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LATEST ASPECTS OF MECHANICAL FILTRATION

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Abstract

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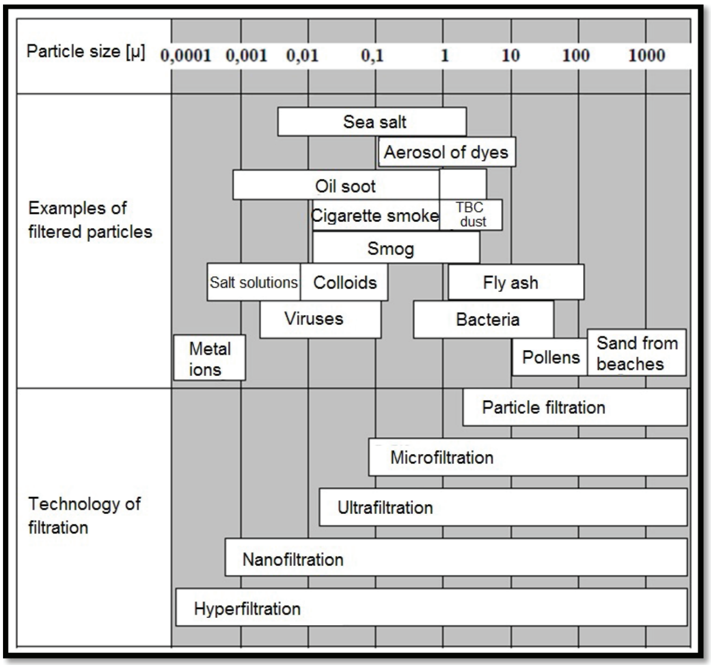
The aim of this study was to describe and unify all knowledge about mechanic filtration. The first part deals with the parameters and properties of filtration. Here some important basic concepts are explained such as pressure gradient, filter life, etc. There's also a description of convenient filtration technology for coarse and fine materials, such as sand, smoke or soot. The second part primarily focuses on the real use and application of filters for liquid and gaseous media. The differences in construction between different types of filters for filtration of fuels, oils, hydraulic fluids, air and cabin filters are described. The last section is focused mainly on new materials for the production of filters. These materials are ceramic or nanomaterials, which can actually be enriched for example with antibacterial silver or some fungicides.

filtration, filter, fuel, oil, air, nanofibers

Filtration is a process in which there comes to separating of dispersed particles from the dispersion medium by means of a porous medium (eg fiber formation). Dispersion medium may be gaseous (air) or liquid (water). Particulates are solid or liquid (aerosol). In liquid filtration the most applicable method is the surface filtration, especially network effect. Some filtering mechanisms are suppressed due to large pressure of the flowing fluid. They are applied when the flow rate is reduced, or in areas of turbulence. The filtration is used for drinking water treatment, the desalination of sea water in laboratory equipment, the manufacture of electrical fluids, the fuel filtration, oil and other fluids (brake fluid, hydraulic oil...). All these media require a higher mechanical resistance of the filter material. In air filtration both basic filtering methods are applied, depending on parameters (particle size and speed of their movement). The application can be for cabin, air and flue gas filters, masks, medical equipment, electronics, clothes, etc. (Hrůza, 2005).

Distribution of the filtration process (Fig. 1):

a) Surface filtration – particles collected on the filter surface create a layer called filter cake. We divide it into:
   - particle filtration – greater than about 1µm, often visible with the naked eye (yeast, flour, cells, precipitates, etc.). The driving force of this process is the pressure difference.
   microfiltration – from about 0.1 µm to 1 µm (pigments, bacteria, asbestos). The driving force of this process is the pressure difference.
   - ultrafiltration – from about 3 nm to 0.1 µm (proteins, viruses, gelatin). The driving force of this process is the pressure difference.
   - nanofiltration – here the range of molecular weights of filtered substances is given, namely from approximately 200 g/mol to 15,000 g/mol, which corresponds approximately to particles' size from 1 nm to 10 nm (dyes, pesticides, herbicides, sugars). The driving force of this process is the pressure difference.
   - reverse osmosis – molecular weight less than 200 g/mol (ions, salts). The driving force of this process is the pressure difference.
   - diffusion dialysis – separation of ions and uncharged particles (blood dialysis – blood purification from metabolic pollutants). The driving force for this process is the difference in concentration.
   - electrodialysis – separation of anions and cations (cleaning sulfate waters from uranium). The driving force for this process is the electric field – the electric potential difference.



