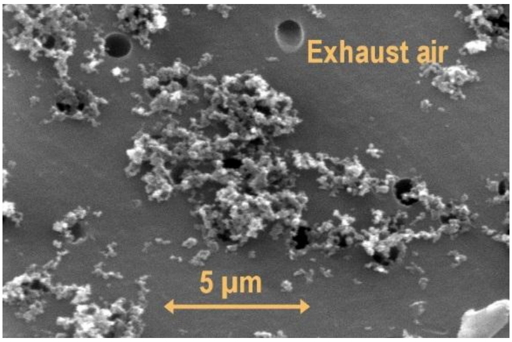
1 AIR FILTRATION IN A NUTSHELL

During the last decades, the potential benefits to health have been increasingly recognized as the primary purpose of filtration. The important criteria for selecting an air filtration system are based on external pollutants, indoor air quality, energy requirements and hygienic conditions.

Pollutants



Example of particles in exhaust air.

Outdoor and indoor air pollutant characteristics vary greatly with place, time and local conditions. Huge numbers of particles of different sizes, shapes, concentrations and toxicity are found in the air, as well as different gases ranging from harmless to irritating and unhealthy. Airborne impurities differ in size and composition, from ultrafine or nano-particles (less than 0.1 µm) to fine particles (0.1 µm to 2.5 µm) and coarse particles (dust >2.5 µm).

The distribution of the particles in the atmospheric aerosol may be expressed in different ways (see **Error! Reference source not found. Error! Reference source not found.**). With respect to number, most of the particles are less than 0.1 µm (nano particles). With respect to mass most particles are larger than 0.1 µm (Figure 1.1). It is worth considering that one particle of 10 µm weighs the same as one million ultrafine particles. The total number of particles in a city can exceed 10 000 000 000 particles/m³, which a standard air filter for 1 m³/s has to treat every second.

It is possible to see individual particles down to 10 µm with naked eye. Particles in tobacco smoke are less than 1 µm, but can also be seen due to the high concentration of the ultrafine particles. Some common pollutant sizes are found in Figure 1.2.

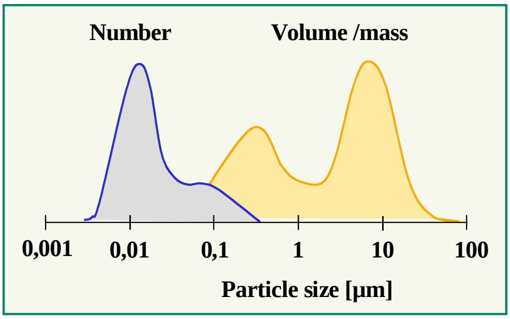


Figure 1.1 *Example of number and mass size distribution of atmospheric aerosol. Made from EPA, 2004.*

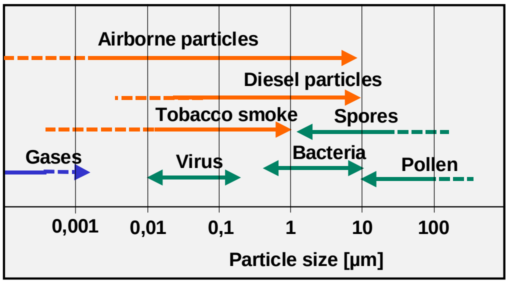


Figure 1.2 *Examples of particle size for some pollutants.*

The concentrations of many common pollutants in different places or cities can be found on the government authorities web pages. The selection of air filters depends on the quality of the outdoor air and the desired indoor air requirement. EN 13779:2007 defines three categories of outdoor air, ODA 1 (pure air, except for temporary pollutions such as pollen) to ODA 3 (very dirty air with high concentrations of both gas and particulates). Four classes of indoor air, IDA 1 (high quality) to IDA 4 (low), are used as the basis for selecting air filters (see **Error! Reference source not found. Error! Reference source not found.**).

Indoor air requirements

Epidemiological studies worldwide have demonstrated adverse effects of even low levels of air pollution on health (see **Error! Reference source not found. Error! Reference source not found.**). Air contaminants such as particles, sulphur dioxide, ozone and nitrogen dioxide have serious effects on health. In Europe, indoor and outdoor air pollutants are the most important contributory factor of diseases related to the environment. Particles are currently considered the worst. There is a clear connection between raised pollution levels of fine particles below 2.5 µm and increased mortality caused by cardiovascular and respiratory illness.

We spend 90 percent of our time indoors and breathing healthy indoor air is a human right-and all groups, individuals or organizations associated with a building have a responsibility to work to achieve an acceptable air quality (WHO 2000). Air filtration may improve indoor air quality and occupants productivity as well as reduce the costs associated with building and HVAC cleaning (see **Error! Reference source not found. Error! Reference source not found.**).

EN 13779:2007 defines the requirements of filter classes to meet different indoor air qualities with reference to the outdoor air environment (see **Error! Reference source not found. Error! Reference source not found.**). This is accomplished in most cases by using a two stage filtration with minimum F7 filter quality for the treatment of outdoor air. However, as the filter classes do not cover in-situ performances, the **minimum efficiency**[1] according to the EN 779:2002, Eurovent (rec. 18 2009) or an independent test of in-situ operation should be specified (see **Error! Reference source not found. Error! Reference source not found.**). This will give Minimum Life Efficiency (MLE) in service and is the *only efficiency which can be guaranteed and checked in the installation.*

The filters should be **replaced** for hygienic reasons and the service intervals may be 2 000 h for the first filter stage and 4 000 h for the second filter stage (see **Error! Reference source not found. Error! Reference source not found.**). The filters should be replaced in the autumn after the pollen season and in demanding applications also in spring after the winter heating season to avoid organic odours. If possible, the relative humidity should be kept below 80% to avoid microbial growth.

Energy requirements

The air flow resistance in air filters consumes fan energy and is indirectly responsible for the global climate change. The United Nations roadmaps on cutting emissions and the European Directives on saving energy will encourage measures to reduce the air flow resistance and the amount of energy used by air filters. This has to be implemented not only in the initial clean conditions but during the whole service life of the filter. However, at the same time the delivered air quality should not be compromised by simply lowering the efficiency of air filters. The correct design and good maintenance of air filters is important to minimize the energy consumption without affecting the removal efficiency (see **Error! Reference source not found. Error! Reference source not found.**).

Energy consumption is linked to the air resistance of the filter. The energy cost operating the filter can be 80% of the overall cost of the filter. The rest includes filter replacement, labour and disposal costs. The air flow of the filter, replacement intervals and pressure drops are the parameters to be chosen based on acceptable air flow changes in the system (**Error! Reference source not found.**), life cycle costs (**Error! Reference source not found.**) or life cycle assessments (**Error! Reference source not found.**). About 80% of the filters environmental load results from the energy used to overcome the air flow resistance during operation.

