

CABIN AIR FILTRATION

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Preface

Starting in Europe, it became more and more common during recent years, to clean the air inside all kinds of passenger compartments and transportation vehicles. These applications include: agricultural vehicles, heavy trucks, coaches and buses, construction machinery, forestry machinery, cable cars, trams, railroad cars, airplanes and automobiles. This paper will focus on the latter application.

Though the auto market is by far the largest the other applications can be both as technically challenging and financially attractive. In some of the fields, the products are highly specialized. For example, the agricultural manufacturers ask for media to treat pesticides, insecticides or fertilizers. Other transportation filters, used in military vehicles, should be able to treat all kinds of chemical warfare agents.

We are basically interested and able to provide products for the most of the above-mentioned applications. However, we strongly focus on classical road transportation, i.e. cars and trucks. All what will be said later has to be seen in that context. The air of the interior of a common automobile is usually drawn from the region above the plenum, below the windshield. Depending on the geographical region, this air is conditioned either with simple heater radiators, manual a/c units or even more sophisticated automatic air conditioners. In all cases, the air can be pushed or drawn through the a/c unit. New cars often provide a possibility to recirculate the air in the cabin. The option to recirculate the air in the compartment competed against the use of cabin filters in the beginning. But soon it was realized that the recirculation switch in the car did not do the job. First, the time one can run on recirculated air is limited, due to fogging problems and as today's vehicles have reached an amazing level of tightness. Second, once the driver detects bad odors and smells, it is already too late. Studies in Europe have shown that switching to recirc mode after a certain substance is smell able inside the cab extends only the residence time of the agent in the car's interior, which is even worse than having no protective device at all. And it became evident soon that filters are necessary to really improve the air quality inside a passenger car. The reasons are basically similar to those, which apply to buildings and common indoor air quality in general. The following statements can be considered as facts in our hardly questionable debate:

- Worldwide increasing pollution, especially in areas with high population densities.
- An increasing number of people suffer from allergic reaction.
- Irritations caused by chemical agents used in textiles and plastics cause increasing problems.
- Especially the air quality along heavily traveled roads can be polluted and poisoned badly (studies proved in the late '80's that the inside of a road transportation vehicle has one of the worst air quality levels of all known working places).
- Even as significant improvements to the engine management and exhaust treating systems have been developed, automotive and transportation emissions have still increased until the late '90's due to a simple increase in traffic density (see 1995 Shell Survey). Chances are a turning point could be reached around the year 2000.

- Bad air deteriorates the human ability to concentrate; therefore, air quality is even a traffic safety issue.
- Car buyers ask for improved comfort and safety.
- Last but not least cabin air filters have helped to protect the A/C units in cars. The evaporator or condensers stay clean and dry and consequently are less affected by bacteria and fungi.

The most common substances, which pollute the cars interior, are:

<u>Particles</u>	<u>Gaseous Substances and Odors</u>
Emissions from incineration processes (traffic, power plants, waste incinerators and the like)	Products of incomplete fuel incineration, from traffic as well as from energy and heating (benzene derivatives, cyclic hydrocarbons, sulfur compounds and other contaminants)
Mineral dust (climate, wind, erosion, uplifted by other vehicles)	Product of improper working catalytic converters (SO ₂ , NO _x , H ₂ S, etc.)
Smoke, fumes and hydrosols (splashing water)	Agricultural odors (liquid manure, ammonia, methane, etc.)
Biogenous particles (pollen, fungi, bacteria)	

As can be seen from the above distinction between particulate and gaseous contaminants, filters can and should be divided into particulate, odor (gas phase) filters or combination filters. Media for particulate filtration rely on mechanical and electrostatic effects. The air cleaners in gas phase filtration utilize mainly physical absorption or chemical absorption. Recent research work is dedicated to the development of catalytic conversion at room temperature. There is a whole range of so-called adsorbents on the market ranging from charcoal, activated carbon, zeolites, and bituminous carbons to porous carbonized plastic materials (polystyrene for water purification, ion exchangers, and others).

Particle Filtration:

Every process, which separates solid or liquid particles from a gaseous or liquid flow, i.e. filtration of aerosols and emulsions or suspensions, is called particle filtration. An aerosol is a gas (usually air), which carries solid particles or liquid droplets. An emulsion is a liquid substance, which carries a second phase of insoluble liquid droplets. This example shows that the several phases of the mix can be in the same physical state. A suspension is a liquid mix, which carries solid particles. Generally speaking, particle filtration is the separation of so-called two-phase systems.

Odor Filtration:

Gas phase filtration is the separation of one or more constituents of a gaseous mixture. This is usually achieved by adsorption and/or catalysis. There are equivalent applications concerning the purification of liquids, especially water, but as these processes play no role in what we call cabin air filtration, these phenomena will be neglected in this paper.

SECTION I: FILTRATION MECHANISMS

Chapter 1: Particle Filtration

1.1 Particle Classifications

As mentioned before, we refer to particle filtration as the separation of one or more phases from a multi-phase mixture. In a multi-phase mixture, two or more substances distribute over space, where each phase consumes defined volumes and shows borders. The phases do not necessarily have to be in different physical states (i.e. emulsion). If the carrying substance is a liquid, we refer to it as hydrosol, if the carrier is a gas, we call the mixtures aerosols. Hydrosols can be split into emulsions and suspensions. Examples for aerosols are smoke, fog, sprays and dusts, generally speaking. In cabin air filtration, only aerosols are of interest.

Characterizations of Aerosols:

Aerosols can be classified according to different criteria. Which of these criteria are appropriate in certain context mainly depends on the field of interest. In meteorology or climatology the focus is different than, for example, in medical science.

Distinction According to Origin:

If human society or mankind with its industrial, technical and social activity is responsible for the development of airborne particles, we call them anthropogeneous aerosols. If the living nature itself produces aerosols (fungi, spores, viruses or bacteria), we call them biogenous aerosols. The third important source of "air contamination" is inorganic nature. Here we have to consider erosion and climatic processes, which produce, for example, dust and clouds.

Distinction According to Type and Constitution of Aerosols:

In many cases, it is sufficient what substances the particles are and how react under certain conditions.

Distinction According to Physical Criteria:

For investigation of filtration phenomena, it is necessary to determine the relevant physical parameters of an aerosol: particle diameter, concentration (mass concentration and/or number concentration), mass and particle size distribution, state of charge (how are the particles electro statically charged), state of motion (with what velocity do particles move in a given flow, Boltzmann-Equilibrium). Only if these data are known the behavior of an aerosol under certain conditions can be predicted, this holds especially true for filtration.

Caused by the growing awareness of interactions between certain in nature and the concentration of particles in ambient air (which can be harmful in many cases for man, creature and plants), the importance for measures for air purification became evident even since the last century. Hence it makes perfect sense, that the earliest research papers and reports have been generated where the effects of air contamination on human health have been observed at first. This occurred in mining industry, where dust led to typical miner's diseases, e.g. dust pneumonia and coal miner's disease. It is no surprise that the mining academies and research institutes cope with filtration issues for more than a century.