1: *Effect of particle size on distribution technology of filtration (HRŮZA, 2005)*

b) Depth filtration – particles passing through a porous environment are trapped inside the filter cartridge (sand filters in wastewater treatment plants). The thickness of the filter is much larger than in surface filtration (Wikipedie, 2001).

1.1 Parameters of filtration

It is useful to distinguish parameters and properties of the filter that determine the process of filtration. All filtering parameters can be variables that change values of filtration properties. Eg. properties of textile filters are given according to the need of the usage. During the filtration process the filtration changes as a result of filling the filter with collected particles, which makes difficult to find appropriate testing methods.

The main parameters of the filtration:

1. The parameters of filter material: the filter surface, the thickness of the filter, the surface and volume weight of the filter, the material uniformity, the material and its criteria – the bulk density, the electrical conductivity.
2. The parameters of nanofibers: the diameter, the shape, the softness, the orientation in space, the particle size of dispersed share, the particle size distribution of dispersed share, the concentration of particles, the shape and surface of the particles, the density weight of particles, the electrical properties.
3. The parameters of the filtration process: the speed of particles' raid on the filter, the viscosity of the flowing medium, the temperature, pressure and humidity (Hrůza, 2005).

1.2 Main properties of the filter

Efficiency = Separation of particles:

$$E = 1 - \left[\frac{G_1}{G_2}\right] (\%) \tag{1}$$

(P = G_1/G_2 is marked as penetration)
G_1..... amount of dispersed phase behind the filter
G_2..... the total amount of dispersed share (sometimes stated amount dispersed share before the filter).

Pressure drop:

$$\Delta p = p_1 - p_2 \text{ (Pa)} \tag{2}$$

Δp .... pressure difference
p_1...... pressure before the filter
p_2...... pressure behind the filter.

The service life of the filter = need to replace the filter

For disposable filters the service life of the filter is determined by the amount of dust, which the filter is able to collect until the pressure loss is too high. For filters with cleaning it is expressed by intervals between cleanings and their number. Generally the service life is expressed eg by the absorption capacity of the filter (EN 779).

$$J = Es \times m \tag{3}$$

J........ the absorption capacity of the filter
Es ..... the filter efficiency
m...... the amount of particles collected on the filter.

The resistance to external factors comprises : chemical and mechanical effects, temperature and their combination.

Other features associated with filtration: air permeability – how much fluid passes through 1m^2 filter per 1 minute at a defined pressure gradient (typically 196 Pa), the unit (l/m^2/min), the porosity – the pore size determined as normal, medium, or maximum, or by the average value of their size (Hrůza, 2005).

2 FILTERS

The presence of the filters is the only way how to sustain the prescribed cleanliness of the machines while working and the correct operation of the machines and their accessories. By using filters we achieve lower wear of functional groups, and thus a longer service life of the machine. When the regular intervals of filter change are not respected, the resulting machine performance is reduced and fuel and other fluids consumption gets increased.

The main three basic filters for automobiles are: fuel filter, oil filter and air filter. The choice of a suitable filter is given by the filtered material, the required degree of purity, but also by the working environment. From the economic point of view it is important, that the filter was cheap, and its installation simple. These requirements are complied with filters with paper inserts, which have proved long run good usage. Changing the filter or filter cartridge should be long enough before the sediment layer reaches the limits impeding the continuous and efficient flow. This limit is in practice given by the filter manufacturer (in vehicles) and is usually expressed by kilometers, hours, etc.