To meet the directives of a low energy future and lower Specific Fan Power it is necessary to reduce air flow resistance of the filters by optimising the design and the operation of the filter. Most air handling units today are designed for a face velocity of 2 to 3 m/s, but reducing final pressure drop and air flow per filter, considerably savings in energy and costs can be achieved (see **Error! Reference source**

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[1] Lowest efficiency in the EN 779 test including efficiency of neutralised filter material (discharged efficiency).

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Air filtration

The filter design has to be a compromise between the construction and amount of media to meet costs, stability, air flow resistance and service life. Today there are thousands of different filter sizes and to improve the situation it is recommended to use only a few standard sizes according to EN 15805 (see Table 3.1 Face dimensions of air filters according to EN 15805).

The removal of contaminating particulates is usually performed by fibrous filtering media. Fine fibres are the crucial factor in achieving higher efficiency and glass has been the most frequently used material to produce fibres with diameter around 1 µm and below. The process development has progressed quickly and nowadays it is possible to produce high efficiency filter media sourced from various polymer substances. If the filter material is able to hold significant electrostatic charge the initial particulate efficiency can be much improved.

Air filter in air handling unit.

The overall fractional particle efficiency of an air filter is the result of the sum of different filtration mechanisms (diffusion, interception, inertia and electrostatic forces. See 2 PARTICULATE FILTRATION PRINCIPLES). There is a specific particle size which is the most difficult to collect in a filter or easily penetrates (Most Penetrating Particle Size, MPPS). The minimum efficiency for HVAC filters depends on the air velocity and type of media. However, it is normally determined by particles in the 0.1 to 0.3 µm range. See Figure 1.3.

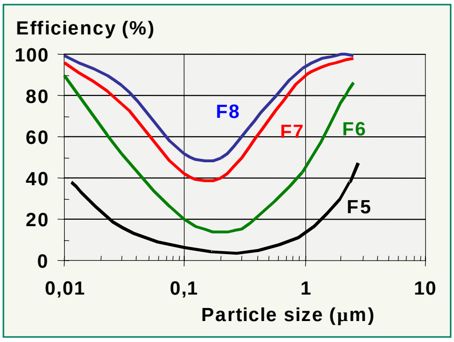

Figure 1.3 *Efficiency vs. particle size for different Fine (F) filters. (From Hanley et al,1993).*

The removal of gaseous contaminants is usually accomplished by physical adsorption and/or chemisorption through the use of various dry untreated or chemically impregnated granular activated carbons, aluminium oxide, silica gel and zeolites (see **Error! Reference source not found. Error! Reference source not found.**). The efficiency and service life of an adsorbent depends on its total surface area, i.e. the overall surface of the porous solid adsorbent that extends into the interior of the solid and is accessible. Activated carbon is the most common material that offers a large and accessible surface area per unit volume (up to 1400 square meters per gram). Physical adsorption involves comparatively weak interactions between the adsorbent surface and the molecule. The process is reversible and desorption may occur depending on concentration, temperature and interaction with other gases (Figure 1.4). Chemical adsorption involves irreversible chemical reactions taking place after physical adsorption has occurred (see 4.1 Adsorption).

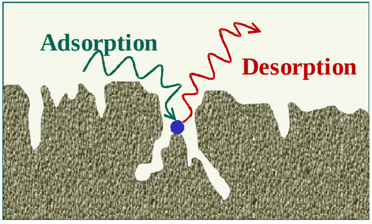

***Figure 1.4** Physical adsorption inside an adsorbent. Desorption can be avoided by chemical impregnation.*

Test methods for gas phase filters are very complex. Types of gases, concentrations, conditions and instruments have to be specified. In service, behaviour of gas phase filters is difficult to predict because they are sensitive to temperature, humidity and the type of gas and its concentration. There is also a strong interaction between different gases.

Classification of air filters

The European standard EN 779:2002 includes the measurement of the particle removal efficiency and a classification system based on filters loaded with synthetic (ASHRAE) dust injected at high concentration. The classification is based on standard size filters (610 mm x 610 mm) tested at 0.944 m³/s. For fine (F) filters the classification system uses an average of 0.4 µm particle efficiency measured along the whole artificial clogging process up to unrealistically high pressure drops (450 Pa). For coarse filters the removal efficiency (arrestance) is evaluated by means of captured mass of the same test dust at 250 Pa final pressure drop (see **Error! Reference source not found. Error! Reference source not found.**).

The results can not be used for evaluation of air filters in operation. The final pressure drops are unrealistically high and the efficiencies and dust loading capacities are misleading.

*Classification of air filters (0.944 m³/s) in accordance with EN 779:2002.**

Filter Type	EN 779 Class	Average arrestance (A_m) synthetic dust, (%)	Average Efficiency (E_m) 0.4 µm particles, (%)	Final Pressure drop, (Pa)
Coarse-filter	G1	50 £ A_m < 65	-	250
	G2	65 £ A_m < 80	-	250
	G3	80 £ A_m < 90	-	250
	G4	90 £ A_m	-	250
Fine-filter	F5	-	40 £ E_m < 60	450
	F6	-	60 £ E_m < 80	450
	F7	-	80 £ E_m < 90	450
	F8	-	90 £ E_m < 95	450
	F9	-	95 £ E_m	450

** EN 779 will be revised in the end of year 2011, including a new classification system.*

High efficiency filters, EPA, HEPA and ULPA are classified according to the minimum efficiency of the most penetrating particle size (see **Error! Reference source not found.**).

In the US, the standard ANSI/ASHRAE 52.2-2007 prescribes the measurement of particle removal efficiency by the particles size on the clean filter after loading it with ASHRAE synthetic dust. At the end of the test the filter is given one of the 16 MERVs (Minimum Efficiency Reporting Value) that are based on the minimum efficiency (averaged for some fixed particle size ranges) achieved during the whole loading process (see **Error! Reference source not found.**).

There is no direct connection between the EN 779 and the ASHRAE 52.2 methods but a tentative conversion between the two classification systems is found in **Error! Reference source not found.** page **Error! Bookmark not defined.**.

The artificial test dust is not representative of the atmospheric dust and the concentration used during the artificial clogging is about 1000 times higher. Hence, test dust capacity and efficiency obtained in the laboratory cannot be used to predict quantitative filter performance in operation (see **Error! Reference source not found. Error! Reference source not found.**). There is a big discrepancy between laboratory filter tests and actual operational performance. In laboratory the efficiency increases rapidly when loaded with the artificial dust. Several studies have shown that filters with electrostatically charged media lose efficiency when exposed to fine atmospheric aerosols. Figure 1.5 shows the case of a filter with an average efficiency of 85% obtained in laboratory and consequent classification is an F7 filter. In operation, when exposed to atmospheric dust, the efficiency could be fairly constant or even drop substantially, depending on amount of electrostatic charge efficiency of the base media.

