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THE PRINCIPLES OF AIR FLOW, AIR PRESSURE, AND AIR FILTRATION

Adapted from the *NAFA Guide to Air Filtration*, published by the National Air Filtration Association. Reprinted with permission.

PRINCIPLES OF AIR FLOW

The flow of air between two points is due to the occurrence of a pressure difference between the two points. This pressure difference results in a force placed on the air, usually by a fan, causing the air to flow from the area of higher pressure to the area of lower pressure. The quantity of air, usually referred to in cubic feet per minute (cfm) is represented by the symbol Q. The speed of flow or velocity of the air, usually referred to in feet per minute (ft/min), is represented by the symbol V. The size of the conduit through which the air flows, usually ductwork, is referred to as area expressed in square feet (ft^2) and is represented by the symbol A.

The air flow through a conduit (ductwork) or a filter is expressed by the equation:

$$Q = V \times A$$

Therefore, to find either of the other values, the equation can be rewritten as:

$$V = Q \div A$$
$$A = Q \div V$$

An example of the application of this equation would be a 24-in. × 24-in. × 2-in. flat panel filter ($A = 4$ ft^2) placed in an airstream of 2000 cfm ($Q = 2000$ cfm). The velocity through the filter in this example would be 500 ft/min ($V = 2000$ cfm $\div$ 4 ft^2 = 500 ft/min).

PRINCIPLES OF AIR PRESSURE

As air travels through a conduit, it creates a pressure called *velocity pressure* (VP). There is a relationship between velocity of the air and the velocity pressure based on the density of the air. This relationship can be expressed in the equation:

$$V = 4005\sqrt{VP}$$

where:

V = velocity in feet per minute
4005 = standard density of air derived from gravitational acceleration (32.2 ft/sec^2 and air density of 0.075 lb/ft^3)
VP = velocity pressure in inches of water.

Velocity pressure is measured in the direction of flow through a conduit and is *always positive*.

Air confined in a conduit (whether in motion or not) creates another type of pressure, which exerts itself in all directions at the same time. Sometimes referred to as "bursting pressure," this pressure is called *static pressure* (SP). Static pressure is independent of the velocity of the air and can be *either positive or negative*, depending on where it is measured in the conduit. Static pressure can be measured using a Pitot tube. Figure 1 on the next page shows the relationship of velocity pressure and static pressure, which is expressed in the equation:

$$TP = SP + VP$$

where:

TP = total pressure
SP = static pressure
VP = velocity pressure.

To understand the pressure relationship, recognize that the lowest pressure in a system is at the fan inlet

