Air Filtration for Gas Turbines

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Introduction

Gas turbines ingest a large amount of ambient air during operation. Because of this, the quality of the air entering the turbine is a significant factor in the performance and life of the gas turbine.
A filtration system is used to control the quality of the air by removing harmful contaminants that are present.
The selection of the filtration system can be a daunting task, because there are many factors to consider.
The system should be selected based on the operational philosophy and goals for the turbine, the contaminants present in the ambient air, and expected changes in the contaminants in the future due to temporary emission sources or seasonal changes.
This paper outlines the primary considerations for selecting and installing a gas turbine inlet filtration system.

In this research, I will provide a review of the considerations for selecting an inlet filtration system by covering:

A. The Consequences Due to Improper Inlet Filtration.
B. Filtration Characteristics Review
C. Components of Filtration Systems

The consequences due to improper inlet filtration

When the quality of the air entering the gas turbine is not well controlled, there are several consequences which can occur. Some of the most common degradation mechanisms are reviewed below including foreign object damage, erosion, fouling, turbine blade cooling passage plugging, particle fusion, and corrosion (hot and cold).

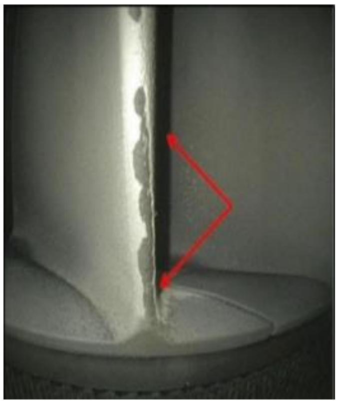
Foreign Object Damage: Foreign Object Damage (FOD) can be significant in a gas turbine if there is not proper protection.
It usually occurs in the early stages of the compressor. Large objects or relatively large particles can be trapped or screened to avoid their entry into the fan or compressor section of a turbine.
This accomplishment is a significant gain, because FOD has the greatest potential for secondary and extensive damage to the compressor and later parts in the air flow path. The filter system and its components are designed to prevent FOD. Poorly designed filters or systems, including filters, hardware in ducting and silencing, and other aspects lead to a risk of FOD damage and should be considered.

Gas Turbine Damage from FOD

Often FOD screens are installed upstream of the filters for protection. Depending on the screen location and mesh size, the pressure loss across these screens can be negligible or significant.

Erosion: Erosion occurs when solid or liquid particles approximately between 5 to10 μ meter and larger impact rotating or stationary surfaces in the gas turbine.
The particles will impact the surface and remove tiny particles of metal which eventually lead to changes in the geometry of the surface.

Sand is one of the most common causes of erosion due to its prevalence at the installations of gas turbine.
Impingement of small, hard particles against blade and stator aerodynamic airfoil shapes repeatedly removes tiny particles of metal, eventually re-shaping portions of the parts. In finely tuned contours of highly stressed parts, this is a double problem.
Re-shaping aerodynamic surfaces changes the air flow paths, roughens the surfaces, changes clearances, and eventually reduces the cross-sectional areas that provide the strength necessary to resist the very high stresses of parts with minimal margins of safety.

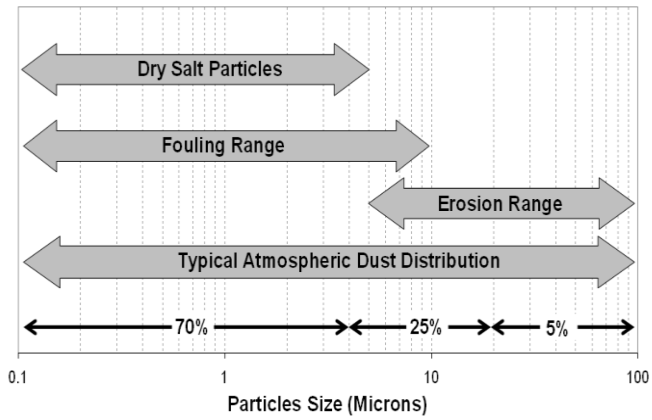


Erosion on the Leading Edge of a Turbine Blade

The efficiency of the gas turbine is reduced until excessive stress takes over as the main cause of problems. Also, changing the blade shape can create stress concentrations that reduce the fatigue strength, thus leading to high cycle fatigue failures.

Fouling: Fouling of compressor blades is an important mechanism leading to performance deterioration in gas turbines over time.

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



Commercial filters can remove the majority of particles that cause fouling. But there are several submicron particles that are difficult to remove from the flow stream. The buildup of particles not removed by the inlet filtration system is removed with the use of compressor washing. This process recovers a larger portion of the compressor performance but can't bring the gas turbine back to its original condition.

Typical Particles Size Distribution for Erosion and Fouling Range

Corrosion: When chemically reactive particles adhere to surfaces in the gas turbine, corrosion can occur.

Corrosion that occurs in the compressor section is referred to as “cold corrosion” and is due to wet deposits of salts, acid, and aggressive gases such as chlorine and sulfides.

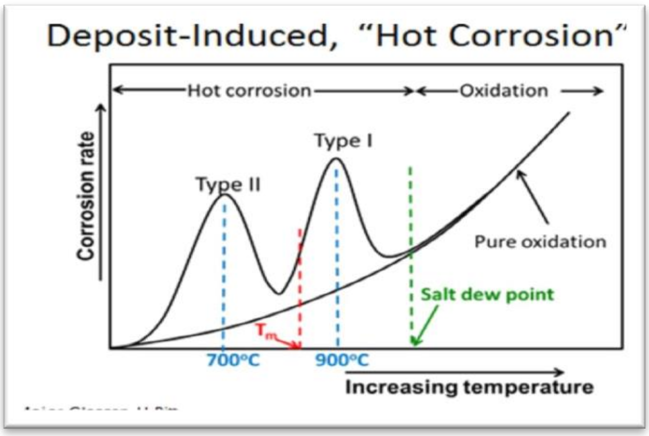
Corrosion in the combustor and turbine sections is called “hot corrosion.” It is also referred to as a high temperature corrosion.

Hot corrosion requires the interaction of the metal surface with another chemical substance at elevated temperatures. Hot corrosion is a form of accelerated oxidation that is produced by the chemical reaction between a component and molten salts deposited on its surface. Hot corrosion comprises a complex series of chemical reactions, making corrosion rates very difficult to predict. It is the accelerated oxidation of alloys caused by the deposit of salts (e.g., Na2SO4).

Turbine blade failure due to hot corrosion

<u>Type I</u> or high temperature hot corrosion occurs at a temperature range of (730 to 950◦C).
<u>Type II</u> or low temperature hot corrosion occurs at a temperature range of (550 to 730◦C).
Some of the more common forms of hot corrosion are sulfidation, nitridation, chlorination, carburization, and vanadium, potassium, and lead hot corrosion.

Sulfidation hot corrosion requires the interaction of the metal surface with sodium sulfate or potassium sulfate, salts that can form in gas turbines from the reaction of sulfur oxides, water, and sodium chloride (table salt) or potassium chloride, respectively. It is usually divided into Type I and Type II hot corrosion, and Type I hot corrosion takes place above the melting temperature of sodium sulfate (1623◦F (884◦C)), while Type II occurs below this temperature.



Hot corrosion is caused by the diffusion of sulfur from the molten sodium sulfate into the metal substrate which prevents the formation of the protective oxidation film and results in rapid removal of surface metal.
One should note that for hot corrosion to occur both sulfur and salt (e.g., sodium chloride or potassium chloride or chloride) have to be present in the very hot gas stream in and downstream of the combustor. Sulfur and salt can come from the inlet air, from the fuel, or water (if water is injected).
The potassium hot corrosion mechanism is similar to sulfidation but is less frequently observed in gas turbines, unless the fuel contains significant quantities of potassium.

Corrosion is a nonreversible degradation mechanism. Therefore, corroded components must be replaced in order to regain the original gas turbine performance. Corrosion also initiates or advances other damage mechanisms in the gas turbine.