Today the technical applications can be classified into industrial, energy technology, medicine and hygiene applications, as well as the military sciences.

Industry:

In industrial applications workplace safety, reduction of emissions and the hygiene of production and manufacturing are of importance. Especially the latter gained importance during recent years in so-called clean room technology as the importance of ultra clean environments in sensitive technologies like semi-conductor industry became evident.

Energy Technology:

Particle filtration is a vital instrument to reduce emissions caused by power plants, waste incinerators and other combustion equipment. Today all industrialized countries all over the globe have issued regulations defining maximum levels of emissions, which make the purification of processes effluents unavoidable. Usually these applications require very special filtration media, as far as temperature resistance is concerned. The so-called hot-gas filtration utilizes filter elements composed of fiber ceramics, which, even at temperatures of 800°C and more, maintain their function. Furthermore, these elements gain economically reasonable service life, which is achieved by sophisticated methods of cleaning and regenerating.

Medical Science and Hygiene:

Medical applications also require filters and filter media with highly specialized collection performance. Especially in the surgical field, where environments free of germs are demanded, filters have to be effective over a wide spectrum of particle sizes. But even in the everyday life, the constantly growing contamination of air and the increase of new symptoms and diseases forces our society into protective measures in other areas, which seemed ridiculous years ago. We all know the photographs from Tokyo, where pedestrians, wearing a breathing mask, are a common phenomenon. They simply try to protect themselves from pollutants caused by vehicles in areas of high traffic density. But the contamination in heavily frequented areas caused by motorized vehicles is not restricted to outside air. The concentration of contaminants is even worse inside more or less closed compartments like the cabins of passenger vehicles. So during the last decade automotive industry began to implement devices into motor vehicles, which showed the ability to reduce contaminants carried by the air entering the passenger compartment.

As a consequence of increasing allergic reactions caused by pets, pollen and other substances, even simple devices like room air cleaners are equipped with effective filters. In areas with a high density of residential air-conditioning units, the installation of particle filters is state-of-the-art. Even microcomputers today use filtered air for cooling purposes.

1.2 Collection Mechanism

To gain a certain understanding for particle filtration technology, we have to look at the basic mechanisms, which lead to the separation and collection of solid or liquid particles on certain surfaces. Without considering mathematical calculations or even simulations and modeling, we will try a qualitative approach to understand the basic effects of particle filtration. This will enable us to understand the basics of particle filter testing and performance testing.

All types of particle collection are related to specific properties of particles, as their mass and inertia, their density and size or even electrostatic charges carried by the particles. It does not matter, if we investigate a cyclone type separator, an electrical filter, a filter element comprised of fiber media or membranes, we will always find the same basic filtration mechanisms. Based on the positive cost/effect-ratio in cabin air filtration, pleated fiber media are commonly utilized; there are some exotic devices available though, especially as retrofit systems. To study particle filtration with fibrous media, the so-called single **fiber model** can be beneficially used. For that model a quite precise theory has been developed using Monte Carlo simulation and providing reasonable results and predictions.

Impaction

Figure 1 shows the cross-section through a fiber, which is passed by an air stream. The passing air stream is characterized by so-called streamlines. We define a streamline as that path, which a particle with infinite, little mass and infinite small size would exactly follow. As shown in a diagram, such a particle would never hit a fiber because all the streamlines pass the fiber. It should be mentioned, that in areas where the streamlines are close to each other, according to Bernoulli's law, the air velocity is high and the static pressures are low and vice versa. In addition, the fiber has to be considered as covered by a very thin static layer of air, where no movement at all takes place. This so-called boundary layer is adhered to the fiber. The collection phenomenon shown in Figure One is based on the fact, that real particles have a certain size and carry a mass. As known from basic physic lessons, all bodies have a mass and show the effect of inertia. In the area in front of the fiber where the streamlines are deflected and bent around the fiber, massive parts cannot follow this deflection and hit the fiber as a consequence of their inertia. It is evident that this effect is stronger the larger the velocity of the particles and the larger the mass. For now we simply assume, that once the particle hits the fiber, it does not bounce but sticks to the surface.

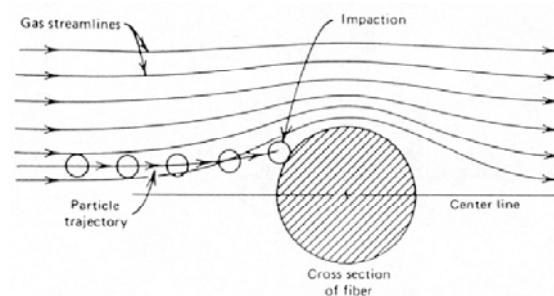


Figure 1: Single Fiber Efficiency by Impaction

Sieving and Interception

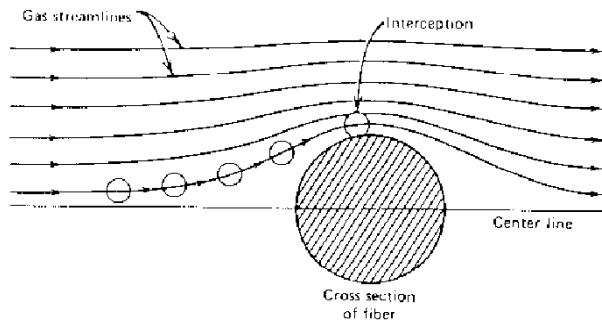


Figure 2: Single Fiber Efficiency by Interception

The second important mechanism, called interception, is shown in Figure Two. It is based on the fact, that real particles are not infinitely small, but show a certain size. Therefore, even if these particles follow a streamline, they still can touch the fiber if the streamline is close enough to the fiber. That means if the distance is smaller than half the diameter of the particle. Especially if we consider real fibrous media, this interception effect gains importance as simple sieving.

Comment:

The assumption that the sole contact between particle and surface is sufficient to provide a permanent adhesion between both bodies is not totally justified. Bouncing effects do occur, but in our regime of velocities, they are of minor importance and can be neglected for theoretical calculations.

Diffusion

Figure 3 shows a collection mechanism, which is due to a phenomenon called Brownian motion. All molecules in a gas are in motion. Their velocities depend mainly in temperature and pressure. Of course this motion is statistically randomized and the molecules do not move with the same speed in the same direction at any point of the time. In reality the molecules or atoms collide with themselves or solid substances and gain or loose momentum during these collisions. To visualize the molecular

