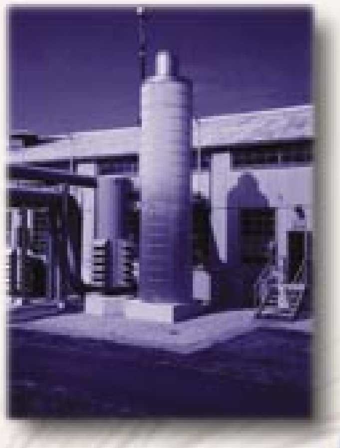
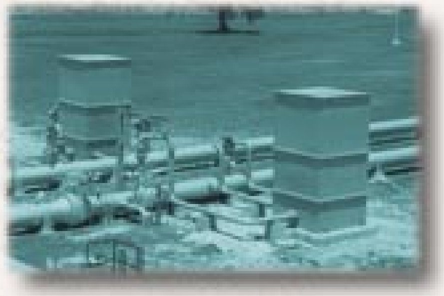


PRINCIPLES OF AIR FILTRATION

Mueller Environmental Designs, Inc.



Air Filtration
Evaporative Cooling
Noise Control
Mist Elimination
Turnkey Projects

Introduction

The removal of airborne particulate from an air stream is called air filtration and is accomplished through mechanical, aerodynamic, and electrostatic phenomenon. The following information is a review of the basic concepts through which it is accomplished.

Photograph 1

How Small is a Micron?

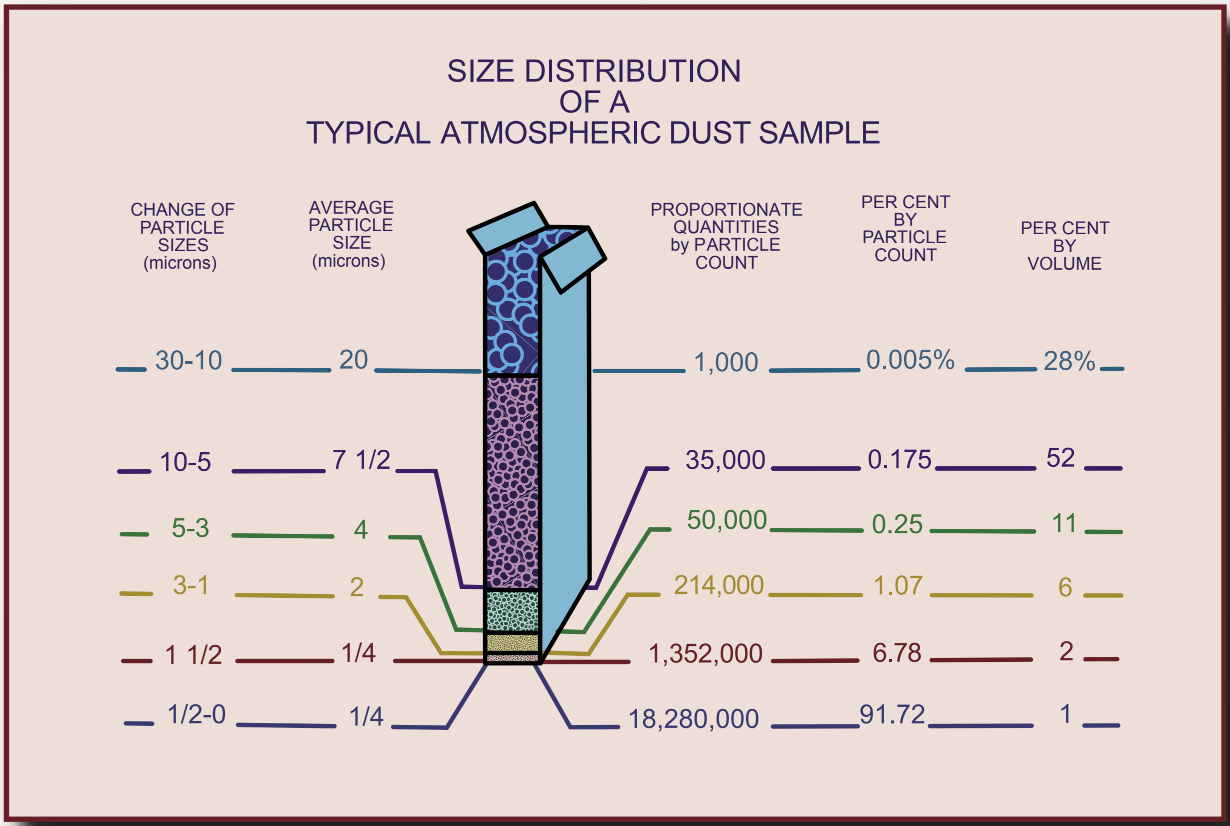
1 Micron = 1/25,400 of an inch

318 Human Hairs = 1 inch
Head Pin = 1500 microns
84,667 Smoke Particles = 1 inch
33 Smoke Particles = 10 microns (smallest size visible with naked eye)