Filtration characteristics review

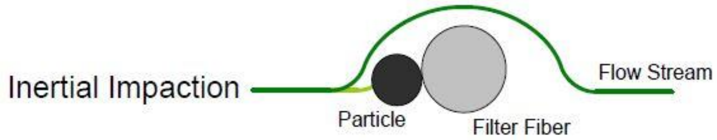
Filters have various parameters which must be considered in the design and selection in order to obtain the filtration system most suitable for the application.

There are major parameters must be discussed as below for consideration in selection of inlet filtration system:

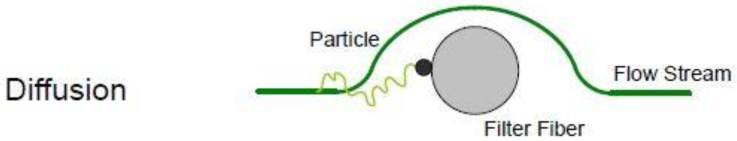
Filtration Mechanisms

Filters are designed to use various mechanisms to remove the particles of various sizes. The mechanism employed by the filter depends on the velocity through the media, fiber size, packing density of the media, particle size, and electrostatic charge. In a single filter, the various mechanisms work together.
Few basic filtration mechanisms are described below:

1- Inertial impaction
This type of filtration is applicable to particles larger than 1 micron in diameter. The inertia of the large heavy particles in the flow stream causes the particles to continue on a straight path as the flow stream moves to go around a filter fiber.
The particulate then impacts and is attached to the filter media and held in place.
This type of filtration mechanism is effective in high velocity filtration systems.

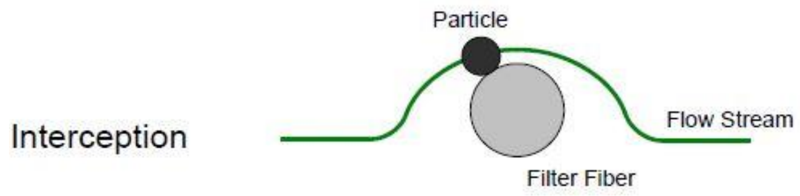


2- Diffusion
This is effective for very small particles typically less than 0.5 micron in size with low flow rates. These particles are not held by the viscous forces in the fluid and will diffuse within the flow stream along a random path. The path the particle takes depends on its interaction with nearby particles and gas molecules.



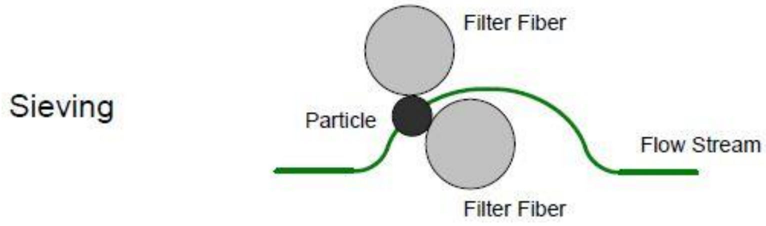
As these particles diffuse in the flow stream, they collide with the fiber and are captured. The smaller a particle and the lower the flow rate through the filter media, the higher probability that the particle will be captured.

3- Interception
Interception occurs with medium sized particles that are not large enough to leave the flow path due to inertia or not small enough to diffuse. The particles will follow the flow stream where they will touch a fiber in the filter media and be trapped and held.



4- Sieving

Sieving is the situation where the space between the filter fibers is smaller than the particle itself, which causes the particle to be captured and contained.



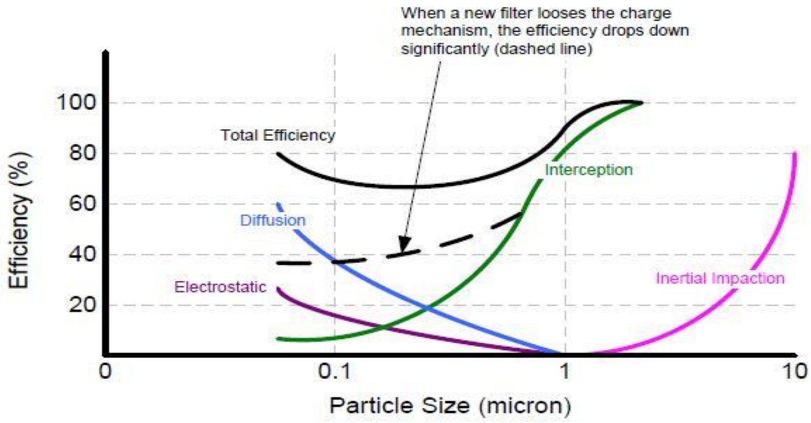
5- Viscous impingement

This type of mechanism uses the inertial impaction mechanism to capture particles. What makes this mechanism unique is that the filter is covered with a thin layer of oil which causes the captured particles to adhere to the filter surface, thus preventing them from being released downstream. The amount of particles captured is maximized by creating a torturous path for the air.
This results in a filter with many changes in flow direction.
This filtration mechanism is effect for medium to large size particles.

6- Electrostatic charge

This type of filtration is effective for particles in the 0.01 to 10 micron size range. The filter works through the attraction of particles to a charged filter. In gas turbine applications, this charge is applied to the filter before installation during the manufacturing process. Filters always lose their electrostatic charge over time because the particles captured on their surface occupy charged sites, therefore neutralizing their electrostatic charge. As the charge is lost, the filter efficiency for small particles will decrease. However, it should be noted that as the filter is loaded, the filtration efficiency increases. This will offset some of the loss of filtration efficiency due to the lost charge.

The figure below shows a comparison of a filter’s total efficiency based on the various filtration mechanisms that are applied. The figure shows the difference between the filter’s efficiency curve before and after the charge is lost. The performance of the filter should be based on the discharge condition.



Filter Efficiency and Classification

Filter efficiency is a broad term. In general, the filter efficiency is the ratio of the weight, volume, area, or number of particles entering the filter to the weight, volume, area, or number of the particles captured in the filter and ratings, respectively.
The weight efficiency is calculated as shown in Equation below:

$$\eta = \frac{W_{entering} - W_{leaving}}{W_{entering}} * 100\%$$

The efficiency can be expressed in several ways: maximum, minimum, or average lifetime value. Many filters have poor performance against small particles at the beginning of their lives, but as the filter media becomes loaded with particles, it is able to catch smaller particles. In this case, the average efficiency would actually be higher than the initial efficiency.

Some of the filters will never reach the quoted maximum efficiency before they are replaced. Filter efficiency is a trade-off against the pressure loss and dust holding capacity of the filter. Normally, the filtration system pressure loss will increase with an increase in filtration efficiency.

As filters become more efficient, less dust penetrates through them. Also, the air flow path is more constricted with higher efficiency filters. This leads to higher pressure loss.
Filter engineers must determine the acceptable pressure loss and efficiency for their application. Studies have shown that a higher pressure loss due to using a high efficiency filter has a lower effect on gas turbine power degradation than poor inlet air quality.
The figure below shows data collected by the AAF International which shows an example of this. The gas turbine which used a F7 filter (lower filtration efficiency) had significantly more performance degradation due to fouling than the gas turbine with the F9 and H12 filters (higher filtration efficiency).

Comparison of Gas Turbine Degradation with Different Levels of Filtration

The efficiency of a filter cannot be stated as a general characteristic. The filter efficiencies vary with particle size, typically being lower for small particles and higher for large particles.
They also vary with operational velocity. ***Filters designed for medium and low velocities will have a poor performance at higher velocities and vice versa.*** Therefore, a particle size range and flow velocity must be associated with the stated efficiency.

For example, a filter may have 95% filtration efficiency for particles greater than 5 microns at a volumetric flow rate of 3000 cfm, but the efficiency could be reduced to less than 70% for particles less than 5 microns or at a volumetric flow rate of 4000 cfm.

When comparing filter efficiencies, it is important that the same type of efficiency is compared. ***An efficiency that is calculated using a mass ratio cannot be compared to an efficiency that is calculated using a volume ratio.***
The different types of efficiencies can have very different values.

