



# Mechanisms of Air and Gas Filtration

## Overview

There are several mechanisms at play in air filtration of particles or microorganisms. Some of these mechanisms are the same ones that influence liquid filtration, and some of them are unique to air filtration. Contaminant retention is influenced by contaminant characteristics (size, mass, type), air properties (humidity, velocity), filter media characteristics (membrane, depth filters) and the filtration mechanisms involved. The main filtration mechanisms in air and gas filtration include direct interception or size exclusion, inertial impaction, diffusional interception, and electrostatic attraction. The combination of all of these mechanisms enable contaminant removal in air filtration.

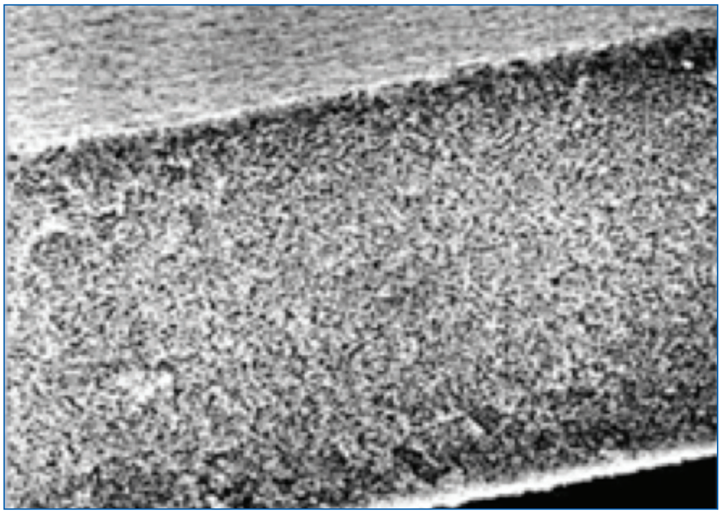
## Manufactured Filter Media Structure Aids Filtration

The most common lay person's understanding of filtration is that of a sieve. Openings of a certain sieve mesh size retain or pass contaminants based on their size. Relatively quickly, the sieve is blocked because of the build-up of retained contaminants at the sieve's surface. Industrial filters are different. All of them have some depth to them. In the case of membrane cartridge air filters, the filter media has a typical depth of approximately 40-150 µm, whereas depth cartridge filter media thickness is in the range of 1000-2000 µm. In effect, the structure of industrial filtering media is akin to a sponge, which contains a three-dimensional matrix of microscopic pores of varying sizes and media fibers or filaments of varying thickness (Figure 1). There is a narrow or wide distribution of pore sizes around a mean value, on the surface and within the depth of the filter media. The pore size rating should not be used as the main criterion for which air filter to select, but rather, the focus primarily in sterile air filtration must be placed on microbial validation that proves the required retention performance.

Contaminants are trapped both at the surface and inside the filter media, as they navigate a tortuous path through the filter, and both filter media structure and thickness influence retention.

The depth of the filter also increases contaminant holding capacity. Due to its depth, industrial filter media blocks less easily than a sieve, due to the number of alternative flow paths available.

Figure 1: Most manufactured filter media has depth, and retains contaminants as they navigate a tortuous path through the filter.

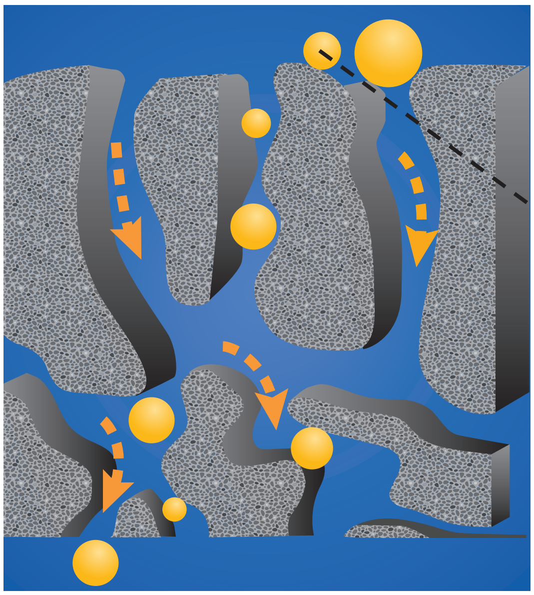


## Mechanisms of Contaminant Retention in Air and Gas Filters
### Direct Interception or Size Exclusion

Direct interception is based exclusively on size exclusion, and this filtration mechanism works equally well in both air and liquids. Particles are removed by the filter media when they are larger than the filter media pore size or flow path. Filter pores larger than the contaminant sizes enable contaminants to enter the interior of the filter. Filter pores may be blocked by irregularly shaped particles or by two or more particles as they “bridge” a filter pore, effectively reducing the pore size and excluding smaller particles (Figure 2).