Figure 1

Particle Size

A typical human hair has a diameter of just over 150 microns (Photograph 1). The smallest particle that can be seen by the naked eye is about 10 microns. To see a 10 micron particle you must have perfect 20/20 vision and the particle must be viewed in a darkened room with the particle positioned in a high intensity narrow light beam. In reality, most people do not see anything smaller than a 30 micron particle. Figure 1 depicts micron size comparisons.



SIZE DISTRIBUTION
OF A
TYPICAL ATMOSPHERIC DUST SAMPLE

CHANGE OF PARTICLE SIZES (microns)	AVERAGE PARTICLE SIZE (microns)	PROPORTIONATE QUANTITIES by PARTICLE COUNT	PER CENT BY PARTICLE COUNT	PER CENT BY VOLUME
30-10	20	1,000	0.005%	28%
10-5	7 1/2	35,000	0.175	52
5-3	4	50,000	0.25	11
3-1	2	214,000	1.07	6
1 1/2	1/4	1,352,000	6.78	2
1/2-0	1/4	18,280,000	91.72	1

Table 1

Particle Distribution

Table 1 is a size distribution of a typical atmospheric dust sample. As this example shows, there is a greater proportion of particles in the 1/4 to 5 micron size than the 6 to 30 micron sized particles.

Particle Concentration

Photograph 2 depicts a coastal or seaside environment where normal dust concentrations are in the order of 0.01 grains per thousand cubic feet.

Photograph 2

Photograph 3

Photograph 3 represents a typical city/industrial environment where dust concentrations are in the order of 0.4 to 4.0 grains per thousand cubic feet.

Photograph 4 is a sand storm where dust concentration is in excess of 300 grains per thousand cubic feet.

Photograph 4

Based on the three environments depicted, the ratio of dust concentrations is about 30,000:1. Subsequently, particle size and concentration affect air filter system selection.

Principles of Operation

There are four basic principles of operation which apply to the various types of air filtration systems.

- Inertial Separation
- Impingement
- Diffusion
- Electrostatic

Inertial Separation

In inertial separators, particles are collected by centrifugal forces arising from a rapid deflection of the airflow such that the dust particles, having mass and kinetic energy, are unable to follow the path of the gas molecules and, proceed in a different path to the main airstream. In this manner, inertial separators do actually separate dust and air into two distinctly separate paths. See Figure 2.