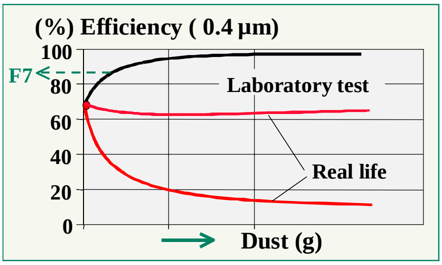

Figure 1.5 *Example showing the difference in efficiency vs. dust loading between filters behaviour in the laboratory loaded with artificial dust respective in real life exposed to atmospheric aerosol.*

It is important to address these problems and in service tests are the best way to verify a filter's performance. In HVAC systems with Fine (F) filters, it is therefore useful - and sometime mandatory – to test and control the actual removal efficiency of an installation (**Error! Reference source not found. Error! Reference source not found.**). It is possible to determine the type and composition of particles by analysing samples from membrane filters in a Scanning Electron Microscope (SEM).

Another quick and effective solution, to predict the filter behaviour in operation, is to measure the discharged efficiency according to EN 779:2002, which will indicate the possible minimum life efficiency (MLE) in an installation. The test and reported value is mandatory in the standard, but many filter manufacturers do not show these figures and the test is not even included in the Eurovent[2] certification of air filters (see **Error! Reference source not found. Error! Reference source not found.**).

An efficiency specification of air filters should, besides the filter class include the required minimum efficiency of the filter in operation (see *Error! Reference source not found. Error! Reference source not found.****).***

Particles previously captured by the filter may be released into the air stream. Re-entrainment of particles, particle bounce and shedding are likely to occur to some extent during the life cycle of an installed filter. These effects can be clearly detected for low efficiency filters while for higher efficiency filters they are usually negligible when compared with the total amount of dust collected by the filters used in common outdoor applications (see **Error! Reference source not found. Error! Reference source not found.**).

Hygienic consideration of air filters

Supply air filters prevent the downstream air handling unit and duct internal surfaces from getting soiled, and reduce air particle concentrations (See **Error! Reference source not found. Error! Reference source not found.** page **Error! Reference source not found.Error! Bookmark not defined.**). Nevertheless, they are also able to degrade the air quality and particularly the perceived air quality. Filters are often

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[2] Eurovent, European Committee of Air Handling and Refrigeration Equipment Manufacturers

considered to be the problem but it is worth remembering that the problem is not with the air filters but with the pollutants. Air filters are part of the solution and by proper filter selection for the operating conditions any negative effects from the air filters will be eliminated or made insignificant.

Initially new filters have a negligible impact after a few days of low level “off-gassing”, but numerous studies have stated that soiled filters can have a negative effect on both the immediate and longer term perception of indoor air quality. It may increase the incidence of Sick Building Syndrome (SBS) and affect working productivity. The effects on perceived air of the pollution loading the filter are similar in magnitude to the pollution given off from occupants.

Some new studies have indicated that a combination of particle filters and activated carbon will improve the acceptability of the filtered air. Such filters can replace existing filters and would have particle removal efficiencies and air flow resistance comparable to standard filters. These would remove sensory offending pollutants and would have the added bonus of also removing a significant fraction of ozone from the air stream. This would mean improvements in air quality with little or no modification to the existing air handling system. The deterioration over time in air quality is minimized if filters are frequently replaced.

Microorganisms will always be present in the air and the elimination of possible growth sites within the HVAC system is an effective way of controlling bio-aerosol contaminants. Efficient supply air filters effectively collect microorganisms from outdoor air. Airborne microorganisms are continuously collected in the filters, but they will not survive for long periods in the airstream. However, at higher humidity levels there is a risk and even if the filter is not a source of microorganisms there may be a release of biologically originated particles from dead and decaying microbial cells, which will cause deterioration in the indoor air quality (see **Error! Reference source not found. Error! Reference source not found.**).

From hygiene point of view, it is important to design the air intake to avoid drawing in impurities and to prevent snow and rain entering the ventilation system. The air intake configuration, together with the air filter, prevents pollutants from entering the HVAC system (**Error! Reference source not found. Error! Reference source not found.**). A correct design of the air intake together with the proper choice and operation of air filtration and the other HVAC components can lead to a good indoor environment (see **Error! Reference source not found. Error! Reference source not found.** and **Error! Reference source not found. Error! Reference source not found.**).

Replacement

When replacing the filters, the installation should be carefully inspected for leaks and other filter problems. A small leak may not affect the class of the filter but contaminants and microorganisms will easily pass through.

Soiled air filters when replaced should be carefully put into a plastic bag, sealed, marked, and classified according to European Directives or national legislation ready for disposal. The filter installation should be cleaned, inspected to check for leaks and other problems before installing new filters (see **Error! Reference source not found. Error! Reference source not found.**).

Disposal. The regulation of waste in the form of soiled air filters must follow European Directives of treatment and classification. Most soiled air filters are considered combustible, and organic waste from a legal perspective and should be incinerated. However, the legislation varies in different countries and the local recycling and incineration plants can have different acceptance criteria for waste (see **Error! Reference source not found. Error! Reference source not found.**).

Certified filters (see **Error! Reference source not found. Error! Reference source not found.**). Eurovent has a certification program for air filters, which guarantees the air filters to be within the claimed filter class and pressure drop measured in accordance with EN 779:2002. But the discharged efficiency, although included in the test method, has been excluded and is not reported in the certification. A Eurovent certified F7 filter can have 50% efficiency of 0.4 µm particles while another certified F7 filter can have only 20% in actual service (see **Error! Reference source not found. Error! Reference source not found.**).

The National Building Code of Finland is more demanding than the Eurovent Certification program and requires the filter manufacturer to have an internal quality system and that the discharged efficiency is reported in the manufacturer's data sheet.
The Swedish Technical Institute, SP, has a P-marking system, certification program, that guarantees the quality of the filter in the laboratory and production as well as in real life. A P – marked F7 filter shall for instance have minimum 50% efficiency of 0.4 µm particles during a 6-months test with outdoor air.

Air filtration CHECK LIST
Selecting an air filter is not an easy task and is more than just a question of efficiency or price. To help with the design and selection of air filtration systems a *“CHECK LIST"* has been added at the end of this guidebook (see **Error! Reference source not found. Error! Reference source not found.**).

2 PARTICULATE FILTRATION PRINCIPLES

The theory of particle filtration is well documented and verified down to the lowest size range of currently available measuring equipment (*Davies* 1973, Brown 1993, *Lee and Liu* 1980).

A filter's ability to collect particles depends on various physical phenomena, both mechanical and electrical. Since fibrous filtration is a very complex process it is common practice to analyse it at its most elementary level, i.e. the collection of a particle (e.g. a sphere) by an individual fibre (represented by a cylinder or by a circle in two dimensions).

The mechanical effects are related to Brownian diffusion, interception, inertial impaction and straining. Electrostatic effects can be remarkable when fibres carry electrostatic charges that are created intentionally. Such techniques can be adopted when filter media contains fibres made of polymers or materials with suitable dielectric properties. To some extent both mechanical and electrostatic particle capture mechanisms are involved in most filter material.