Direct interception is the only filtration mechanism which has a connection to filter pore size. The majority of contaminants in air filtration are removed by other means.

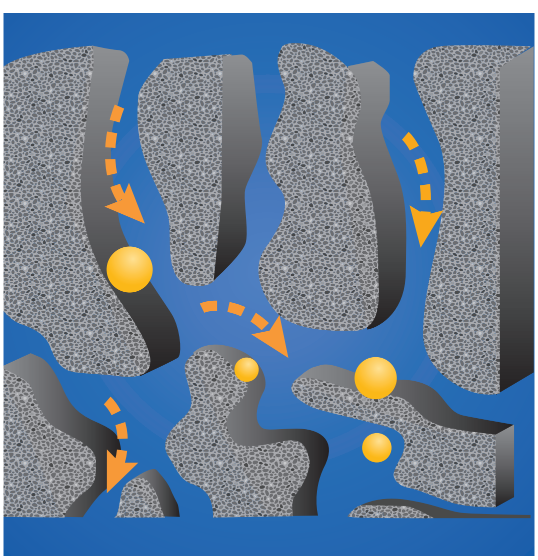
Figure 2: Filtration mechanism of Direct Interception




### Inertial Impaction

Inertial impaction has a greater impact in air filtration, and occurs to some extent in liquid filtration. It takes place when the air stream changes direction as it passes through the flow paths in the filter media, and contaminants leave the streamlines of fluid flow due to their momentum, caused by their mass and velocity. As they impact the filter media, they are embedded into the media due to forces of molecular attraction. Contaminant sizes smaller than the filter pore sizes can be retained. This mechanism is very effective for contaminants greater than 0.5-1 micron in size (Figure 3).

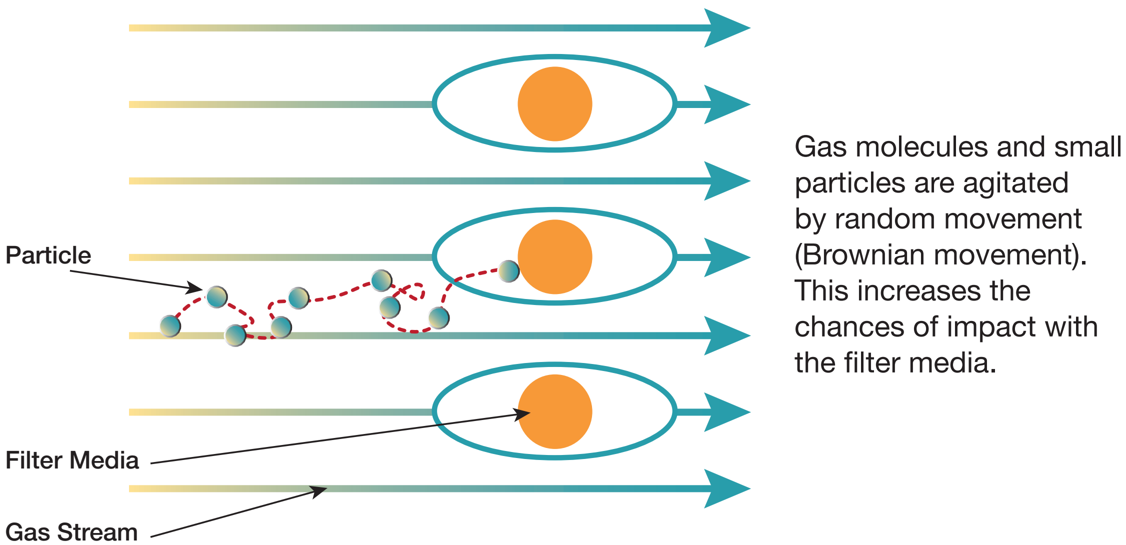
Figure 3: Filtration mechanism of Inertial Impaction



## Diffusional Interception

Diffusional interception is only found in air filtration. It is the main reason very small particles, smaller than the filter media pore size or flow path, are retained (Figure 4). It occurs because air molecules are always in a state of random motion. As air molecules impact contaminants in the air stream, they displace them in different directions, and this movement of the contaminants is known as Brownian motion (Figure 5a, 5b). As these contaminants impinge on the filter media, they can be retained due to forces of molecular attraction. A filter pore can be up to 5-10 times larger than the contaminant and still intercept it, due to this phenomenon. This filtration mechanism is very effective in dry air, especially for smaller contaminant sizes, less than about 0.1-0.3 µm.