2.1 Filters for automotive fuels

The task of the fuel filters is the dirt collection from petrol, diesel and even LPG systems. At present time it is impossible for suppliers to guarantee that the fuel was always 100% pure. Therefore each fuel system filters must be optimally adapted to the requirements of the engine, fuel quality and expected operating conditions. The engine requires trapping dirt of size from 3 to 5 µm with efficiency greater than 90%. In order to meet these requirements more than one filter is often installed in the fuel system. The fuel filter is deliberately installed without the by-pass valve, which would open the fuel supply when the filters are completely clogged. The rule is that only perfectly clean fuel can come to the combustion chamber. It is therefore better when the engine stops due to lack of fuel (clogged filter) than when working with contaminated fuel (Filtron, 2009).

Contamination of the fuel occurs by careless handling during transportation or improperly designed distributor's storage areas. On the surface and inside the fuel tank there occurs to flaking of paint, creating sludge, dust or cause abrasion and corrosion particles (Šimáček, 2011).

Diesel engines are unlike gasoline engines more sensitive to the presence of impurities. Diesel system is exposed to higher working pressure. For comparison, gasoline direct injection system operates at pressures of about 50 bars, old diesel engines with indirect injection of about 150 bars. Current diesel engines with Common Rail generate injection pressures between 1 500–2 200 bars. Manufacturers of fuel systems have already crossed the border of 3 000 bars. These stated values can give a dependency as follows: With increasing injection pressure the tolerance of lapped surfaces and clearance of parts must decrease up to 2 µm. If a dirt gets into this tiny space, it will soon cause seizing the contact surfaces. The most threatened parts of fuel systems are the injection pumps and nozzles. Neglecting regular maintenance can cause a non-repairable defect worth thousands of crowns (Šimáček, 2011).

The requirements for diesel (and by analogy also gasoline) filters include:

- The possibility of venting the fuel system
- Low flow resistance
- Easy maintenance and exchangeability of filter cartridges
- High efficiency of the filter
- The presence of a drain bolt or a pump (Ždánský, 2003).

The basic material for the production of fuel filters is fine paper. Porosity inserts reach 4–10 µm. Efficiency and specific surface area of the filter can be increased by a suitable paper folding into various shapes such as stars, harmonicas or rolls. In diesel fuel at low temperatures there is an increase of viscosity, therefore many filters are complemented by a heat exchanger. The exchanger is connected to the engine cooling water system. It is thus in operation only during the opening of the thermostat when warming up to operating temperature. This conception does not allow warming up fuel when starting a cold engine, therefore filters have another electrical heating. It is controlled by a thermal switch, which itself maintains the optimum viscosity of oil in the winter. Current filters are manufactured in cassettes and in-line design and more recently with regard to the environment in the ECO version. The organic removable insert does not contain metal parts and thus is recyclable (Ždánský, 2003).

Gasoline filters are not essentially different from filters for diesel engines. Petrol retains good fluidity at most temperatures and so the specific surface inserts are often smaller and the filter is more compact. As well there is no need of the drain bolt, because additives of gasoline are resistant to the formation of sludge and water in the tank. According to the structure and type of fuel two-stage or multistage filtration can be used. The first step consists mostly of a fine mesh which captures only the gross contaminants from the fuel tank. The filter can be complemented by a transparent flask, which indicates the current state of pollution and the necessary maintenance. In the second step very fine impurities which adhere to the replaceable insert are removed. The filter element is made of a material with very good filtering properties, such as filter paper or felt. At the multistage filtration the fuel continues to other fine filters, and then the injectors (Motejl, 1998).

The situation for LPG gas fuel is rather different, where the compressed gas flows from the tank to the reducer as a liquid and when passing through it changes into a gas. LPG filters are thus divided into the filters of liquid or gaseous phases. Filters for the liquid phase are in the container under the solenoid valve controlling the supply of liquid gas. The filter captures rust and other coarse impurities in the gas tank. Very often there is a magnetic particles collector, with the injection system that prevents the engine from damaging by metal chips and abrasions (Mitsubishiclub, 2008).

Filters for the gas phase are placed between the regulator and injection of fuel to cylinders. The cartridge contains a fine filter with pores sized about 80 microns. Maximum allowable pressure for this filter is 250 kPa (Neptun Harfa, 2011).