In an ideal filtration process, each particle would be permanently arrested at the first collision against a filter fibre or against an already captured particle. For particles smaller than 3 µm and air velocities through the filter media lower than 0.15 m/s, the energy of adhesion (Van der Waal's forces) greatly exceeds the kinetic energy of the airborne particle in the air stream. Hence, once captured, such particles are unlikely to be dislodged from the filter (Figure 2.1). As particle size and air velocity increase, larger particles may "bounce" off the fibre (especially for fibres larger than 10 µm). Also some previously captured particles may be released into the air flow downstream of the filter. These phenomena are called "bouncing" and "re-entrainment of particles" and are described in **Error! Reference source not found.**.

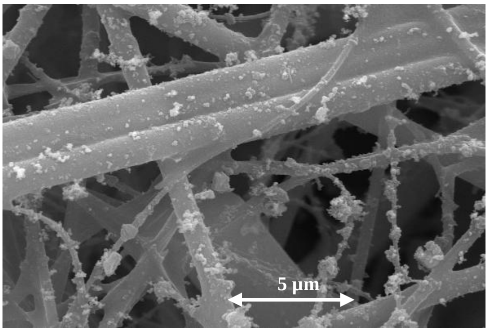


Figure 2.1 *Collected outdoor particles on a filter fibre. The distance between fibres is normally much larger than the size of the particles.*

The mechanisms involved in particle filtration are illustrated in Figure 2.2 and described below.

Straining. Particles with a diameter greater than the distance between two fibres cannot pass through the gap. This effect does not occur when atmospheric airborne particles are considered because most of the particles are smaller than 1 µm.

Inertial impaction. The inertia of the particle is such that it is not able to follow the stream line around the fibre. The particle continues on its original path, collides against the fibre and remains attached to it. The inertial force increases when the air velocity increases and also when the size or the mass of the particle increases. If the filter material is thicker the particle has more chances to hit a fibre.

Interception. Smaller particles follow the stream lines around the fibres and are captured when the surface of the particle touches the surface of the fibre. This mechanism improves with larger particles, smaller fibre diameters, smaller distances between the fibres and the amount of fibre material.

Diffusion. Particles smaller than 1 µm are affected by the Brownian movements of air molecules and deviate randomly from the normal stream lines around the fibres. If the deviation is large enough, the particle will strike the fibre and become attached to it. The diffusion effect increases with decreasing particles and is the dominating effect for ultrafine particles. This mechanism improves when the air velocity through the filter material reduces, the fibres are finer and when the number of fibres and fibre density increase (the solid fraction or thickness of the material).

Electrostatic attraction. Electrostatic deposition can be important but it is difficult to quantify since it depends on both the charge of the fibres and of the particles. The electrostatic mechanism increases at reduced air velocity through the filter material and for finer fibre diameters and smaller particles. It is also enhanced when there is a larger number of fibres and increased fibre density.

Electrostatic precipitators operate under continuous charging, while electrostatically charged filter material is charged "only once". The electrostatic charge is difficult to control and the efficiency can be influenced by storage, temperature, humidity and captured particles, which could weaken the electric field caused by the charges on the fibres.

The electrostatic effect will affect the filter performance and is interesting to consider in combination with the mechanical filtering mechanisms.

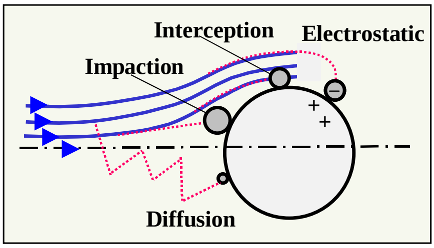


Figure 2.2 *Air flow stream lines around a fibre to illustrate the different filtration mechanisms.*

Total particle efficiency

The efficiency of a filter is the result of the sum of the various filtration mechanisms. Both the interception effect and the inertial effect increase with larger particle sizes while the diffusion and electrostatic effects increase for smaller particles. There is a specific particle size which is the most difficult to collect in a filter or which penetrates easiest (Most Penetrating Particle Size, MPPS).

The minimum efficiency and shape of the total efficiency curve depends on the sizes of the fibres, the air velocity and collected particles. Depending on the kind of filter material and on the properties of the collected particles the efficiency can increase or decrease with dust loading.

Figure 2.3 shows data measured in service for new F9 and F7 standard filters at 0.944 m^3/s. The filters have been tested down to 0.02 µm or 20 nm. The right part of the curve (> 0.1 µm) is obtained from measurement following the EN 779 standard and the left part (< 0.1 µm) is measured with condensation nucleus counter in combination with an electrostatic classifier. The minimum efficiencies are normally in the range of 0.1 µm to 0.2 µm for HVAC air filters, independent of level of efficiency (0% to >99%). Smaller and larger particles are easier to collect.

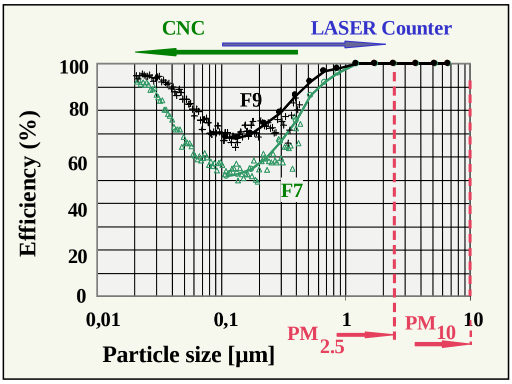


Figure 2.3 *Fractional efficiency of new F-filters in outdoor aerosol (Gustavsson 2008).*

The performance of air filters during their service is strongly affected by the loading of particles. In the beginning when a filter is loaded by atmospheric aerosol its resistance to the air flow is not significantly influenced by the material collected. Solid particles smaller than 2 µm are attracted and adhere to each other forming dendrites or agglomerates that are attached to the fibres, while liquid particles will wet the fibres. Subsequently when the filter becomes more and more loaded with particles, the resistance to the air flow increases. The collected particles increase the efficiency of the filter. The effect may be different if the fibres are electrostatically charged and the efficiency of the filter may decrease substantially until the effect of the electrostatic charges is more or less completely inhibited. At this stage of the clogging process, if the filter is well designed, the particles are captured within the depth of the filter medium. The loading process continues until the particles have occupied all the space available inside the material. After that the particles adhere to the upstream surface of the filter and pressure drop increases sharply and structural damage of the filter may occur.

Figure 2.4 and Figure 2.5 illustrate the phenomena for an F6 filter (Ginestet and Pugnet, 2005). The filter was in service in an installation supplied by outdoor air and was taken out of its installation from time to time in order to measure weight, air flow resistance and fractional efficiency in the laboratory.