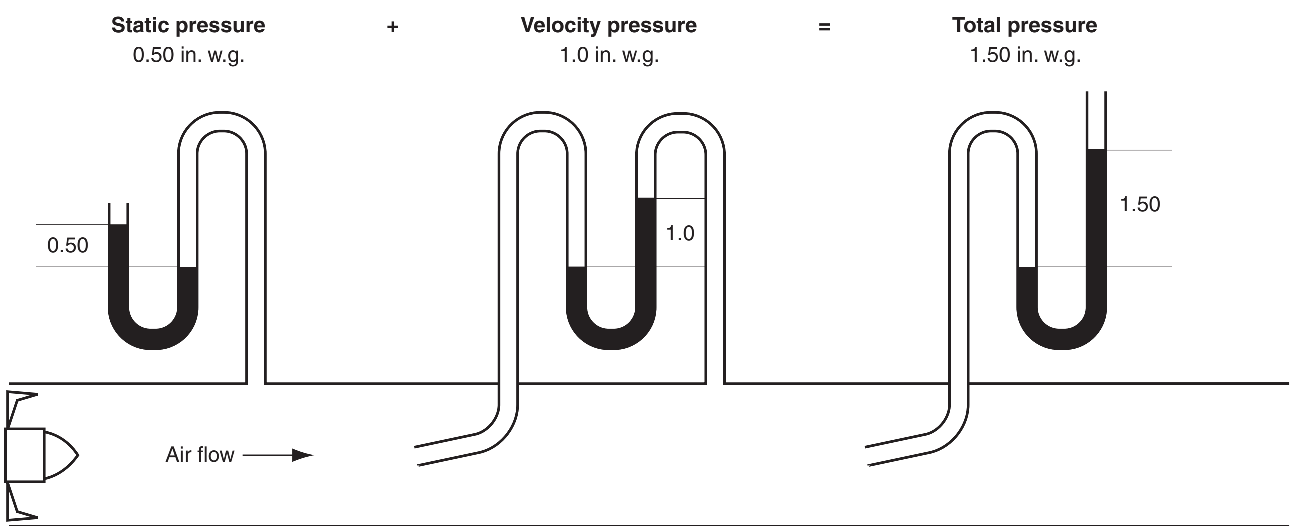


Figure 1. Pressure relationship

(point A in Figure 2) and the highest pressure is at the fan outlet (point B). As a filter loads, for example, the resistance to flow causes an increase in the pressure on the upstream side of the filter and a resultant decrease on the downstream side. This decrease in pressure between upstream and downstream is referred to as "pressure drop."

Devices that measure filter pressure drop usually measure static pressure increases in the system created by a filter as it loads. This pressure is expressed in inches of water gauge (see the inclined tube manometer in Figure 3).

As a filter loads in a system (depending on the type of fan and its place on the fan curve), velocity of the air decreases as static pressure increases, causing the system to work harder to deliver air to the space. This increase in work by the fan results in increased energy consumption and higher owning and operating costs (see *NAFA Guide to Air Filtration* Chapter 13: "Owning and Operating Costs"). Figure 4 shows the effect of this pressure in the system.

PRINCIPLES OF PARTICULATE AIR FILTRATION

Air filters are devices that remove aerosols from an airstream as the particulate-contaminated air passes through them. There are three types of air filtration categories—mechanical air filters, filters incorporating electrostatically charged filter media, and electronic air cleaners.

- *Mechanical air filters* capture particulates on the filter media, the material that comprises the filter element. This capture involves two different

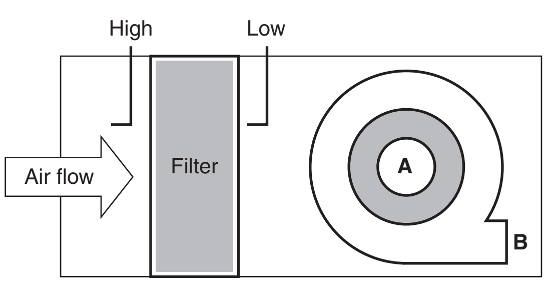
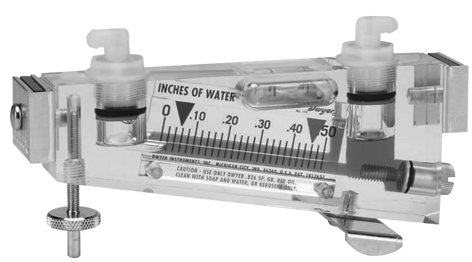


Figure 2. Typical location of pressure drop measurement devices



DWYER INSTRUMENTS

Figure 3. Pressure in a system is measured by an inclined tube manometer filled with red oil

considerations. The first is the probability that a particle will collide with or be removed by the "fibers" that make up the filter media. (The word "fibers" is used in the broadest sense to cover any component of a filter media.) The second is the probability that the particle, once contacting the filter, will continue to adhere to the fiber.

- *Electrostatically charged filter media* (passive and active) have been used for several decades. The advantage of charged filter media is that the charge on the fibers increases initial filtration efficiency without affecting resistance to air flow. Particles have a natural charge, or pick up an electrical charge as they pass through the air. These particles, in turn, tend to stick to filter fibers. Electrostatically charged filter media may be used on stand-alone filters or may be combined with other technology to enhance their performance.

- *Electronic air cleaners* (two-stage) are externally powered devices that impose a charge on airborne particles in the "ionizer section." The charged particles are then collected on oppositely charged plates in the "collector section."

MECHANICAL AIR FILTERS

There are four different processes responsible for the capture of particulates in a mechanical filter. Usually one prevails in a specific filter, but rarely is it the exclusive mechanism. These functions are:

- impingement
- interception
- diffusion
- straining.