Figure 4: Filtration mechanism of Diffusional Interception




Diffusional interception is the primary reason why it is easier for filters to remove contaminants from dry gas than from moist gas or liquids. It also explains why a filter used on air can have both a liquid and a gas removal performance and "rating". In general, a liquid-rated air filter would have a removal rating in dry gas approximately 5-10 times smaller, meaning a given liquid-rated filter may remove contaminants of 5-10 times smaller size in dry gas.

However, the effect of diffusional interception is lost when a filter pore or flow path wets out either partially or completely. Under this condition, the contaminants rather follow the streamlines of liquid flow, and the filter's performance reverts to its liquid (more open) removal rating. As an example, a filter rated at 0.2 µm in dry gas conditions would, if wetted, revert to a more open removal rating of approximately 1-2 µm. Figures 5c and 5d shows a conceptual illustration of the difference in filter retention of contaminants from a dry gas or a liquid.

The practical implication of this phenomenon is that for critical applications in which worst case conditions apply, the most conservative approach is to validate air filter performance in liquids. A further discussion of this is discussed in *Evaluating Microbial Retention Performance in Sterile Air and Gas Filters for the Food and Beverage Industry*[1] and in *Liquid and Aerosol Bacterial Challenge in Sterile Air Filter Validation*[2].

Figure 5: Conceptual illustration of the limits of diffusional interception: comparing filter retention of contaminants in a dry gas and in liquid conditions.

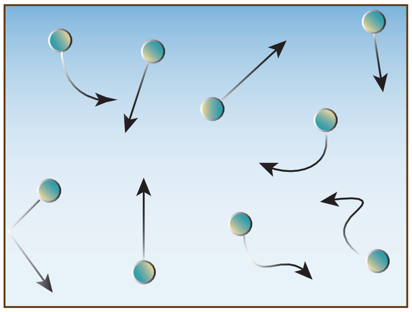


Figure 5a: Air/gas molecules are in a state of random motion.

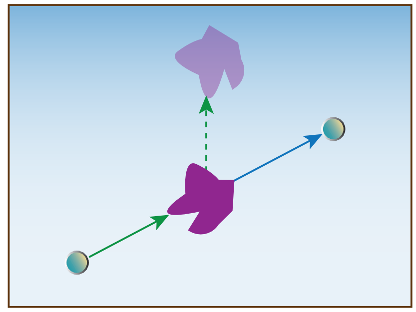


Figure 5b: Small contaminants in the gas are struck by the moving air/gas molecules and displaced, causing Brownian motion.

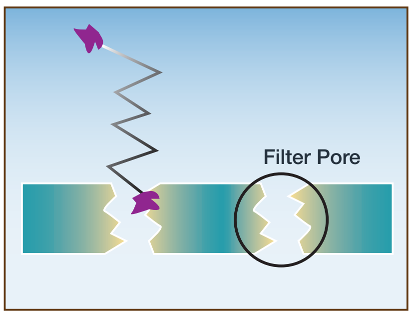



Figure 5c: Due to Brownian motion of the contaminants, diffusional interception is the key filtration mechanism occurring in dry gas. Contaminants many times smaller than the filter pore size are intercepted

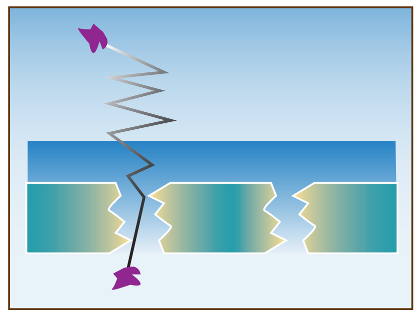


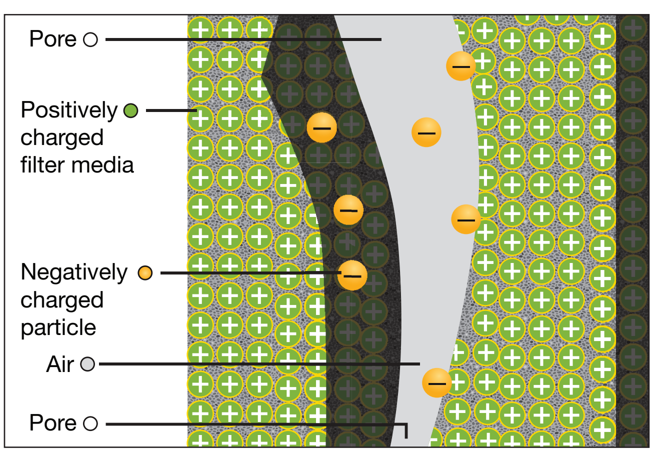
Figure 5d: Diffusional interception does not work under moist conditions. Filter pores would need to be much smaller to capture contaminants from a liquid stream.