For example, consider a test air that consists of 101 spheres of the same density.
There are 100 particles with a diameter of 1 micron and 1 particle with a diameter of 10 microns.
Assume the filter only captures the 10 micron particle. The efficiencies based on weight (arrestance), area (dust spot efficiency), and particle count are calculated below. The efficiency values range from 0.99% to 90.91%.
This example clearly shows that these different efficiencies cannot be directly compared.

Efficiency by weight (arrestance)

$$\left(\frac{1000}{1000+100}\right)*100\% = 90.91\%$$

Efficiency by area (dust spot efficiency)

$$\left(\frac{100}{100+100}\right)*100\% = 50.00\%$$

Efficiency by particle count

$$\left(\frac{1}{1+100}\right)*100\% = 0.99\%$$

Filters are rated for performance based on standards established in the United States of America and Europe. These filter ratings are based on the results of standard performance tests.

In the United States, ASHRAE standard 52.2: 2007 outlines the requirements for performance tests and the methodology to calculate the efficiencies. In this standard, the efficiencies are determined for various ranges of particles sizes. The filter is given a Minimum Efficiency Reporting Value (MERV) rating based on its performance on the particle size ranges (particle count efficiency) and the weight arrestance (weight efficiency).
The weight arrestance is a comparison of the weight of the dust penetrating the filter to the dust feed into the flow stream.
In this standard, a filter with a MERV of 10 will have 50-65% minimum efficiency for particles 1 – 3 microns in size and greater than 85% for particles 3 – 10 microns in size.

Japan uses another standard which is called JIC (not common worldwide).

The European standards used to determine performance are EN 779: 2002 and EN 1822:2009. EN 779: 2002 is used to rate coarse and fine efficiency filters.

EN 1822:2009 presents a methodology for determining the performance of high efficiencies filters:

Efficient Particulate Air filters (EPA), High Efficiency Particulate Air filter (HEPA), and Ultra Low Particle Air filter (ULPA).

In EN 779: 2002, the performance is found with average separation efficiency which is an average of the removal efficiency of 0.3 micron particles at four test flow rates (particle count efficiency) for fine filters and with an average arrestance (weight efficiency) for coarse particle filters.
These standards rate the filters with a letter and number designation: G1 – G4 (coarse filters) and F5 – F9 (fine filters).
Filter performance is determined by the Most Penetrating Particle Size efficiency (MPPS) in EN 1822: 2009. The MPPS is defined as the particle size which has the minimum filtration efficiency or maximum penetration during the filter testing.
The particle sizes tested range from 0.15 to 0.3 microns. The filter efficiency is calculated based on particle count. These filters are given a rating of E10 – E12 for EPA type filters, H13-H14 for HEPA type filters, and U15 – U17 for ULPA filters.

The table below gives a general overview of the efficiencies for each filter rating and a comparison of the filter ratings between American and European standards.

ASHRAE Filter Class	ASHRAE 52.2: 2007			EN Filter Class	EN 779: 2002		EN 1822: 2009	
	Average Particles Size Efficiencies in X - Y micron (%)				Average Separation Efficiency (A_m)	Average Separation Efficiency (E_m)	Total Filtration Separation Efficiency (%)	Local Filtration Separation Efficiency (%)
	E_1	E_2	E_3					
MERV	0.3 - 1.0	1.0 - 3.0	3.0 - 10.0					
1			< 20	G1	$50 \leq A_m < 65$			
2			< 20	G2	$65 \leq A_m < 80$			
3			< 20					
4			< 20					
5			20 - 35	G3	$80 \leq A_m < 90$			
6			35 - 50					
7			50 - 70	G4	$90 \leq A_m$			
8			> 70					
9		< 50	> 85	F5		$40 \leq E_m < 60$		
10		50 - 65	> 85					
11		65 - 80	> 85	F6		$60 \leq E_m < 80$		
12		> 80	> 90					
13	< 75	> 90	> 90	F7		$80 \leq E_m < 90$		
14	75 - 85	> 90	> 90	F8		$90 \leq E_m < 95$		
15	85 - 95	> 90	> 90	F9		$95 \leq E_m$		
16	> 95	> 95	> 95	E10			85	
				E11			95	
				E12			99.5	
				H13			99.95	99.75
				H14			99.995	99.975
				U15			99.9995	99.9975
				U16			99.99995	99.99975
				U17			99.999995	99.9999
Note: Correlations between ASHRAE and EN standard classifications are approximate.								

Classification of Filters Based on American and European Standards

Filter Pressure Loss

As mentioned above, a higher pressure loss occurs with a more efficient filter due to air flow restrictions.

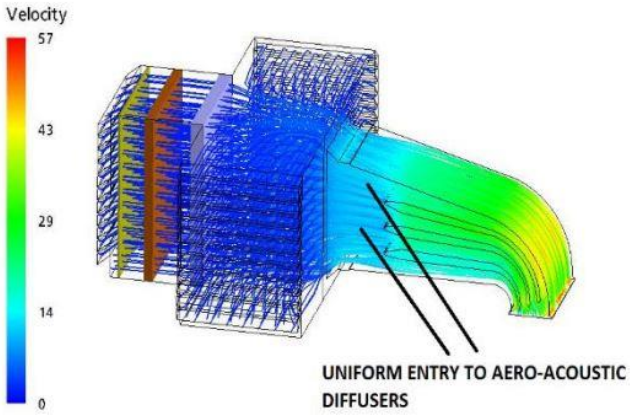
Pressure loss has a direct impact on the gas turbine performance. This causes the inlet pressure at the compressor of the gas turbine to be lower. In order for the compressor to overcome the inlet system losses, the gas turbine must consume more fuel, and it also has a reduced power output.
The relationship between the inlet filtration system and pressure loss is linear as shown in the figure below.
This shows that as the pressure losses increase at the inlet, the power decreases, and the HR (heat rate) increases linearly.
A 50 Pa (0.2 inH2O) reduction of pressure loss can result in a 0.1% improvement in power output.
Typical pressure losses on inlet filtration systems can range from 2 to 6 inH2O.

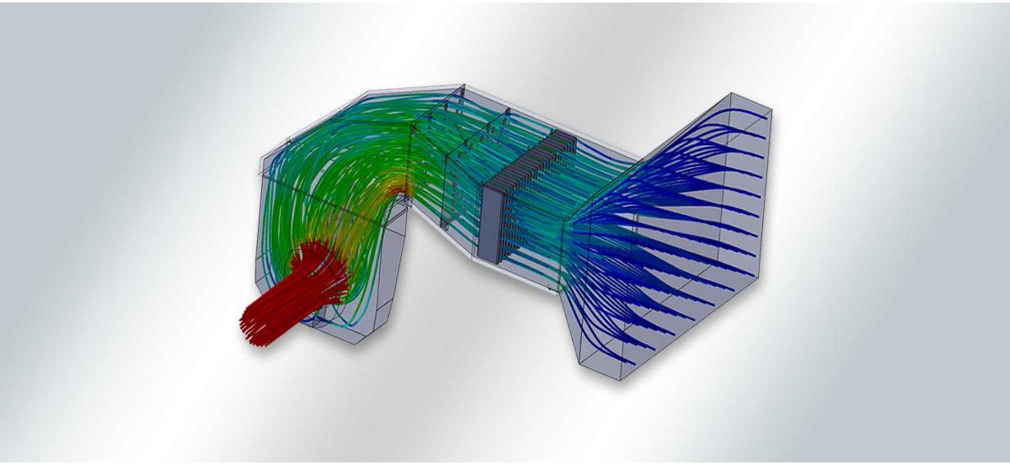
Effect of Pressure Loss at Inlet on Gas Turbine Power and HR

The filter's performance needs to be assessed for the full pressure loss range over its life, not just when it is new. ***The pressure loss will increase over the lifetime of the filter***.
If a filter is selected only based on the initial pressure loss, then the filter engineer can expect a lower gas turbine performance over the life of the filter or to be frequently changing out filters in order to maintain the lower pressure loss required for gas turbine performance. The change of pressure loss over time is highly dependent upon the filter selection and the type and amount of contaminants experienced.

