0.9 (Single data point)
E12	0.4 (Single data point)	0.25 (Two data points)

each wash indicate that the filters are performing well at preventing compressor fouling. Table 4 reports the relationship between performance recovery due to offline washing and the type of filter.

4.2 Near-Shore and Off-Shore Filtration Systems. For these applications, the removal of salt from the airflow stream is essential in order to diminish the fouling issues of the compressor section. In early marine applications, vestibules were added to the main air intakes to prevent the induction of heavy salt spray under severe weather and ship roll conditions [36]. Starting from this structural change, in the 1960s some air filtration methods were presented. Separators were employed in order to separate the sea salt from the airflow stream [106,107] in conjunction with electrostatic precipitators in order to collect particles less than 5 μm. In 1976, Yoshimoto et al. [108] proposed some analyses related to a new demister applicable to gas turbines employed in ships. In the first part of their work, they provide data regarding concentration and size distribution in the light of geophysical theories and other effects such as elevation and ship velocity. More recently, the authors in Refs. [109,110] reported the results of some tests related to salt separators used for reducing the salt ingestion of the gas turbine. In this work, a detailed description of a sea-salt aerosol test facility, and the real-time test techniques and instrumentation employed is provided.

In the 1980s, evaluation of the commercially available moisture separators, statistical description of the salt level, and the field experience related to ships, platforms, and coastal applications were reported in Refs. [111,112].

Since relative humidity in maritime air very rarely falls below 45%, salt will almost always be present in droplet form. The exception to this could be gas turbine installations using anti-icing systems to heat the inlet air. Based on the assumption that the inlet heating system adds negligible moisture to the air, Fig. 9(*a*) shows the temperature rise required to decrease the relative humidity to 45%, as a function of ambient conditions. If the inlet heating schedule has a temperature rise equal to or greater than that defined by the appropriate curve, the relative humidity of the heated air will drop to levels such that salt will exist as dry crystals [111]. Wind action changes the salt particle concentration and dispersion. Wind action in terms of concentration at off-shore and coastal installations is summarized in Fig. 9(*b*), while Fig. 10 shows data taken during onshore winds, plotted in such a way as to emphasize the rate of decay of salt level with distance. It is obvious that a drop of one order of magnitude is experienced in going from the surf line to the leeward side of the barrier beach—it can be assumed that this is due to the fall-out of spray generated by the waves [111].

Experimental evaluations on the filtration systems used in marine applications are reported in Refs. [113,114]. Their papers cover various aspects with respect to the selection and operation of air filtration associated with offshore gas turbine installations. Other contributions to marine air filtration systems can be found in Refs. [115–117] related to a high velocity spray salt eliminator and in Refs. [118,119]. McGuigan [119] described how salt is produced, how it varies climatically and how it varies from location to location. Salt concentrations are reported using useful maps as

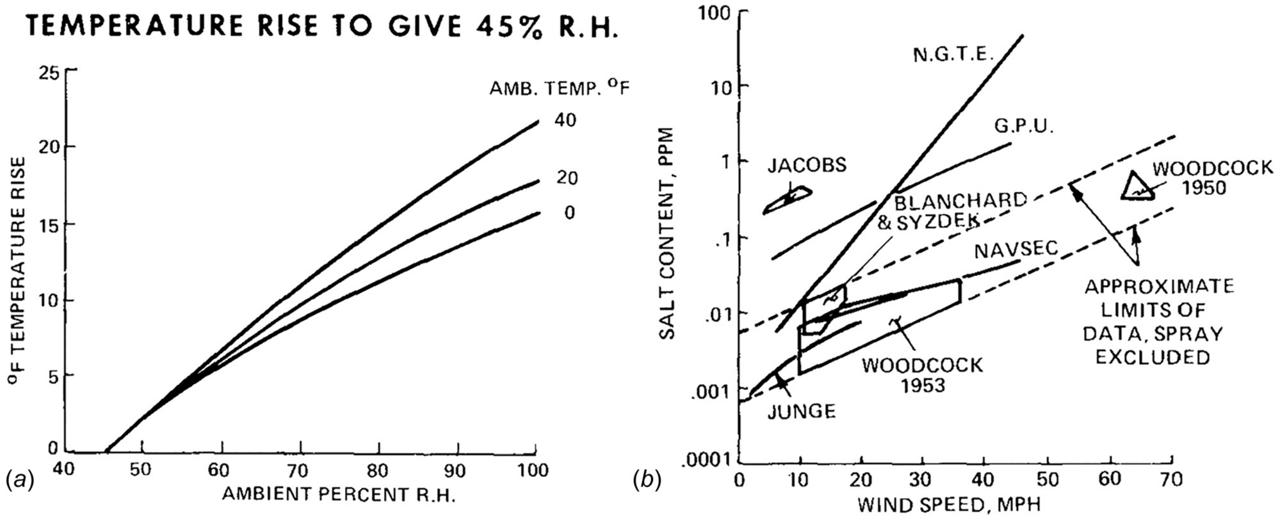

Fig. 9 (*a*) Inlet heating which would result in the generation of dry salt crystals as a function of relative ambient humidity and temperature, (*b*) salt content of maritime air (parts per million by weight) as a function of wind velocity. Several data were reported provided by different authors and locations: Blanchard and Syzdek (Windward shore of Oahu, Hawaii), GPU, General Public Utilities, now FirstEnergy Corporation (New Jersey shore), Jacobs (Seashore, La Jolla, CA), Junge (Round Hill, MA), Navsec (no data available), NGTE—National Gas Turbine Establishment, Woodcock 1950 (Lighthouse, FL), Woodcock 1953 (data taken from ship, Florida, Hawaii, and Australia) [111].

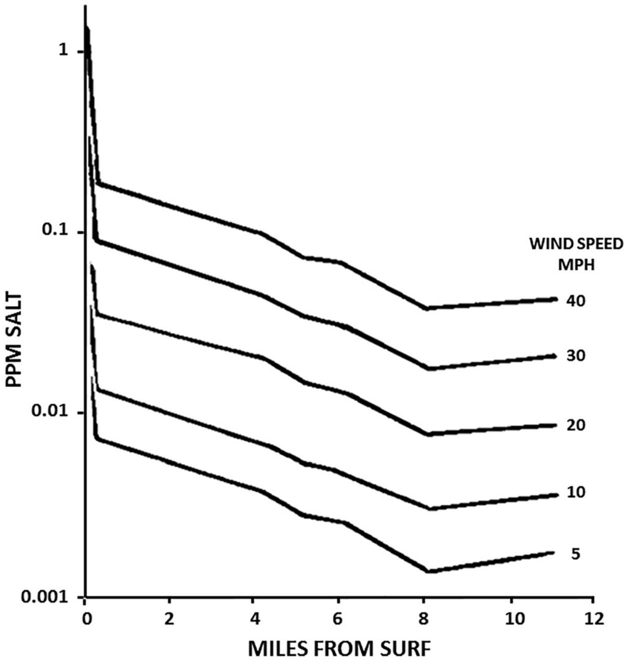

Fig. 10 Variation in salt level (parts per million by weight) as a function of distance from the surf. Data were taken during onshore winds of varying intensity [111].

a function of the boreal seasons. More detail regarding specific issues regarding offshore platform applications can be found in Refs. [120–123].

4.3 Filter Versus Environmental Conditions and Filter Selection. In this section, the resources reported are related to the study realized in order to evaluate filter performance as a function of the environmental conditions. Ernst [124] reported the different operating environments of gas turbines and described the filtration characteristics that are required in different environments. Six typical installation sites of gas turbines are reported: (i) countryside, (ii) large cities, (iii) industrial areas, (iv) desert, (v) tropics, and (vi) mobile installation. Each condition requires a different set of filtration systems as a function of the contaminant typology. With the same accuracy level used in Ref. [124], Giannotti [125] described the primary filtration methods (impingement, diffusion, electrostatic, and sedimentation) and the secondary methods of separation (viscous air cleaner, ultrasonic agglomerator, thermal precipitators, and wet scrubber), while Mund and Guhne [126] cover three types of gas turbine air cleaners, both in the laboratory and the field, on wheeled and tracked vehicles, in helicopters and air cushion vehicles. In the same way, Hill [35] reported the differences in the air filtration systems as a function of the environment (large cities, industrial areas, desert locations, tropical environment, and arctic environment) summarized in Tables 5 and 6. In many instances, it is possible to encounter several environmental situations in one location, thus making proper selection of the intake filters even more critical.

Table 5 Relationships between locations and local contaminants on the gas turbine. Some environments experience very different conditions over the years, determining variable effects on the power unit [35].

Environment	Country side	Coastal (sea side)	Large cities (power station and chemical plant)	Industrial areas (steel works, petro-chemical, mining)
Types of dust	Dry-non erosive	Dry-non erosive Salt particles and corrosive mist	Sooty-oily May be erosive also corrosive	Sooty-oily Erosive. May be corrosive
Dust concentration (mg/m^3)	0.01–0.1	0.01–0.1	0.03–10	0.1–10
Particle size (μm)	0.01–3	0.01–3 Salt < 5	0.01–10	0.01–50^a
Effects on GT	Minimal	Corrosion	Fouling (sometimes corrosion and fouling)	Erosion (sometimes corrosion and fouling
Temperature range (°C)	−20 to 30	−20 to 25	−20 to 35	−20 to 35
Weather conditions	Dry and sunny, rain, snow, fog	Dry and sunny, rain, snow, sea mist, freezing fog in winter	Dry and sunny, rain, snow, hailstone, smog	Dry and sunny, rain, snow, hailstone, smog

AQ4

[a] In emission area of chimney.

Table 6 Relationships between locations and local contaminants on the gas turbine. Some environments experience very different conditions over the years, determining variable effects on the power unit.

