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Customized filter concepts for intake air filtration in gas turbines and turbocompressors

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Introduction

Particulate impurities in the intake air represent an important factor affecting the operational characteristics of gas turbines and turbocompressors. Given a dust and dirt content in the ambient air at a particular site, the efficacy of the air filters used will significantly determine the time frame involved in efficiency and performance decline for turbomachinery. The particles introduced together with the air will, depending on the sizes involved, cause material abrasion or dust caking on the surface of the blades.

What air filters have to do

The primary job of the air filters used in gas turbines and turbocompressors is to prevent damage to the turbomachine's blading.

The physical requirements for the air intake system, however, are in some respects irreconcilable. The air filters are asked to provide high quality collection of the particles introduced by the ambient air, and simultaneously to achieve long useful lifetimes with low pressure drops. Figure 1 shows how performance and efficiency of a gas turbine depend on the pressure drop in the air intake system. Given an extremely high collection performance by the air filters, the output loss will be smaller, thanks to reduced compressor soiling, but the high pressure drop in the filters, conversely, will itself reduce the output of the turbomachine concerned. In addition, the filters' useful lifetime will decrease with rising collection efficiency.

The filter's useful lifetime becomes a particularly important factor when the air filters are scheduled for replacement only once a year, at a fixed date as part of a system inspection. If the filter has to be replaced prematurely due to the pressure drop rising too fast, high downtime costs will be incurred, since for safety reasons the filters are usually replaced only when the turbine is at a standstill.

In addition, the user of a turbomachine is obliged to specify high standards of operational reliability for his air filters. For example, there must be no destruction of the filtering medium's material if the filter is soaked through due to lengthy periods of foggy weather. Nor may the air filters be damaged if the turbomachine starts surging, i.e. if there are brief, expansive backflows of intake air.

As a manufacturer of air intake systems and filters with a large fund of empirically acquired data, the Freudenberg company is able to select suitable air filters offering turbomachine users a filtration concept combining technical excellence with optimized cost-efficiency.

This optimization is primarily based on

- the choice of raw materials and filtering medium,
- matching the prefilters and final filters to the air conditions of the site location and to the requirements for clean-air quality,
- ensuring that the filters do not corrode even under a wide variety of different weather conditions,
- the provision of safety reserves against bursting if the air filters are subjected to out-of-the-ordinary stresses, and
- consistently high quality of the products utilized.

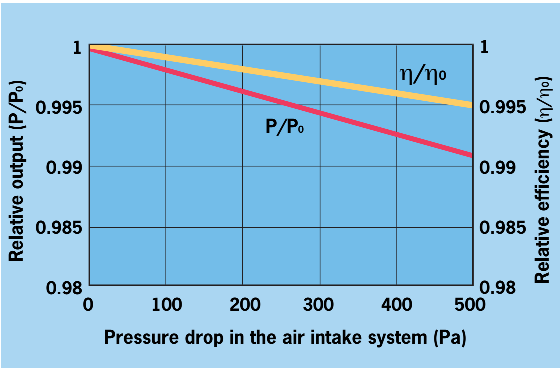


Fig. 1: Output and efficiency losses of gas turbines due to the pressure drop in the air intake system

Fig. 2: Dust encrustations on rotor blades in an industrial gas turbine (6 MW)

Damage due to airborne particles

Figure 2 shows dust caking on the rotor blades of a 6-MW industrial gas turbine. Figure 3 depicts the decline in turbine performance due to soiling of the compres-sor in a 25-MW gas turbine over two operating cycles of 3,676 h and 4,021 h. When a wash procedure is performed, a high degree of performance is restored in each case, thus documenting the significant effect of compressor soiling on gas turbine operation.

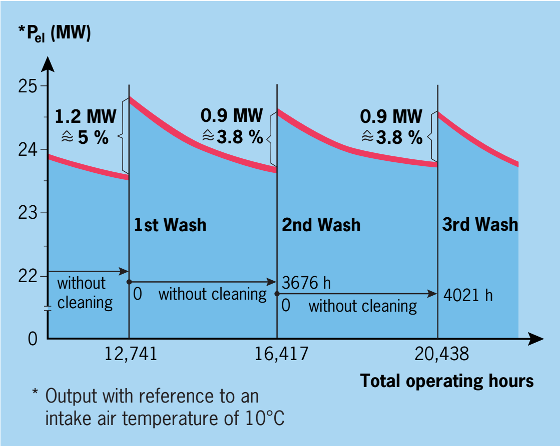


Fig. 3: Output losses due to compressor fouling and output recovery from "washing"

There are two possible washing methods when a turbomachine is enclosed. While off-line washing removes the deposits from the blades by soaking them in wash solution, on-line washing injects a washing agent solution into the compressor. Off-line washing is more time-consuming and therefore more cost-intensive, but is more effective than on-line washing, though this latter can be performed while the system is still running. If a gas turbine is taken off-line during the wash procedure, then in the case of the 25-MW machine described in Fig. 4 a wash time of five hours will mean 125,000 kWh less electricity produced.