2.2 Oil filters for the lubrication system

In the early history of the engine construction, the oil filtration was not important. Oil had to be replaced every 800 to 3 000 km. Engine design did not allow to seal the combustion chamber, thus the oil accidentally got burnt. Other excessive losses were caused by leaks in the oil circuit. Old leaking oil was supplemented by a new one. Mixing old and new oil restored the oil charge. Today, it is unimaginable because of emissions. Today, there is a pressure to extend oil change intervals and also because of the ecology of the environment (Synlube, 2010).

In addition to lubrication oils and oil filters also have the following functions:

- Cooling: they absorb and dissipate the heat from the friction point and combustion space
- Cleaning: pollutant particles generated by friction are washed away into the oil filter where they are captured. (MJauto, 2009).

Oil filters are now available in two basic designs, as the cassette or the insert version. Cassette oil filters (spin-on) are used for filtration of oil in combustion engines. Newly designed engines use such filters less and less. Previously appreciated advantages such as high resistance to damage, easy replacement of worn filters and almost eliminated risk of dirt in the oil system, are no longer a priority. In terms of ecology filter cartridges in removable casing are preferred. Cassette oil filters are very similar in external appearance, but they vary in their internal structure. The operating parameters and structural properties of this filter group must ensure proper operation of the engine oil system. Particular attention should be paid to valves, which are located inside the filter, because they are crucial for the proper function of filters in the oil system. According to the type of construction the cassette filters are equipped with reversible or relief valves (Filtron, 2009).

The full flow cassette filter contains a bypass relief valve that allows continuous lubrication even with a clogged insert or in dense oil. The rule applies, it is better to lubricate immediately after starting the engine and during operation with any oil, than not to lubricate at all (Ždánský, 2000).

The material used for the filtration of engine oil can is usually filter paper based on cellulose fibers impregnated with special phenolic or epoxy resins, protecting it from the influence of high temperatures and aggressive chemicals. The filter materials for filtration of synthetic oils are used admixtures of synthetic fibers or fully synthetic materials. The reason is a greater strain on the filter septum. To increase the absorption capacity of the filter multi-layer materials with different structures and different filtration properties of each layer are used. Combining these materials can achieve the effect of the selective separation of impurities on each layer. The result is a considerable increase in absorption of impurities (Filtron, 2009).

2.3 Hydraulic filters

The high degree of purity is also required for hydraulic fluids. It is proved that over 80% of failures in the hydraulic system are caused by impurities in the liquid.

The primary contaminants penetrate into the hydraulic circuit when filling liquids and during the maintenance and repairs. They appear in the form of chips from machining, debarring of metal and rubber parts, sand, paints etc. Other impurities penetrate through vent valves and filling over poorly sealed joints such as pour through lid containers, vents etc. Dirt flowing into the system has an influence on corrosion and erosion of entire pipes. Impurities from the fluid are created by thermal-chemical changes such as aging and wear of the pressure liquid, clogging debris from the factory, etc. (Škopán, 2004).

The suction filters have the function of gross pre-filtration protecting the hydraulic pumps. They consist of a system of sieves with a mesh size of 40–20 μm. They are usually placed directly on the suction pipe in the tank forming a suction basket. Pipes are equipped with a bypass valve (bypass) to ensure a continuous supply of oil at filter clogging or high viscosity oil. As the pressure for hydrogenerator can reach up to 41 MPa, inserts are enclosed in metal and sufficiently resistant cases. The filters protect particularly sensitive valves, hydraulic motors, brake systems, etc. In addition to the resistant casing the filter containers are equipped with an electro-visual indicator of the state of the object and with a magnetic insert for the fine filtration. Waste filters are often put in the return line. Filters must have low resistance and high flow. Otherwise, there is an increase in pressure in the hydraulic circuit and the hydraulic engine does not operate as required. Only for the purpose of improving the overall purity content, can be inserting Additional filters can be inserted when improving of the overall purity content is needed. Such a design consists of a low-pressure filter and a self-propelled pump or it may be powered from the main pump. There is also a portable version of the device, which according to the needs and at specified intervals cleans the entire contents of the tank with hydraulic fluid (Škopán, 2004).