Environment	Deserts (sand storms, dusty ground)	Tropical	Artic	Mobile installations
Types of dust	Dry-erosive in sand-storms areas Fine talc like in areas of non-sand storms but dusty ground	Nonerosive may cause fouling	Nonerosive	Dry-erosive Sooty-oily corrosive
Dust concentration (mg/m^3)	0.1–700	0.01–0.25	0.01–0.25	0.01–700
Particle size (μm)	1–500^a	0.01-10	0.01–10	0.01–500^b
Effects on GT	Erosion (Plugging of filter with insect swarms)	Fouling	Plugging of air intake system with snow and ice	Fouling, erosion and corrosion
Temperature range (°C)	–5 to 45	5–45	−40 to 5	−30 to 45
Weather conditions	Long dry sunny, high winds, sand and dust storms, sometimes rain	High humidity, tropical rain, insect and mosquito swarms	Heavy snow, high winds, icing condition, insect swarms in summertime	All possible weather conditions

[a] During severe sand storms.

[b] At track level and/or during dust storms [35].

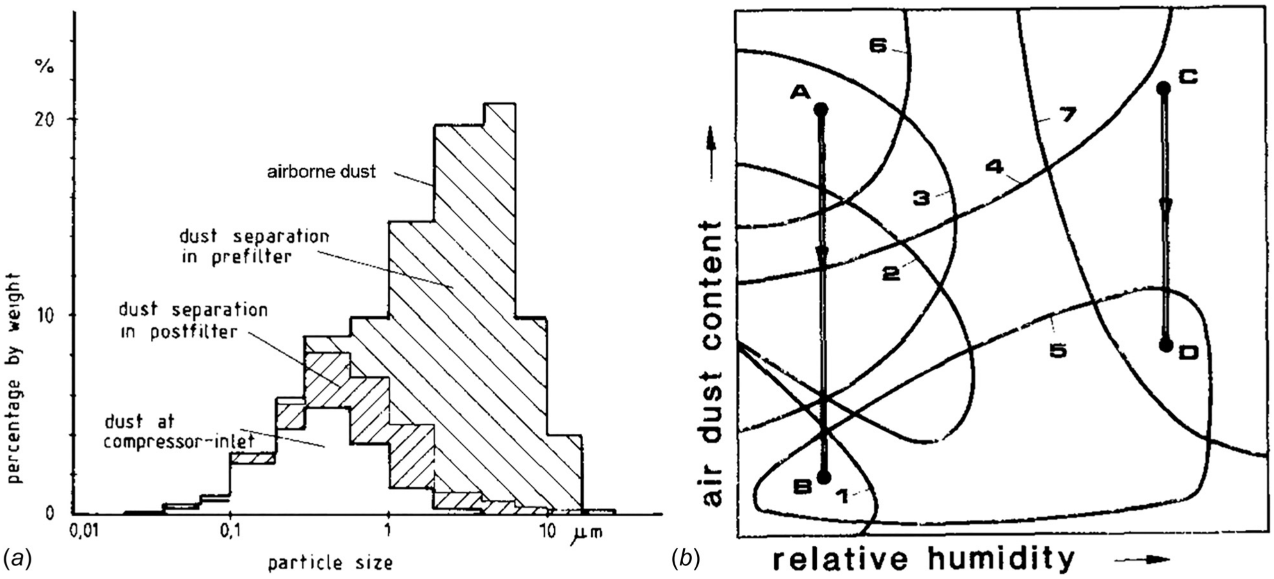

Fig. 11 (*a*) Dust particle distribution in a two-stage filtration system. The reduction in the weight percentage of contaminants is provided by the multiple stage filtration system. (*b*) The practice of filter system selection. The zones are: (1) high efficiency filters, (2) roll and mat type filters, (3) pulse and bag filters, (4) oil bath filters, (5) electrostatic filters, (6) inertial separators, and (7) wet separators. The selection has to be made beginning with the initial condition (air contaminant concentration and humidity) [129].

Goldbrunner and Savoie [127] estimated the effects of the air filtration system by means of a field test. Their paper reports the results of a controlled site test program on two gas turbine units to evaluate the effectiveness of inlet air filtration in reducing maintenance costs. One unit incorporated two-stage inlet air filters; the other had no inlet air filtration. The units were located next to each other, and each unit was run simultaneously, exposing both to the same environment and operating conditions. The inlet air filter selected for this test was a two-stage type, consisting of an inertial separator as the first stage and a 5-μm fiberglass media as the second stage. The test consisted of operating these engines simultaneously, exposing both the filtered and unfiltered engines to the same operating conditions. The data collected during the test are very useful in evaluating filtration efficiency. The findings of Goldbrunner and Savoie [127] can be summarized as follows: (i) the filters should have a guaranteed, field demonstrated, airborne salt removal efficiency of at least 90 percent and (ii) the filter should have a guaranteed removal efficiency, utilizing standard Arizona Road Dust (85% mean efficiency on atmospheric test, 95% on particles of 2 μm and larger using gravimetric tests and 99.7% on particles of 10 μm and larger also using gravimetric tests). The authors also reported the results obtained by engine inspection, which showed that unfiltered engines have nearly twice as much tip wear, thus implying greater values of tip clearance. The authors do not report which filter type (inertial separator or fiberglass media) contributes most to erosion reduction. Regarding salt deposits, Labadie and Boutzale [128] reported the relationship between increasing levels of air filtration and decreasing sulfidation corrosion over a 6-year period for a 17 MW gas turbine located adjacent to a dry lake. The authors propose a procedure for the selection of adequate air filtration based on air sampling data and known filter properties.

Zaba and Lombardi [129] report their experience in gas turbine filtration systems. Some interesting results are reported in Fig. 11. Figure 11(*a*) shows the filtration effect of the two filters as a function of the size of the particles. The first filter stage is of a sturdy structure and is designed to remove coarse dust particles. The high efficiency filter that follows is designed to remove fine dust particles. Figure 11(*b*) reports an example of an easy-to-use qualitative filter selection. The zones depicted in Fig. 11(*b*) are: (1) high efficiency filters, (2) roll and mat type filters, (3) pulse and bag filters, (4) oil bath filters, (5) electrostatic filters, (6) inertial separators, and (7) wet separators. According to Fig. 11(*a*), point A has been selected as the initial condition for the first example. According to Fig. 11(*b*), an inertial separator can be selected as the first-stage filter. The amount of dust in the inertial separator will be reduced to Point B. It can be seen that a dry filter is suitable for the second stage. In the second example, the air is relatively moist. The initial condition is located at Point C. A wet separator or an oil-bath filter would be considered for the first-stage filter. The amount of dust in this filter will be reduced to Point D. An electrostatic filter would be advantageous for the second stage.

Comparing the results reported in Fig. 11(*a*) with the results reported in Fig. 12, taken from Ref. [130], it can be observed that the amount of dust at the compressor inlet is less. Different filtration systems determine highly significant differences in the amount of dust that could afflict the power unit. Gilani and Mehr [130] reported their operating experience related to different types

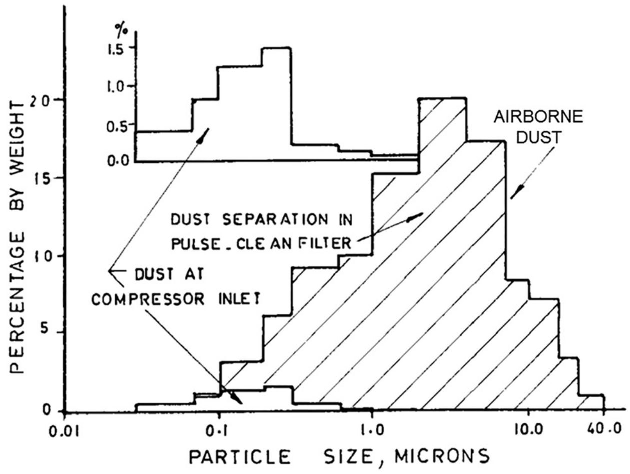

Fig. 12 Dust separation in a pulse-jet self-cleaning filter. The reduction in the weight percentage of contaminants is provided by the self-cleaning type filter [130].

of filters on a Saturn power unit. Figure 12 reports the improvement in the filtration efficiency of an existing gas turbine. A preexisting two stage filtration system was substituted by a pulse-jet filter that worked in more efficient way. In fact, only 4.3% of the total dust could penetrate through the filter, which means that this system is about seven times more efficient than the existing one. The system utilizes 64 cylindrical cartridges in a single stage of filtration with a paper media of P12-5306 and P14-6555 types. Pulse-jet filters were also studied by Brusca and Lanzafame [131], who propose a mathematical model for evaluating the variation in the performance of the gas turbine before, during, and after the cleaning procedure. Local evaluation of air filtration systems and particular environmental conditions can be found in Refs. [132,133].

4.4 Experimental Tests and Standard Methods. Reports on filtration tests are not widespread in the literature. Tests are conducted especially for the filter used by the manufacturer and, for this reason, the type of filter which is tested is strongly related to the filter development. The first tests are related to louvre and media filters. Tests on louvre and glass-fiber media filters are reported by Czerwonka and Carey [134]. The authors proposed a general purpose centrifuge method for measuring the particle-size distribution of the air filter inlet, outlet, and collected dust samples. The efficiency of a collector can be computed by obtaining a particle-size distribution of the dust to be collected. Other test methods for determining the effectiveness of air filters used for the collection of atmospheric dust are reported by May [135]. The three proposed methods are: (i) weight, (ii) dust spot, and (iii) DOP. The weight method consists of the evaluation of the weight of the dust passing the test filter and entering the clean-air stream. In conducting dust-spot efficiency determinations, samples of air are taken upstream and downstream of the filter in question. The dust removed from each upstream and downstream sample produces a spot or target as it passes through the filter paper. The DOP method consists of the evaluation of the filter capability to remove dioctyl-phylate droplets (with a controlled diameter) from the airflow stream. The weight method provides an excellent basis for comparing the relative performance of air cleaners in the medium-efficiency range but it has certain shortcomings where high efficiencies are concerned. In this case, the dust-spot test is more suitable to evaluate filters with higher filtration efficiency. The third method is used for the determination of the efficiency of super interception types of filters.