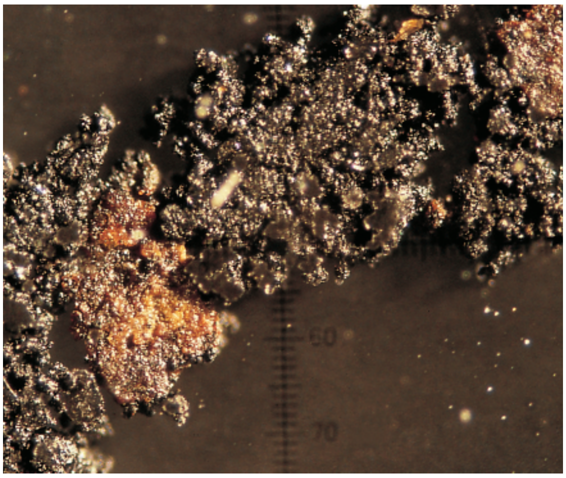
In the case of on-line washing, it is particularly difficult to transport the dirt particles detached from the front blades as far as the combustion chamber, and thus to prevent caking on the rear blades of the compressor. Blading deposits of this kind cannot be completely removed until the scheduled system inspection when the turbomachines concerned are opened up.

Damage	Particle size range	Gas turbine	Turbo-compressor
Erosion	> 5 - 10 µm	●	●
Fouling and resultant unbalance and reduced air mass flow	appr. 0.1 - 5 µm	●	●
Fouling of the intercoolers and down-stream system components	appr. 0.1 - 5 µm		●
Wet corrosion	appr. 0.1 - 5 µm	●	●
High-temperature corrosion	appr. 0.1 - 5 µm	●	
Clogging of cooling air slits	from 0.1 µm	●	

Fig. 4: Damage to turbomachinery

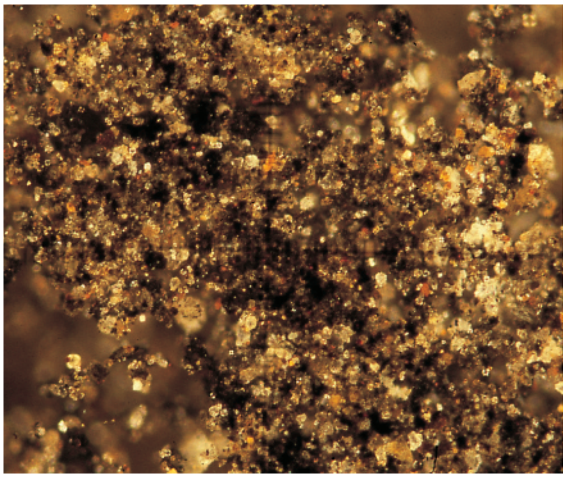
There is an important causal connection between the damage pattern and the correlating particle size (see Figure 4). Particles of approx. 5 µm and larger have an abrading effect on the compressor blades, and the air filters have to provide practically complete collection here. Particles smaller than approx. 5 µm, in particular, will cause deposits to form on the blades, which not only alter the blade geometry but also reduce the free cross-sectional area for air flow. The first of these factors will cause a decline in compressor efficiency, and the second a reduced air mass flow. In the case of gas turbines, this will lower output and efficiency, while with turbocompressors the power input will rise if a constant pressure ratio is demanded.

For this reason, the air filters used should collect not only the particles larger than 5 µm in the intake air, but also a large proportion of the smaller sizes. A rise in collection performance, however, necessarily entails an increased pressure drop at the filter, with adverse effects on efficiency and output of the turbomachine concerned.