One method that many filtration system manufacturers have taken to reduce the pressure loss is to decrease the filter face velocity.
Decreasing the face velocity reduces the viscous and flow restriction effects which leads to lower pressure losses. ***Decreases in face velocity are achieved with larger filter surface area.***
The larger surface area also creates more fiber material for particles to be trapped in, so the filter is able to retain more dust during its life. Increased surface area seems like an ideal solution, but one must consider that more surface area means a larger filtration system.
This will require more material and higher initial costs. Also, more filters will need to be replaced during maintenance intervals.
Reducing the pressure loss cannot only be done with increasing surface area, but also ***through design of the inlet system ducting***. Designs that have many flow path changes and turns can cause added pressure loss or high velocities across the filters or poor aerodynamics in the ducting.

Computational Fluid Dynamics (CFD) can be very useful in designing an inlet ducting to minimize pressure loss and keep filter velocities at minimal levels. This tool allows designers to view the flow streams and estimate the pressure loss associated with the proposed design. It is easier to modify a computational model during the design stages to reduce pressure loss and minimize velocities, than a system already in operation.
CFD can also be used to determine if the flow is being evenly distributed among the filter elements. Correcting this in the design phase will help to ensure that each filter element in the system is loading with dust at approximately the same rate. An example of a CFD particle flow analysis of a filtration system is shown in Figure the figure below.



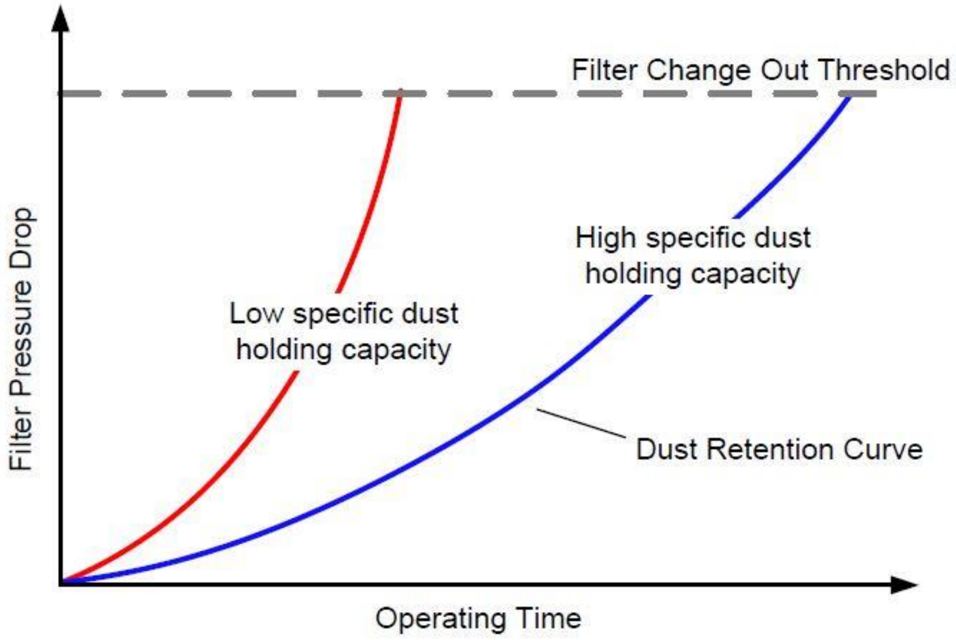


Filter Loading

During operation as the filter collects particles, it is slowly loaded until it reaches a "full" state. This state is usually defined as when the filter reaches a specified pressure loss, or when the maintenance interval has been met. ***Filters are loaded in two different ways: surface and depth loading***.

Depth loading is the type of filtration where the particles are captured inside of the filter material. To regain the original pressure loss or condition, the filter must be replaced. The life of these types of filters is often monitored based on pressure loss.
When using depth loaded filters, it is important to understand what dust holding capacity the filter has. A high specific dust holding capacity indicates that the filter can collect more dust, while the pressure loss increases at a slower rate.

The low capacity filter will have a higher pressure loss with the same amount of dust collected as the high capacity filter. The dust holding capacity is not only dependent upon the filter construction but also the particle size distribution. A filter will load up more quickly with fine dust than with large dust. For a given pressure loss, a filter can hold a greater mass of large particles than of small particles.



Comparison of High and Low Specific Dust Holding Capacity Filters

The low capacity filter may be used in an environment with a low amount of dust in the air where minimal filtration is required. In areas with medium to high dust concentrations or with fine dust particles, a high capacity filter is used to maximize the time between filter replacements and reduce maintenance and replacement costs.

The other type of filter is a ***surface loaded filter***.
With this type of loading, the particles collect on the outside surface of the filter. Some of the particles may infiltrate the fiber material, but not enough to call for replacement of the filter. Surface loaded filters are most commonly used in, but not restricted to, self-cleaning systems. This is due to the fact that the dust can easily be removed with pulses of air once the filter differential pressure reaches a certain level.
Once the filter is cleaned, the pressure loss across the filter will be close to its original condition. The surface loaded filter's efficiency actually increases as the surface is loaded with dust. This is due to the fact that a dust cake develops on the surface of the media creating an additional filtration layer and also decreases the amount of available flow are in the filter media.

Face Velocity

Filtration systems are distinctively classified as high, medium, or low velocity systems.
The velocity of the filtration system is defined as the actual volumetric air flow divided by the total filter face area.

Low velocity systems have air flow at less than 500 fpm (feet per minute) (2.54 m/s) at the filter face.
The low velocity systems are characterized by large inlet surface areas, large filter housings, and usually multiple stages of filters.
The two or three stage filters provide an advantage over high velocity systems, because they have a high efficiency filter stage as the final stage to remove many small particles (especially salt) below 1 micron and to keep water from entering the gas turbine. The lower velocity also provides a lower pressure loss and higher filtration efficiency. This increase in efficiency provides more time between compressor washings and filter replacements leading to a lower lifecycle cost.
Overall, low velocity systems can be more effective at reducing the mass of contaminants which enter a system.

Medium velocities are in the range of 610 to 680 fpm (3.1 to 3.45 m/s).

High velocity systems have air flows at the filter face in excess of 780 fpm (4 m/s).
Historically, high velocity systems are used on marine vessels and offshore platforms where space and weight is premiums.
High velocity systems have the advantages of reduced size (cross sectional area), weight, and initial cost.
From a lifecycle cost perspective, the reduced size also results in fewer filter elements to replace. A disadvantage is that there are more performance losses due to higher pressure loss through the inlet system.
Also, filter efficiencies for small particles are significantly lower than those of lower velocity systems, and dust holding capacities are lower.
Ultimately, this type of system requires more filter replacements when compared to the lower velocity system.
The size and weight of the filtration system is usually only important if one of these is a criterion. Filter housing design should be based on the environment it is operating in rather than size, weight, or cost.

Operation in Wet Environment

Many environments where gas turbines operate will have wet ambient conditions. This could be in a jungle or at a coast where it rains a significant amount of time or a location with ocean/ lake mist.

Most filters are not designed to operate in a wet condition, but some filters are required to do this due to their ambient conditions. The difference between filter operation in wet and dry conditions can be significant.
In some cases, the pressure loss across a filter can increase significantly even with a little moisture. This is true for cellulose fiber filters which swell when they are wet. These filters will also retain the moisture which can lead to long periods of time when the pressure loss across the filter is elevated.
If the environment where the gas turbine is operating has high frequency of moisture entrainment in the filtration system, then ***filter fiber materials can be selected for wet operation.***

Salt Effects

Salt can have a direct effect on the life of a gas turbine if not removed properly.