The standard methods used for testing and verifying the capacity of a filter are not well reported in the literature. Gidley et al. [136] pointed out that the standard tests have, for the most part, been developed for the heating, ventilating, and air conditioning industry, using developed synthetic dust that simulates an air composition comprised mostly of recirculated air blended with outdoor make-up air. Other available standard tests and standard test dusts have been developed for diesel and gasoline-powered engines. At the same time, in the early 1990s, no standard air filter test method had been developed for filters to be used on combustion turbine air intakes using typical outdoor air. The standards have to provide sufficient detailed information on the extent of penetration of small micron particulates. In the 2010s, Wilcox et al. [137] pointed out the same problem relating to the lack of standardized methods for the filter test in the case of liquid or soluble particles. The liquid phase can greatly influence filter performance as the filter is affected when loaded with salt and/or water.

4.5 Side Effects: Pressure Drops, Maintenance Costs and Power Unit Management. All of the aforementioned separation methods determine pressure losses at the compressor inlet. DuRocher and Giannotti [92] were the first authors to address this issue. They pointed out the gas turbine power penalty from air cleaners, and their results are summarized in Fig. 13. Their application refers to vehicle systems characterized by limited space which is reflected in a smaller inlet surface area than in power plant installations and consequent higher inlet velocity and pressure drops. Schroth and Cagna [102] also reported the differences in terms of the pressure drop between the two filtration methods. The comparison is depicted in Fig. 14, where the curves marked with "two-stage system" and "three-stage system," respectively, represent the total pressure drop of the two-stage or three-stage systems. The significantly lower pressure drop in the two-stage filter system can be seen, with the average pressure drop over the entire year being approximately 300 Pa less compared to the three-stage system. Different filter selections and sequences are implemented—for the two-stage system, F6 and F8 classes were used, while for the three-stage system, F6, F9, and H11 classes were adopted according to EN779:2002 and EN1822:2009 filter classifications.

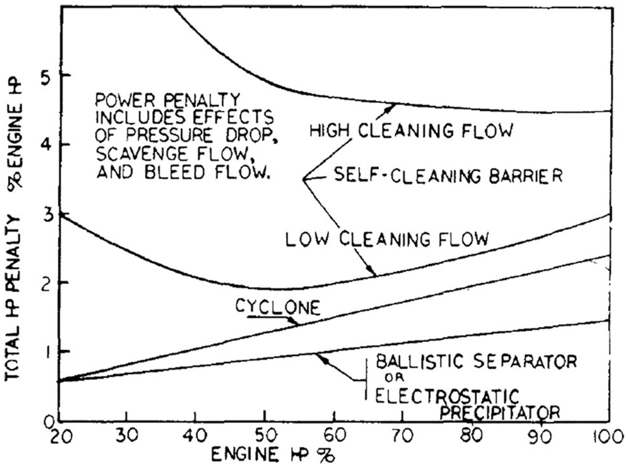

Fig. 13 Gas turbine power penalty from different types of air cleaners (the 100% hp points would apply to the single shaft, or free turbine at full power) [92]

Pressure drops may also generate another side effect due to the humid condition that could occur after the filtration barrier. As reported by Zaba and Lombardi [129], the airflow accelerates at the level of the first rotor, and the static temperature decreases immediately. Figure 15 reports this aspect with a qualitative superimposition of first compressor blade rows. Multiple stage filtration systems (where applicable, matching the space requirements) reduce this phenomenon, although it remains strongly dependent on the environmental conditions. Analogous considerations are reported in Ref. [138].

Regarding the pressure drop due to the inlet duct and filtration systems, numerical simulations have been used to reduce the impact of these aspects. Cuvelier and Belcher [139] showed an improvement in the design of the inlet compressor chamber in order to diminish the footprint area and improve the filtration capability. In this work, numerical simulations are used to validate the new filter chamber project, and filed data validate the results obtained by the new design. Other authors, including You and Goulding [140] used numerical simulation to improve the filtration capability of high-efficiency filters. In their paper, through a mathematical analysis and design optimization, a new type of ultra-high efficiency (<97% for 0.3 μm diameter particle) filters were developed. The authors pointed out that numerical simulation allows the improvement of the filter which, together with the correct match of air filter system to environment and duty, will greatly improve combustion turbine protection. Numerical simulation is also used in Refs. [141,142] in order to improve the separation capability of the intake separator used in marine gas turbines. In these cases, the design quality was established using CFD without the use of a costly physical scale model of the installation. AQ5

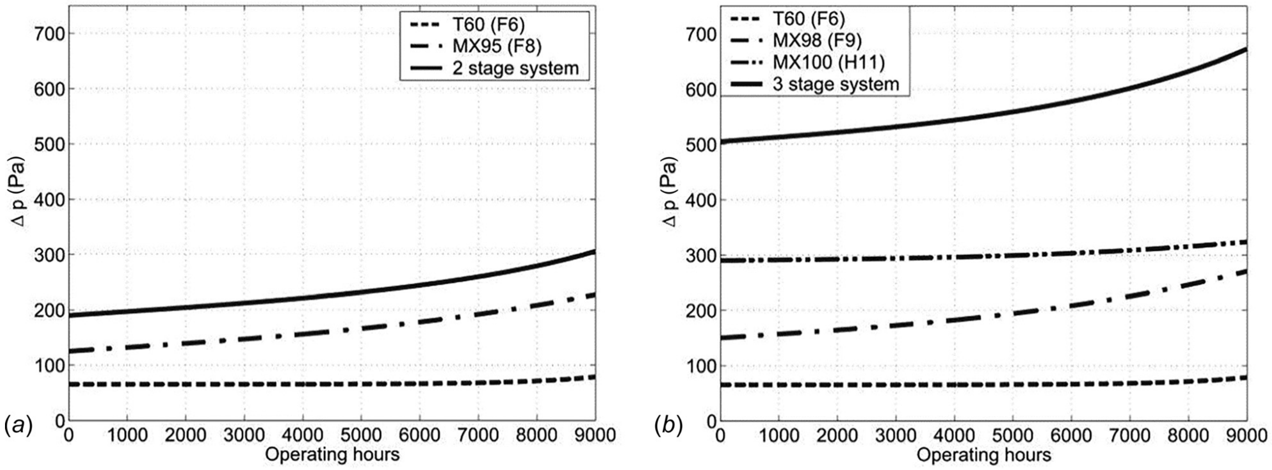

Fig. 14 Pressure drop curve (Pa) at 4250 m^3/h volume flow rate per filter element: (*a*) two-stage filter (classes F6 and F8), (*b*) three-stage filter (classes F6, F9, and H11) according to EN779:2002 and EN1822:2009 filter classifications [102]

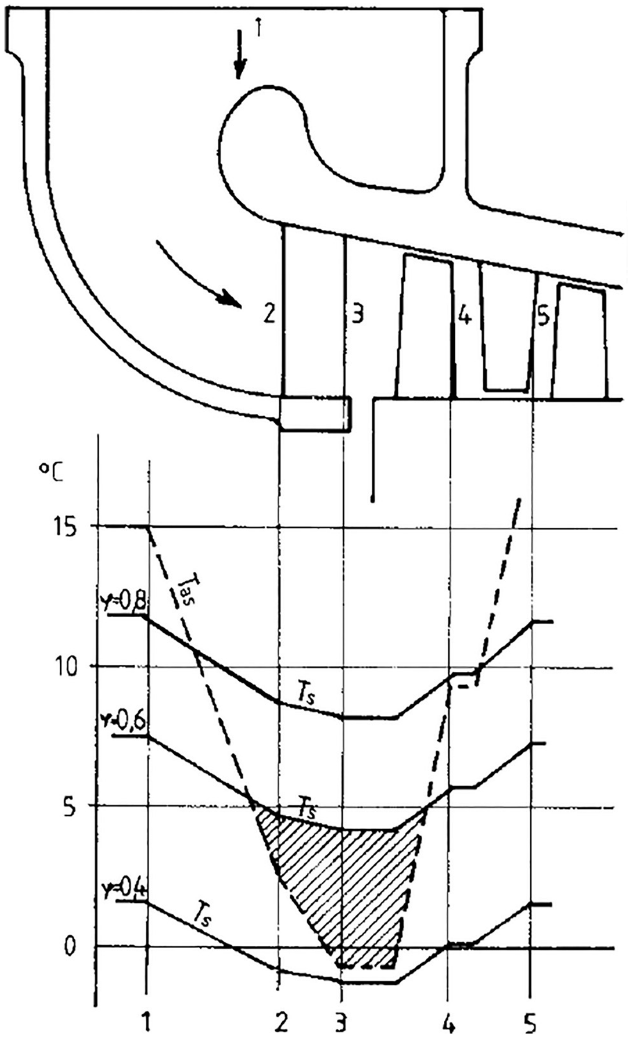

Fig. 15 Change in the saturation temperature at the compressor inlet. T_{as} is the static air temperature, T_s is the saturation air temperature, and φ is the relative humidity [129].

The cost management of inlet filtration systems only gained attention in the 1990s. Lyons and Morrison [143] introduced cost management of the power plant in the evaluation of the filter. Cost management is related in particular to the installation phase, compressor damage (and consequently, maintenance), and losses. Modern power plants have to be designed to fulfil the requests related to power production and to revenue. Filtration systems and their maintenance play an important role in this topic. The filter engineer must consider the efficiency of the filtration system, particle sizes to be filtered, the maintenance necessary throughout the life of the filtration system, acceptable pressure losses across the filtration system, the required availability and reliability of the gas turbine and how the filtration system affects this, washing schemes for the turbine, and the initial cost of any new filtration systems or upgrades [144,145]. Wilcox and Brun [145] proposed a life cycle cost analysis of inlet filtration systems, which provides a fairly straightforward method for analyzing the lifetime costs. It provides a method to directly compare different filter system options based on: (i) initial cost, (ii) maintenance cost, (iii) cost due to the gas turbine power loss and heat rate increase, (iv) failure, (v) availability and reliability, and (vi) the overall gas turbine degradation.