200 µm

Fig. 5: Light-microscope picture: fouling sample taken from the guide vane carrier of a large-size gas turbine



50 µm

Fig. 6: Light microscope picture: dust sample from blade fouling, taken from a gas turbine without intake air filter

Figure 5 shows a light microscope picture of blade deposits in a large-size gas turbine (100 MW). The black particles indicate a high proportion of soot. High efficiency filters (collection efficiency for particles of 2 µm and larger was approx. 100 %) were used for intake air filtration at this gas turbine. The deposit basically consists only of particles smaller than 2 µm with a marked tendency to agglomeration.

In comparison, Figure 6 shows blade deposits from a gas turbine which was operated without an intake air filter. The translucence observable in patches is an indication of natural particles originating from erosion of the Earth's crust. Since these particles exceed 5 µm in size, they cause not only deposits on the blades, but also erosion of the actual blade material.

Figure 7 shows the spectrum of an energy-dispersive X-ray analysis (EDX analysis) of the blade deposits found in a 50-MW gas turbine which was operated with roll filters as the sole filter stage. The high peak for silicon indicates the presence of natural particles, which are mostly larger than 5 µm. The sulfur peak is an indicator for combustion products (soot) and sulfates. The particles over 5 µm introduced into the turbine had caused severe material abrasion on the blades.

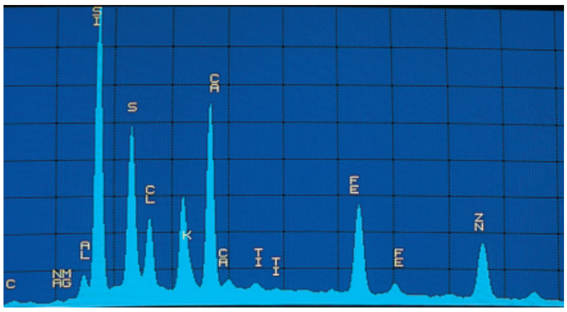


Fig. 7: EDX analysis: fouling sample taken from the first row of rotor blades in a gas turbine with roll filters

An EDX analysis of the microfiber layer in a pocket filter (see Fig. 8) shows that particles with a sulfur and chlorine content, in particular, are arrested here. The proportion of natural particles is low, since due to their size most of these will already have been collected by the prefilters. Sulfur is an element predominantly found in particles smaller than 2 µm.

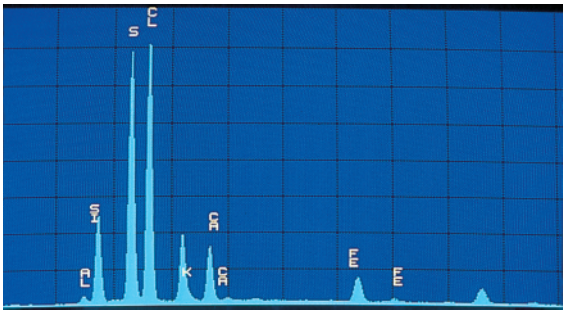


Fig. 8: EDX analysis: microfiber layer of a Compact pocket filter after use in a gas turbine

These analyses illustrate the necessity of high-quality intake air filtration. The use of plane filter material (e.g. roll filters) cannot achieve a clean-air quality of the level required for turbomachines, since erosion of the blade material will not be prevented. The pocket filter examined, conversely, provided practically complete arrestance of particles larger than 2 µm, plus a high proportion of the smaller sizes.

The different types of air filter

In the laminar flow range (Re < 1), the pressure loss caused by a filtering medium is in approximately linear proportion to the air velocity through the medium concerned. For higher Reynolds numbers, the pressure loss rises disproportionately. Out of cost-efficiency considerations, then, it is necessary to install a maximized effective filter area in the inflow cross-section available. The second parameter affecting the pressure loss is the porosity (proportion of void volume) of the filtering medium concerned. Given an identical weight per unit area and an identical fiber diameter, a compressed filtering medium will have a greater pressure loss and a lesser dust holding capacity than a more voluminous medium.

Customizing techniques employed for HEPA-filters (High-efficiency particulate air filters) have fostered the development of a type of intake air filter suitable for turbomachines, referred to as a cassette or rigid filter. The glass-fiber paper mostly used as the filtering medium is made out of coarser glass fibers than those used in HEPA filters, in order to reduce the pressure loss to a level acceptable for turbomachinery.