Impingement is the mechanism by which large, high-density particles are captured. As air flows through a filter, it must bend or change direction many times to flow around the filter fibers. Because of their inertia, larger particles resist change in direction and attempt to continue on in their original directions. For this reason, they collide with, and adhere to, the fibers (see Figure 5).

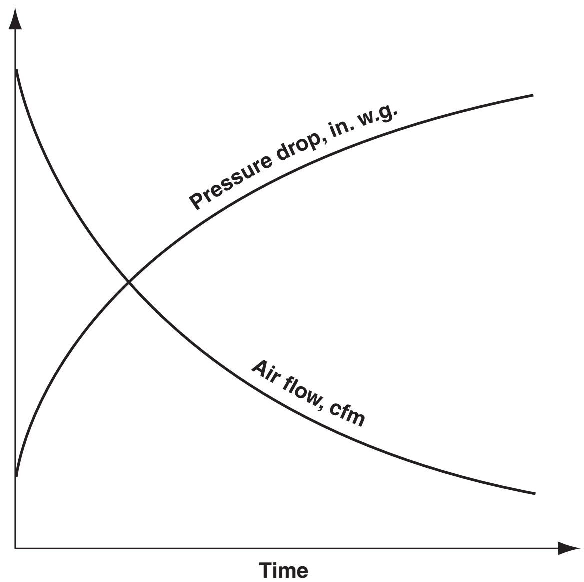


Figure 4. Pressure drop graph

Interception occurs when a particle follows the airstream, but still comes in contact with the fiber as it passes around it. If the forces of attraction between the fiber and the particle are greater than the force of the air flow to dislodge it, the particle will stick to the fiber. Interception is enhanced when the size of the fiber is closest to the size of the particle (see Figure 6 on the next page).