5 Particle Deposition

Wet and dry contaminants are able to stick to blade surfaces in very different ways. The deposits can contaminate multiple stages of a compressor as a consequence of the different type, nature, and path of a single particle. Experimental evaluation and tests are not widespread due to the complexity in the quantification of the deposits that stick to the blade and vane surfaces. At the same time, numerical analysis involves complexities due to particle motion/impact modelization. Experimental tests and analytical/CFD approaches have to be developed in order to define general rules for fouling characterization. Figure 16 reports the timeline that summarizes the principal contributions in this field.

The finely dispersed aerosols in the air supplied through the filter are the principal source of compressor fouling. Compressor deposits can become a problem over extended periods of time in the smoky, oily atmosphere of engine rooms and factories. Deposits determine a modification of the airfoil shape and the increment of blade surface roughness. Both of these effects determine the deterioration of compressor performance. This review aims to report only the study and experimental evaluation of the deposit characteristics on the blade surface. The impact of fouling effects

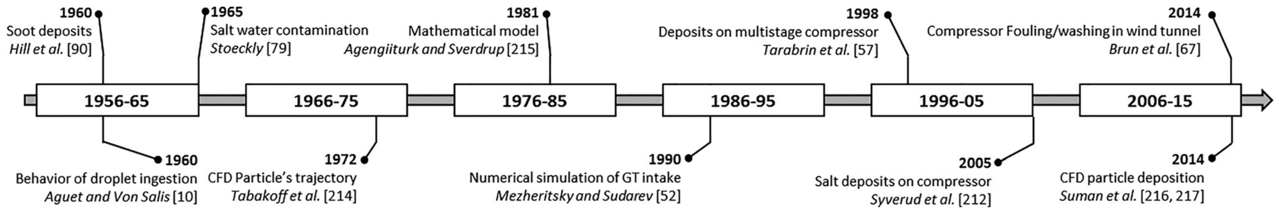

Fig. 16 Particle deposition timeline

on compressor performance are not reported here, but are highlighted in some studies and analyses [146–156]. Meher-Homji et al. [4] reported some examples of compressor deposits exemplified in Fig. 1(*a*). The authors split the fouling deterioration into two aspects: (i) the susceptibility of a gas turbine to fouling, i.e., the compressor's propensity to foul given a certain environment and foulants and (ii) the sensitivity of the gas turbine to the impact of fouling on its performance. According to these definitions, some analyses can be found in the literature.

5.1 Particle Sticking Mechanisms. Particle sticking is the phenomenon on which compressor fouling is based. Particle adhesion on a clean blade surface or particles which stick to a previously deposited layer determine all the phenomena discussed in the previous chapters. Therefore, in this section, attention is given to the contributions regarding particle sticking. Mezheritsky and Sudarev [52] discussed the baseline principles and deposit formation mechanism in axial and centrifugal compressors. The authors provided a detailed description of the fouling mechanism in a multistage axial compressor. Finely dispersed particles of an aerosol liquid fraction impact the compressor guide vanes and rotating blades under a large angle of attack, even with a gas turbine operating at the design point. When impinging, the droplets are deformed and splashed over the entire blade surface, generating favorable conditions for dust, soot, and salt particle sticking. The dust particles coagulate and serve as a basis for the formation of viscous deposition. As the pressure and temperature increase, the moisture evaporates, resulting in a reduction in the deposit volume in the direction of the air motion (from the first to the last stages) in a multistage axial compressor. The authors proposed a numerical approach in order to establish the adhesive ability of the blade profile relative to the particles, by using the entrainment factor. The entrainment factor depends on the Stokes critical number, the air flow velocity, and the blade chord. By using the blade entrainment capability value, one can determine the amount of deposition in any compressor section. Mezheritsky and Sudarev [52] also proposed adhesion criteria able to predict the capability of a compressor to collect particles. In addition, the authors give an estimation of the thickness of the deposits based on experimental data. In axial compressors, the stability deposition layer of the first stages takes place at a layer thickness of (0.8–1.5) mm. The layer stability is provided by the effects of air stream pressure, generating the shifting stresses on the deposition surface. At the beginning, the thickness of the deposition layer is inconsiderable and the cohesive forces between the particles and the blade metallic surface (adhesive forces) are greater than the shifting forces. As the deposition layer on the blade becomes thicker, the cohesive forces between the particles decrease and the flow velocity increases because of the narrowing of the flow section area. Equilibrium between cohesive/adhesive forces thus ensures a definite deposition layer thickness. Other contributions are related to the modelization of the particle-boundary layer interaction. Numerical studies on the interaction between particle and boundary layers are reported by Gökoğlu and Rosner [157], while El-Batsh and Haselbacher in Refs. [158,159] studied the effect of turbulence models on particle dispersion, deposition on turbine blade surfaces, and detachment from the surfaces. Kozlu and Luis [160,161] focused, respectively, on the experimental study of the deposition of particles with a diameter in the range (1–5) μm, and on the interaction between transpiration and the inertial impaction of particulates using glass particles (0.5–3) μm.

Other contributions related to particle sticking are devoted to the study of turbine sections. Studies related to the hot particle deposition that takes place in the turbine nozzle are widespread in the literature, using both experimental and numerical approaches. Turbine sections represent a critical component, especially in aeronautical applications, since deposits and turbine section obstruction could be highly detrimental. These contributions could be a starting point, in terms of methodology, experimental setup, and numerical strategy, to improve the knowledge of fouling phenomena related to compressor sections. Several models exist, and just a concise explanation is reported here.

The critical film height model is applied by Georgiou and Paleos [162]. The turbine blades of gas turbines operating with dirty fuels are sometimes covered by a very thin liquid film, which originates from the condensation of the alkalic sulfates in the flue gases. These films may drastically influence the collision coefficient of the impinging particles. This phenomenon influences the future trajectories of these particles and their adhesive properties. In the same decade, Kladas and Georgiou [163,164] applied a method based on a stopping-distance reported in the literature. This was able to predict particle deposition as a function of the diffusion phenomena taking place in the boundary layer compared with cascade characteristics [165]. Diffusive deposition is also presented in Refs. [166,167] in relation to thermophoresis and eddy impaction phenomena. Fackrell et al. [167] reported two approaches for accounting the deposition of smaller particles. The first one takes into account only the heat exchange, while, the second one models the particle diffusion within the boundary layer and calculates the particle deposition using the stopping distance criterion. Sticking model and the subsequent particle deposition mechanism due to liquid film is reported also by Nagarajan and Anderson [168]. Their analysis refers to different coal fuel in order to investigate the effects of the coal-ash constituents on sticking regime.

The critical viscosity method is widespread in the literature. Many authors have applied this method and validated its results with experimental tests [169]. Critical viscosity relates particle sticking to material-dependent properties like viscosity. In terms of sticking probability, viscosity at or below the critical viscosity is assumed to have a sticking probability of unity and at all other particle temperatures. Sreedharan and Tafti [169] proposed also a modification in order to account the transition across the critical viscosity value. Critical viscosity method is applied for numerical analyses on particle deposition [170–174]. Barker et al. [175] reported the deposition on a gas turbine section using the critical viscosity model and the critical velocity model. Singh and Tafti [176] modified the critical viscosity model to cover particle sticking at lower temperatures (lower compared to the melting temperature). At lower temperatures, energy losses due to particle-surface impact will determine whether an impacting particle will be able to leave the surface. These energy losses are a function of impact parameters such as the properties of particle/surface, impact velocity, and angle. In order to account for these energy losses due to collision, an improved model is proposed in this study which accounts for both the mechanisms of collision losses and particle temperature, to predict final sticking probability. The model for particle rebound based on an energy-based balance model is reported by the same authors in Ref. [177]. Other contributions can be found in relation to the effects of the electrostatic charge on particle deposition [178,179] and for evaluating the effects of the temperature of the particle and target surface and the turbulence intensity [180–187].

Regarding experimental tests, particle deposition is investigated in order to understand the turbine section contamination and the interaction between cooling hole and particle deposition. The setup of the test bench and the postprocess could be useful in understanding how to create a fouling-oriented compressor test bench. Ahluwalia et al. [188] formulated an analytical scheme to extract sticking coefficients from the measured weight gain data, particle size spectrum, and particle density and composition. Other experimental contributions can be found in Refs. [171,173,185,189–210].

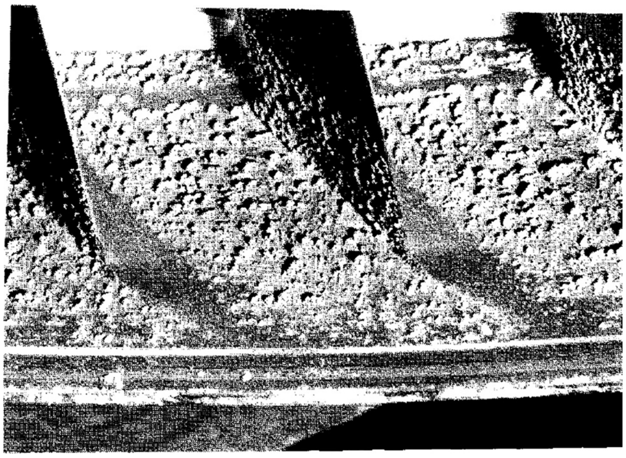

Fig. 18 Stator blade deposits [211]

5.2 Experimental Analysis. Regarding deposits on the blade surface, the first study conducted by Aguet and Von Salis [10] reported that the only occasion when deposits build up in air compressors is during heavy rain conditions, when water can enter the subterranean air passage between the air intake and the inlet flange of the low-pressure compressor. This water is then carried away as droplets in the airstream and evaporates in the compressors, so that the solid particles contained therein remain on the blades. Another heavy-duty application is reported [90]. During overhaul, some fouling issues were found in the compressor sections. Fouling of the compressor took the form of solid particles of dust or soot sticking to stator blading and, to a lesser degree, to the rotating blades. Figure 17 shows this type of deposit and although the rate and magnitude of fouling varied from machine to machine, appreciable magnitudes occurred in very few hours.