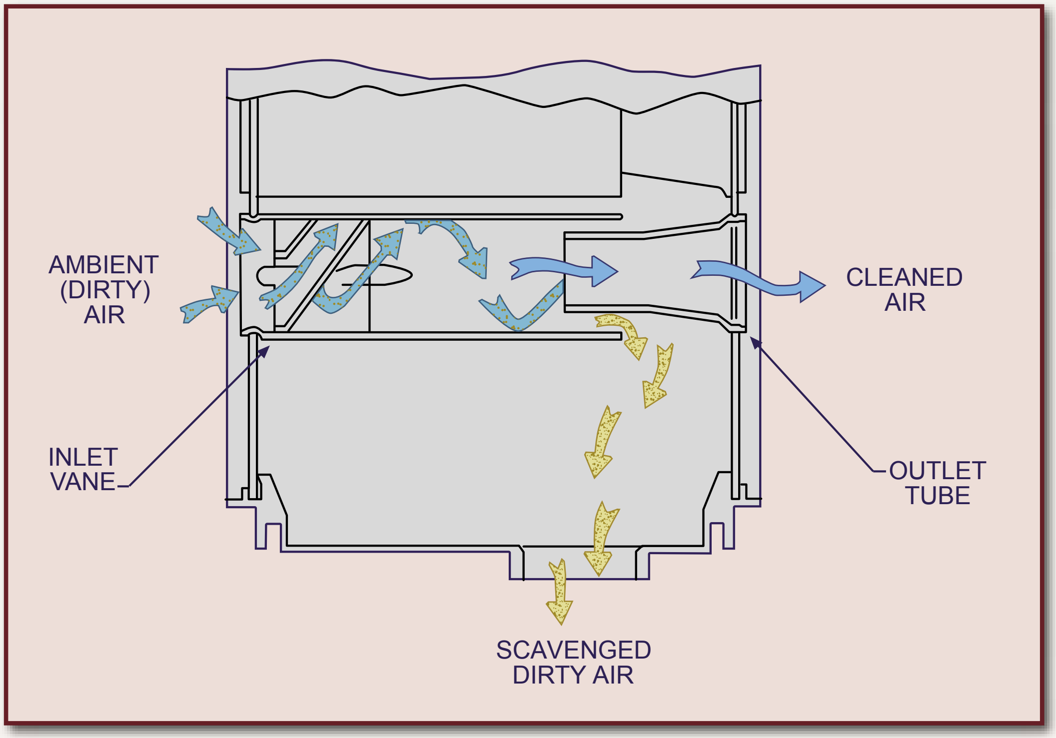


Figure 2

Generally, inertial separators can only satisfactorily collect particles above 10 microns in size and, therefore, are normally used as pre-filters in multi-stage filtration systems intended for installation in areas of very high particulate concentrations. The higher the velocity of the airstream entering an inertial separator, the greater is the kinetic energy imparted to the dust particles and greater is the effectiveness of the principle of inertial separation.

Inertial separation is an excellent way of removing the larger dust particles, which are difficult to remove and retain by filters employing any kind of filter media. However, there is a high pressure drop associated with this type of filtration.

Viscous Impingement

The term “viscous” is in front of the impingement principle of operation because the air filter media is oiled with a sticky adhesive and, therefore, operates as a “viscous” filter.

Viscous impingement filter media is made up of synthetic fibers, glass fibers, or expanded metal foil mesh in a pad, or mat, in multi layers or pleated forms.

Figure 3 depicts the aerodynamic behavior of particles within the fibrous media of a typical viscous impingement filter. The primary aerodynamic force

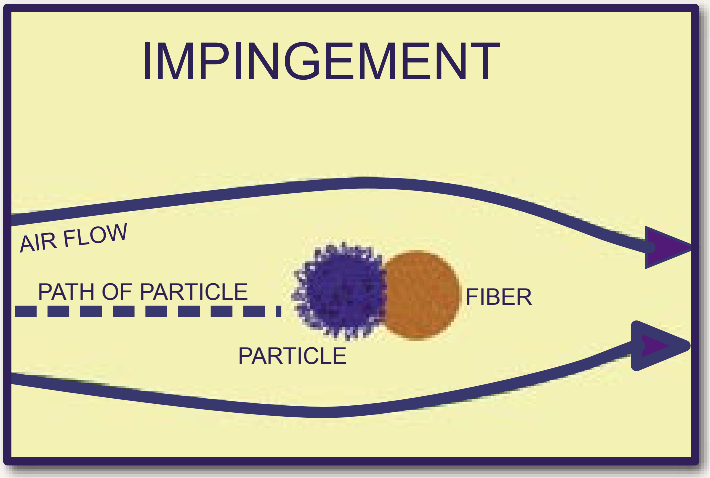


Figure 3

involved in the capture of dust particles due to impingement, is a boundary layer of still air surrounding each of the fibrous targets of a media. The depth of this boundary layer is a function of the fiber diameter, and the velocity of the airflow passing around the fiber targets. The larger the fiber diameter, and the higher the gas velocity, the greater is the depth of the boundary layer.

Viscous impingement filters operate at gas velocities in the range of 300-600 FPM, and have fiber diameters of about 35 microns. As such, the boundary layer is not insignificant. In order for a particle to impinge onto a target, it must have sufficient kinetic energy to break through the boundary layer surrounding the target.

If a particle does not have sufficient kinetic energy, it bounces off of the boundary layer back into the general airstream until it encounters another fiber target of the media. In the course of its path through the depth of the filter media the particle will make literally hundreds of attempts at breaking through boundary layers, but on each occasion, will suffer particle bounce and will eventually exit the filter media on the downstream side of the filter.

In this manner it can be seen that viscous impingement filters favor the larger dust particles. Also it can be seen that, the higher the gas velocity through the filter media, greater is the kinetic energy imparted to the particulate; unfortunately, depth of the boundary layer also increases.

There are two important parameters relating to the design of an air filter. First, is the target efficiency to consider; that is the probability of a particle to approach a target on which to impinge. Second, and equally important, is retention efficiency. This is the ability of the particle to be retained on the target.

The force that holds a particle to a fiber target is Van Der Waals Force (intermolecular attraction). These forces vary inversely as the seventh power of the interatomic distance; they are therefore, weak attractive forces, although in most cases are sufficient to hold smaller particles to the target.