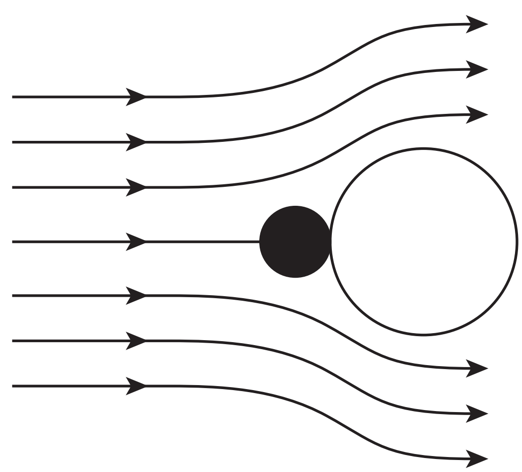


Figure 5. Impingement

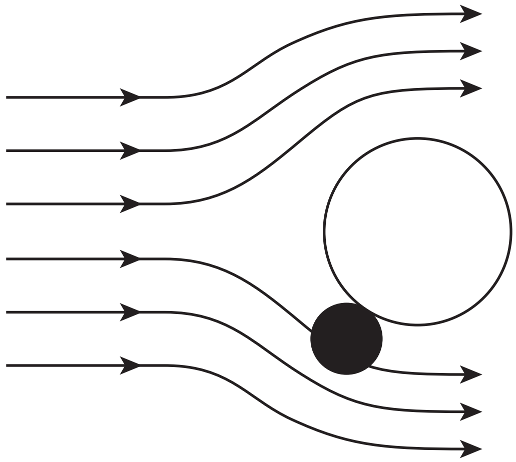


Figure 6. Interception

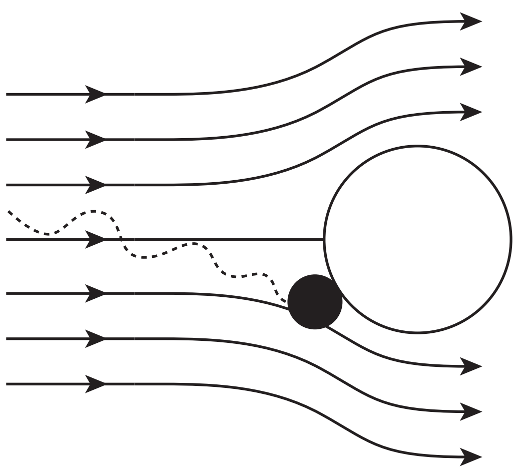


Figure 7. Diffusion effect

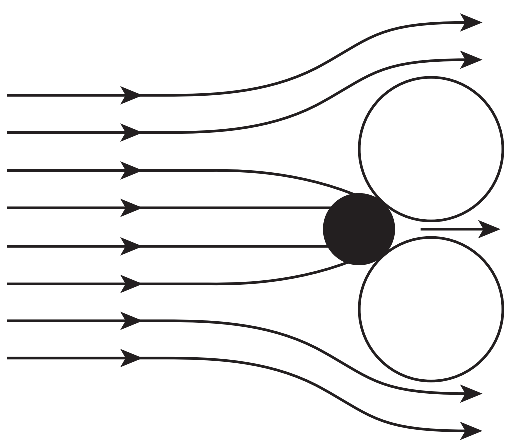


Figure 8. Straining

Diffusion explains the capture of very small particles at lower air velocities. As the contaminated air passes through the filter media, minute particles tend to move from areas of higher concentration and take an erratic path described as *Brownian motion*. This erratic path increases the probability that particles will come in contact with fibers and will stay attached to them. Diffusion works best with fine filter fibers and very low air velocities (see Figure 7).

Straining occurs when the smallest dimension of a particle is greater than the distance between adjoining filter media fibers (see Figure 8).

Impingement filters

The effectiveness of the impingement process depends on the following:

- *Particle size.* The larger the particle, the greater the mass and the greater the possibility that it will have enough inertia to resist change in direction and collide with a fiber.

- *Particle density.* The greater the density of a particle, the greater the mass and the greater its inertia.

- *Depth of the filter media and orientation of fibers.* The thicker the filter media and the closer the orientation of fibers, the greater the possibility of collision by a fiber.

- *Velocity of air flow through the filter.* The greater the velocity of air through a filter, the greater the kinetic energy of the particles in the airstream, and the greater the inertia of the particles. Overrating and underrating filters not only impacts the pressure drop and service life of a filter, but can also impact filter efficiency. If a panel filter is underrated, its overall efficiency on larger particles may actually be reduced. This is because most lower MERV filters utilize impingement as the main capture mechanism. Reducing the air flow decreases the velocity. Decreasing the velocity will decrease the impingement process by reducing the kinetic energy of the particle in motion. This may