## Electrostatic Attraction

In electrostatic attraction, contaminants which carry a charge (*e.g.*, negatively charged bacteria and yeasts) are attracted and retained by oppositely-charged filter media (*e.g.*, positively charged filter media). The drier the air, the stronger the force of electrostatic attraction, whereas humidity decreases it. The higher the air velocity, the shorter the contact time between charged contaminants and the charged filter media, and the lower the efficiency of the electrostatic attraction.

The attraction only lasts until all the charge sites are exhausted, and then the effect of this filtration mechanism drops off.

Figure 6: Filtration mechanism of Electrostatic Attraction



## Net Filtration Retention Efficiency

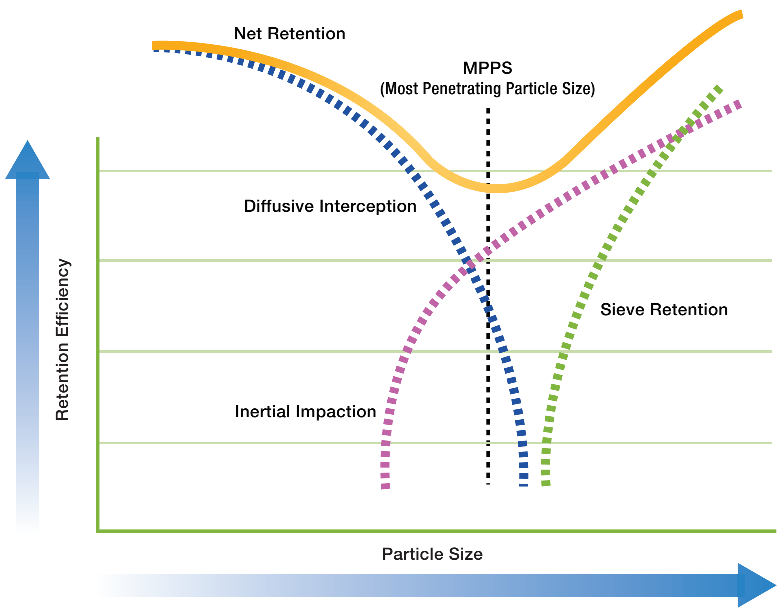
Each of the filtration mechanisms of retention work best for certain contaminant types, sizes, or mass. Overlaying the retention performance of each filtration mechanism yields a combined net retention performance curve. Figure 7 illustrates both the individual and cumulative retention efficiencies as a function of contaminant size, in dry gas filtration at a given air velocity.

The cumulative or net retention curve shows that there is a small range of particle sizes that are "most penetrating", meaning overall retention efficiency for these contaminants is least effective. This Most Penetrating Particle Size (MPPS) varies for different types of filters, and generally speaking, for depth filters this value is around 0.1-0.3 µm, and for cast membrane filters it is around 0.04-0.08 µm.

Air velocity and humidity would shift these curves.

This illustration simply provides a greater understanding of the challenges of air filtration and how the total retention results from each of the filtration mechanisms.

Figure 7: Effect of various retention mechanisms of contaminants retained from a dry air stream as a function of contaminant size[3]




## Summary

There are several mechanisms involved in air and gas filtration of particles or microorganisms. Unique to air filtration as opposed to liquid filtration is a filter's capability to remove contaminants much smaller than the rated pore size of the filter under dry conditions. Contrary to what might seem logical, the smallest contaminant sizes are not necessarily the most difficult to retain; rather for a given filter type, the least effective retention efficiency occurs at the most penetrating particle size (MPPS). In air and gas filtration, it is important not to confuse nominal pore size ratings with actual pore sizes in the filter, or to expect a certain filter retention performance based on pore size only. Rather, one must rely on the performance claims specified by filter manufacturers, which result from particle removal or microbiological validation testing.

## References

[1] Pall Corporation. *Evaluating Microbial Retention Performance in Sterile Air and Gas Filters for the Food and Beverage Industry*. 2020.

[2] Pall Corporation. *Liquid and Aerosol Bacterial Challenge in Sterile Air Filter Validation*. 2020.

[3] Parenteral Drug Association (PDA). *Sterilizing Filtration of Gases*; PDA Technical Report No. 40 (TR 40); PDA J. Pharm. Sci. Technol. 2005, 58 (No. S-1).

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**Pall Food and Beverage**

25 Harbor Park Drive
Port Washington NY 11050
+1 516 484 3600 telephone
+1 866 905 7255 toll free US

foodandbeverage@pall.com

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