Salt can deposit on the compressor blades which leads to fouling and reduced aerodynamic performance.
Gas turbine manufacturers usually recommend stringent criteria on the amount of salt which can be allowed to enter the gas turbine (less than 0.01 ppm). In coastal environments, the air borne salt can easily range from 0.05 to 0.5 ppm on a typical day.
Salt is present in the air due to two main sources: seawater (sodium chloride, magnesium chloride, and calcium sulfate) and exhaust gases (SOx and NOx). Salt may also come from localized sources such as a dry salt bed.
In land based filtration systems, dry salt particles can be removed with common filtration practices (for example, use of high efficiency fiber filters). However, removing salt that has dissolved into the moisture in the air is more complicated. The moisture in the air is present in two forms: as liquid water droplets and as water vapor (humidity). The majority of the liquid droplets can be removed with a coalescer or vane separator.
These devices are effective for particles larger than 5 microns in size. The water droplet removal efficiency depends on the air velocity through the device. The remaining liquid droplets may make it to the high efficiency filters.
There are many high efficiency filters which prevent water from penetrating the filter, but not all filters have this capability. If liquid droplets are allowed to penetrate the filter, then they can carry any absorbed salt downstream into the gas turbine. Gas turbines in high moisture and salty environments should have filters which minimize or eliminate liquid penetration.

Water vapor cannot be removed by mechanical filtration, however, a vapor at ambient conditions will most likely remain in the gas phase as it travels through the gas turbine.

COMPONENTS OF A FILTRATION SYSTEM

In order to protect the gas turbine from the variety of contaminants present in the ambient air, several filtration devices are used.

Weather Protection

Weather protection is either weather hood or weather louvers or both depending on the gas turbine type, surrounding weather (snowy, sandy, etc.)

Weather hoods are sheet metal coverings on the entrance of the filtration system.
The opening of the hood is pointed downward so the ambient air must turn upwards to flow into the inlet filtration system. The turning of the air is effective at minimizing rain and snow penetration. Weather hoods is used on the majority of inlet filtration systems, and they are essential for systems in areas with large amounts of rainfall or snow. In tropical climates, weather hoods deflect a large mount of rain, so the inertial separators are not overloaded and the amount of water traveling to downstream high efficiency filters is minimized.

Medium size hoods can be used to deflect rain. The maximum recommended inlet velocity for a weather hood minimizing rain in the flow stream is 650 ft./min.
In arctic environments, snow penetration is minimized with weather hoods. Since snow falls at a slower rate than rain, the weather hood must be larger. This larger hood increases the air entrance surface area which decreases the upward flow velocity. The maximum recommended face velocity for a weather hood with snow is 250 ft./min.
Weather hoods or another comparable weather protection system are strongly recommended for all systems with high efficiency filter.

Weather louvers
After the weather hood is a series of turning vanes called weather louvers which redirect the air so that it must turn. The weather louvers are also effective at minimizing water and snow penetration. After the weather hood or louver is a trash or insect screen. Trash screens capture large pieces of paper, cardboard, bags, and other objects. If these pieces are allowed to enter the gas turbine, they can obstruct the air flow through the filters. The screens also deflect birds, leaves, and insects. Screens that are installed specifically for preventing insects entering the filtration system are referred to as insect screens.
These screens will have a finer grid than trash screens.

Weather Louvers (The project took place in Iraq/Baghdad/Al-Taji power plant 2017 by Braden Europe B.V)

Anti-icing protection

Anti-icing protection is used in climates with freezing weather. Freezing climates with rain or snow can cause icing of inlet components which can result in physical damage to inlet ducts or to the gas turbine compressor. This ice can also affect the performance of the gas turbine. If ice forms on filter elements, then ice on those filters will be blocking the flow path which will cause the velocity at the other filters to increase. This causes a decrease in filtration efficiency. Also, the filter elements with ice can be damaged.

At the inlet bell mouth to the compressor, the air pressure decreases slightly due to the increase in velocity from the converging cross section of the mouth. This decrease in pressure causes a decrease in temperature which can lead to the water vapor in the air condensing and freezing on the bell mouth, inlet guide vanes, and initial compressor stage blades.
Buildup of this ice will cause a decrease in the performance of the gas turbine or worse. If the ice breaks off the components and enters the compressor, it can cause FOD.
Heaters or compressor bleed air are often used in the inlet system in frigid environments to prevent the moisture in the air from freezing on the inlet bell mouth or filter elements.

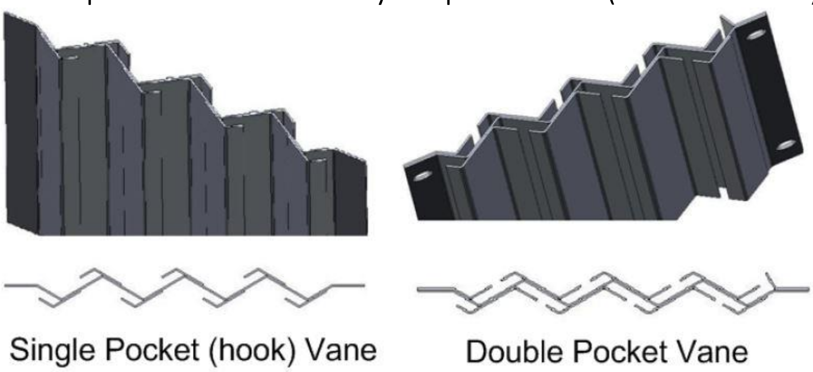
Cartridge Filters with Frost Build-Up Due to Cooling Tower Drift
(Courtesy of Camfil Farr)

In the Middle East, this option is not available due to high ambient temperature, while we can see this option in Europe and North America.

Inertial Separators

Inertial separation takes advantage of the physical principles of momentum, gravity, centrifugal forces, and impingement, and the physical difference between phases to cause particles to be moved out of the gas stream in such a way that they can be carried off or drained. The higher momentum of the dust or water particles contained in the air stream causes them to travel forward, while the air can be diverted to side ports and exit by a different path than the dust. There are many types of inertial separators, but the ones commonly used with gas turbine inlet filtration are vane and cyclone separators.

Vane axial type separators are an axial flow device with hooks or pockets on the side-walls which capture water droplets. *There are two primary types: single pocket vane (or hook), and double pocket vane.*
Vane separators have a relatively low pressure loss (0.1 to 0.5 inH2O)

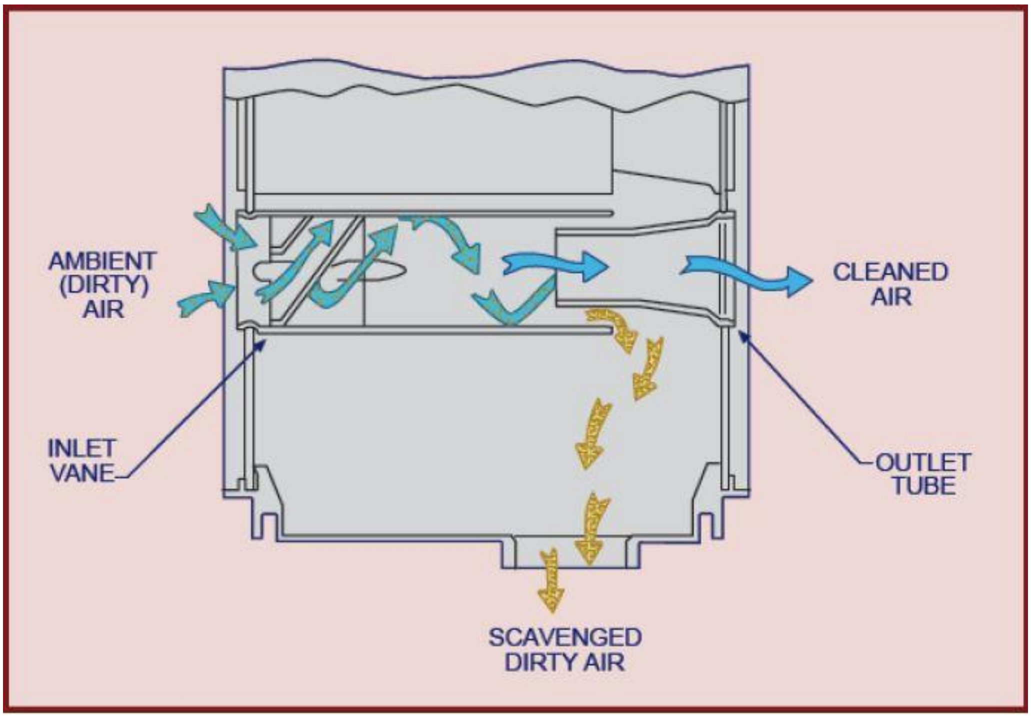


As the gas turns along the vane, the water droplets impinge on the metal surface, are pushed to the pocket by the forces of the gas flow and are then captured in the pockets.