However, with particles greater than 5 microns, and at flow velocities greater than 300 FPM, there comes a point when aerodynamic drag acting on the particle overcomes the Van Der Waals forces holding the particle to the target, and the particle is pulled back into the main airstream, thereby reducing the retention efficiency of the filter media. In order to assist the Van Der Waals attractive forces, filter manufacturers coat the filter media with an adhesive thereby making the principle of operation - viscous impingement.

Viscous impingement filters are designed to remove that fraction of dust particles in the size range of about 3 to 30 microns. They are relatively inexpensive, have the ability to handle moderate dust concentrations and operate at medium pressure drop: typically about 0.25"w.g. when clean to 1.0" WG when dirty.

Diffusion

When a gas flow carries a substantial amount of aerosol (suspended particles in gases), the detailed patterns of its motion are often visible. Thus we are able to see the complex turbulent patterns of the exhaust from a smoke-stack, or the curls which rise from a blown-out match or candle (see Photograph 5). These are examples of eddy diffusion. Three things can be observed about this type of gas flow:

1. The gas exists in relatively independent bundles or masses of gas, called eddies. These eddies show an essentially

Photograph 5

random motion for a period of time; they rise and fall about as they move in the general direction of the gas flow.

2. The eddies do eventually lose their identity, mixing together into a homogeneous gas cloud or flow as the gas moves away from the source of the disturbance, and flow velocity diminishes. This mixing process is very thorough and surprisingly rapid.

3. In many cases (as for example, a blown-out match), the flow will begin as a smooth laminar flow and progress a bit before turbulent eddies appear. The point at which eddies appear is called the onset of turbulence.

From the standpoint of the aerosols being carried, this type of flow is an effective mixing and transport device. Transport in this context means the conveying of particles from one part of the flow to another across the general flow direction of the stream. This cross-transportation action does not take place in laminar flow. If a small aerosol stream is introduced into a true laminar flow, it is seen to continue as a small stream. In a turbulent situation, the stream breaks up and spreads very rapidly, losing its identity into the main stream. The physics and mathematics of eddy diffusion are quite complicated.

The second kind of diffusion effect is called Brownian Motion. It is significant only for very small particles (less than 0.5 microns) which, when suspended in fluid, are observed to be under constant motion on jagged and randomly directed paths. This motion is the result of bombardment by molecules of the fluid (air). As a result of this motion, the length of the path traveled by a particle in any given direction from a given point will increase in proportion to the time elapsed since it left that point. This effect operates in perfectly still fluids as well as moving fluids: it is due to thermal energy of the fluid molecules, not to their flow. The effect is present in both gases and liquids.

In the case of aerosols moving through a filter, Brownian motion will manifest itself as a wobbling, erratic motion of the particles about the steady aerodynamic path (see Figure 5). This motion would not of itself result in additional collection of particles by fibers if the particle concentration were everywhere identical. But since the motion is totally random, the transfer of particles across any surface near a fiber will be proportional to the concentration on opposite sides of that surface. It can be shown that there is a net transfer of particles across a surface and that this transfer is in the direction of the fiber surface itself. The rate at which such transfer takes place is proportional to a diffusion coefficient.

