PM-Metalit Advanced – the Innovative Particulate Filter for Nanoparticle Reduction

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Kurzfassung:

Zukünftige PKW (Otto und Diesel) sowie Heavy-Duty Emissionsgesetzgebungen fordern neben der Partikelmassenreduktion auch eine Verminderung der Partikelanzahl. Herkömmliche Filter, mit heute üblichen Porositäten und in Verbindung mit neuen niedrig Ruß emittierenden Motoren, können aufgrund des fehlenden Rußfilterkuchens die Feinstpartikel nicht mit ausreichender Effektivität filtern. Eine notwendige Verkleinerung der Porengröße resultiert in höheren Druckverlusten.

Der PM-Metalit Advanced stellt eine neue Generation von Partikelfiltern für den automobilen Einsatz dar. Aufbauend auf dem bewährten Nebenstrom Tiefbettfilter-Konzept wird vor allem die Abscheidung der Nanopartikel durch elektrostatische Kräfte als „Diffusions- und Adhäsionsverstärker" verbessert. Die in einem elektrischen Feld aufgeladenen Partikel können zu weit über 90 % ohne Gegendruckerhöhung abgeschieden werden.

Der Vortrag beschreibt die theoretische Auslegung, den Aufbau und Testergebnisse mit dem PM-Metalit Advanced.

Abstract:

Future emission legislation for passenger cars (petrol and diesel) and heavy-duty vehicles will require a reduction in particle numbers alongside a reduction in particle mass. Conventional filters that combine current levels of porosity with new, low soot-emitting engines are unable to filter nanoparticles with sufficient effectiveness due to the lack of a soot filter cake. The necessary reduction in pore size would lead to greater pressure loss.

The PM Metalit Advanced represents a new generation of particulate filters for the automotive industry. Building on the proven partial-flow deep-bed concept the separation of nanoparticles in particular is improved by the application of electrostatic forces, which act as a diffusion and adhesion booster. The system is able to separate well over 90% of particles that have been charged in an electric field without any increase in backpressure.

This paper describes the theoretical design, the construction and test results using the PM Metalit Advanced.

1. Introduction

EU 6 legislation for passenger cars and EU VI legislation for commercial vehicles for the first time also limit particle numbers alongside gaseous emissions and particle mass. Attention is focused mainly on the reduction of nanoparticles, which are considered harmful to health. Table 1 lists the relevant limits for diesel engines.

	Passenger Car			Heavy Duty (ETC)		
limit value	PM [mg/km]	PN [#/km]	NOx [g/km]	PM [mg/kWh]	PN [#/kWh] (in Diskussion)	NOx [g/kWh]
EU 5 / V	5	-	0,18	30	-	2,0
EU 6 / VI	4,5	6 x 10^{11}	0,08	10	6 X 10^{11}	0,4

Table 1.1: Heavy duty EU V/VI and passenger car EU 5/6 limit [1]

Particle number limits for commercial vehicles and for passenger cars with petrol engines are still under discussion. The original approach to limiting particle numbers included the following points.
The number limit should correlate with the mass limit and also be based on best available technology.
However, this poses the question as to what is best available technology and whether it also represents the best technology to meet the new requirements of particle number reduction.

The EU PMP project (Particulate Measurement Programme) created a database for passenger cars and commercial vehicle engines. However, measurements and comparisons of particle mass and particle number did not distinguish between raw emissions and tailpipe emissions. In particular, the correlation of tailpipe emissions did not take account of the different filter rates during number and mass measurements.

For example, a mass limit of 10 mg/kWh relating to the raw emissions from a typical commercial vehicle diesel engine corresponds to a number limit of approximately 1 x 10^{13} particles per kWh [2]. By contrast, the currently discussed heavy-duty limit of 6 x 10^{11} particles/kWh would correspond to a raw emission mass limit of less than 1 mg/kWh. As a result, particle number legislation stipulates a ten times more stringent mass limit. Engine-based measures and optimised combustion processes reduce consumption and emissions and hence also particle mass.
Hastily introduced particle number limits will hinder or even prevent further engine developments that could give European engine manufacturers a competitive advantage over the rest of the world. These innovative engines are able to meet the mass limit but still require a particulate filter to comply with the number limit, which increases fuel consumption and hence CO_2 emissions (because of greater pressure loss and the necessary active regeneration measures).