The closed pockets have a space for the liquid droplets to collect and drain out which reduces the potential for re-entrainment.

The vane type separators are effective for water particles greater than 10 microns.
The double type pocket separators are also effective for capturing particles in the range of 5 to 10 microns.
The efficiency of the separators is based upon the design air velocity.

Another type of inertial separator uses stationary blades to put the flow into centrifugal motion. This spinning action causes the solid and liquid particles to move to the outside of a created vortex or cyclone flow due to centrifugal forces.
The heavier particles on the outside are then scavenged by a bleed fan system, while the cleaner air is drawn through a center tube to the gas turbine. These devices have a higher pressure loss than vane separators.
Acceptable pressure loss levels in these systems range from 1 to 1.5 inH2O. These devices require significant frontal area for their inlets.
A well designed inertial separator can remove about 99% of particles larger than 10 microns. These devices are effective at preventing erosion and corrosion caused by particles greater than 10 microns in size.



(Courtesy of Mueller Environmental Design, Inc.)

Moisture Coalescers

In environments with high concentration of liquid moisture in the air, coalescers are required in order to remove the liquid moisture. The coalescer works by catching the small water droplets in its fibers.

As the particles are captured, they combine with other particles to make larger water droplets. Coalescers are designed to allow the droplets to either drain down the filter or be released back into the flow stream.
If the larger drops are released, then they are captured downstream by a separator.

Prefilters

The air has a mixture of large and small particles. If a one-stage high efficiency filter is used, the buildup of large and small solid particles can quickly lead to increased pressure loss and filter loading.

Prefilters are used to increase the life of the high efficiency filter by capturing the larger solid particles.
This allows the high efficiency filter to only remove the smaller particles from the air stream which increases the filter life. Prefilters normally capture solid particles greater than 10 microns.
Some prefilters will also capture the solid particles in the 2 – 5 micron size range. These filters usually consist of large diameter synthetic fiber in a disposable frame structure.
Bag filters are also commonly used for prefilters. These offer higher surface area which reduces the pressure loss across the filter.
Sometimes a charge will be applied to the filter in order to increase the initial efficiency of the filter. This charge will be lost as the filter neutralizes and the filtration efficiency for smaller particles will decrease.

Panel Filter

Camfil pre-filter (G4)

Bag Filter

Camfil pre-filter (F7)

Guard Filter

Camfil pre-filter (G4)

High Efficiency Filters

There are filters for removing larger solid particles which prevent erosion and FOD.
Smaller particles which lead to corrosion, fouling, and cooling passage plugging are removed with high efficiency filters. These types of filters have average separations greater than (80%).

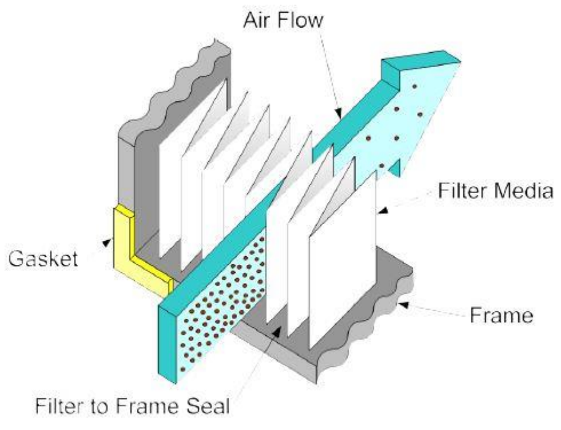
Three common types of high efficiency filters are ***EPA, HEPA and ULPA.***

EPA and HEPA filters are defined as having a minimum efficiency of 85% and 99.95%, respectively, for all particles greater than or equal to 0.3 microns.

ULPA filters have a minimum efficiency of (99.9995%) for particles the same size or larger than 0.12 microns.
Often, these names are used loosely with discussion of high efficiency filtration.
However, the majority of the high efficiency filters used in gas turbine inlet filtration do not meet these requirements.
The high efficiency filters used with gas turbines have pleated media which increases the surface area. In order to achieve the high filtration efficiency, the flow through the filter fiber is highly restricted which creates a high pressure loss. The pleats help reduce this pressure loss. Initial pressure loss on high efficiency filters can be up to 1 inH2O with a final pressure loss in the range of 2.5 inH2O for rectangular filters and 4 inH2O for cartridge filters. The life of the filters is highly influenced by other forms of filtration upstream. If there are stages of filtration to remove larger solid articles and liquid moisture, then these filters will have a longer life. Minimal filtration before high efficiency filters will lead to more frequent replacement or cleaning. High efficiency filters are rated under various standards.
The majority of filters used in gas turbines are not classified as EPA, HEPA, or ULPA. The filters used in gas turbines are rated with ASHRAE 52.2: 2007, EN 1822:2009 and EN 779: 2002.

High efficiency filter media is ***fiberglass, treated paper, or synthetic fibers*** which is comprised of extremely large number of randomly oriented micro-fibers which utilizes the majority of the filtration mechanisms to achieve its effectiveness on sub-micron particles.
There are many different constructions of high efficiency type filters: ***rectangular, cylindrical/ cartridge, and bag filters.***

The rectangular high efficiency filters are constructed by folding a continuous sheet of media into closely spaced pleats in a rectangular rigid frame.
Rectangular filters are depth loaded; therefore, once they reach the maximum allowable pressure loss, they should be replaced.

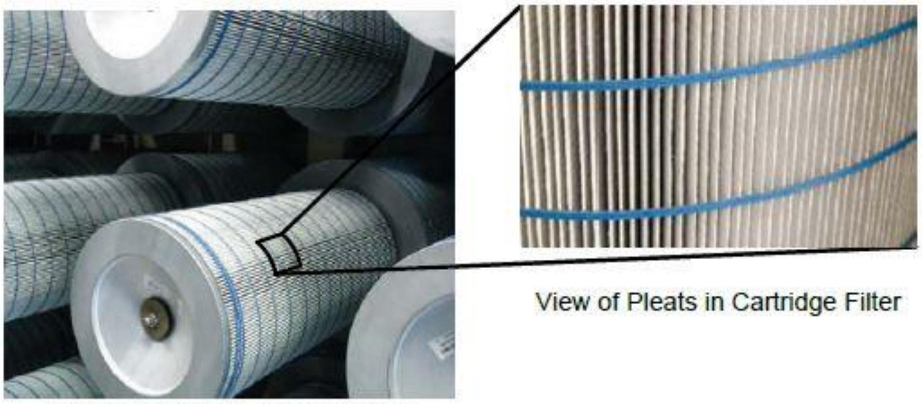


Construction of Rectangular Pleated High Efficiency Filter

There is a critical sealing points in rectangular filters, such as the filter to frame seal.
This is where the filter media connects to the filter frame. Polyurethane is commonly used for this seal.

In addition, a seal is required on the outside frame of the filter when it is installed to prevent air from passing around the filter elements. These sealing requirements are true for all types (low and high efficiency) of rectangular filters.
They are more critical to high efficiency filters due to the small sized particles being removed from the air stream.

Cartridge filters typically have a higher dust holding capacity than rectangular filters.
Another advantage of cartridge filters to rectangular filters is that the sealing mechanism on the cartridge filter is made up of a single sealing element.
For rectangular filters, multiple sealing elements or a single sealing element with a complex geometry is required. This makes the construction of the cartridge filter's sealing gasket easier, and there is less potential for a poor seal between the fiber media and filter frame.