Since glass-fiber papers cannot be manufactured in a voluminous version, pleating is employed in order to accommodate up to 20 m^2 of filter surface on an inflow cross-section of 0.37 m^2. This is done to compensate for the very much higher pressure loss and lower dust holding capacity of the material when compared to voluminous nonwovens. In practice, however, the problem is to ensure that the filtering material is effectively coated in the depths of the folds, and thus to actually utilize the total filtering area available. In addition, the moisture resistance of the glass-fiber paper is also problematical if exposed to water over lengthy periods. Filtering media made of cellulose paper have not proved very suitable, since when exposed to moisture this material tends to swell, entailing increased pressure loss. This change in the material may even result in destruction of the filtering medium concerned.

Another variant of intake air filters for turbomachines is the cartridge filter, which incorporates filtering media folded in a star configuration and brought into a cylindrical shape. These filter cartridges are familiar from dust removal technology, where they offer an alternative to bag filters, and just like these latter can be freed of the dust cake formed by means of pulse-jet cleaning. The argument that these filters can be cleaned has won them numerous adherents for turbomachinery intake air filtering applications.

In practice, however, it has emerged that the typical characteristics of atmospheric dust in temperate latitudes render this cleaning process very difficult. Due to its adhesiveness, the dust sticks tightly to the filtering media, causing an irreversible rise in pressure loss.

Frequent pulsing of the filters in an attempt to reduce the pressure loss nonetheless, promotes the transport of fine particles through the filtering medium due to the mechanical stresses involved, thus increasing the concentration in the clean gas.

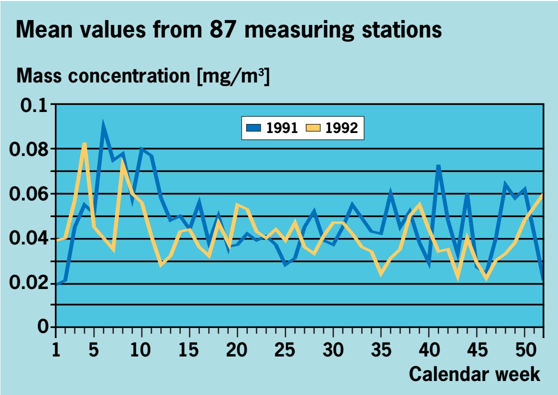


Fig. 9: Airborne particle concentration in Germany in 1991 and 1992

There is another aspect which makes it extremely difficult to clean filter cartridges soiled with atmospheric aerosol, and this is the dust concentration to be expected in temperate latitudes at the site locations in question. Figure 9 shows the weekly mean values for airborne dust concentration in Germany for 1991 and 1992, as an average determined at 87 different measuring stations. The highest weekly mean value is approx. 0.09 mg/m^3. Peak values from single measuring stations, however, significantly exceed the weekly mean value as averaged out over all the measuring stations. The highest weekly mean value from a single measuring station during 1991 was 0.19 mg/m^3. These relatively low figures make it clear that an appreciable dust cake cannot be built up on the surface of the filtering medium, and thus the intake air filters often cannot be cleaned with sufficient effect.
A third type of filter is represented by depth-loading filters in the form of pocket filters. For use in pocket filters, moisture-resistant, non-breaking synthetic-organic fibers have proved to be a reliable and appropriate filtering material for jobs demanding high filter performance and operational dependability. These fibers are processed into a voluminous nonwoven and incorporated in a suitably designed pocket filter which satisfies these requirements in numerous applications.
The current state-of-the-art enables synthetic fibers to be manufactured with a relatively large diameter, and also microfibers for high-efficiency filters. The properties of polymer materials mean they can be processed to form a leakproof configuration by welding the filtering media at the edges.

The use of voluminous filtering media, however, restricts the usable filtering area: in the case of pocket filters, if the clean-air sides of adjacent filtering media touch each other, these areas will become inactive, because no air is now flowing through them. Sophisticated spacer design now enables the ratio between active filtering area and free inflow cross-section to be as much as 23 for an overall depth of 650 mm.