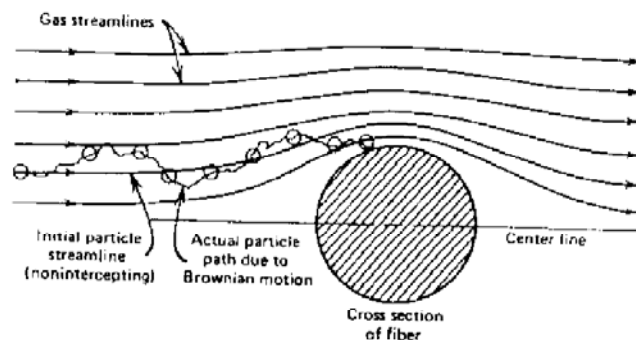


Figure 3: Single Fiber Efficiency by Diffusion

motion in a gas a three-dimensional billiard table might be a good picture. Some of the gas molecules have enough momentum to even change the direction and momentum of small solid particles, forcing them to zigzag through space. This movement is even visible. One just have to imagine light rays from the morning or evening sun falling into a room through a window. Now, if these beams are observed from a shadowed area, it seems that the light rays are visible from the side. This is of course not the case, as light just excites our optical receptacles only if it hits them directly, which would not be the case if we look into that beam from the side. What is actually seen is the light reflected by dust particles in the air. These particles show effects of light deflection and this effect will be of immense importance later in this paper if we refer to particle measuring techniques. What is of interest is that if the particles in the light are observed, it can be realized that these particles

go zigzagging through the air and do not follow monotonous paths. According to what was said above, the smaller the mass of the particle, the larger is the effect of transfer of momentum. Returning to the single fiber model, this means, if the bodies are very small and light weighted, they do not care at all for the streamline, but follow a zigzagging pattern around the fiber. If we consider a layer of many subsequent fibers, the probability for a single particle to hit a fiber is then significant. Summarizing the said, that means the collection probability caused by diffusion is the larger, the smaller the particles.

The fourth important effect is electrostatic charging. This effect utilizes attractive electrostatic forces between two bodies. To visualize this effect we remember simple experiments in school physics when by rubbing a plastic toothbrush or a plastic comb at, for example, chemical fiber textiles, enabled us to lift small paper pieces by attractive forces. These electrostatic forces between opposite charges can also be utilized to collect dust. This mechanism plays an important role with so-called electro filters. As far as textile filtration media are concerned, this effect gained importance during recent years in the form of so-called electret media. Unfortunately this effect is sensitive to electrostatic shielding. As in most generated and natural aerosols the particles carry charges themselves, the electrostatic fields around the fibers of an electret media can be completely shielded after short periods of use. If the filters strongly depend on that effect, they show poor efficiency vs. lifetime performance.

Leaving the single fiber model and returning to the real world filters consisting of fibrous materials we make the following observations: a) Filtration is in some respect a statistical process. b) Collection probabilities for a particle of certain size, mass and matter depend on media parameters as thickness, fiber density, fiber strength, charges, etc. c) Apparently, the ratio between open volume and solid matter in a given filter media controls this probability. d) At a given open volume the thickness of the fibers (deflection of the streamlines) and present electrostatic charges control the collection efficiency of a media.

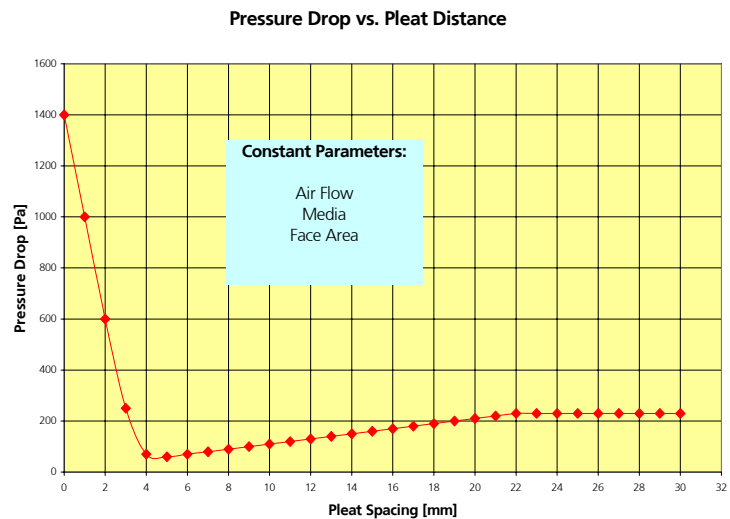
As shown above, the charging of media has to be used carefully and should not be the predominant collection mechanism. The other parameters give a wide range of possibilities to optimization. The fiber densities and diameters often show gradients through the depth of the media and a progressive structure.

1.3 Pressure Drop and Pleat Distance

On the other hand, reducing the open volume as well as reducing the fiber diameter increases the pressure drop flow restriction. As the available energy on the car is restricted, air permeability is of prior importance for all OEMs. The specifications usually allow a certain maximum pressure drop (measured either in inch H₂O or Pa) at a definite flow rate (measured in m³/min, m³/h or SCFM).

For a given media the ratio of open area, or more exact open volume, to the volume occupied by fibers is a constant. Hence, the only possibility to let the air pass the filter more easily is to increase the amount of open volume, that is, the amount of media. For that reason the media are usually pleated. Depending on the type of media the effective filtration area can be increased significantly compared to the face area of the filter.

However, this increase is limited depending on the thickness and the surface properties of the media. The variation of pressure drop vs. pleat distance is shown in Figure Five. If the pleat distance is about the length of the filter, the filter acts like a sheet of plain media. Increasing the number of pleats per length reduces the pressure drop. The relation between the amount of media and the pressure drop is linear in that regime. Below a certain pitch the oncoming air does not "feel" a pleated filter anymore but a compact block of media. This "block-effect" occurs long before the pleats actually touch each other. Further reducing the pleat distance makes blocking the dominant regime and pressure drop increases dramatically. The increase is exponential. For thin paper-like surface media the effective area is about one order of magnitude larger than the face area. For thick deep bed filters the enlarging factor is typically 4 to 5. If the specified pressure drop for a certain filter does not require to chose the optimum pleat distance a whole range of possible pleat adjustments is feasible. The right choice will be determined by cost and performance considerations. The predictability of pressure drop based on theoretical models is usually poor, because randomized distortions (e.g. pleat quality, material inhomogeneities) cause significant noise, which could be eliminated by statistical means. This is expensive and time consuming. Creating a database of real filter data and predicting future products using interpolations is a more practical approach. This might not be the most scientific way, but it is at least as accurate as any theoretical calculations.



1.4 Collection Efficiency and Pleat Distance

Reduction of pleat distance is equivalent to increasing the available open volume. This means, that according to basic laws of fluid dynamics, the flow velocity inside the media is reduced as well. Considering what was said above for the single fiber model we expect an improvement of collection efficiency also because the statistical probability of a particle-fiber contact increases. The dependency is nonlinear and theoretical models vary with every specific type (or even brand) of media. Therefore it is difficult to predict the performance of a filter in a pure theoretical basis without having base of real filter data.

1.5 Pressure Drop and Air Flow

For pleated filters the pressure drop is usually not proportional to air flow. Pressure drop correlates to airflow:

$$\Delta p = C \cdot (dV / dt \cdot A^{-1})^\alpha$$

V: Air Flow

A: Filtration Area

C: Material and Element Constant

α : Number between 1 and 2

In the above given equation the parameters C and α depend on media and filter design, that means, these parameters have to be determined for each specific filter design. α for typical chemical fiber media is somewhat smaller than 2. For paper-like media it could get close to 1.

dV/dt is a flow volume per time, usually referred to as flow rate. The area A is the effective filtration area. $dV/dt \cdot A^{-1}$ is identical to the virtual air velocity through the filter. This is the velocity resulting theoretically if the flow would pass an area as large as the media area. This assumption is not accurate as a part of this area is occupied by solid matter and not available to flow. If the filter media are compared, this velocity is the key to all performance data. Filters can be compared with regards to collection efficiency, dust loading, etc., if this velocity was identical during the tests.