A particular compressor blade deposit was found by Bultzo [211]. He reported that the fourth to the eighth stages were fouled with the pigmentation material used in paint (titanium dioxide, verified by X-ray diffraction). Use of a scanning electron microscope showed the layering of the primer and finished coats. The author concluded that since painting was in progress within 30 m (100 ft) of the turbine inlet, airborne aerosol-like droplets were being ingested by the gas turbine. After sufficient work had been done on the air by the axial compressor, the solvent was still contained in the droplets of aerosol, resulting in localized fouling. The heaviest fouling was in the sixth-stage position. As shown in Fig. 18, the deposited material was very tightly bonded to both the rotating and stator blades of the axial compressor. It would have been impossible to clean the rotor and the stator blades in place.

Tarabrin et al. [57] reported an investigation of compressor blade contamination for a Nuovo Pignone MS5322 R(B) gas turbine engine. This power unit operated for a long time without blade washing but only the first five to six stages of 16 were subjected to blade fouling due to deposits. Figure 19 depicts the weight distribution of deposits for rotor blades (Fig. 19(*a*)) and stator vanes (Fig. 19(*b*)). The inlet guide vane blades, as well as the rotor and stator blades of the first stage have more deposits on the blade convex side. The deposit masses on the blades of the other stages are approximately equal for the convex and concave side, with deposit masses decreasing from the first to the sixth stage. From the seventh stage, the amount of deposits on the blades is insignificant. The authors point out that the amount of deposits is greater on the stator blades than on the rotor blades due to the cleaning effects provided by the centrifugal forces on dirt particles.

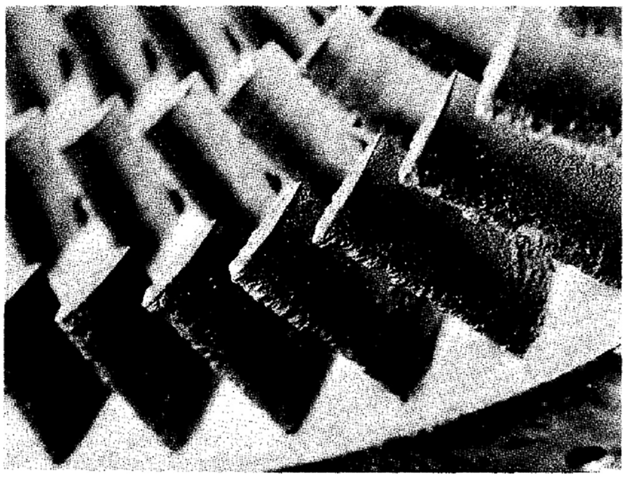

Fig. 17 Axial-flow compressor stator blading showing oily carbonaceous deposits [90]

Recently, Brun et al. [67] and Perullo et al. [105] have provided a detailed picture of compressor deposits. Figure 20 depicts several fouled blades (convex and concave sides), reported by Brun et al. [67], which have varying degrees of contamination but also some common characteristics: (i) the deposits were primarily on the front (convex) portion of the blade (see pictures of the front and back of Blade 13 and Blade 10), (ii) the streaking patterns evident on all the blades suggest that the material is deposited via radial flow from the root of the blade outward, and (iii) the cleaned area in Fig. 20 (Blade 14) shows where a paper towel was rubbed lightly on the blade to remove the material. The dirt does not appear to adhere tightly to the blades. A small amount of force is all that was required to dislodge the material, (iv) the leading edge of the blade was cleaner than the rest of the blade. This suggests that areas with a high velocity and incident angle are less susceptible to dirt deposits. However, other blades suggest that potential separation areas are less susceptible to having the dirt stick, (v) some deposits, like those shown for Blade 9, appear to have a substantial amount of hydrocarbon mixed in with the "dirt." Brun et al. [67], starting from a sample of blade surface fouling dirt taken from various field sites, develop a representative dirt formula and blade coating procedure. With this procedure it is possible to generate a dirty compressor blade in agreement with the actual contamination behavior and to study compressor fouling (flow deviations, washing operations, etc.) in a wind tunnel.

Perullo et al. [105] also reported a visual inspection of IGVs and first-stage compressor blades when using the F8 and E10 filters. The results of inspection are reported in Fig. 21. These two units are located at the same site, with similar operating profiles, which reduces the possibility of operating environments leading

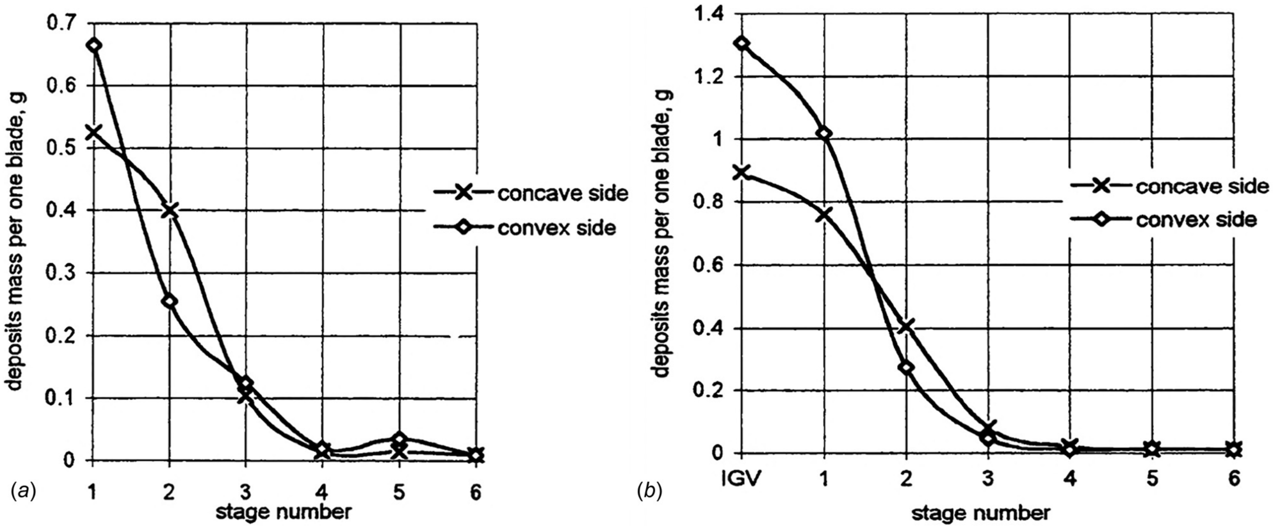

Fig. 19 Weight distribution of deposits on the convex and concave sides of the axial compressor blades: (*a*) rotor and (*b*) stator [57]

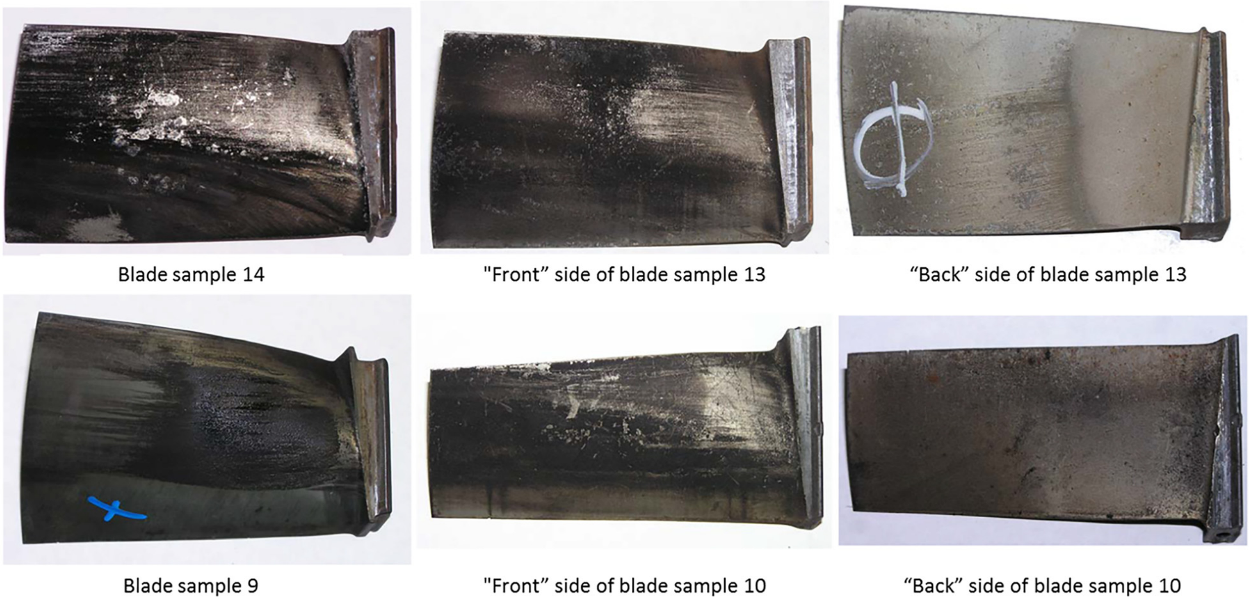

Fig. 20 Blade samples with varying degrees of contamination. Blade 9 shows deposits with a dirt mixed with hydrocarbon; blades 10 and 13 show deposits located on the front portion of the blade and blade 14 shows the manual cleaned area where the deposits are not too sticky [67].