Matching the prefilters and final filters

As already explained, the causal connection between the damage pattern and the particle size enables the requirement profile for the filtration function to be clearly defined. In most cases, a two-stage filtering concept is chosen: besides the final filter, which is the crucial factor influencing the clean-air quality, the prefilter used is also of major importance. The main job of a prefilter is to prolong the useful lifetime of the final fine filter. The prefilter should be tailored to the outside air-quality obtaining at the turbomachine's actual location. For a defined collection performance, it must exhibit as low as possible a pressure drop coupled with high dust storage capacity.
Since the efficiency of turbomachines depends on the pressure loss in the air intake system (see also Figure 1), the mean pressure loss at the prefilter should for cost-effectiveness reasons be not more than half as great as that of the final filter. This requirement can only be met by a prefiltration unit with a sufficiently large filtering area. Plane filtering material, e.g. in the form of roll filters, will entail high pressure loss. At the face velocity of approx. 2.5 to 3.2 m/s customarily used in intake air filtration for turbomachinery, the pressure drop of a coarse filter mat not yet loaded with dust is approximately 50 Pa, and due to the relatively low dust holding capacity of the plane material will rise rapidly. Conversely, for the pocket filters customarily used as prefilters, the figure for pressure drop is only 20 Pa. Due to the pocket filter's high dust holding capacity, the pressure drop increases only slowly.
Figure 10 shows pressure drop curves for roll filters (plane filtering medium) and pocket filters of the same filter class as classified by DIN 24 185 (EN 779, ASHRAE 52-76, BS 6540), with figures taken from actual operation. The user had recorded the changes in pressure drop increase for the two types of filter over 11,000 operating hours for each one. The mean pressure drop of the roll filters was approx. 160 Pa, while the corresponding figure for the pocket filters was approx. 60 Pa.

This means that for a comparable collection performance the pressure drop of the pocket filter is substantially lower than that of the plane filtering medium.

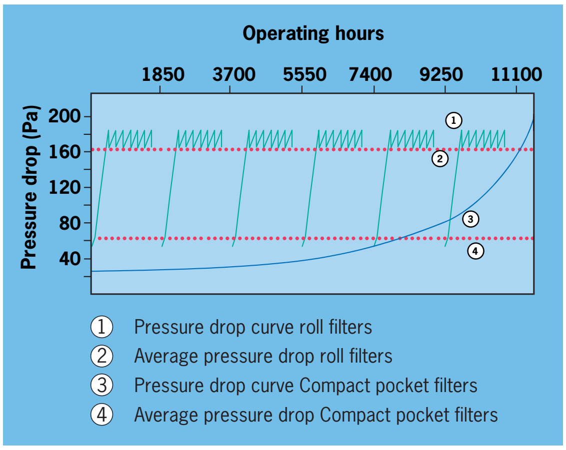


Fig. 10: Field data comparison: pressure drops of roll filters and Viledon Compact pocket filters

The requisite clean-air quality can be achieved only by using high efficiency filters (collection efficiency for particles larger than 2 µm is approx. 100 %). A filter of this kind generates approx. 80 Pa initial pressure loss, with a slow pressure drop increase over its period of operation. Since the dust holding capacity of an high efficiency filter for physical reasons (porosity of the filtering medium, fiber fineness required) cannot be as high as that of a coarse filter, it is significantly easier to achieve a long useful lifetime for the final filter when it has been optimally matched to the prefilter involved.
The useful lifetime of the final filter, however, is not independent of the prefilter's lifetime: if the prefilter has to be replaced frequently, this will shorten the useful lifetime of the final filter, since the collection performance of filters unsoiled by dust is lower than that of dust-loaded filters. This means that after every replacement of the prefilter the final filter will be subjected to a higher dust loading, and will therefore reach its final pressure loss more quickly.

The constituent parts of an air intake system

Figure 11 shows a schematic sketch of a filter housing with depth-loading filters. After passing through the weather louvers and bird screen, the air is fed through the first and second filter stages and the sound attenuator into the plenum chamber upstream of the turbomachine's bellmouth.

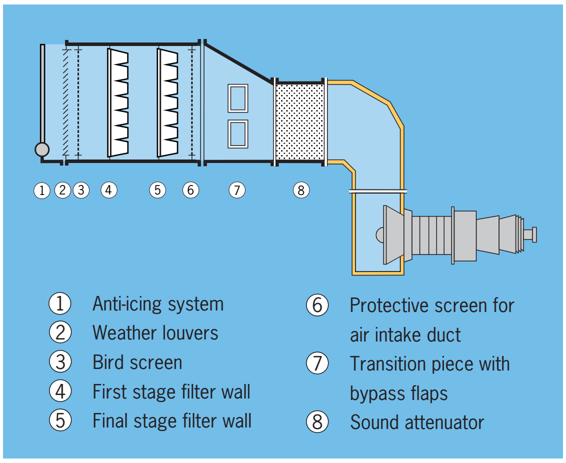


Fig. 11: Modules of an air intake system for turbomachinery with Compact pocket filters

If particularly high dust loadings are involved (e.g. in arid zones during sandstorms), an inertial separator (see Fig. 12) may be installed upstream of the prefilter. When using inertial separators, however, it must be taken into account that the collection performance depends on the air velocity, and therefore there has to be a relatively high pressure loss in order to ensure that the inertial separator functions properly. The operating pressure drop is usually in the range of 200 – 250 Pa at a face velocity of 2.3 – 2.7 m/s. Generally, the inertial separators used for intake air filtration at turbomachines achieve approximately 90 % collection for particles of 10 µm and larger. Inertial separators are relatively ineffective, however, for smaller-sized particles.