2.4 Engine intake air filters

Originally damp sieves were preferred for filtration, later wet oil filters and currently dry type of filters are used. The filter should have a high efficiency to capture a large amount of debris while having little resistance in the intake. Another prerequisite is a good occlude ability of excessive noise from the intake. 1 m^3 intake of ambient air contains approximately 0.001–1 g of dust with size from 0.005 to 0.05 mm. These particles are very easy to clump together in the intake and combustion chamber, where, together with the engine oil they create an abrasive paste (Ždánský, 2003).

Progress in the design of filters and filter materials caused that currently manufactured air filters achieve filtration efficiency up to 99.9%. Taking into account that during combustion process the engine consumes large quantities of air (on average about 10 m^3 of air per 1 liter of fuel), it is difficult to maintain the filtration efficiency on the optimal level throughout the life of the filter (Filtron, 2009).

A properly designed air filter will not only enhance the life of the engine but also reduce the regeneration and maintenance cost of the filter itself. Usually air filters are designed for better flow efficiency and better acoustic performance. The acoustic performance is important, because government regulations dictate the maximum air mass flow level that vehicles can make during a pass by test. The speed of air generated by the intake system can be a significant contributor to the noise levels. A complete understanding of the flow dynamics of an air filter is important, since a properly designed air filter can deflect and distribute air in such a way that major dirt will be separated out before it enters the main filter. If the flow distribution is proper, the loading on the filter will be uniform, replacement intervals can be improved. Mathematical and numerical modelling nowadays plays an important role in the better understanding of filters and designs a better air intake system (Manikantan, Gunasekaran, 2013).

Circular air filters (i.e. the insert in the shape of a ring or cylinder) have a traditional design used for passenger cars. The engine compartment for the air intake has been considerably diminished. Therefore, systems with circular filters are already replaced by panel filters which are characterized by favorable ratio of filter area to volume casing (Filtron, 2009).

The filter element is made of a composite paper suitable for achieving a large specific surface area. This design is very simple and popular with all current cars. The service life of the inserts ranges from 10 000 to 50 000 km. It is produced only as a single use without renewal. (Ždánský, 2003).

2.5 Cabin filters

Dust filters, also called cabin filters are used to clean the air taken in directly above the road surface and blown through the ventilation or air conditioner into the cabin of the car. Today they are fitted in the cars of the lowest price classes. The presence of dust filters is a result of the fact that the manufacturers ensure the comfort and safety of the crew. Rapidly emerging fatigue, allergies, hay fever, watery eyes and breathing problems have a negative impact on the acumen of drivers and can become a real threat to road safety. The only way to prevent this is the air filtration.

The air contains various impurities: fixed – such as dust, soot, ash, spores, fungi and mould, plant pollen, dust mites and even insects. Liquid – in the form of different types of mists and water solutions that float over the ground, especially during atmospheric precipitation. And gas – as harmful hydrocarbons, sulphur and nitrogen compounds that come from automobile exhaust and industrial emissions. The concentrations of different types of pollution depend on the season, weather, local industry concentration and intensity of the road transport. The cabins of cars that are not equipped with a dust filter, the air can include up to six times higher concentration than outside the car. Human respiratory tract absorbs most of the impurities from the air. Particles larger than 10 µm are retained in the nose and mouth. In the trachea and bronchi are absorbed impurities size 3 to 10 µm, while contaminants smaller than 3 µm are no problem reach to the pulmonary cellars. Lungs do have self-cleaning ability, but impurities in the form of solid particles and gases can be long-term harmful to human health (Filtron, 2009).

Cabin filters supplemented with activated carbon form a separate group. The filtration medium is composed of two layers (coarse and fine), synthetic fabrics, capable of capturing particulate matter and aerosols with efficiency comparable to conventional cabin filter. The third layer of filter media consists of granular activated carbon, which is inserted between the fabric and cleans the air from the gas.