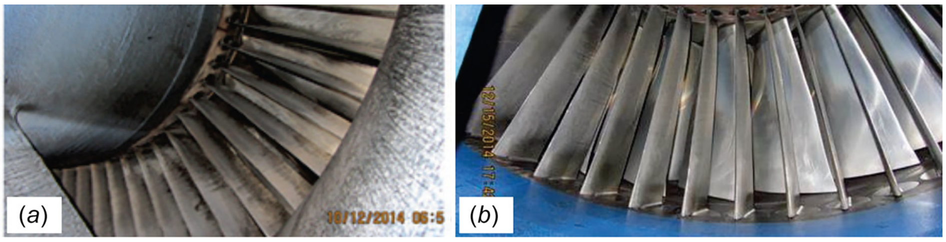

Fig. 21 Different deposit patterns after visual inspection: (*a*) deposits after 5000 h with two off-line washes and F8-type filter, (*b*) deposits after 6500 h without washes and E10-type filter. The differences in the deposit patterns are located at the leading edge zones [105].

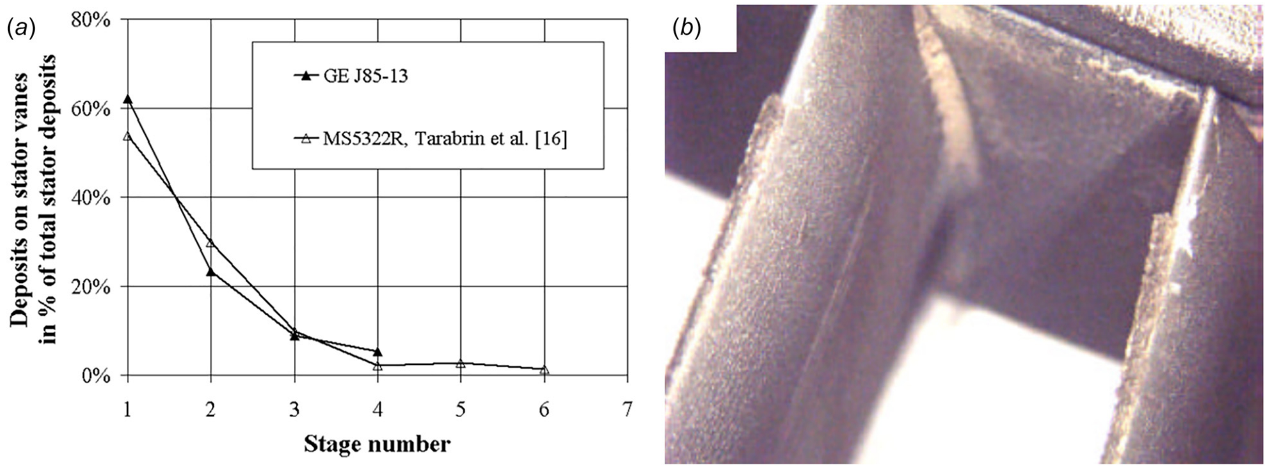

Fig. 22 Salt deposits found after experimental tests with salt ingestion: (*a*) percentage distribution of deposits with respect to the total stator deposits on stator vanes, (*b*) salt deposits at the leading edge of the second-stage stator vanes (at 6.5× magnification). The hub is at the top in this image. The partial detachment of the salt deposits close to the hub is clearly visible [212].

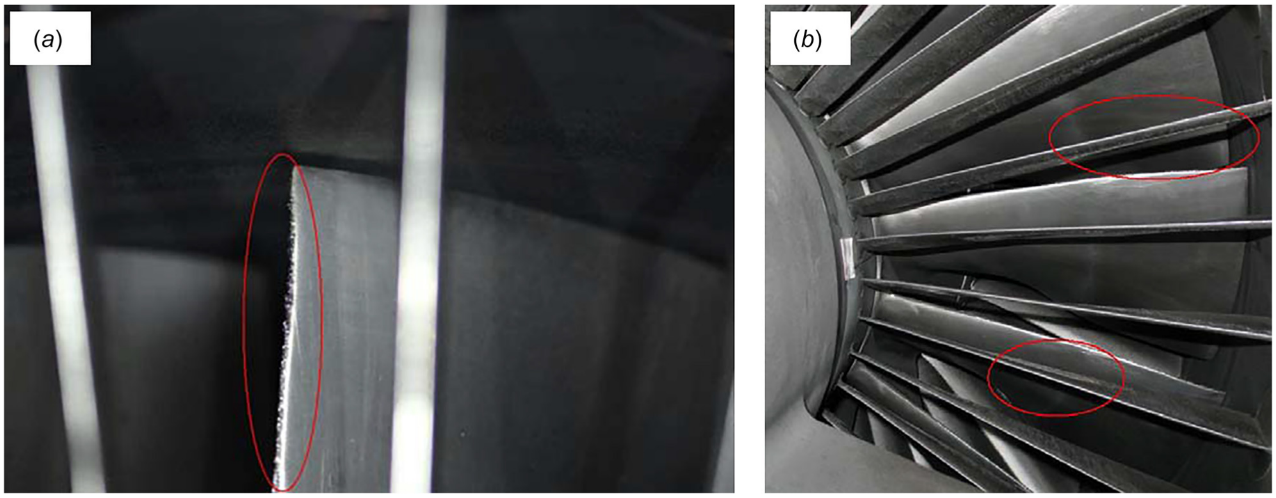

Fig. 23 (*a*) deposits on the leading edge of a first-stage rotor blade and (*b*) deposits on the inlet guide vanes [213]

to any observed differences. The F8 filter, which had two offline washes during 5000 h of operation showed significant fouling on the IGVs and first-stage blades. After 6500 h, the E10 filters showed little evidence of fouling compared to the F8 filter. This is especially noticeable when examining the leading edge of the first stage blades.

Regarding offshore and nearshore applications, salt deposits are presented by Stoeckly [79]. A 10 h endurance test was performed to determine the effects of ingesting salt water into the engine inlet at a rate of one part of salt solids per million parts of air. Post-test inspection of the compressor revealed moderate to heavy dirt and salt deposits over the inner half of the first-four stages. The stator vanes and passages were covered with a white powdery substance determined to be salt. Areas in line with the salt-water sprays on the front frame struts had their protective coating worn away and were rusty.

More recently, Syverud et al. [212] and Brekke et al. [213] showed the compressor deposits due to salt ingestion for two gas turbines installed in offshore platforms. Syverud et al. [212] reported the location of salt deposits in a General Electric J85-13 axial compressor. The experimental tests have shown that the salt deposits were mainly found along the leading edge of the first-four stages and on the pressure side of the stator vanes along the hub, as reported in Fig. 22(*a*). The salt deposits were generated by the salt carried by the water droplets and, for this reason significantly fewer deposits were observed on the rotor blades compared to the stator vanes due to the centrifugal force. Figure 22(*b*) depicts the salt deposits on the leading edge of the stator blade. Heavy leading edge deposits are probably caused by the constant shaft speed during salt ingestion. Close to the hub, a part of the deposits were broken off by the airflow probably due to the variation of the incident angle when the compressor was tested at a different rotational velocity. In the same way, Brekke et al. [213] report the location of salt deposits in a General Electric LM2500+ axial compressor. Figure 23(*a*) shows the salt deposits on the leading edge, while Fig. 23(*b*) shows the deposits on the inlet guide vane. The authors point out that the apparent separation lines (indicated by two red ovals) between the cleaner and more heavily deposited areas of the vanes were typically seen on all of the inlet guide vanes in this unit.

5.3 Numerical Analysis.

Even though the first numerical calculation of particle motion was reported by Tabakoff et al. [214], the first conference contribution concerning theoretical and numerical approaches regarding particle deposition is provided by Agengiiturk and Sverdrup [215]. The authors present a theory for the prediction of deposition rates of fine particles in

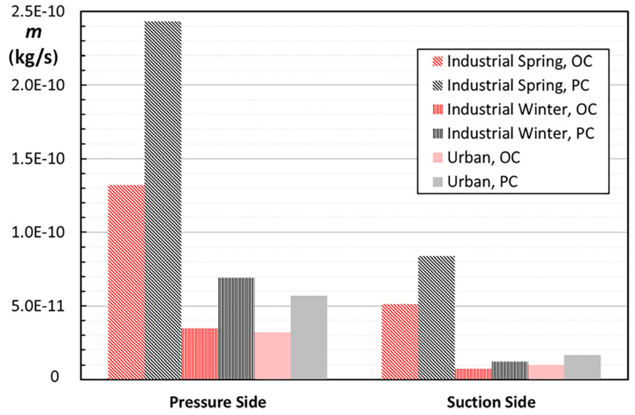

Fig. 24 Contaminant mass on the blade surface with filtration system. Contaminant mass flow rates were reported as a function of the blade side (pressure and suction), environmental condition (Industrial Spring, Industrial Winter, Urban), and charge level of the electrostatic filters (optimal charge, OC and poor charge, PC). The environmental conditions are characterized by different contaminant concentration—Industrial Spring is the most detrimental condition, while Urban is characterized by lower levels of particle concentration [219].

two-dimensional compressible boundary layer flows. The mathematical model developed accounts for diffusion due to both molecular and turbulent fluctuations in the boundary layer flow. Particle inertia was taken into account for the particle flux near the surface. The theory was compared with a number of pipe and cascade experiments, and good agreement was obtained. This model was applied to a cascade turbine but represents the first theoretical and numerical model for studying particle deposition.

Numerical studies related to the particle deposition on axial compressors are not widespread in the literature, and some analyses have only become available in the last few years. The challenges involved in this type of analysis are linked to the size of particles (submicron particle) and computational efforts. Suman et al. [216–218] reported the combination of the impact/adhesion characteristics of the particles obtained through a CFD numerical simulation and the actual size distribution of the contaminants in the air swallowed by the compressor. Their works combine the kinematic characteristics of particle impact on the blade with fouling phenomenon through the use of a quantity called *sticking probability* adopted from the literature. The analysis shows that particular fluid-dynamic phenomena such as separation, shock waves, and tip leakage vortex strongly influence the deposition pattern. The combination of smaller particles (0.15–0.25) μm and larger ones (1.00–1.50) μm determine the highest amounts of deposits on the leading edge of the compressor airfoil. The same analyses were conducted for a transonic rotor [216,217] and subsonic rotor [218].