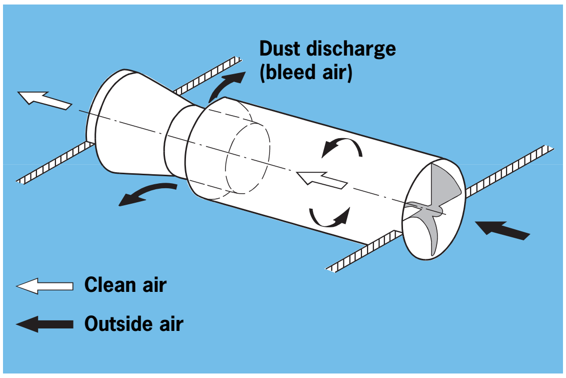


Fig. 12: Inertial separator for intake air filtration of turbomachinery

An anti-icing system is sometimes used as well: the intake air is preheated in order to prevent ice formation on the weather louvers, the downstream filters, and the first stage blades of the compressor. Different methods of anti-icing are employed, depending on the heat source involved: Figure 13 provides an overview.
In practice, it is advisable to operate an anti-icing system when relative humidity is greater than 70 % and the temperatures are between -5°C and +5°C. The enormous power requirement of an anti-icing system should not be overlooked. In the case of a turbomachine with an intake volume of 300,000 m³/h, for example, a thermal output of more than 100 kW would have to be provided for each Kelvin of air warm-up.
An anti-icing system should offer as small a surface as possible for dirt caking, since for engineering reasons it has to be installed upstream of the air filters. This is why lamelliform damper registers are less suitable than blower pipes, for example.

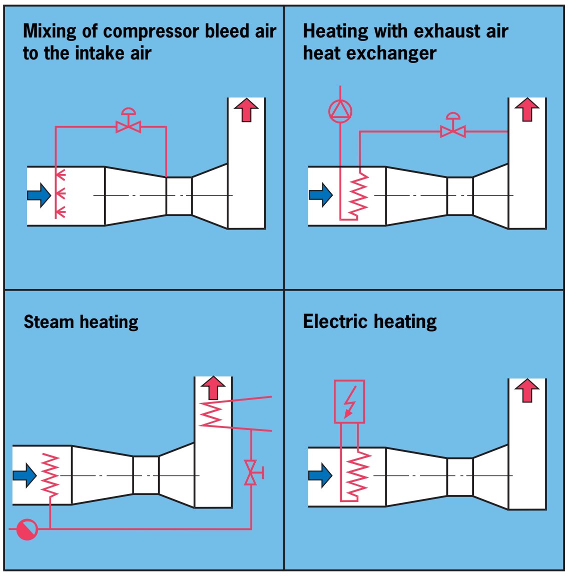


Fig. 13: Anti-icing systems

Summary

Soiling on guide and rotor blades of gas turbines and turbocompressors affects their output/power consumption respectively, and their efficiency, causing dust caking and material abrasion in proportion to the size of the particles introduced with the intake air. The air filters used must offer not only the requisite collection performance and an acceptable useful lifetime but also a high standard of operational reliability. For turbomachinery applications, depth-loading filters and surface filters are used in many customized forms (e.g. as roll filters, rigid filters, pocket filters, filter cartridges).
Studies of blade deposits and loaded filters show different typical chemical elements and particle structures, depending on the quality of the intake air filtration system employed. The particles larger than 5 µm originate principally from erosion processes at the Earth's crust, containing elements like silicon, calcium and iron, and exhibit sharp broken edges. Sulfur is a typical element for particles smaller than 5 µm which are formed in combustion processes (soot). The blade deposits and dust-loaded filters examined show that adequate protection for turbomachinery is possible only when high efficiency filters of the requisite arrestance are used in the final filter stage.

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