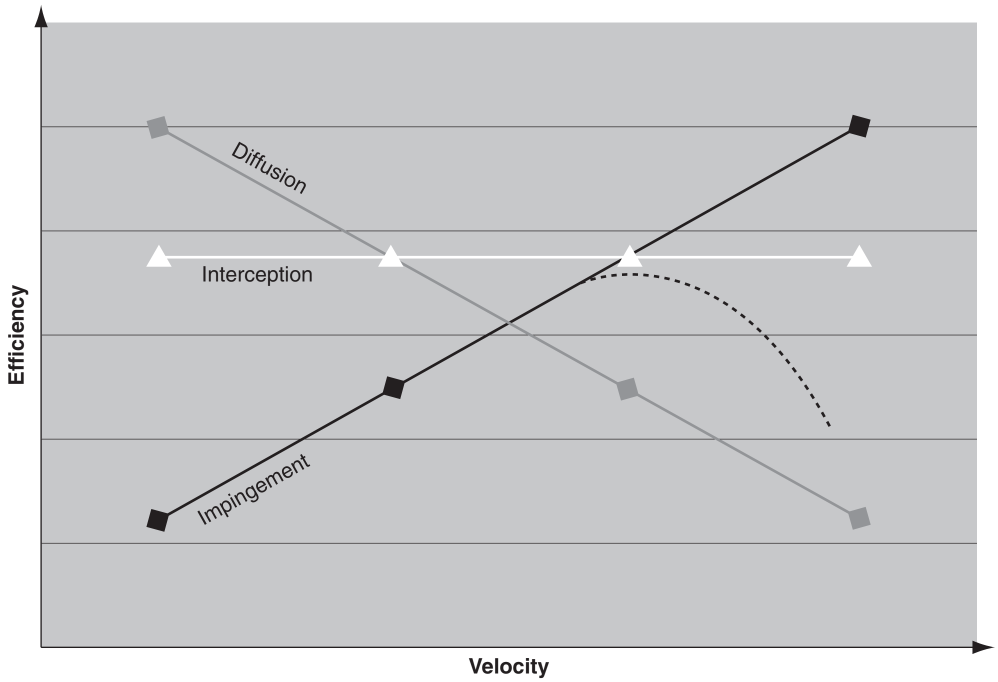


Figure 9. Theoretical effects of impingement, interception, and diffusion on filter efficiency

increase the capture of smaller particles by diffusion and interception. Conversely, overrating an impingement filter by increasing the air flow may increase its overall efficiency on larger particles (see note below) by increasing the impingement process, but decrease the capture of smaller particles.

Note: Lower MERV (minimum efficiency reporting value) filters, which predominately utilize the impingement capture principle, experience efficiency decreases at a given point as velocity increases and turns downward (see dotted line in Figure 9), resulting in lower efficiencies even on larger particles. Filters MERV 12 and higher do not usually experience this phenomenon because they utilize the principles of interception and diffusion as the predominant capture principle. Consult the manufacturer's recommended flow rates and values before underrating or overrating any filter.

Use of adhesives

The forces between a filter fiber and a dust particle captured by impingement are relatively weak (see "van der Waals forces"). There is a good possibility that the particle may become dislodged from the fiber by the velocity of the air passing around the fiber or by system vibration. In order to overcome this possibility, impingement filters are frequently treated with adhesives that coat the fibers and create a bond between them and any particles that may impinge upon the fiber. The ideal adhesive is:

- fireproof or fire-resistant
- able to maintain its tackiness between filter changeouts
- nontoxic
- odorless
- non-migrating, meaning that it will not entrain into the airstream.

Interception and diffusion filters

Interception poses a stronger influence with larger particles, whereas diffusion explains the capture of

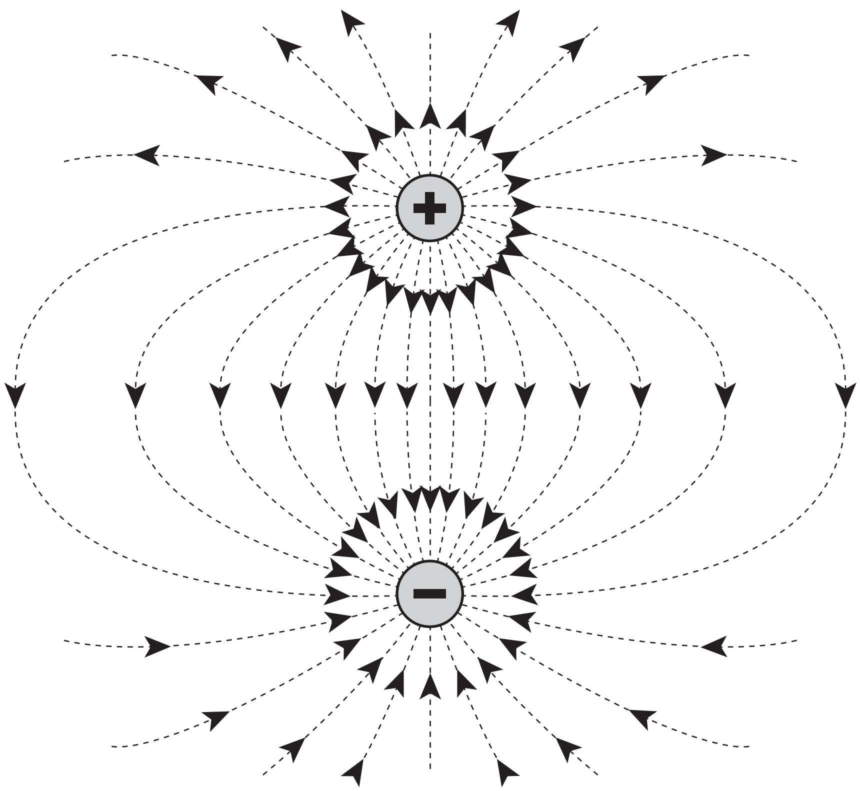


Figure 10. Dipole moment

smaller particles. Both are intended to cause a particle and a filter fiber to come in contact. The strength of the bond between the fiber and the particle depends on several forces of attraction:

- *van der Waals forces.* The perfect gas law states that if the pressure on a gas is doubled, its volume should be cut in half. However, researchers found that when gases were subjected to high pressures, the volume reduction was greater than expected. Some force drew the gas molecules together. A theory was developed by Johannes van der Waals based on molecular attraction to explain why this occurred. This same force of molecular attraction helps keep a dust particle attached to a fiber. The original equations developed as a result of studies by van der Waals have been modified by a series of researchers. However, these forces still carry his name.
- *Dipole moment.* Most molecules, even when they carry no charge, have a "dipole moment." This happens when there is a greater concentration of electrons at one point or end of a molecule than there is at another. This is especially true of large molecules. As a result, when a particle (even though its charge is electrostatically neutral) comes in contact with a fiber, it tends to align itself so that the more negatively charged side of the particle is adjacent to the more positively charged sectors of the fiber. Neither the particle nor the fiber has to be charged for this to occur (see Figure 10).

Disruptive forces

As was mentioned for the impingement filter, there are forces that tend to disrupt the attraction between a particle and a fiber. The two most important forces are:

- the flow of air through the filter, which may re-entrain the particle in the airstream (the particle's drag force opposes its forward motion)

- system vibration, which may dislodge the particle. Normally the effects of vibration can be minimized by proper filter installation, including vibration isolation.

Filter equilibrium

In most filter systems, *equilibrium* exists between the forces of adhesion holding a particle to a fiber and the drag force of air on the particle. There will be minimum re-entrainment when the forces of adhesion are equal to or greater than the drag force.

Factors affecting interception and diffusion

Particle capture by interception and diffusion is affected by the following factors:

- *Particle size.* Larger particles are more likely to be captured by impingement. Smaller particles, on the other hand, have an enhanced opportunity of coming in contact with a fiber because of their wider effective path created by Brownian motion and media velocity. There is a *most penetrating particle size* (MPPS) for any high-efficiency filter operating at a specific media velocity.

- *Fiber diameter.* The strongest force occurs between particles and fibers that are approximately the same diameter. Consequently, the smaller the filter fiber, the greater the retention of smaller particles.

- *Depth of the filter media and orientation of fibers.* The thicker the filter media and the closer the orientation of fibers, the greater the possibility of capture by a fiber.

Mixed-type mechanical filters

Much work has been done and continues to be devoted to determining the contribution of different mechanisms of filtration to the overall performance of different media, and to developing a more precise mathematical formula to describe their performance. Rarely is an exclusive mechanism responsible for all the collection observed. Normally, however, impingement is the predominant influence in filters intended to capture large particles traveling at higher velocities, and interception and diffusional effects are the main influences in the capture of smaller particles traveling at lower velocities.

Factors affecting mechanical filter selection

The following considerations are involved in the selection of a mechanical air filter:

- *Efficiency.* The most important consideration is the ability of a filter to remove from an airstream the greatest number of particles. This ability is generally described as "efficiency" (see also *NAFA Guide to Air Filtration* Chapter 7: "HVAC Filter Testing").

- *Pressure drop.* The resistance to air flow created by an air filter is an important consideration. The higher the resistance, the greater the energy required to overcome it. Consequently (all other considerations being equal), the filter with the lowest pressure drop is preferred.

- *Capacity.* This is the amount of air that a filter can handle. Usually capacity is defined as the volume of air per unit of time that a clean filter can handle at a specified pressure drop. This volume is expressed in cfm (cubic feet of air per minute) or in as m^3/sec (cubic meters of air per second). Changing the amount of air being handled by a filter will affect other performance values, such as pressure drop and efficiency.