From these works, it is possible to describe the main difference involved in the two compressor types. In particular, the comparison related to the particle impact behavior can be summarized as follows: (i) for both rotors the percentage of the particles that hit the blade surface increases with the diameter of the particles but the transonic rotor is more affected by the particle impact; (ii) for both rotors, by increasing the particle diameter the pressure side is more affected by the impacts, thus the particles tend to hit the pressure side in increasing quantities as the particle diameter increases and (iii) by increasing the particle diameter the suction side is less affected by the impacts in the case of the transonic rotor, while in the case of the subsonic rotor, a particular impact pattern in the leading edge (thicker than the transonic rotor) influences the results. Starting from the results reported in Ref. [217], the authors in Ref. [219] proposed an estimation of the deposits that afflict a transonic blade surface. The quantitative analysis of the deposits on a blade surface is strongly related to: (i) actual air contamination data, (ii) actual filtration efficiency, and (iii) particle adhesion. Transonic blade surfaces appear more contaminated on the pressure side and in the leading edge area. However, even if the peak of contaminant is higher on the pressure side, the deposits on the suction side appear more distributed on the blade surface.

Suman et al. [219] also reported the influence of the electrostatic filter charge and its relationship between air contaminant concentration. Figure 24 reports the results related to blade contamination. Two conditions are reported: optimal charge and poor charge of the filtration system. The charge level influences the overall mass deposits on both of the blade sides and in particular, the optimal charge allows a consistent reduction of mass deposits. The reduction is in the range of (39–50)% depending on the environmental conditions. It is possible to observe that the characterization of the contaminant concentration in the air is more important than the filter charge. In fact, Industrial Winter and/or Urban conditions in the case of poor charge, are less dangerous than the Industrial Spring condition in the case of optimal charge.

6 Remarks

In the last part of this review, a brief recap of the principal contributions proposed in this work and an analysis of the contributors in fouling analysis are reported. Figure 25 shows the timeline related to the 60 years of ASME Turbo Expo proceedings and highlights the first contributions related to a particular analysis or innovation. Starting from 1960s, the first application of two-stage

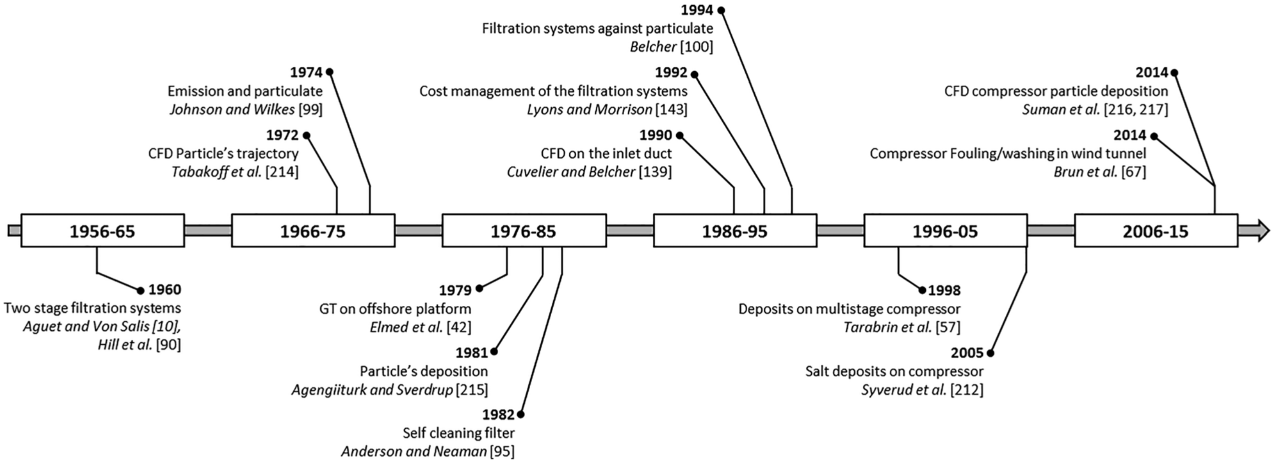

Fig. 25 Timeline showing the progress in the field of fouling contributions

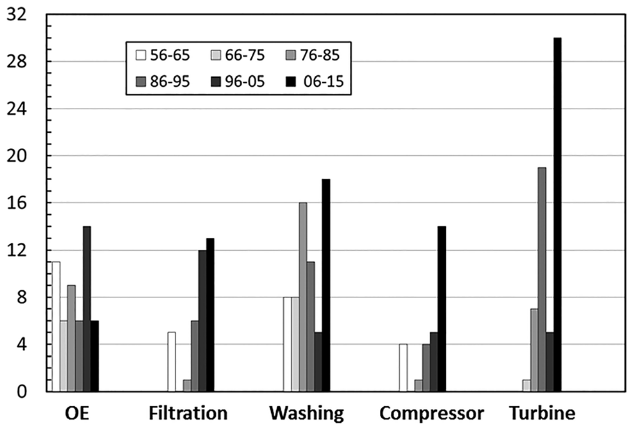

Fig. 26 Overall contributions in gas turbine fouling

filtration technology was reported [10], while in the 1970s the first numerical analysis of particle trajectory [214] and the first-air contaminant data concentration (realized specifically for the particulate analysis by Johnson and Wilkes [99]) were proposed. Subsequently, the first report on gas turbine platform installation [42] and the first numerical analysis on particle deposition [215] were reported. Filtration technology covers a very wide range of interest, in fact in almost 10 years applications related to self-cleaning filters [95], numerical investigation of the inlet duct system [139], analysis of the cost management of filtration systems [143] and new filters that work against the particulate [100] have been reported. In the last 20 years, contributions have been dedicated to compressor deposits. In fact, deposits on a multistage compressor [57] and salt deposits due to the platform operation of axial compressors [212] have been reported. Finally, experimental [67] and numerical [217–219] determinations of compressor deposits have been carried out.

As previously mentioned, Fig. 25 reports the first contributions in the different fields of interest related to the fouling issue but a different analysis can be performed by dividing all the contributions reported in this review according to the previous timeline block division. Figure 26 shows the contributions grouped into five categories: (i) operational experience and field data sources, named operational experience (OE), (ii) filtration technology and filter performance, named Filtration, (iii) washing operation and optimization, named Washing, (iv) deposits and fouling characterization on compressor sections, named Compressor, and (v) deposits and fouling characterization on turbine sections, named Turbine. From the data reported in Fig. 27, it is possible to note that operational experience is the only topic with a negative trend. Through the years, in fact, reports on gas turbine operation with special attention to the issue of fouling are even more scarce. By contrast, data and analyses related to the other fields of interest are even more numerous due to the overall increment in the number of Turbo Expo proceedings. Figure 27 reports the contributions divided according to three main topics analyzed in this review. In detail, the operational experience and filtration systems are subdivided according to the land-based and offshore (and near shore) field of interest, while compressor deposition is divided according to experimental and numerical analyses. Land-based contributions are more numerous than offshore contributions, which refer to two main gas turbine applications—(i) in early marine gas turbine applications, offshore analyses are only related to ship installations, while (ii) starting from the 1980s, marine gas turbine applications refer in particular to platform installations. An analogous trend can be found for filtration system analyses, which involve in particular salt separation in the case of ship and platform installations. Regarding particle deposition on the compressor, experimental and numerical analyses are on the increase, even though numerical analyses have only been available since the 1990s (due to the increase in computational resources).

The last analysis is related to the contributions and contributors involved in this review. Starting from the contributions reported in this work, Fig. 28 summarizes the contributors and their affiliations. The number of papers related to the fouling issue has increased from 35 (in the first decade) to 170 (in the last decade), as reported in Fig. 28(*a*). This trend is related to the global conference trend, reported in Fig. 28(*b*), which shows the increasing number of contributions (ordinate) through the years (abscissa). In the latter decades (1996–2005 and 2006–2015) the number of papers regarding fouling represents almost 0.6% with respect to the overall total. This value is lower than that of the first three decades, when it was equal to 9.9%, 1.3%, and 1.4% for 1956–1965, 1966–1975, and 1976–1985, respectively.

Regarding affiliation, from Fig. 28(*c*) it is possible to note that the academic contributions cover 51% of the global production in the last decade while in the first decades, academic contributions were very scarce. Government actors are especially related to military factors (in the first decades) and to research institutes (in the last decades).

In conclusion, compressor fouling is an operational problem highlighted by the manufacturer which, over the years, has involved academic researchers in a bid to limit and manage the fouling issue. Compressor performance drops are strongly related to the fouling issue, and therefore, the reliability, performance, and efficiency of gas turbines will only reach higher levels if knowledge is improved by the use of experimental tests and numerical models.

7 Perspectives

Based on the ASME Turbo Expo contributions presented in 2016, it is possible to highlight the most recent research trends. In this paragraph, contributions related to compressor fouling and gas turbine hot section particle deposition are reported separately.