The pressure drop increases slowly for the first 3000 hours. But because the filter is losing its electrostatic charge, the filtration efficiency at first decreases (0 to 1500 hours) before staying more or less constant (1500 to 3000 hours). Then the filter becomes more and more loaded by particles deposited within the depth of the medium and the efficiency increases while the pressure drop still increases linearly (3000 to 6000 hours). After 6000 hours of use the particles start adhering to the upstream surface of the filter causing clogging and a sharp increase in the pressure drop and the efficiency.

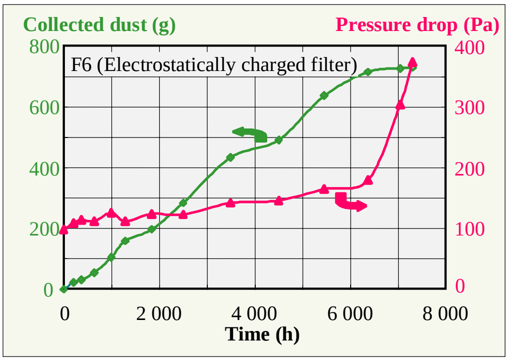


Figure 2.4 *Air flow resistance and collected dust as function of time for an F6 electrostatically charged filter loaded with outdoor air at 1 m³/s (Ginestet and Pugnet, 2005).*

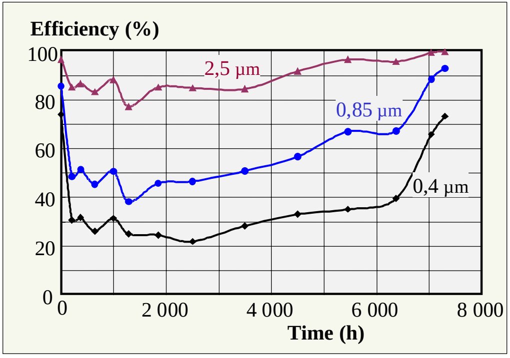


Figure 2.5 *Fractional efficiency as function of time for the same filter as in previous figure. Figure 2.4. Efficiency was determined by neutralized latex particles. (Ginestet and Pugnet, 2005).*

3 PARTICULATE AIR FILTERS

3.1 Fibre filters

Fibrous media

The removal of contaminating particulates is usually performed by fibrous filtering media made of randomly arranged fibres (Tronville et al 2006, Zhou et al 2009). A large variety of filtering materials is available on the market. The fibrous media are available in different materials, thickness, rigidities, densities and colours.

The theory of particles capture in fibrous filters is well documented and fine fibres (around 1 μm diameter) are required for the efficient mechanical collection of urban aerosols. Glass has proved to be a suitable substance for producing fine fibres. During the last few decades the development of polymer fibres and processes for producing filter materials has progressed quickly and it is possible to manufacture polymer fibres commercially down to a few micrometers in size for air filtration applications. To enhance the efficiency of coarser polymer fibres it is possible to add electrostatic charges to some materials to make them more effective in removing smaller particles. In such cases the initial efficiency will result from the combination of the mechanical effects and of electrical forces. However, the exposure to combustion particles, fine particles or liquids can inhibit the effectiveness of such charges.

Besides glass, the most common polymers used to produce fibres consist of polypropylene, polyester, polyethylene and polyamides. Several different techniques are employed for producing fibres and filter materials.

Glass fibres

For a very long time glass has been used to produce fine fibres, which is a decisive factor achieving high efficiency. As of today glass is the dominating material for the filtration of fine particles in high efficiency filters (HEPA and ULPA) used in contamination controlled environments or critical applications.

The finest fibres are produced by a flame attenuation process. Molten glass flows by gravity from melting furnaces to form filaments that are drawn down and thinned by passing in front of a high-velocity gas burner flame. This produces fibres 0.01 µm to 10 µm in size.

Another process used is the rotary spin process: molten glass is forced through numerous small orifices in the side wall of a spinner to form continuous glass fibres that are then broken into discrete lengths by high-velocity air jets.

The fibres can be mixed with a binder and collected on a moving mat. After drying, the fibres will form a suitable layer of filter material. The fibre sizes and thickness will be controlled by temperature and velocity of the process. The alternative to this *air-laid* process is to use the glass fibres in a *wet-laid* process, like making paper out of cellulose fibres.

The air-laid filter material is rather airy (not compressed). Thanks to the fine fibres (Figure 3.1) the material obtained can have a high efficiency, a low pressure drop and a long lifetime. The disadvantage is its mechanical strength: the fibres are rather brittle and some precautions must be taken during the production process to avoid inhalation of glass fibres.

Some people have been alleging that glass fibres are dangerous and a possible cause of cancer. This would be a strong argument against the use of glass fibre media. However, glass fibres for HVAC air filters will meet the European directives EU directives 97/69/EC of Man Made Vitreous Fibres in which case they are classified in ”category **0**, irritant”. The International Agency for Research on Cancer (part of the World Health organization (WHO) has moved glass wool to a Group “**3”** classification ("not classifiable as a human carcinogen).

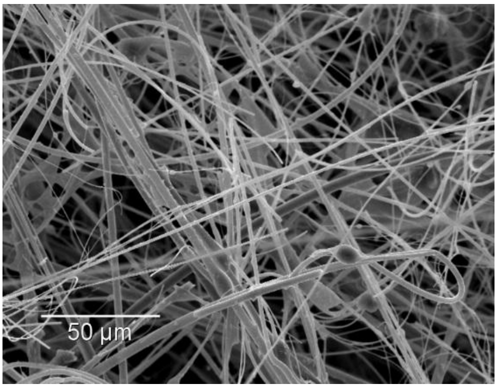


Figure 3.1 *Magnification of air-laid glass fibres used in an F7 filter.*

Polymer fibres

Polymer fibres can be processed by wet or air-laid processes similar to the glass fibre manufacturing. Most manufacturers of glass-filter papers add synthetic fibres to increase strength and make the pleating process easier. The fibre material can be bonded chemically or with heat to achieve desired thickness and physical properties.

The **carding process** is an air-laid process based on ready-made fibres. Different sizes of fibres can be mixed. In carding, a thick porous material is produced which is later needled together, or thermobonded, into the desired thickness. Needled material is often treated with binders and pigment to improve the physical properties, such as stiffness, bondability, colour, etc.

The carding process is a very old method but it is not suitable for processing fine fibres. Such a technique is normally used for filter materials with lower efficiency or as prefilter layer. Very often the filter material is electrostatically charged during the manufacturing process to enhance the efficiency of the new material.

Electret fibres are fibres which are electrostatically charged during their production. A plastic film passes through a strong corona field, whereby the electrons are displaced so that one side of the film becomes positive, while the other, which contains more electrons, becomes negative. By dividing the film and stretching it, rather large size fibres are obtained. These fibres can be used in a carding process to produce the filter material. During actual use the particles are collected by the fibrous material using electrostatic force instead of other physical mechanisms. Atmospheric aerosols in the urban environment can quickly reduce the electrostatic enhancement, and, since the fibres are coarse, the efficiency can drop remarkably in actual operating conditions.