View of Pleats in Cartridge Filter

High Efficiency Cartridge Filters

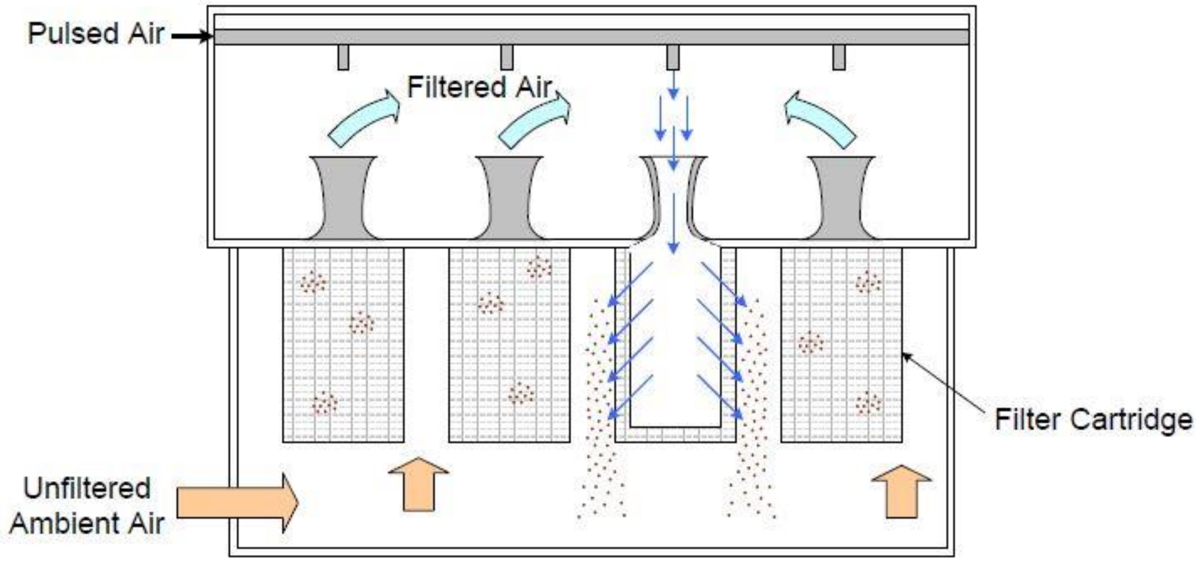
(Courtesy of Camfil Farr)

Cartridge filters are also made up of closely spaced pleats, but they are in a circular fashion.
Air flows radially into the cartridge. They are installed in a horizontal or vertical fashion (hanging downward). These types of filters can be depth or surface loaded.
The surface loaded filters are commonly used with a self-cleaning system, but not all of them are designed for self-cleaning.
Cartridge filters used in self-cleaning systems require a more robust structural design in order to protect the filter fiber media during the reverse air pulses. The more common structural support is a wire cage around the pleated media on the inside and outside of the filter.

Self-Cleaning Filters

All of the filters with fiber type media previously discussed are required to be replaced once they reach the end of their usable life. In some environments, the amount of particles can be excessive to the point where the filters previously discussed would have to be replaced frequently to meet the filtration demand.
A prime example of one of these environments is a desert with sandstorms. In the 1970s, the self-cleaning filtration system was developed for the Middle East where gas turbines are subject to frequent stand storms.
Since then, this system has been continually developed and utilized for gas turbine inlet air filtration.

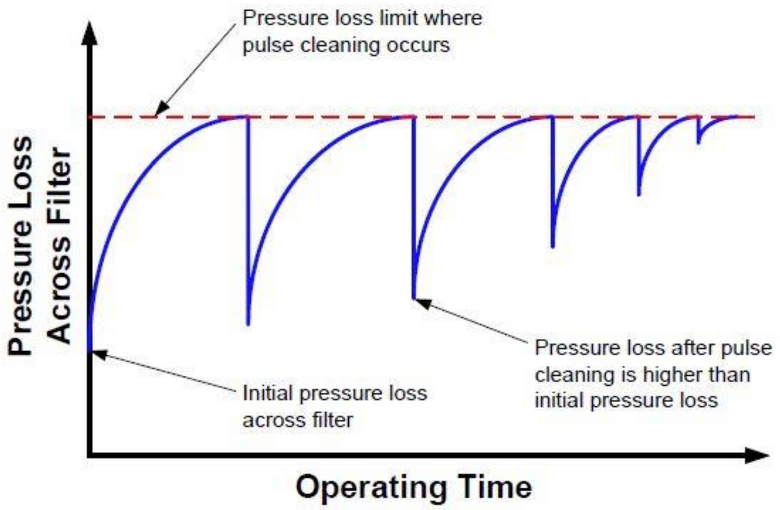
The self-cleaning system operates primarily with surface loaded high efficiency cartridge filters. The surface loading allows for easy removal of the dust which has accumulated with reverse pulses of air. The pressure loss across each filter is continuously monitored. Once the pressure loss reaches a certain level, the filter is cleaned with air pulses.
The pressure of the air pulses ranges from 80 to 100 psig. The reverse jet of compressed air (or pulse) occurs for a length of time between 100 and 200 ms.
To avoid disturbing the flow and to limit the need for compressed air, the system typically only pulses 10% of the elements at a given time. With this type of cleaning, the filter can be brought back to near the original condition.
It should be noted that the filter elements in a pulse cleaning system will degrade overtime. This is due to the effects of some types of particulates captured by the filter, UV rays, heat, and the life of the filter media. Because of these effects, after a pulse cleaning the filter can return to near the original condition.



Example of Operation of an Updraft Self-Cleaning Filters

The figure above shows an example of how the performance of the filter degrades overtime.
In this example the pulse cleaning slowly becomes less effective at reducing the pressure drop of the filter. Once the pulse cleaning of a filter is no longer effective, it should be replaced.
The filter should also be replaced once it reaches the materials maximum recommended life.
Cartridge filters in a self-cleaning system have a life in the range of 1 to 2 years.

These filters are constructed of specially treated cellulose, synthetic fibers, or a combination of both types of fiber. A metal cage around the outside of the filters helps them retain their shape during pulse cleaning. There is also a metal cage on the inside of the filters to retain the filter shape during normal operation.
The filters are used in low approach velocity systems. The low air velocity assists in preventing dust that is being removed from a filter with air pulsing from being re-entrained in the airflow stream, when normal flow is re-established. The efficiency of the filters actually increases over time.



Pressure Loss Curve over Time on a Self-Cleaning Filter

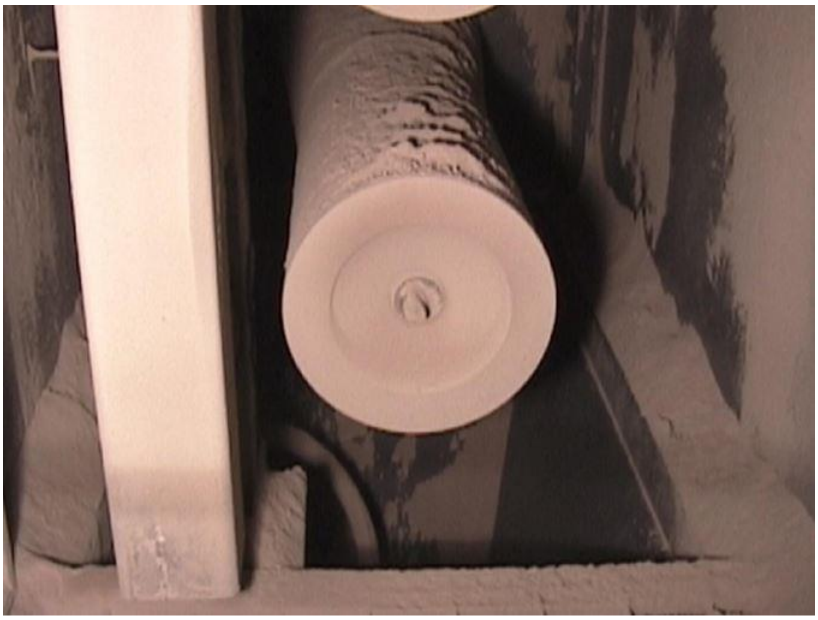
As the surface of the filter is loaded with particles, it decreases the available flow area through the filter which increases their efficiency. The pressure loss for cleaning is set based on the filtration system design and the design performance effects on the gas turbine.

Self-cleaning filters provide an attractive system for maintaining filter performance while controlling filter pressure loss, but they also have their disadvantages. This type of filtration system is very useful in dry environments with high levels of dust. However, pulse clean filter systems are not necessary with medium or low levels of airborne particles due to the fact that they operate on the basis of surface loading.