ELECTROSTATICALLY CHARGED MEDIA

Passive electrostatic attraction

It is possible for a filter medium to become electrostatically charged by the flow of air (especially dry air) through it. Filters incorporating such media are described as *passive* electrostatic filters. Most particles are charged naturally, and are held by strong electrostatic forces to the oppositely charged fiber with which they come in contact (see Figure 11 at the top of the next page). The smaller a particle or a fiber, the relatively stronger the electrostatic forces will be.

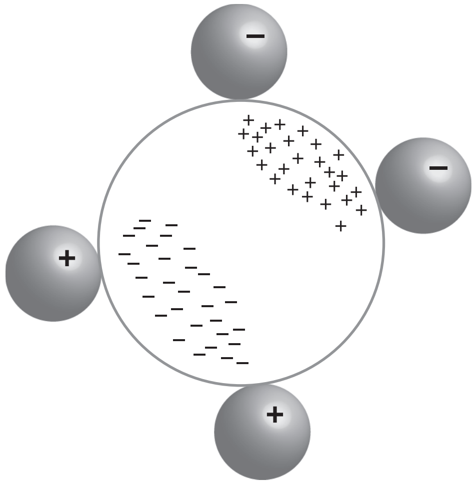


Figure 11. Particle attraction to charged filter

Active electrostatic attraction

Synthetic filter fibers can be *actively* charged during manufacture to be either positively or negatively charged and then made into a non-woven filter material called "electret" media. Charged fiber technology can be classified by the method used to create the electrostatic charge. Methods include:

- triboelectric charging
- corona charging
- charging by induction.

Triboelectrically charged material results from the rubbing together of dissimilar polymers. The first use of this technology involved wool with a resin treatment. Wool is an excellent conductor and the most electropositive fiber. Resin is an extremely good insulator and, when combined with wool and rubbed together, will exchange charge with the wool and become negatively charged. Thus, the resulting product contains both positive and negative charges that will attract and hold particles of the opposite charge. More recently, triboelectric-charged material has been developed by blending together two fibers of dissimilar characteristics. The rubbing together of these fibers causes an exchange of electrons, resulting in one material developing a positive charge

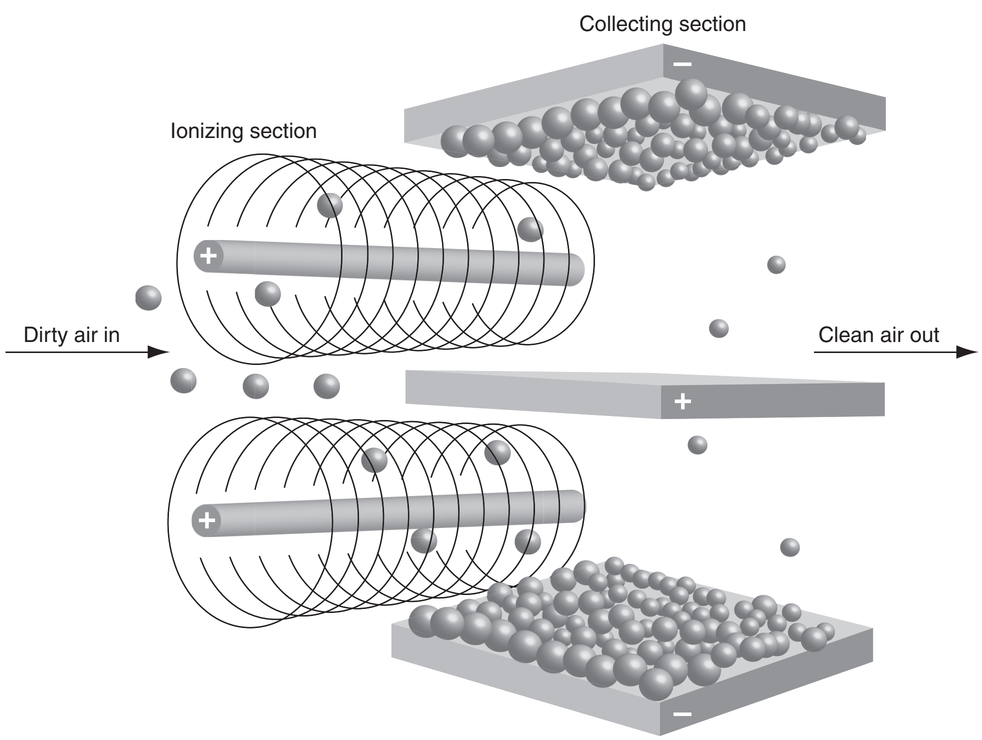


Figure 12. Ionizing and collecting sections of electronic air cleaner

and the other developing a negative charge. The most common materials currently used for this product are polypropylene and modacrylic. Blends of other binary dissimilar fibers also result in triboelectric properties.