The **meltblown process** or the spunbond technique produces fibres with a diameter of only a few micrometers by extruding molten polymer through high-temperature and high-velocity air streams. Meltblown fibres are formed on a moving belt equipped with a suction box. The technique and application areas for meltblown fibres are gaining ground for all air cleaning products.

The efficiency of the media obtained by this process can be high, and further improved by the application of electrostatic charging. The material generated is fragile and compact with low test dust capacity. By combining it with supporting scrims and layers of “prefilters” it is possible to obtain a material with an improved performance which is easy to process.

In the **rotary process** a molten polymer is fed to a spinning disc containing a myriad of small holes through which the material flows due to the centrifugal force. The rotary method enables large quantities of fibre to be produced at a rapid rate.

In the f**lashspun process a** polymer is dissolved in solvents and is pressed through a spinning orifice with small holes. When the solvent evaporates, fibres are produced which, by means of electrostatic charging, are collected on a moving belt or a wire where they form the fibrous mat.

Electrospinning technique is a fairly old method that recently has been improved to produce very fine fibres (nanofibres, i.e. fibres with diameter less than 150 nm). It is a process, which uses electrical charge to draw very fine fibres from melted polymer.

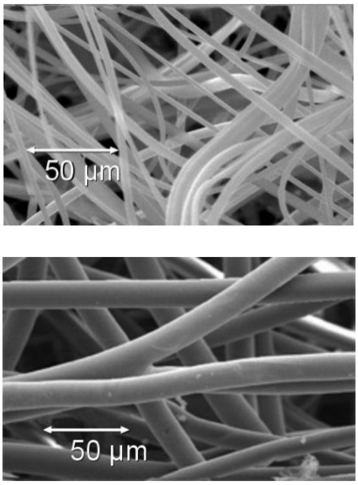


Figure 3.2 *Magnification of two polymer media used for F7 filters. The top is a melt blown media with fine fibres and the other is formed by coarse fibres. Depending on electrostatic charge, both filters manufactured with these media could belong to the same class.*

Air Filters assembly

Air filters are manufactured by assembling the filter material and frame to hold it in place. The performance of the final product is clearly dependent on the performance of the filter media, but the quality of the final product is influenced by many other factors. There are too many examples where the filter manufacturer does not use enough media or when the filtering pack is not properly fixed to the frame.

The capture efficiency is the decisive factor in choosing an air filter. Normally a filter has a limited space and must treat a certain air flow rate. Therefore the air flow resistance and service life (test dust capacity) are a compromise of hygienic conditions, life cycle costs and environmental considerations. Other requirements could be mechanical strength, flammability and processing possibilities.

There are three main types of air filters used in HVAC installations. One is the "prefilter type", a 25 to 100 mm deep filter, with one flat or pleated layer of coarse fibre filter material. Another design is the "bag filter", which consists of pockets made of the filter material and kept together in a frame. The third version is the "compact filter", which is made of shallow depth pleat packs manufactured from thin paper-like filter media.

The history of air filtration technology is filled with thousands of different filter products that have been developed and are used in different applications and installations. In such situations fair competition is hampered and filter costs increase because, even today, many filters have to be manually assembled. To improve this situation CEN/TC195 “Air Filters for General Air Cleaning” has introduced EN 15805:2009 to standardize the face dimensions of the air filters for HVAC installations. Where applicable the header frame dimensions are also included (Table 3.1 and Figure 3.3).

A common standard **”bag” air filter** has a face dimension of 592 mm x 592 mm and consists of 4 to 12 bags installed in parallel. The length or the depth of the filter varies from 300 mm up to 900 mm. The filter media could be chosen from very low efficiency (coarse filters) to very high efficiency (fine filters) materials. The filtering materials are made of glass or polymer fibres of different thicknesses or number of layers depending on the required filter performance.

There are two main types of bag design - tapered and straight (Figure 3.4). The air flow resistance can be minimized by choosing an optimum design of the filter taking into account the number of bags, the desired efficiency, the type of material and space available.

Table 3.1 *Face dimensions of air filters according to EN 15805.*

Holding frame (nom. dimensions)		Filter (header) (dimensions)	
Width (mm)	Height (mm)	Width (mm)	Height (mm)
610	610	592	592
508	610	490	592
305	610	287	592
610	305	592	287
508	305	490	287
305	305	287	287

- Tolerance holding frame: +0 mm and – mm.
- Tolerances for filter (header dimensions): +3 mm and – 2 mm.
- The header frame depth shall preferably be 25 mm or 20 mm (± 0.5 mm).
- The header frame minimum width W shall be minimum 16 mm.
For other frame systems as side access systems, the filter shall be designed to accommodate filter dimensions and tolerances in the table.

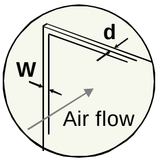


Figure 3.3 *Header frame width and depth.*

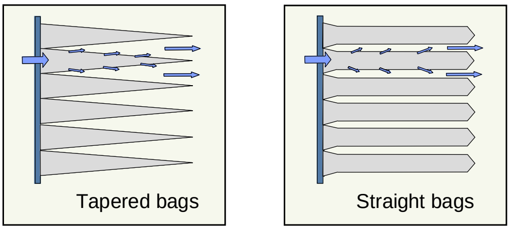


Figure 3.4 *Air filters made from tapered bags and straight bags.*

Air filters with **tapered bags** allow a smooth air velocity entrance and exit through the material. The medium velocity is about equal throughout the filter. The dynamic pressure is equal throughout the bag which allows the flow to be equalized through the media. The production of the bags has to be individually optimized depending on the number of bags and the length of the filter.

Air filters made with **straight bags** have a different flow design. The bags have a contraction at the opening but, since the cross section of the bag is uniform, the dynamic pressure along the length of the bag is uneven. The result is an uneven air velocity, higher pressure drop and lower dust loading capacity (due to uneven clogging). The advantage in using this shape is during the production process. The bags do not need to be individually optimized for each filter type. The straight version of the bags will cause 10% to 30% higher air flow resistance compared with the tapered version using the same type of filter material.

Traditionally, the bags are stitched to seal the edges and bottom of the bags and to allow enough space between the pockets. The purpose of the spaces is to fix the media in the correct position and to prevent the filter pockets from over-inflating and coming in contact with the bag or bags adjacent to them resulting in an additional pressure drop across the system. Materials based on polymers can be sealed using heat (ultrasonically or by other means) while glass fibre material can only be stitched.

3.1.1 Coarse (G) filters

The basic filter material for coarse filters (G-filters) is produced from glass fibre, cotton or polymer fibres – polypropylene, polyester, acrylic, and polyamide. The fractional efficiency is almost zero for particles below 1 µm but close to 100% for 5 µm particles and larger. Collected particles can be released by the shedding effect (**Error! Reference source not found. Error! Reference source not found.**) and efficiency for larger particles can drop significantly. Many prefilters are 25 to 100 mm deep with one flat or one pleated layer of coarse filter material to fit in narrow ventilation systems. In commerce pleated filters are indicated as corrugated filters. If space is available deeper bag filters can be used to extend life and increase efficiency.