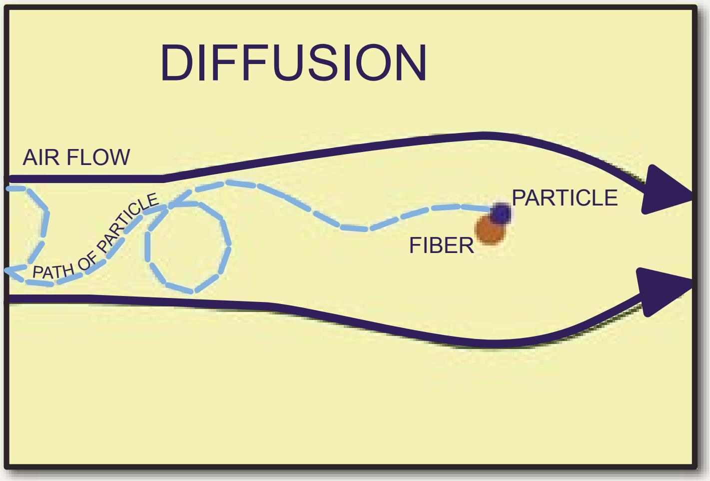


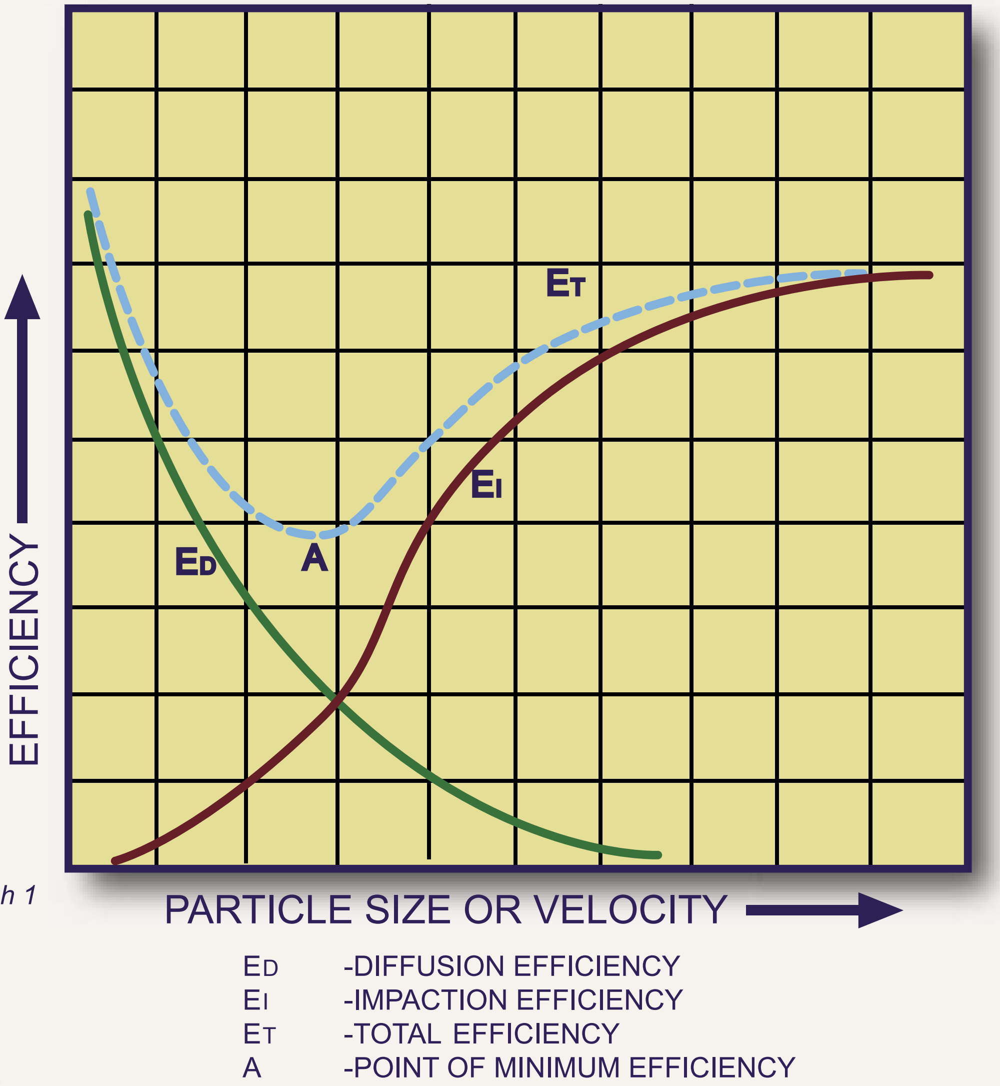
Figure 5

The combined properties of aerodynamic impingement, Brownian motion, and eddy diffusion enable us to state qualitatively, at least, how aerosol (suspended particles in gases) filtration will be effected. Graph 1 depicts the effect which would result if aerodynamic collection alone were operative and if Brownian diffusion alone were operative. The top curve depicts the sum of these two effects.

It is apparent that the Brownian diffusion curve falls toward zero for particles approaching molecular size (an aerosol filter does not filter out gases). In addition, it is not at all unusual for filter efficiency to drop somewhat toward zero for large particles because of their poor retention after capture by some filter media. The mere transport of particles to the fiber surface is not sufficient of itself to ensure their collection. They also have to remain on the fiber surface.

Fiber (target) diameter in diffusion filters range from 5 microns for filters having an ASHREA efficiency of 50-70%, to 0.5 microns for HEPA filters having an efficiency of 99.999% on 0.1 micron. Air velocity through the media is the order of 50 FPM for the ASHREA filter and 6 FPM for the HEPA filter.

Because of these small fiber diameters, and low gas velocities, there is not problem of particle bounce from the boundary layer. Also, since the particulate diffused onto the filter media fibers are small in size, the effects of aerodynamic drag is negligible. For this reason diffusion filters are dry type, they are not adhesive coated as in the case of viscous impingement filters.