Chapter 2: Gas Phase Filtration

Gas phase filtration occurs when one or more constituents of a gaseous mixture are removed. This can be achieved in either one of two basic ways. The filtered phase can be either stripped from the gas by “adhering” the molecules or atoms to an adsorptive surface (referred to as physical adsorption) or by alteration and chemical decomposition of the molecules into tolerable products. These products can either be adsorbed as well or remain in the air stream. The latter process always includes catalytic reactions. This process is usually referred to as chemisorption. If all products are desorbed after the reaction and the surface remains unaltered the process is called catalytic.

2.1 Activated Carbon

The oldest and best known adsorbent is activated carbon. It is used in process technology for air and water purification and recovery of volatile solvents, in medicine (still in use as a simple and soft medication against diarrhea, especially with children) and many other applications.

Activated carbon can be derived from mineralic carbon, plants, plastics and petrochemical products. If certain solid hydrocarbons are dehydrated so that basically a carbon structure remains the result is a porous skeleton like sponge with a huge specific surface. (The specific surface is the area per mass of adsorbent.) Specific surface range from several hundred m^2/g up to more than $2000 \text{ m}^2/\text{g}$.

Fig.: 2.1 shows a schematic cut through an activated carbon granule. The surface can be modified in several different

ways called activation. The activation usually controls properties like surface polarity, adsorption potential etc.. Due to the provenience of the carbon and the manufacturing process the products vary in regards to mechanical stability, shapes and adsorption properties. Within certain limits the carbon can be custom-tailored to specific applications. As discussed later in that paper one of the most important parameters besides the specific pore surface or pore volume is the pore size distribution.

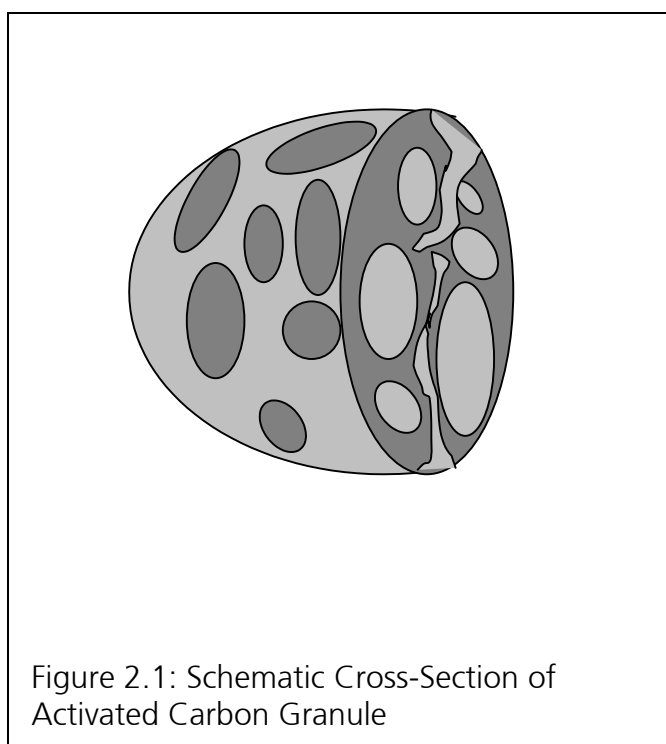


Figure 2.1: Schematic Cross-Section of Activated Carbon Granule

2.2 Adsorption

The deposition of gaseous substances to solid surfaces is called adsorption. Adsorption does not only occur within activated carbon but is a phenomenon occurring everywhere. However, it takes large surfaces with certain properties to make this effect a technical valuable means of filtration.

First of all the forces and mechanisms acting between a solid surface and a single molecule or atom shall be described and explained. A good model of the basics is the surface of water reservoir. In the atmosphere above the water there is always a certain amount of water molecules in a gaseous state. The amount of molecules (or the concentration) depends on the ambient pressure, ambient temperature and the temperature of the reservoir. Within the liquid phase of the water the H₂O-molecules are attracted by so-called Van der Waals forces. These forces are a result of the dipole structure of the water molecules. At low temperatures the molecules in the liquid carry relatively small quantities of kinetic energy. As the energy distribution is statistical there are always some molecules with enough kinetic energy to overcome the Van der Waals attraction at the surface of the water and actually leave the liquid phase. This is why water evaporates even at room temperature if given enough time. If the temperature of the reservoir is increased, the average kinetic energy of the molecules increases, the molecular mobility increases and more and more molecules can leave the liquid phase. Finally, at boiling temperature the average energy is higher than the dipole-dipole forces, a phase transition occurs and every molecule will transit into the gas phase. Figure 2.2 visualizes a comparison of adsorption and the water model.