Resistance against air flow depends on the type and amount of media used and filter design. For a typical standard size at 0.944 m³/s, the initial pressure drop varies normally within 25 Pa to 60 Pa. However there are examples of filters with too narrow pleats or too little filter media which may cause the pressure drop to reach more than 100 Pa.

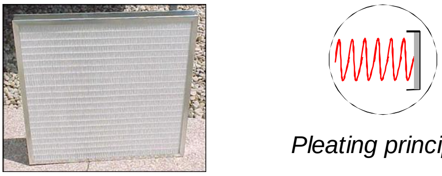
3.1.2 Fine (F) filters

Two types of fine filters (F-filters) are commonly used in HVAC systems. One is the "bag filter" type, which consists of bags made of “air laid” filter material and held together in a frame. The other version is the "compact filter", which is made of narrow pleats obtained by fairly thin (~ 0.5 mm) and stiff filter material of glass or polymer fibres.

Resistance against air flow depends very much on the type and amount of media used and filter design. For a typical standard size at 0.944 m³/s, the air velocity through the filter material normally varies between 0.1 and 0.2 m/s for bag filters and down to 0.05 m/s for compact filters (Tronville et al 2003). The initial pressure drop normally varies from 50 Pa for the low efficiency (F5) and up to 150-200 Pa for F9 filters (Table 3.2). However there are examples of much higher pressure drops for badly designed filters.

Figure 3.5 *Example of pleated G- or F-filters.*

Figure 3.6 *Example of G-filter of bag type.*



Pleating principle

Figure 3.7 *Example of deep minipleated G- or F- filters. The medium can be of glass or polymer fibres.*

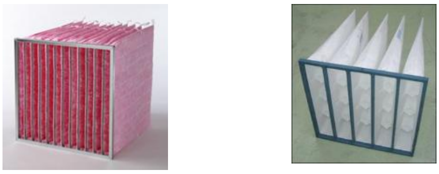


Figure 3.8 *Examples of fine filters. The media in the pink bag filter is made of glass fibres, while the media in the other bag filter is made of polymer fibres.*

Pleating principle

Figure 3.9 *Examples of fine filters. The compact filters are made of thin (~ 0.5 mm) and stiff pleated filter material of glass or polymer.*

Figure 3.10 *Example of HEPA and ULPA filters. The panel type (left) is mainly used for unidirectional (previously called laminar) flows in clean rooms or clean benches at a face velocity of 0.45 m/s. The compact type (right) is used for inlet or exhaust air system with high air flows, up to 3 m/s face velocity.*

Table 3.2 *Initial pressure drop of fine filter at 0.9444 m³/s.*

Filter type	Class EN 779	Initial pressure drop (Pa)
Pleated (Figure 3.5)	F5	95 to 110
Deep minipleated filters (Figure 3.7)	F5	55 to 80
	F6	100 to 160
	F7	105 to 185
	F8	150 to 240
Long bag with glass medium (Figure 3.8)	F5	50 to 70
	F6	60 to 80
	F7	85 to 125
	F8	140 to 170
	F9	130 to 190
Long bag with polymer medium ((Figure 3.8)	F5	40 to 60
	F6	50 to 95
	F7	75 to 110
	F8	105 to 190
	F9	185 to 215
Long bag with a glass and polymer mixture of medium	F7	around 195
	F8	around 280
Rigid minipleated filters with glass medium (Figure 3.9)	F6	75 to 140
	F7	80 to 155
	F8	85 to 165
	F9	100 to 180
Rigid minipleated filters with polymer medium (Figure 3.9)	F6	70 to 90
	F7	90 to 95
	F8	100 to 110
	F9	100 to 140

3.1.3 EPA, HEPA and ULPA filters

High efficiency filters (EPA, HEPA and ULPA) are used in many critical applications; military, nuclear, hospital, semiconductor and virus laboratories.

These filters are normally manufactured with glass fibres 0.1 µm to 1 µm in size. The filter media is compact and thin (0.5 mm to 1 mm). To ensure low pressure drop and long life the material in the filter is pleated and the filtering area is 20 to 75 times larger than the face area. Today it is also possible to manufacture HEPA and ULPA filters using Teflon (PTFE) material.

3.2 Electrostatic precipitators (ESP)

Electrostatic precipitators or electronic air cleaners are uncommon in HVAC installations, but smaller units are often used as separate room cleaners, circulating the air in the room. Due to their low air flow resistance and the increasing demands on low energy devices they may be used more frequently in HVAC applications.

Figure 3.11 shows the working principle of an electrostatic precipitator. The filter consists of an ionising section and a collecting plate section. The air passes through the ionising section first where the particles become electrostatically charged. In the collecting plate section the particles are then forced by the electrical field onto the collector plate.

ESP's on the market are very different from each other and can be very efficient at removing and collecting small particles with low air flow resistance and noise. However, to maintain their initial efficiency, they must be cleaned periodically. The frequency of cleaning depends on the type of contaminants and their concentrations. Some applications may require cleaning once a day, while others may require intervals of several three months. The cleaning schedule is essential to keep the unit performing at high efficiency. Since the air flow resistance does not increase as the electrostatic precipitator becomes dirty it is not possible to know exactly when cleaning is necessary.

The efficiency of these devices depends very much on the velocity of the air stream. Since the air flow resistance of an electrostatic precipitator is low, care must be taken to ensure that connecting ducts are designed to give an even air flow across the precipitator section. The charged collector plates must also be protected against fibres, insects, leaves and coarser dust by a mechanical prefilter. The energy consumption is low but the amount of energy required for pre- or after- filters has to be included in the LCC calculation.

ESP's produce ozone to some extent. Ozone is a gaseous substance banned by many authorities due to its irritant effects on respiratory apparatus. When properly designed and maintained the level should be low. However, it is important to note that ozone may react with other chemical substances and form undesired by-products.

Finally it must be pointed out that particulates not removed by the collection plates are still charged and could stick to and blacken the walls and interior surfaces in the conditioned environment.

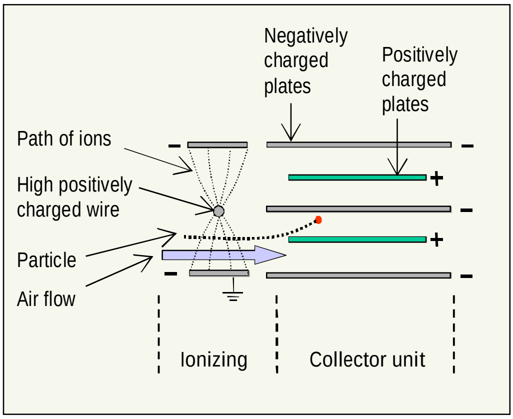


***Figure 3.11**. Working principle of electronic air cleaners.*

3.3 UVC

UV (ultraviolet light) has been used for many years for water and surface cleaning, often in medical facilities. UVC refers to the "C" wavelength of the ultraviolet light spectrum (280 to 100 nm), which is the most effective wavelengths for germicidal control. The energy of UVC neutralizes or kills the microorganisms.