Corona charging involves exposing fibers or filter material to an electrode designed to create high voltage (either positive or negative). The ions generated by the electrode are collected on the surface, creating the static charge. Split-fiber technology involves extruding a sheet of polymer (polypropylene), stretching it to create a molecular alignment, and permitting the sheet to be split into fibers by a process called *fibrillation*. The entire sheet is subjected to positive charges on one side and negative charges on the other. The resulting fibers, therefore, have both positive and negative charges.

Charging the finished material as a whole is a second method of corona charging. The corona charge is applied to the surface of the finished material, which is a much simpler process, but one that results in a product with a lower charge density.

Material charged by *induction* involves a process similar to that used in the production of electrically charged sprays. Fibers produced by electrostatic extrusion are typically quite fine and indicate the presence of both charges. Filters produced from fibers that have been charged by induction are generally quite efficient, due to their mechanical capture efficiency complemented by their electrostatic action. However, this method has not proven as effective as either triboelectric charging or corona charging.

While the additional charge increases the forces that attract and hold particles, it may not last the life of the filter. Depending on the type of charging technology, other factors—such as humidity, time in storage, and dust loading—may erode or blind the electrostatic charge.

ELECTRONIC AIR CLEANERS

Electrostatic precipitation

In the first stage (the *ionizing* section), the particles in an airstream are given an electrostatic charge. In

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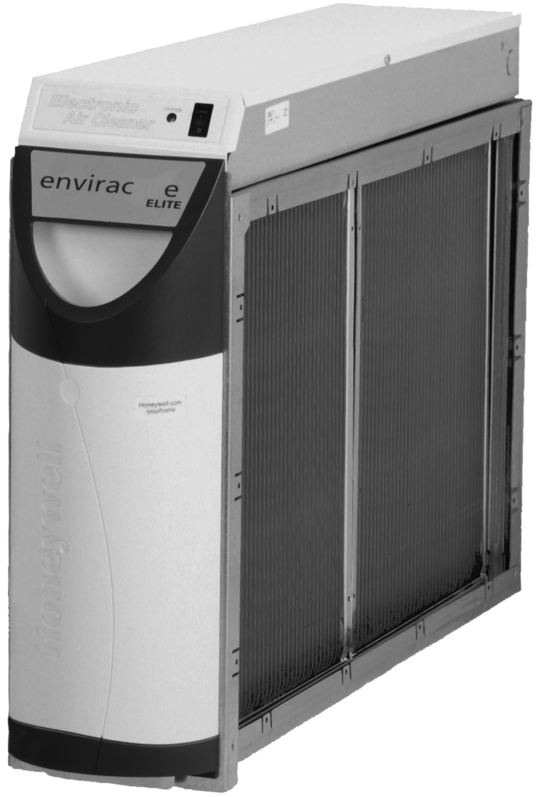

Figure 13. In-duct electronic air cleaner

the second stage (the *collecting* section), these particles are removed from the airstream by electrostatic attraction to oppositely charged plates (see Figure 12). In earlier designs, a 12-kV charge was placed on the ionizing section to give the particles an electrostatic charge. This section was made small and was designed with ionizing wire and grounded struts so that ozone generation was minimized. In the collecting section, the alternately charged plates were sized and spaced so that a 6-kV charge was enough to collect the particles, but not enough to create ozone.

Devices used in air conditioning and ventilating systems are now called "electronic air cleaners" to distinguish them from the earlier high-voltage, stack gas cleaning electrostatic precipitators. Figure 13 above shows a typical in-duct residential electronic air cleaner. Electronic air cleaners are discussed in detail in *NAFA Guide to Air Filtration* Chapter 6: "Air Cleaners."

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