Graph 1

Electrostatic

Electrostatic filtration is an extremely effective method for removing dust, smoke, and other small particles from air over a particle size range from about 10 to 0.01 microns. The principle involved is that of passing the air through an ionizer screen where electrons colliding with air molecules generate positive ions which adhere to dust and other small particles present, giving them a positive charge. The charged dust particles then enter a region filled with closely spaced parallel metal plates alternatively charged with positive and negative voltages of the order of 6000 volts DC. Positive plates repel the charged particles which are attracted by and retained on the negative plates by electrostatic forces, further supplemented by intermolecular forces, causing the dust to agglomerate. (see Figure 6)

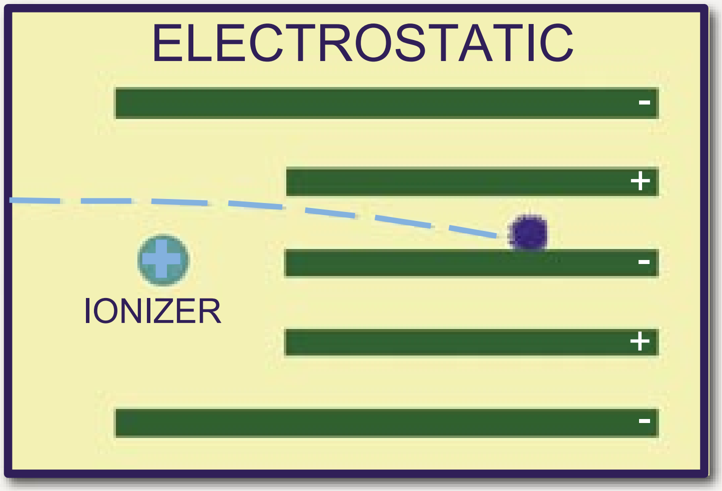


Figure 6

Industrial Air Filtration

Intake air filtration is necessary for top operating performance of blowers, air compressors, reciprocating and gas turbine engines. Intake air filtration equipment protects against excessive wear due to:

- Erosion
- Fouling
- Corrosion

The level of sophistication of air filtration equipment is dependant on the service of the air and the environmental conditions of the rotating machinery's location.

Fouling is normally due to one of two elements. The first is solid particulate mineral and/or plant matter, and the other is carbon smokes and/or hydrocarbon fumes which create a sticky "flypaper" substance when deposited on internal parts of rotating machinery.

One contributing source of carbon is the engine itself with its exhaust combustion gasses and lube-oil vent vapors.

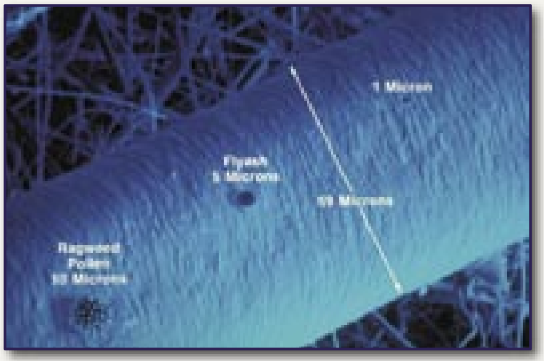
While a course mineral dust may erode the rotor and stator blades of a combustion gas turbine, a fine, sticky dust would create deposits on the blades. In both cases the profile of the blade is changed from its ideal design shape with subsequent continuous drop in efficiency of the compressor. What differentiates both cases is that in the former the damage is permanent and the parts must be replaced: while in the latter the dirty parts can be cleaned. This fundamental difference in the nature of damage caused, determines the choice of a suitable air intake air filter.

Generally, average airborne dust does not of itself result in ambient corrosion of the compressor blading. However, moisture and airborne aerosols (such as those containing sea salt or ammonium compounds) may well cause appreciable corrosion of the hot gas paths.

Airborne NaCl (sodium chloride), contributes to massive hot section corrosion in a gas turbine. The corrosion occurs after sodium combines with sulfur and/or oxygen during the combustion process and is deposited as a liquid flux on the hot section components. Other metals, primarily potassium, vanadium and lead, either as sulfates or oxides will also contribute to hot section corrosion. There are two primary sources of these metals, the inlet air and the fuel. Maximum allowable concentrations of these metals in the inlet air can be calculated, using the concentrations in the fuel, but most manufacturers are currently using 0.01 ppm of sodium chloride, (0.004 ppm of sodium), as an air quality specification downstream of the air filtration system.