UVC can be designed to treat specific surfaces within the HVAC systems, particularly the cooling coils and the condensate drain pan, to prevent biological growth. Another application is to use UV lamps in the duct system to destroy the bioaerosols in the air stream as it passes through the device

In developing techniques and methods for addressing risks posed by biological terrorist attacks, the US Environmental Protection Agency (EPA) tested some units for HVAC ducting system. (see EPA, Biological). Three organisms were selected because of their different sizes and influence from UVC. All of the units were very effective against vegative bacteria (> 99.9%), while the effect on spores from bacteria varied from 0% up to 99.9%. Between 40% and 99.8% of the viruses were removed. Generally, vegetative bacteria are easily killed but bacterial spores are more difficult to deactivate.

It is possible to destroy microorganisms with UVC lamps, but the effect and cost in designing and using UV systems must be considered as well as the safety issues (radiation, high voltage, ozone). By killing microorganisms, growth could be stopped but dead bacteria in the air stream could still cause allergies (see **Error! Reference source not found. Error! Reference source not found.**).

4 GAS PHASE AIR FILTERS

4.1 Adsorption

The theory of adsorption, i.e. the process used to remove gases is well documented. However, the results are often expressed in a way not easily understood and practical for HVAC practitioners and interested parties.

Several distinct steps are involved in the overall removal mechanisms of gases from air. The removal is based on **adsorption**, a process where gas molecules (**adsorbate** is the name of the adsorbed molecules) are held on the surface of the material used (i.e. the **adsorbent**). Adsorption is an exothermic reaction like condensation. A material with high internal surface area, a suitable pore structure and appropriate surface chemistry is essential for effective operation.

Before gas molecules can be adsorbed they need to travel through the pore structure of the media to the internal surface. The first step is the diffusion of gas molecules from the air stream into the network of large (macro-) pores that are open on the external surface of the adsorbent. The phenomenon of diffusion occurs as a result of the concentration gradient of contaminant molecules between the air flowing around the granule of adsorbent compared to the air inside its pore structure.

Once contaminant molecules are inside the pore structure of the adsorbent, the role of the internal media surface becomes important. The vast majority of the internal surface area can be attributed to the micro-pores, those with radii less than 2 nm. The internal surface area is physically and chemically heterogeneous and provides a massive number of different active sites, suitable for adsorption of a wide range of molecules with different boiling temperatures.

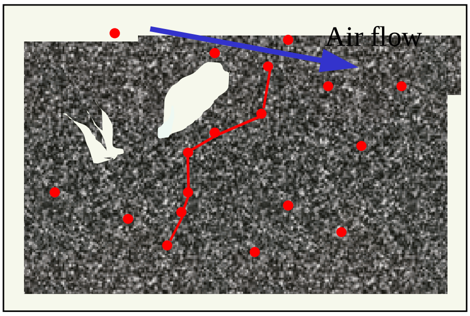


Figure 4.1 *Schematic diagram of the diffusion and adsorption processes in the micropores.*

Two adsorption mechanisms are possible: **physical adsorption** and **chemical adsorption**. Physical adsorption involves the comparatively weak interaction between the carbon surface and the molecule. The process is reversible and desorption may occur if the concentration gradient induces it. Desorption is enhanced by heat.

Chemical adsorption involves irreversible chemical reactions taking place after the physical adsorption has occurred. Chemical adsorption mechanisms involve the addition of specific chemical substances into the adsorbent matrix as a secondary manufacturing process. Such materials are called **impregnated media** and their purpose is also to increase the capacity or the service life against specific target compounds.

In the case of physical adsorption, there is an equilibrium between the concentration of gaseous contaminant and the quantity of adsorbed molecules.

The capacity is very much influenced by the characteristics of the gas, particularly its molecular weight, boiling point, molecular functionality and its vapour pressure value. The adsorption capacity increases when the inlet gas concentration increases (Figure 4.2). If the inlet concentration decreases the adsorbent cannot maintain the same capacity and some molecules will be released. In the case of chemical adsorption the capacity depends on the quantity of chemical impregnates, and the adsorption will continue as long as chemicals remain and are able to react. The adsorption capacity is often given at very high concentrations (g/m³), while the actual use of HVAC filters is at concentrations of 100 µg/m³. One kg of an adsorbent with 40% adsorption capacity of a gas can adsorb as much as 40% of its weight (400 grams of the gas) at very high concentrations, but only a few percent in very low concentrations of the same gas.

Figure 4.3 is a typical example of the efficiency change of physical adsorption with constant loading of a gas. In this example the initial adsorption efficiency is 95%. As the pores of the filter become saturated, the downstream concentration increases and then the efficiency decreases. The total possible adsorption capacity is the amount of gas retained by the filter when all the pores are saturated and efficiency is zero. The useable adsorption capacity in an installation is the amount of gas retained by the filter at a defined or acceptable minimum efficiency. For instance 70% at point A.

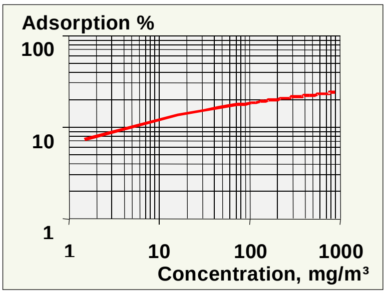


Figure 4.2 *Example of adsorption, expressed as the percentage of the adsorbent's weight, as a function of the gas concentration.*

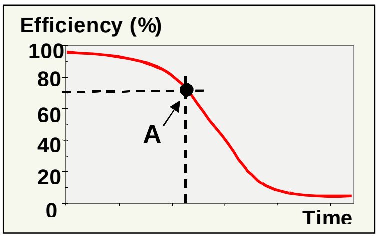


Figure 4.3 *Example of breakthrough curve with physical adsorption.*

Summary gas adsorption

Gaseous contaminants behave very differently from each other and this leads to very different performances of the adsorption materials. The interaction between different gases is difficult to judge.

In case of *physical adsorption*, the adsorption efficiency increases if:

- the air temperature decreases;
- the relative humidity of air decreases; in fact water in molecular form acts as a competitor especially in case of VOCs (Volatile Organic Compounds) adsorption;
- the air velocity decreases. The residence time (time taken by a contaminant molecule to cross the adsorbent bed) is an important parameter;

- the molecular mass of the gas increases.

In case of *chemical adsorption*, the adsorption efficiency is enhanced when:

- the air temperature increases (the reaction is endothermic),
- the relative humidity of air increases. For example the reaction between SO_2 and water is improved. There are exceptions to that in special cases.