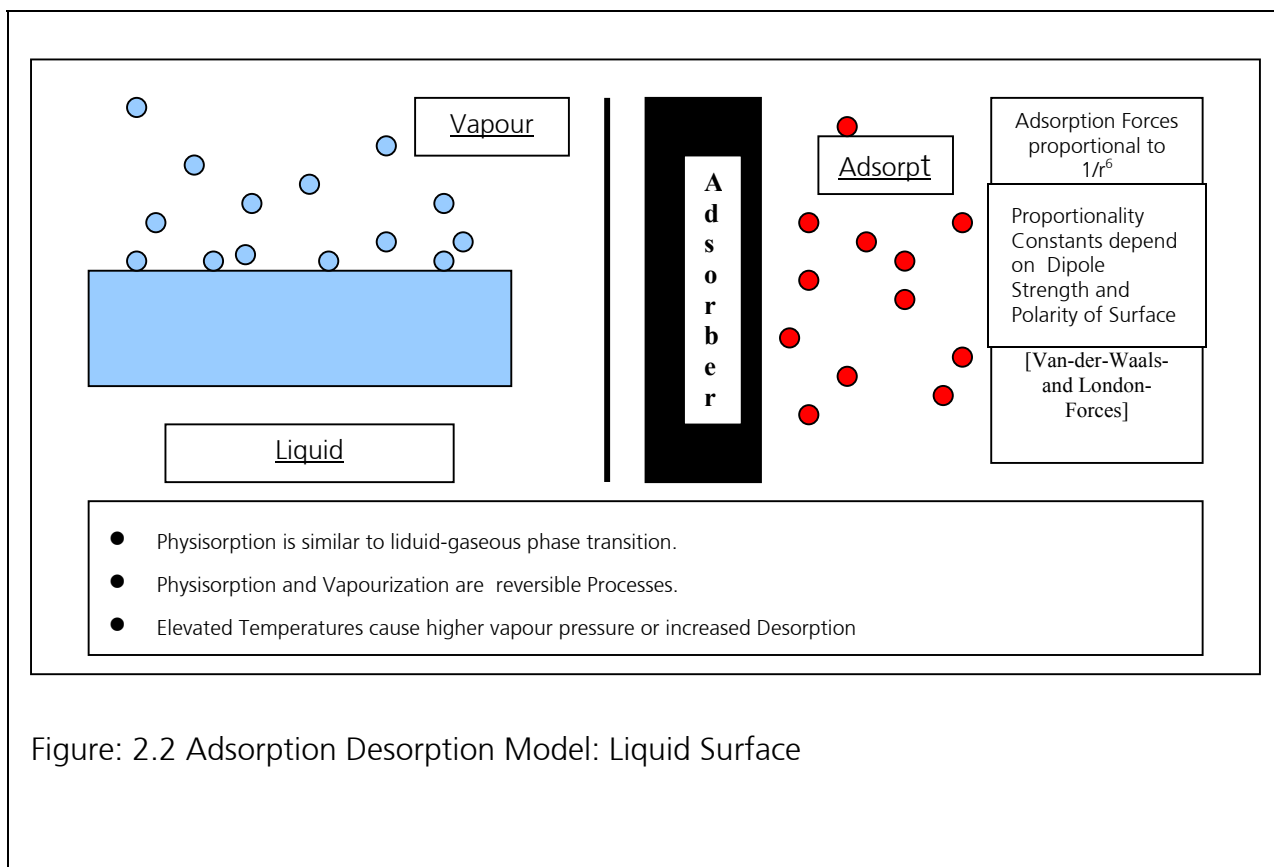


Figure: 2.2 Adsorption Desorption Model: Liquid Surface

2.2.1 Physisorption

This simple everyday experience provides already the basic picture of physical adsorption. There are some differences though. In adsorption the surfaces are not level and the attractive potentials are called London forces. Due to the 3 D-surfaces some additional effects have to be considered. Figure 2.3 shows a cross section through pore in activated carbon. On the right corresponding London potentials are shown. The deeper a potential is the higher the adsorptive forces. The top molecule is in a position where the pore is relatively wide and close to a wall only the potential of this particular spot is experienced. In the middle section the molecule starts to "feel" the potentials of two opposite walls as they begin to superpose. In the bottom section the

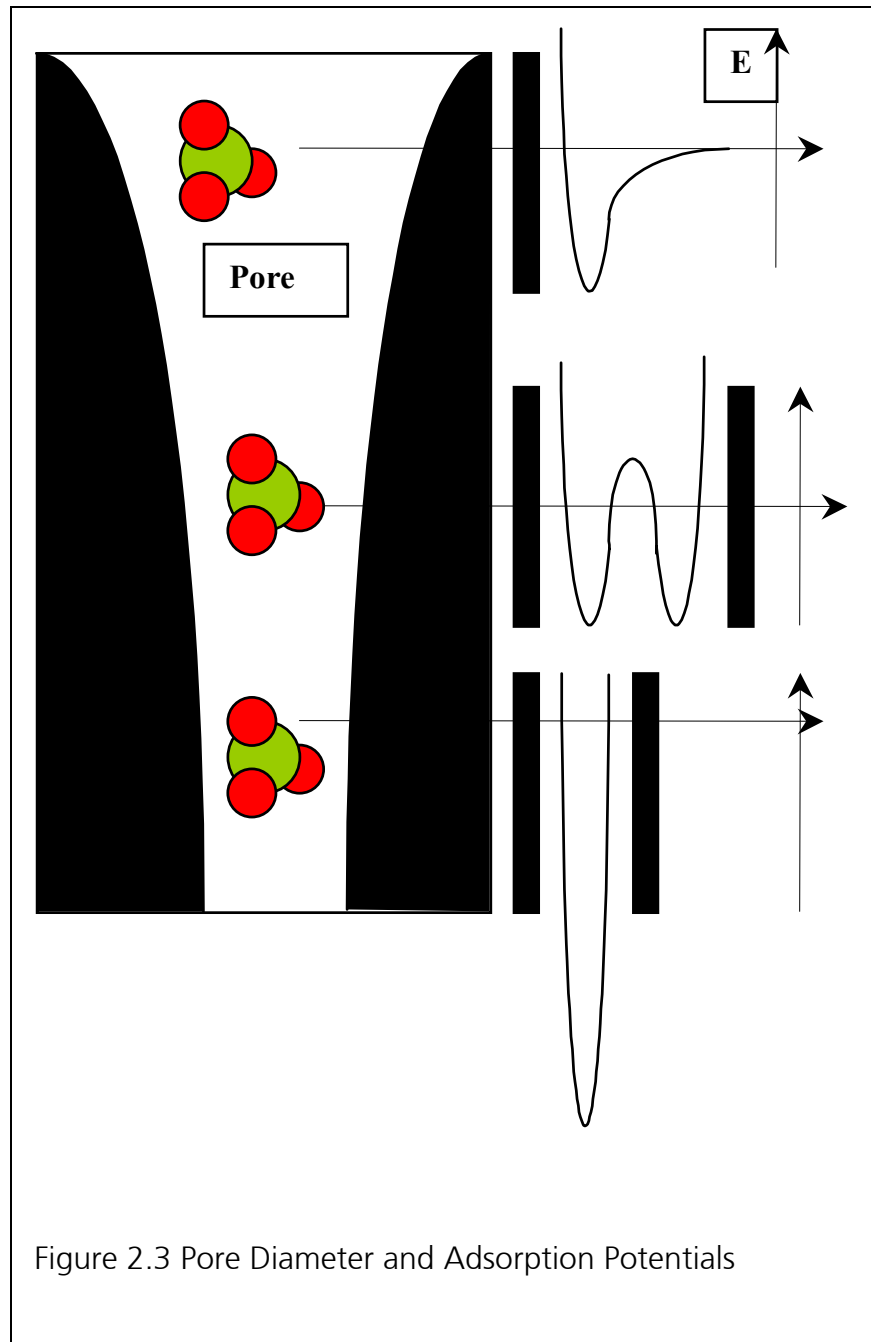


Figure 2.3 Pore Diameter and Adsorption Potentials

two potentials are perfectly superposed and the potential is very deep. This two dimensional model is still inaccurate as in reality the potentials superpose from all sides and this effect is even more significant and orders of magnitude stronger than shown in the picture. The bottom molecule would be hard to remove (desorb), as the potential is very deep. For the top molecule a little increase of energy in form of temperature would cause desorption. This model also explains why the pore size distribution in an adsorbent is of major importance for its adsorption/desorption performance.

2.2.2 Chemisorption

For many inorganic substances the adsorption potential is relatively weak. Consequently, physical adsorption does not work very well. If the carbon surface is modified, however, for many agents the performance improves. The treatments of the carbons range from simple adjustments of the acidity by spraying on weak acids to more sophisticated impregnations with all kinds of metallic salts to complex activation processes. The resulting process is not physisorptive anymore but involves chemical conversion of the contaminants, referred to as chemisorption. This terminology is, based on tradition, still in use, but unfortunately not very descriptive as far as the actual reactions are concerned. Many of these conversions have indeed catalytic character concerning the process kinetics. It is certainly not possible to treat all types of agents with one type of specialized carbon. If a set of contaminants is the target it might even be necessary to use blends of several treated carbons.