7.1 Compressor. Regarding compressor fouling the contributions can be categorized into three main topics:

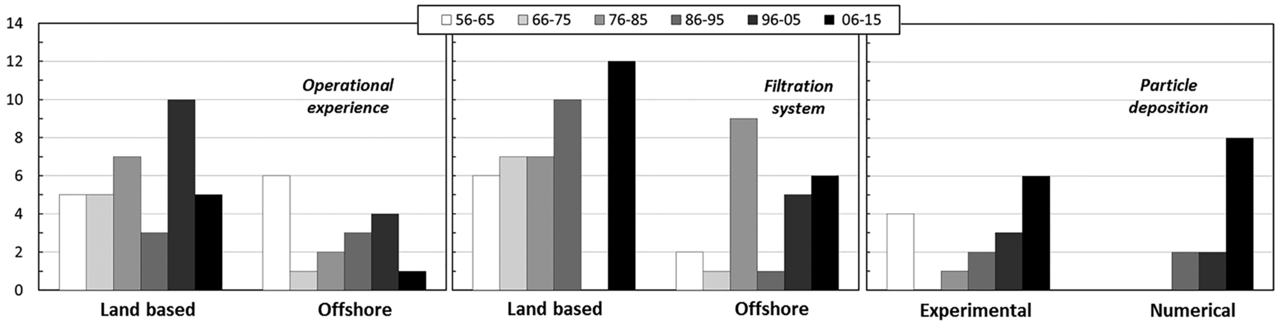

Fig. 27 Detailed subdivision of resources: operational experience, filtration system, and compressor deposition

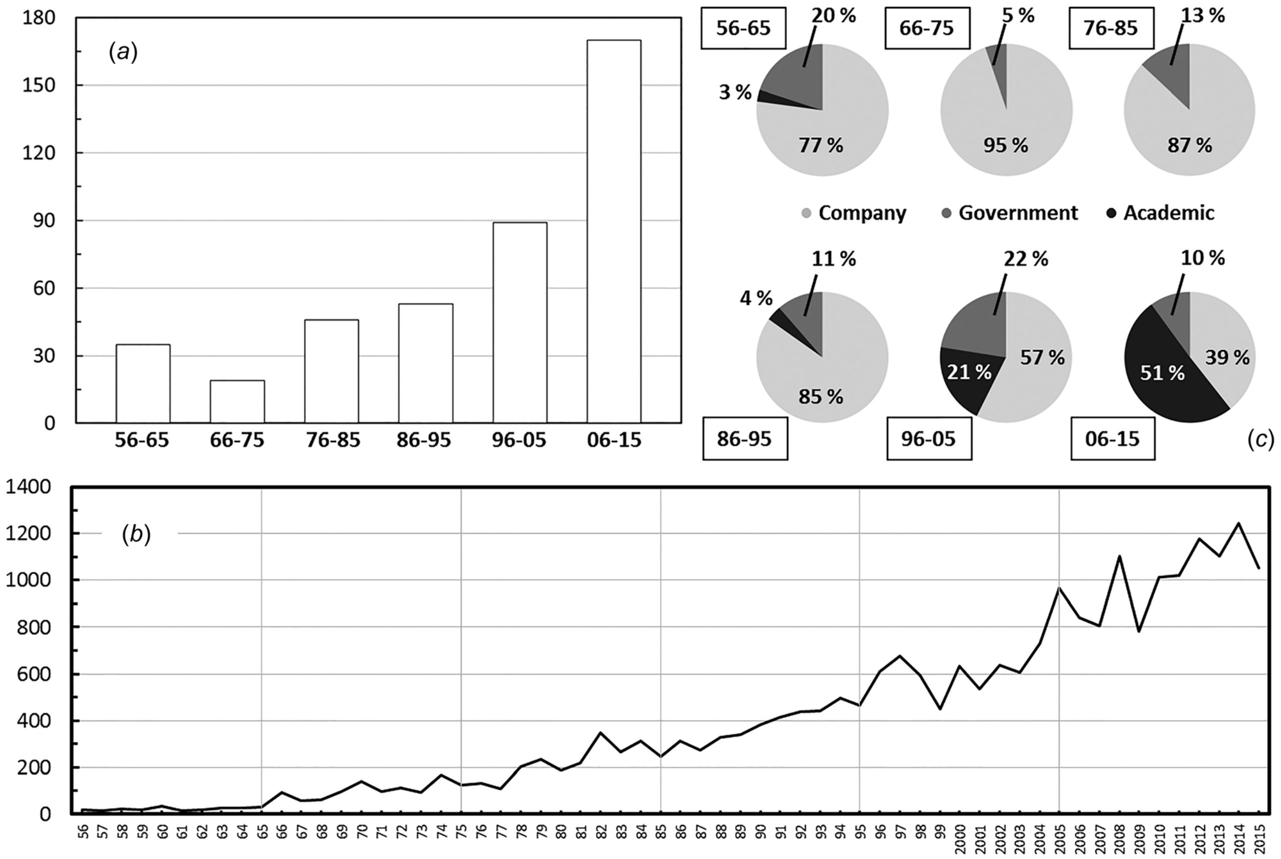

Fig. 28 **Overall count of fouling contributors: (*a*) contributions devoted to the fouling issue, (*b*) overall ASME Turbo Expo contributions, and (*c*) affiliation of contributors involved in the study of fouling**

(1) Prediction models for gas turbine performance able to take into account compressor fouling and other degradation mechanisms,
(2) Numerical and experimental applications in order to investigate which mechanisms mostly drive compressor fouling, and
(3) Filtration systems and washing operations.

Prediction models are reported by four papers: (i) Hanachi et al. [220] base their model on actual data that takes into account the ambient conditions (especially temperature and humidity) for estimating the compressor performance drop due to fouling effects, (ii) Qingcai et al. [221] proposed a gas turbine performance prediction model based on genetic algorithm of 11.8 MW three-shaft unit accounting compressor erosion and fouling phenomena, (iii) Qui et al. [222] proposed a geometry parametrization for dirty compressor blade in order to take into account the geometry effects (nonuniform and stochastic) due to fouling and erosion phenomena and finally, (iv) Roumeliotis et al. [223] realized a gas path analysis coupled with an economic module for the economic assessment of recoverable degradation maintenance actions (compressor washing, filter change, etc.).

Numerical and experimental applications are reported by four papers. Only one of these refers to experimental analysis of compressor fouling [224]. Kurz et al. [224] reported an experimental investigation that provides experimental data on the amount of foulants in the air that actually stick to the blade for different conditions of the surface. The authors run experimental tests with dry and humid conditions. Numerical analysis is reported by Suman et al. [225] related to a subsonic axial compressor blade performing an analysis in line with that reported in Ref. [219]. Aldi et al. [226] studied the particle deposition in a transonic axial compressor stage, based on the model reported in Refs. [216,217], coupled with a particular treatment of particle data across the interface between the rotor and stator. Finally, Saxena et al. [227] reported numerical simulations of erosion phenomena in a multistage axial compressor. A general overview related to fouling phenomena is reported in Borello et al. [228], where the authors provided a wide investigation into the fouling issues involved in a modern power plant (subsonic compressor, turbine vane, internal cooling channel, and extraction fan).

Filtration and washing applications are based on three papers. Two of these refer to off-shore applications, namely Madsen and Bakken [229], who focused on multiple stage filtration systems and Luan et al. [230], who focused on wave-plate separators. Schirmeister and Mohr [231] provided the only contribution related to land-based gas turbine installation. They present a quantification of the effect of different air filter classes on the performance degradation of 12 gas turbines from six different power stations.

7.2 Turbine. Regarding particle deposition and fouling issue in gas turbine hot sections, several contributions are present. In this case, two main topics are present:

(1) numerical applications and analytical models to predict particle deposition, and
(2) experimental analysis.

An analytical model able to predict particle deposition is reported by Casari et al. [232], where the authors propose an innovative model based on an Arrhenius-type equation able to predict the particle deposition on a gas turbine section. The model is based on experimental data reported in the literature that refers to several types of materials. Bons et al. [233] defined a new deposition model that includes elastic deformation, plastic deformation, adhesion, and shear removal, and it is validated against five literature cases. This model is applied in the numerical simulations performed by Prenter et al. [234] for particle deposition in a cooled high-pressure turbine stage. Agati et al. [235] reported a numerical modelization of particle deposition that occurs in gas turbine hot sections over a wide temperature range. Their model is able to account for particle deposition from 500 K to 1500 K. The transition between these two extreme conditions is modeled through a temperature-driven modification of the mechanical properties of both particles and target surfaces. Finally, an innovative numerical strategy for particle tracking in secondary air systems is presented by Forsyth et al. [236], and Boulanger et al. [237] generated a statistical model to predict the effect of gas path temperature (up to 1100 °C) and target angles. The authors estimated the uncertainty due to the surface temperature and particle injection rate based on the experimental results.

Regarding experimental applications, authors focus mainly on the interaction between the particle deposition and film cooling holes and their relative effects. Whitaker et al. [238] performed an experimental campaign to discover how particulate loading, particle size, and temperature affect the deposition and flow blockage development in an impingement-film cooling turbine section. Lundgreen et al. [239] provided an experimental test of dust deposition on a gas turbine cascade with a film cooling hole. Working up to 1350 °C as a temperature inlet, the authors show different deposition patterns on the turbine nozzle. Wylie et al. [240] reported the results of particle deposition in the internal cooling passage of a high-pressure turbine. The authors perform particle deposition using actual volcanic ash. Experimental deposition on film cooling holes is also reported in Wang et al. [241].

7.3 Vision. From the previous analyses, it emerges that recent research is mainly focused on the modelization of particle deposition, especially for gas turbine hot sections. Models should be able to predict particle deposition based on basic boundary conditions such as gas temperature, materials, and contaminant dimension. Numerical analyses are used as a tool for matching the numerical results obtained using the deposition model and the actual experimental data. Experimental tests are devoted to discovering the interaction between the particle deposition and film cooling and the effects of deposits on cooling holes and channels.

Analyses and tests related to compressor fouling remain uncommon in the literature. Although fouling issues for land-based and off-shore gas turbines are detrimental, the difficulties involved in this type of analysis lead to a real lack of contributions to this field. Dry and humid conditions coupled with contaminant type are the main contributors to fouling. Experimental analyses and numerical models have to take into account the effects of the presence of third material (such as water, oily substances, etc.) at the particle/surface interface, implying several difficulties in the modelization of compressor fouling. These aspects represent the upcoming challenges, considering that both experimental and numerical analyses have to reflect the actual condition in which power units operate.

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