By the nature of their design, gas turbines and reciprocating engines, provide a very reliable and efficient source of power. The keys to their efficiency are extremely close tolerances and accurate balance. These features can be rapidly destroyed by contaminated intake air. That is why carefully designed intake systems are crucial to the successful, economical operations of any gas turbine or engine.

The primary function of an intake air filtration system system is the removal of solid particulate, moisture droplets/vapor, and salts (NaCl, KCl, CaCl2). The following methods are used to achieve these objectives:



Photograph 6

Screening

Simple coarse screens will keep out large foreign objects. However, as it can be seen in photograph 6 (atmospheric dust trapped in the media of a high efficiency air filter - 2,500X magnification), screening is not a part of the mechanism by which particulate is removed by air filtration. As can be seen in photograph 6, the spaces between the individual fibers of the media are significantly larger than the size of the particulate trapped in the media.

Weather hoods or weather louvers are used to protect the filter elements from direct exposure to rain, snow or hail. Although a degree of inertial separation takes place, these devices should not be considered as filtration.

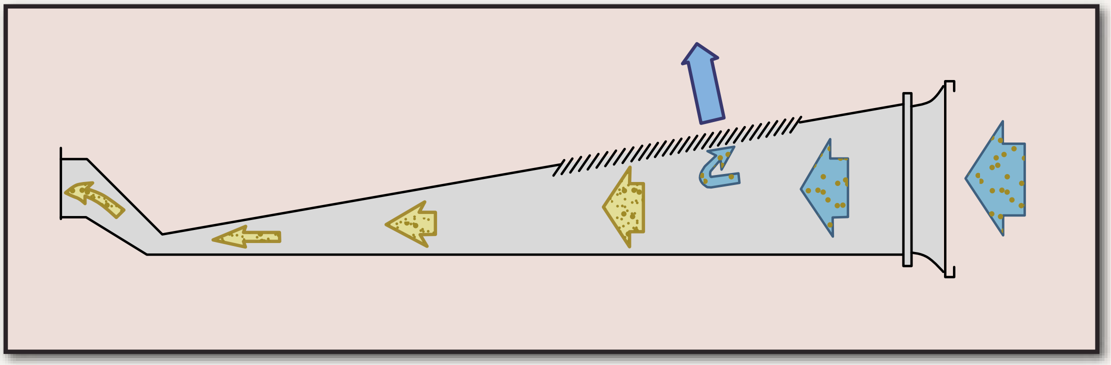


Figure 7

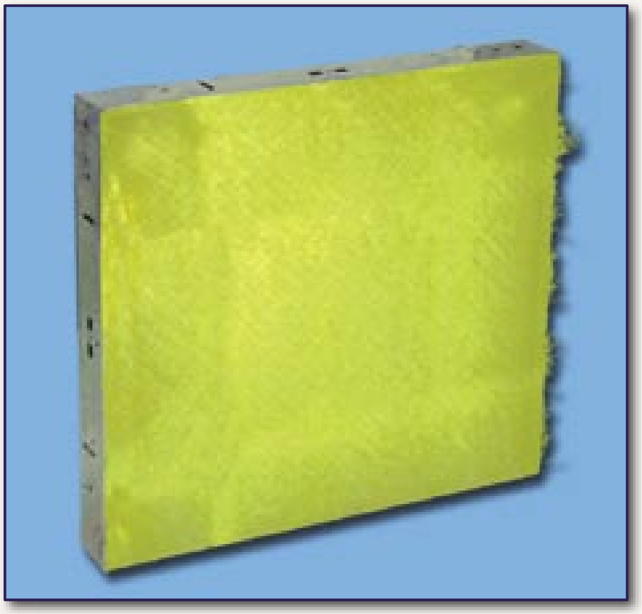
Inertial Separation

For gas turbine applications in areas of heavy dust concentrations, self-cleaning inertial separators are widely used as a first stage of filtration. Their purpose is to remove a substantial percentage of the larger, heavier particles and to cope with surges in particulate loading, e.g. desert sand storms. A well designed inertial separator will remove about 99% of particulate larger than 10 micron. Figure 7 is a slide of an inertial separator pocket.

Moisture Coalescer

Moisture coalescers are used to prevent free moisture reaching subsequent stages of filtration whose performance might be adversely affected when wet. The most effective types are those designed to operate as a combination prefilter/coalescer. An inherent problem associated with single purpose coalescers is where in the filtration system chain should it be located?

Logic would dictate that the coalescer be placed immediately downstream of the weather hood in order to protect the regular air filters from moisture saturation. However, the problem with this approach is that the coalescer will also act in the manner of a low efficiency filter and quickly become loaded with particulate, the consequences of which is that it's performance as a coalescer deteriorates.