2.3 Impregnations

Hydrogen sulfide (cold start emissions from catalytic converters, rotten egg smell) is a typical agent where regular activated carbon does show nearly no effect. But it has been used to treat H_2S for many years. It was common to impregnate carbon with a copper/chrome oxidant to enhance the performance. Unfortunately, these copper/chrome compounds are highly active and therefore the carbon becomes dangerous (several explosions have been reported in that application). Furthermore, this impregnation is rather unhealthy and not appropriate in filters for respirable air. In the meanwhile there are impregnations available like copper permanganate, which are less critical, but also effective. Which type of carbon and which impregnation is appropriate depends on the specific application and the targeted agents.

Hence it is difficult to define specifications with one or two arbitrary selected pilot agents. A specification for this application should actually list all major challenging agents and require specific conversion rates for them. This, however, is rather difficult for cabin air applications as the environmental conditions show a huge geographical variety and therefore a globally accepted standard is not in sight.

2.4 Catalysis

In pure catalysis the catalyst remains available to the process and unchanged. Catalysts usually show no deterioration or degradation during the process, as they are not directly involved in the reaction but only lower the activation energy for a specific reaction.

Catalytic reactions usually involve adsorptive surfaces where molecules are attached. The adsorption potentials change the energetic state of the electron bonds, thus lowering the amount of energy necessary to split these bonds. In reality, especially if undefined mixtures of gases are involved and the process temperatures are close to room temperature, some of the reaction products might stay adsorbed to the surface and therefore act as contaminants. As a result the catalytic surface deteriorates and the conversion rates for certain reactions decline.

Catalytic reactions are well explored in process technology and chemistry. In most of these applications the environmental conditions are well controlled. The available temperatures are high, so that permanent adsorption to the catalyst can be easily avoided. In the recent

past room temperature catalysis is under heavy investigation. For some isolated reactions the work was successful. However, for the majority of contaminants and agents there is no room temperature solution so far.

2.5 Adsorptive Filter Media

Activated carbon comes in many different forms and types. For cabin air applications coconut shell based granular activated carbon has proven to be the most effective choice. It provides an appropriate pore size distribution combined with good mechanical properties.

To convert that raw material into a well performing filter, the granules have to be brought into a processable bed shape with optimized spatial distribution and density.

If the carbon is packed too dense the pressure drop becomes unacceptable and due to the low open volume the local velocities inside the filter bed will be high. As a result the contact time for a given bed depth would decrease. If the packing is not dense enough the filter breaks through under peak challenge.

No matter if the substrate is coated with carbon or the filter layer is built up with carbon and adhesive only, the expertise of a carbon media manufacturer is to select the right raw material with the right grain size distribution and to provide a fixed bed with the correct packing density. The carbon must not be degraded with adhesive and has to show good processing properties.

SECTION II: FILTER TESTING

Chapter 1: General Parameters

1.1 Introduction

All air filtration phenomena can be considered as statistical processes. No matter if adsorption or particle filtration is concerned, whenever an individual object is observed, the actual separation is always controlled by probabilities. These probabilities are determined by a set of parameters. For example the performance of an adsorptive filter depends on the actual contact time between adsorbent and adsorpt. This contact time is for a given configuration a function of the flow rate. The adsorption-desorption equilibrium is determined by the partial pressure or concentration of the adsorpt and the ambient temperature. The presence of water influences the adsorption performance as water might enhance certain chemisorptive reactions. In physisorption water can occupy a significant amount of active sites which are consequently not available for the adsorpt.

Apparently, in particle filtration the airflow also controls the collection probabilities. Humidity and temperature play a roll for certain aerosols as they can lead to particle agglomeration or condensation effects.

Flow restriction is an important criterion for the filter application by itself.

Therefore, measurement, reporting and controlling of temperature, relative humidity, airflow and pressure drop are of major importance for filter testing in general. The following chapter gives a brief review of these measurements.

1.2 Pressure Drop

Measuring the pressure drop over any type of throttle is simple. There are many instruments from inclined tube manometers to electronic pressure transducers available. All types can provide sufficient accuracy for any application if thoroughly selected. All these instruments are commodities. It should be mentioned that in our applications restrictions to be measured are very small: $10 \text{ Pa} = 0.1 \text{ mbar}$!

Although it is not trivial where to place the probes and how to design them. Throttles in ducts as well as filters usually generate turbulence and eddies. If the statistic pressure has to be measured the dynamic pressure components have to be suppressed or compensated. This is achieved by placing several (at least four) probes around the perimeter of the duct. The probes might be simple holes in the duct, but have to be absolutely flat against the surrounding surface. In our applications the diameter would be 2 – 3 mm. Outside the duct small metal tubes could be soldered to these holes. Plastic hoses and several T-connectors hook all the probes up to a ring from where one hose leads to the instrument.

More elaborate designs consist of steel rings with a full perimeter slit opening at the inside, which can be purchased according to several standards.

The easiest way however is to place ring shaped perforated plastic tubes inside the duct along the perimeter and connect it with a T-piece to the instrument.

1.3 Air Flow

The airflow cannot be measured directly, as this would require the actual count of molecules passing a certain cross sectional area of a duct. Usually, the determination of flow is derived from more macroscopically accessible parameters like pressure, temperature, density and velocity. Accurate measurement of flow is of major importance for filter testing. It can be assumed that the majority of consistency problems in round robin tests between filter test labs are due to inaccurate measurement of airflow.

There are two basic approaches to air flow testing. According to the method, either the mass flow or the volume flow is measured. If temperature and humidity are measured simultaneously conversion between the two is trivial. However it should always be reported if the airflow is converted to standard conditions.

Venturi Devices

A classical and still the most accurate and safe method to determine the air flow in a closed system is based on the fact that variations of the cross section of a duct create pressure losses and varying velocities. According to Bernoulli's law the product of pressure and air velocity in a given environment is constant. This also implies, that in a closed duct system the air flow is constant, as long as the pressure involved is too small to produce compression effects. If in that duct the cross section changes from a larger to a smaller diameter, the air has to travel faster to keep the flow constant. We know already, that the product of velocity and pressure is constant. Therefore it can be concluded, that for our situation the pressure will be reduced as the speed increases.

If a long tube contains an orifice and air travels through it the static pressure on the upstream side will be higher than downstream of the device. The pressure drop is a function of the geometric properties of the Venturi and the airflow. For a given device the pressure drop will increase with the square of the airflow. The task to measure the flow is herewith reduced to test a pressure drop. We have already seen that this is not challenging task.

To get the optimum results using Venturi orifices some general rules have to be considered. For example should the length of laminar and homogeneous flow up- and downstream of the device be about five times the diameter of the duct to provide accurate measurements. All calculation procedures and design features as well as the limits of application are summarized in several national or international standards (e.g. DIN 1952). Unfortunately, the measuring range of these gauges is rather restricted and even for the regime of interest in cabin air filtration two or more sizes could be required for reasonable flow determination.