The filter becomes more efficient as particles collect on the outside of the filter. In areas with low dust levels or small particles, the dust may actually be captured in the fibers of the filter. It is extremely difficult to remove particles that have penetrated the filters. These filters are not designed to operate as depth loaded devices.

Also, these filters work poorly in environments with sticky contaminants such as pollen. Once the sticky substances have been captured by the filter, they cannot be removed with air pulses.

Below is an example of a plugged filter due to self-cleaning system failure



In order to mitigate some of the contaminants that reduce the effectiveness of the self-cleaning filter, pre-filter socks are wrapped around the cartridge filters. These socks are inexpensive and can be replaced on a more frequent basis than the cartridges.
They protect the cartridges from the contaminants which would reduce the performance of the self-cleaning mechanism.
The self-cleaning filter is prone to high pressure losses and other problems in high moisture environments.
Some of the filter cartridges are made of cellulose fibers which swell when wet and retain moisture. If particles that are captured on the filter media swell with moisture, then they will become very difficult to remove. Lastly, these types of systems have higher purchase and installation cost than the conventional system.
However, this cost can be justified if they are used in an environment which would require frequent filter maintenance and replacement. Of course, these systems are not maintenance free. Self-cleaning devices may require less filter maintenance, but the equipment on the system needs to be maintained itself. This equipment includes the solenoids, valves, and compressors that are needed to generate the air pulses.

Oil Bath Filters

There are other filters that are of older design and are effective for removing certain contaminants. One type will be briefly mentioned here since it is not normally included in new, modern air filtration systems.
Rotating oil-bath filters use oil to capture dust, creating a sludge that needs to be cleaned by settling tanks or centrifugal motion. The type of oil needs to be matched to the type of dust. Oil carry-over can be a problem to the gas turbine. Oil-coated roll type filters consist of a moving mat that is wetted by an oil bath and then scrolled in front of the turbine inlet. Dust adheres to the oil wetted mat. Problems with this filter design occur when the oil is allowed to dry due to periods of shutdown or excessive heat. Many times, leakage occurs around the edges of the mat. These filters can also retain water and freeze.
Their efficiency decreases when any of these problems occurs.

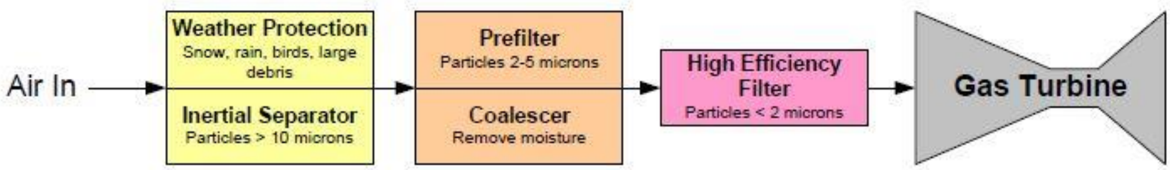
Staged Filtration

Any gas turbine application typically needs more than one type of filter, and there are no “universal filters” that will serve all needs. Therefore, two-stage or three–stage filtration systems are used.
In these designs, 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 microns in size from the air.

Below is an example from my personal experience in Al-Rasheed power plant/Baghdad/Iraq. Braden Europe B.V company installed a self-cleaning system for two Gas Turbines type Siemens SGT-800 using F8 cylindrical and conical filters as a first stage filtration and a rectangular high efficiency as a final stage.

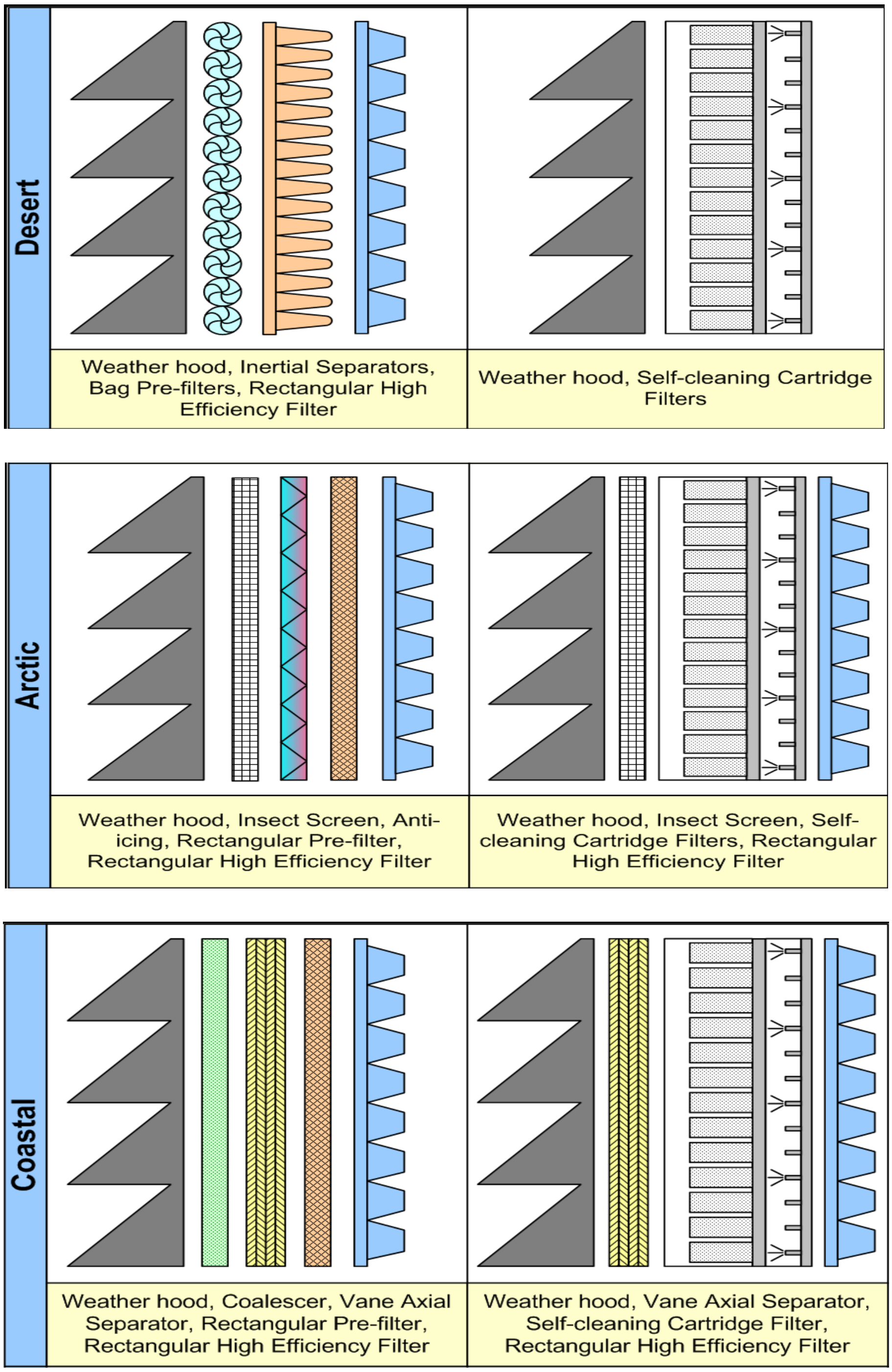
Al-Rasheed power plant/Baghdad/Iraq inside the filter house (the clean area)

The figure below shows a generalized view of a filtration arrangement.



This arrangement is not correct for all cases due to the fact that the filter stages are highly influenced by the environment they are operating in.

Below are a few types of filtration arrangements due to environment operation:



Conclusion

In summary, the selection and operation of an inlet filtration system is highly dependent on the environment where the gas turbine is operating.
The contaminant present in the ambient air will dictate the type filters that are used. It is important to quantify what type and size of contaminants are present in order to correctly select the filters to be used.
Temporary and seasonal variations must also be considered for the inlet filtration system.
A life cycle cost analysis provides a convenient method to quantify and compare various filtration system options such that the optimal system can be selected.

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