Note: Activated carbon has a porous structure similar to graphite. It attracts harmful gasses to its surface due to a phenomenon called absorption. Exploded surface of one gram of activated carbon is almost 900 m^2 and therefore the amount of captured gas can be very large. Practically, the amount of activated carbon in the filter allows to eliminate about 90% of pollutants, such as ozone, hydrocarbons, sulfur and nitrogen mixture (Filtron, 2009).

The main features of congestion and saturation of the cabin filters are:

- Occurrence of foggy haze in the cabin of the car, which is difficult to remove
- Strong odors when starting the car

- Loss of power for the currents of the air ventilation (MJAUTO, 2009).

2.6 New materials for the manufacture of filters

Some last types of filters can be made of ceramic powder and, upon replacement, it may be treated and reused as such, or it may be crushed, treated and remanufactured from the recycled powder. In the process, the entirety of the used motor oil may be retrieved, treated and reused, thus conserving energy and resources, minimizing waste streams and, most importantly, preventing environmental ground-water contamination. The ceramic filter element (made of silicon carbide, cordierite or mullite) is extruded in the typical configuration of a honeycomb-shaped monolith, with adjacent channels plugged at alternate ends. The element is housed in an easy-to-dismantle casing. The filter element may be replaced at every vehicle oil change, but not the casing which is intended to last the lifetime of the engine. The ceramic elements can be manufactured to possess high-filtration efficiency characteristics and have large contaminant accumulation capacity (LEVENDIS, 2013).

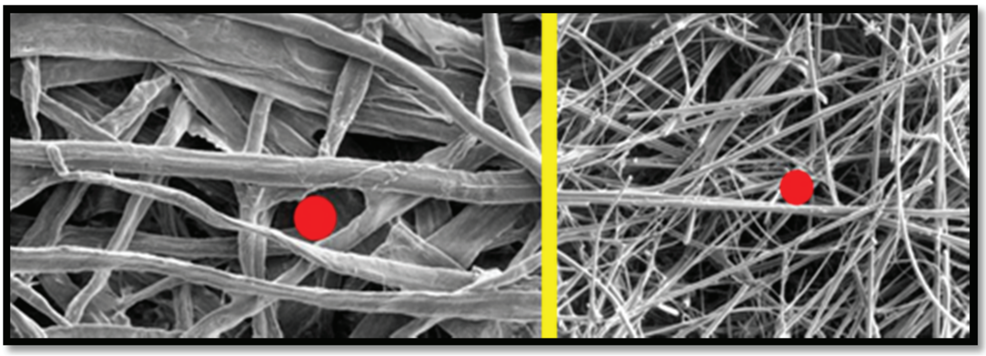
When we add a small layer of nanofibers into traditional filter substrates, the performance of the filter increases several times. This technology can produce a miniature layer with exactly given characteristics and dimensions of the nanofibers. The resulting structure meets the current needs of the filtration industry. Properties of commonly used synthetic, cellulosic or composite fibers are overcome in most cases (DONALDSON, 2012).

From an economic perspective, the use of nanofibers in filtration media is obvious: Affordable substrate + tiny nanolayer = higher quality at a lower price. A thin nanolayer can be incorporated into the existing filter material or as a completely separate filter membrane. Nanofibers made by industrial technologies based on electrospinning increase efficiency and facilitate filtering of liquids in various industries. The current use of membranes does not count only on filtering air, fuel and oil, but also on modification of water, beverages, pharmaceuticals, blood, chemicals, etc. (ELMARCO, 2012).

Unlike polymer, where there is usually no need for post-electrospinning process, ceramics nanofibers can be made from electrospinning of the ceramic precursors and followed by sintering of the electrospun fibers to derive ceramic fibers. Ceramics are materials that composed of both metallic and non-metallic elements and commonly exist as compounds of oxides, nitrides and carbides. As the atomic bonding is either ionic and / or covalent, there are no „free“ electrons in ceramics making them, excellent insulators. The strong ionic and covalent bonding gives the complex structure of ceramics many advantages such as high temperature stability, resistance to chemical attacks and adsorption of foreign. Such rigid configuration also gives ceramics their brittleness. With advances in technology, ceramics have move away from traditional applications which depends largely on its insulating properties and mechanical hardness. Ceramics have found uses as biomaterials, such as calcium carbonate-based ceramics and hydroxyapatite ceramics. Nanoscale ceramics are being manufactured and found huge potential in many areas due to its high surface area to volume ratio (RAMAKRISHNA *et al.*, 2005).