Anemometers

Anemometers determine the velocity of air and are used in a variety of applications. They are mass sensitive devices. The airflow is the product of air velocity and cross section area, if the velocity is constant over this whole area or the measurement represents an averaged value for the cross section:

$$V = v * A$$

There are several basic principles in use. The two most important ones are described in the following.

Wheel Anemometers are used in meteorology and represent most likely the oldest method of air velocity determination. A propeller is rotated by the oncoming air and the frequency of the rotation being a function of the air velocity is used as a measure. The direction of airflow has to be perpendicular to the plane of rotation to produce accurate results.

Heat Transfer Anemometers are used in labs, field studies, wind channels and the HVAC-industry. The principle is also used in state of the art fuel injection pumps to detect and control the amount of required air for optimized engine management. A small droplet-shaped semiconductor acts as negative temperature coefficient resistor. A steady current heats it to a certain temperature. As soon as this temperature is reached, it is kept constant. Moving air cools the device by absorbing energy and removing it. The current required to maintain the temperature level is a steady function of the velocity (molecules per time unit hitting the anemometer, resulting in a mass flow measurement) of surrounding air. This analog signal can be read directly, recorded or used as an input signal into a computer for further processing.

Anemometers are not the first choice for airflow measurements in test benches. The air velocity in a duct is not uniform over the whole width of the duct, but rather shows a more or less parabolic profile, due to the flow conditions ranging from laminar to turbulent. Conventional handheld devices cover a cross section of several mm to several cm in diameter. The reading thus acquired represents just a very local velocity value. It is possible to measure the whole profile and compute the airflow by using an appropriate algorithm. Still this is an inconvenient method, as the profile will change its shape with varying velocities and due to duct designs. There are devices commercially available utilizing an array of anemometers positioned on a grid, feeding the signals directly to a processor, which does the air flow calculation and the averaging involved automatically. This method is comfortable, however costly and is recommended only if detailed information regarding the velocity profile is of interest, which is typically not the case in filter testing.

Concerning wheel anemometers a design with a propeller covering the whole cross-section of the duct can be used. The disadvantage using this method is that the wheel is rather large and inert and therefore requires long times to respond to flow variations. Short fluctuations will not be visible at all. Due to the mechanical friction of the bearings a significant momentum is required before the wheel propels at all. Furthermore, the dust in a filter test bench is critical to the mechanical components involved.

Chapter 2: Particle Filter Testing

2.1 Testmethods And Standards

One decade ago the predominant methods of filter evaluation were defined and used by industries involved in HVAC Applications. The development of test methods was driven by industrial like ASHRAE as well as by national standardization committees. ASHRAE used a dust which was a mixture of AC-Coarse (SAE-Coarse), cotton linters and carbon black. The filters were challenged with a well defined amount of dust and weighed before and after the test, and the percentage of collected dust was calculated. In another procedure air is sampled up- and downstream of the filter. These two streams were filtered with sheets of white absolute filter paper. By comparing the different degrees of discoloration of the paper the collection efficiencies could be determined.

2.2 Sodium Flame Test

A British Standard used a sodium chloride aerosol similar to the applied today in cabin air filter testing. This aerosol is generated from a liquid solution using nebulizers. The efficiencies were measured using Sodium flame detectors. A hydrogen flame has a blue color. If Sodium is led through that flame, the color turns yellow. A certain electron in the sodium atom is energetically lifted from its energy level into an excited state. After a time of typically 10 pico seconds it recombines emitting photons of a defined energy related to the energy gap between the two states. This photon has a wavelength of about 550 nm, which is yellow light. A photo sensor sensitive to the yellow section of the spectrum provides an analog signal which is proportional to the mass of sodium chloride being present in the flame. The efficiency of the filter is tested by sampling air up- and downstream of the filter and measuring the sodium content. Comparison of the concentrations provides the desired information.

2.3 Photometers

Another method to detect concentration of particles in air involves the optical measurement of particles in a collective form. This method gained importance as in situ test method in work environments with notorious high dust concentrations. Optical methods utilize the fact, that particles, when suspended in air and illuminated by a source of collimated light, scatter that light in all spatial directions and extinct the amount of light in the initial direction. This so-called Tyndall-effect has been used in photometer devices.

2.4 Particle Counting

All the above mentioned methods suffer from a significant shortcoming. They provide integral efficiency data and reveal no information about particle sizes. In many applications it is of importance, what percentage a filter removes at a specific particle size range. In the early 1950's the so-called single particle optical counters have been developed. These counters also use light-scattering properties. But now the particles are observed in a tiny

measuring space one at a time. Light extinction as well light diffraction could be used for detection. A general theory regarding the scattering of light has been established by Gustav Mie in 1920. Single particle optical counters were well established in the 1980's and the use of laser light sources improved the performance of these devices. Today they can detect particles down to about 0,1 μm in a diameter. They have first been used in test standards in Europe for the testing of automotive cabin air filters (DIN 71460 Part 1).

It has to be considered, that these devices are usually calibrated with polystyrene latex particles of defined size. The size information of these counters is only correct if the diffraction index of the tested aerosol is identical to the one of the calibrating aerosol. A detailed description of particle counting technology is given in Appendix A.1.

2.5 Aerosol and test dusts

SAE dusts, formerly referred to as AC-dust, have been mentioned already. They are mineral dusts mainly consisting of silicon dioxide and are processed from natural Arizona dust. The particle size distribution is achieved by a sequence of wind sifting procedures. Dust picked from the ground is blown through a wind channel at low air velocities. The particles tend to sediment on the bottom, where the large ones can be found at the front end of the channel and the smallest ones at the end. By selecting certain sections from the channel a uniform and relatively reproducible dust with regards to size distribution can be generated. Major problems using these dusts are:

- they could represent the natural atmospheric aerosol just in Arizona and nearly nowhere else.
- the dispersion creates a highly charged aerosol.
- loading tests and real life aging show no correlation.

Sodium chloride aerosols have also been briefly discussed. The nebulizers used for generation can produce very narrow particle size distributions (quasi monodisperse) as well as rather wide ones. After leaving the generator and while being carried by the air stream the water evaporates and leaves salt crystals as solid particles.

Other frequently used liquid aerosols are DOP and DEHS because of unique properties like controllable and repeatable size distributions and other certain desired properties.

2.6 Aerosol Generation

Aerosol generators should be divided into two groups: generators for solids and dispensers for liquids. Liquid aerosol generation utilizes diverse physical principles from ultrasonic waves to jet injection. Usually very stable and reproducible aerosols can be obtained. The size distribution is extremely small for some of the instruments so that they are frequently used for calibration purposes. Generators for the dispersion of solid particles usually suck particles out of a depot or brush it out of a cylinder (rotating brush generator). A more elaborate design are the fluidized bed generators. For a summary and overview of aerosol generator designs see Appendix A.2.