Photograph 7

If one elects to place the prefilter ahead of the coalescer in the filtration chain, it will act as a low grade coalescer in addition to its assigned prefilter function and, since most prefilters are not designed to handle free moisture, it's performance as a filter is compromised.

Subsequently a combination prefilter/coalescer specifically to overcome the unique location problems associated with moisture coalescers is required. The solution to this problem is a viscous impingement disposable glass-fiber pad of progressive density from air entering side of the pad to the air leaving side (see Photograph 7).

Viscous Impingement Filters

The first viscous impingement filters to be used were the so called "oil wetted" panel filters. These filters consist of metallic media elements that were coated with an oil. When the filter panel had achieved it's maximum dust loading as defined by the increase in pressure drop, each filter element was removed, washed, dried, dipped in fresh oil, and drained and finally reinstalled into it's holding frame. This was a time consuming and unacceptable maintenance chore. Later, automatic rotating screen oil bath air filters were used, along with automatic roll type filters.

These viscous impingement filters did a good job of protecting equipment against erosion. However, it was quickly recognized that fouling of equipment was a significant problem that could only be resolved by use of much higher efficiency intake air filters capable of removing particulate in the size range of 3 micron and below. From this point on, viscous impingement filters were only used as prefilters to the high efficiency barrier filters.

Barrier Filters

Disposable barrier filters operate (Photograph 8) on the diffusion principle and are widely used for locations having moderate levels of contaminants. They should always be preceded by a prefilter. In desert locations, the first stage of filtration is frequently an inertial separator. For coastal and offshore platform applications, it is essential that the barrier filter be constructed utilizing a water-proof media to positively prevent the migration of saline droplets leaching through the filter media and on into the intake of the engine. Generally speaking, bag type and pocket type barrier filters utilize an "air-laid" filter media which is not water proof and, therefore, are not suitable for use on coastal and offshore applications.

Photograph 8

Self-cleaning barrier filters

The most recent development in intake air filtration has been in the field of self cleaning barrier filter systems that utilize sharp blasts of reverse-flow compressed air to clean the barrier filter elements (Photograph 9). These filters have the advantage of very high efficiency in a single stage, the ability to deal with the highest concentration of contaminants, and excellent resistance to ice and hoar frost formation. Usually there is no other filtration stage either before or after the self-cleaning filter system: although a second stage water-proof barrier filter is occasionally used where unusually high salt concentrations are present.

Photograph 9

Intake System Design Parameters

These factors need to be considered when designing an intake filtration system:

The first item of information required is the engine location. Climatic conditions must be ascertained such as annual and maximum hourly rain fall, annual temperature and humidity data, prevailing wind direction and speed.

On the same site, a filter inlet facing into the prevailing wind will undergo entirely different conditions when compared to an inlet facing away from the prevailing wind.

Other important climatic data includes snow, hail, hoar frost, and incidence of fog and mist. The man-made factors to take into account include population intensity and industrial activity in the immediate area of the proposed installation site. For example, in a populated area there would be more contaminants resulting from products of combustion from vehicles, boilers, heating systems etc., than in a substantially rural area.

We also need to remember when considering climatic factors that, it is the conditions in the immediate vicinity of the engine intake that are important. The environment can be completely different on sites only a mile or so apart. Indeed, major differences can be found only a few hundred yards apart on the same site. Finally, but very important, is the need to avoid exposure of the intake system to contaminants from the exhaust of its own engine.

Having taken into account all of the available climatic and environmental data and, possibly having carried out some on site investigation by means of air sampling, the filtration engineer is now able to form an overall profile of the conditions under which the filtration system(s) will be working.

This profile is concerned mainly with the amount, size, composition and characteristics of the contaminants in the ambient air. The defining parameters then are:

Concentration:	The amount of contaminants in a given quantity of air.
Phase:	Are contaminants solid, liquid, or gaseous?
Particle size:	What is the size range of the predominant contaminants?
Composition:	The most common solid contaminants are mineral dusts. Sand, soil, etc. Animal and vegetable dust also gets into the air, for example seeds, pollens, insects and microorganisms. Ash is frequently present as solid particulate. Salt nuclei is often present and presents a special problem to air filters. Water, the most common liquid contaminant and can be present in many forms such as rain, snow, mist or fog.

The best of modern filtration systems can be compact, cost effective and efficient in any environment providing all of the above factors have been duly considered.

Depicts a common agriculture environment

Represents a typical industrial environment

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