2.7 Basic characteristics of nanofibres and their effectiveness

- The fiber diameter is smaller than 1µm: standard size between 0.075 to 0.250 µm; according to the needs the diameter can be greater.
- A large surface area and high porosity, permeability: high porosity 60–90%, a pore size of 0.1 µm and 3 µm, a narrow scatter pore size dispersion, a specific surface area 10–100 m^2/g = low weight (Fig. 2).
- Efficiency and optimization of the air flow: the integration with many different types of substrates, the availability of highly breathable composites with a high filtration efficiency.
- A wide range of materials: a wide range of known polymers and their mixtures, the ability to incorporate the additives (antibacterial silver) into the nanofiber structures (ELMARCO, 2012).



2: *Comparison of cellulose fibers – left and right – nanofibers: the red dot symbolizes the impurity about the size of 20 microns (eg, dust and mold), (AMSOIL, 1996–2010)*

I: *Comparison size of filtered particles*

Filtered medium	Type particle	Size of particles [μm]	Reason filtration
Honey (Burlesons, 2009)	Parts of bees, wax, pollen	0.1 up to 10	Premature crystallization of honey
Diesel fuel (FA-ST, 2008)	Attrition and other particles	2 (ISO 4406 counts 4)	Premature wear
Bacteria (Bionumbers, 2010)	E. Coli	2	Health and environment allergies
Mold and spores (Engineeringtoolbox)		5–30	
Viruses (Engineeringtoolbox)		0.005 up to 0.3	
Pollens (Engineeringtoolbox)		10 up to 1 000	
Dust (Engineeringtoolbox)	Coal	1–100	
	Atmospheric	0.001 up to 40	
Automobile emissions (Engineeringtoolbox)		1–150	Health and environment

CONCLUSION

These facts confirm that modern filters are an indispensable element of machinery systems. Their other application is still growing even in places where they supply or completely replace conventional filters. This need is evident for example in cars with older production date, where the degree of filtration is still sufficient. However, completely unsatisfactory for newly manufactured vehicles. Modern vehicles are more sensitive to the presence of impurities due to miniaturization of components and increasing work pressures. Competition is one of the reasons, why the price falls down, which often does not match the quality and minimum parameters required for conventional filters. Taking into account the real risk of damaging especially new types of engine when refueling poor quality fuel or fluids, then we are facing a serious problem. One of the ways, how to solve this situation effectively and permanently, is to use the nanomaterials for filtration. Their wide range of filtration and specific features allow to exceed the limit of existing conventional filters and move it to the separation of smoke, soot, other harmful gases and even viruses. Applying nanofibres can be used with existing filters. Newly discovered technologies allow to make spun almost any material, such as polyvinylalcohol (PVAL), polyamide (PA) and polyurethane (PU), etc.

These materials can be added with some antibacterial components (fungicides, titanium oxides, activated carbon and antibacterial silver). Different combinations of technologies have improved the mechanical and thermal resistance of nanofiltres. However, filtration at elevated temperatures still remains an inadequately certified area. The oil filtration made with spinning teflon may serve as an example. The spinning teflon (PTFE) is resistant to high temperatures and has non-stick surface = better hydrophobic properties. By obtaining such unique properties it will be possible to protect machines against damage, but also human health. A .large amount of sulfur is still emitted into the atmosphere due to the activities of industrial production, which are the main source of the acid rain and is harmful for our ecosystem. We are constantly improving and optimizing fuel combustion. But this leads to the formation and leakage of even smaller particles such as soot and ash into the air. People moving often in traffic jams in cities breathe these particles through their lungs and get them up into the bloodstream. The application of nanomaterials with small pores and large surface area, is one of the ways, how to eliminate these consequences and hazards effectively.

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