Chapter 3: Testing of Adsorptive Filters

3.1 Evaluation of Activated Carbon

Generally speaking the evaluation of activated carbon can be done by determination of the parameters relevant to adsorption. Physisorption requires surface area to place and store the contaminant. As mentioned before, this area gets available through the pores in the carbon structure. All data containing information regarding the porosity of carbon help to characterize a certain product. Typical relevant physical properties are density, pore size distribution, ash content, iodine decolorization, adsorbed masses of test agents under well defined conditions, just to name a few.

As already mentioned the most important data for characterization of activated carbon are the pore size distribution, pro volume and the pore surface area. These data are determined by methods usually referred to as porosimetry. A defined mass of a conditioned carbon sample is exposed to a challenging agent at a defined low concentration (equivalent to a defined partial pressure). The exposure is of static nature. After equilibrium is reached the amount of adsorbed agent is gravimetrically determined. Now, the partial pressure is increased in defined increments and the adsorption is successively repeated. The resulting curve is called an isotherm. According to adsorption theories developed by Langmuir and Brunaur, Emmet and Teller, the isotherm data can be used to calculate so-called BET surface areas and pore size distributions. The methods and theories are described in literature and will not be repeated here.

To cover the whole range of pore sizes, it is necessary to make use of more than one challenging substance. Typical agents are mercury and Nitrogen. The different agents do not lead to consistent results in the overlapping regimes. For cabin air applications nitrogen data are sufficient.

For all of the above mentioned significant characterizing tests national or international standards are available. For more detailed information these standards are good sources.

3.2 Breakthrough Curve and Filter Characterization

Adsorption testing is in principle identical to any other filter test. The test agent is adjusted to a certain upstream concentration. Environmental parameters like the temperature, ambient pressure and humidity are controlled and kept within close limits. The latter is of prior importance as activated carbon is usually very hydrophilic. The downstream concentration is monitored versus time until the filter becomes saturated and the breakthrough gets close to hundred percent..

For the physisorption of organics the resulting curve has the shape of an integral over a gaussian distribution (lying S). It starts along the base line for filters with sufficient bed depth, then grows monotonously until it reaches a turning point at about 50 % breakthrough. Then it continues to increase at a diminishing rate and fattens out when it reaches 100 % breakthrough. For the commonly use combination filters the bed is hardly deep enough to prevent initial breakthrough. In these cases the first portion of the curve is simply cut off.

Inorganics show in general a more unpredictable behavior as the conversion of the agent does not necessarily show classical saturation effect.

In both cases however, the total amount of adsorbed/converted agent over time can be calculated. This figure is frequently used to specify the performance of gas phase filters.

Another value adequate for specification of performance is the breakthrough level after a certain period of time after measurement was started.

For a more detailed description of the whole method and a mathematical description as well as proposals for very effective filter specifications see our publication in appendix A.3.

For cabin air filters test methods have been established. In Europe, the DIN 71460 part 2 is in general use, the American standard SAE J1669 part B is still in the draft stage. Harmonization efforts to achieve a common standard are making good progress and could be successful in the near future. The main remaining difference is the selection of challenging agents proposed by the standard. As specific substances can always be implemented for a specific filter on a customer - supplier basis this should not be a major hurdle.

3.3 Selection of Challenging Agents

The selection of challenging agents depends how cabin air filter containing a gas phase stage are positioned in the market place. If the emphasis is put on the comfort aspect the filters should show excellent performance against odors. As it is virtually impossible to produce a filter which performs outstanding with every substance, to market these products as safety features is questionable anyway. However, the market's demands are influenced by sociological and regional perceptions. For example, due to the relatively high population density in Europe, the pollution problems caused by individual traffic are reasonably more intense than in the US. The main emissions caused by motor vehicles, benzene derivatives, nitrous oxides and sulfur dioxide are in permanent public discussion. As it could be assumed, that experts investigating improvements in automotive industry and publishing the results, would immediately test the efficiency of cabin air filters against these substances. Hence it was an unanimous decision in Europe to include these substances in the standards, although the first proposals to do so came from an US manufacturer. The benzene derivatives are simulated using toluene. This happened at a time, when no one was aware of the implications regarding detectability and laboratory safety. A globally used contaminant is butane. Butane was an agent of choice for historical reasons: large databases for butane adsorption were already available from other applications, it is cheap, safe easy to detect and can serve as a surrogate for other aliphatic organics. In the cabin environment of a passenger vehicle however, it is of no relevance.

A more problematic example is H₂S. As the major cold start emission from catalytic converters burning commercial fuel it is definitely present on the streets. Furthermore, it is highly toxic and has a strong odor. The odor threshold is typically some 20 ppb (part per billion). Testing at these concentrations is challenging and, if full filters are tested, dangerous, due to the large amounts of agent to be processed. As the appearance in the open is very sporadic (standing at a traffic light behind a car, whose engine did not run longer than 3 to 5 minutes) it can be questioned if the specification of this substance is reasonable.

These problems leads to a listing of criteria for the selection of test agents. In general, a reasonable selection of gases should be based on the following:

- presence of the substance (or chemical similar) in the traffic environment,
- importance to the driver, i.e. can a subjective improvement using a filter be verified,
- is the substance in relevant concentrations dispensable, stable and detectable with reasonable effort?
- can it safely be handled in an industrial laboratory?

Based on these points agents could be determined between customers and suppliers based on marketing strategies, regional specifics and feasibility.

3.4 Detectors

For the detection of most of the above mentioned gases there are several good options available. FID, PID, Infrared Spectroscopy, Chemiluminescence, Photoluminescence, Electrochemical Sensors and Gas chromatography are in use.

For organics the best instrument is certainly the FID (Flame Ionization Detector). It is rather inexpensive, reliable in the range of concentrations for which it is intended. As it detects carbon in any compound, it can be used for hydrocarbons and other carbon containing substances. This means also, that mixtures of gases containing more than one carbon containing agent can not be quantitatively analyzed. But for gas flows with one carbonaceous agent it shows satisfying quantitative accuracy. The working principle is very simple. The gas flow is led through a flame, which the carbon atoms leave ionized. The gas flow then is led between two charged plate electrodes. The ions discharge the precipitator according to their drift to the negatively charged plate. The discharge voltage is directly proportional to the concentration of carbon ions. As the challenging agent is known, the amount of carbon atoms pro molecule of agent is a constant. Using these figures and some calibration data for the device the concentration of challenging gas can be detected directly.

In field studies, where mixtures of unidentified gases have to be determined, an additional gas chromatograph helps, to separate and identify the constituents. The FID at the end of the chain does the quantitative analysis.

For inorganic substances infrared spectrometers are frequently used. Our experience shows, that these devices are more critical than the manufacturers are usually willing to admit. A serious problem are the cross sensitivities to other constituents in the carrier gas. This carrier has to be thoroughly analyzed and controlled in order to chose a detector wavelength which is uncritical. We found for some gases, that using filtered atmospheric air as carrier, the device could not be used at all, in contrary to the manufacturers information. The only way to overcome this problem is using synthetic carrier gas of high purity, which can be excessive in cost.

For the most inorganics we derived good results with chemiluminescence- and photoluminescence devices or electrochemical sensors. For detailed descriptions of operating principles please refer to the manufacturers publications.

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