The aim must therefore be to meet future limits with a minimum of pressure loss and without active regeneration measures. It goes without saying that the potential costs of exhaust gas aftertreatment have to be substantially reduced at the same time.

2. Filter technologies

Particulate filters for automotive applications are subject to very high technical requirements because of high temperatures and rapid temperature changes. The separation rate for particles in the 10 to 500 nm size range should be significantly above 90% while pressure loss should be kept to a minimum.
Figure 1 shows the separation rate of technical filter systems as a function of particle diameter in the 0.1 – 100 µm range.

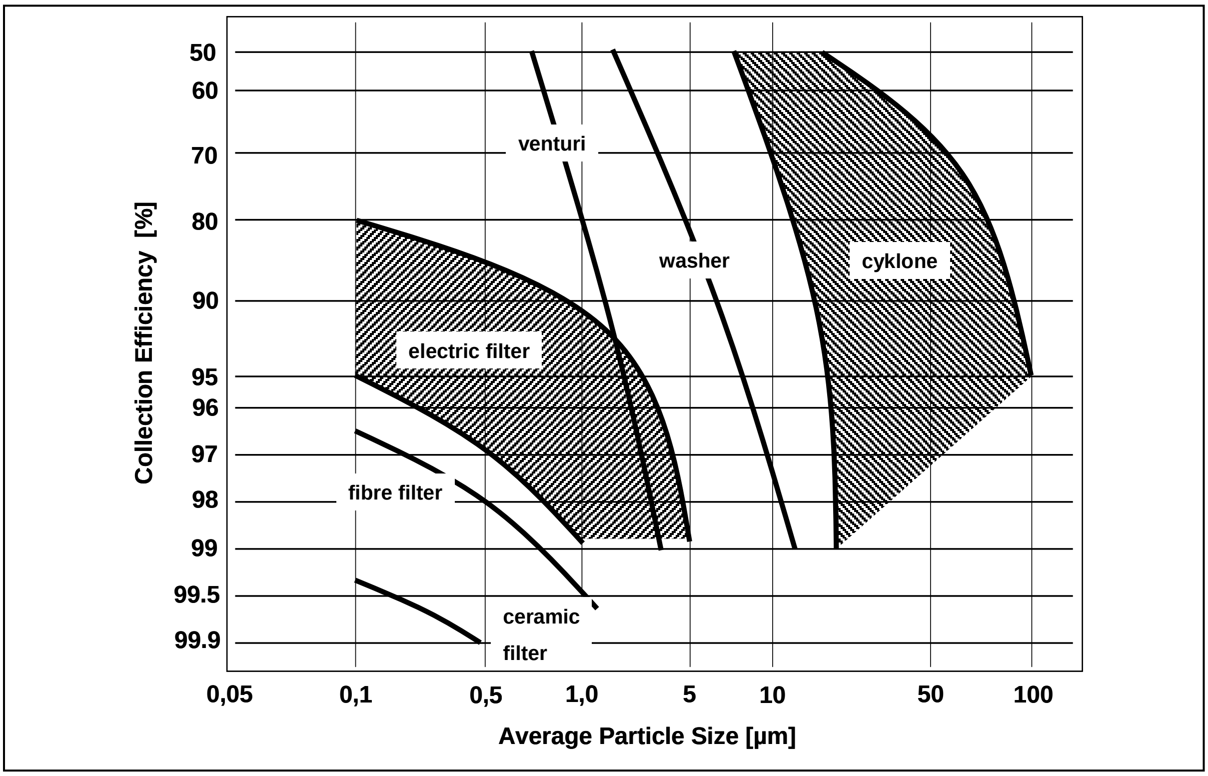

Figure 1: Separation rate of technical filter systems as a function of particle diameter [3]

The overview shows that structures with a large surface area that are made from high-temperature-resistant materials are particularly suitable. However, conventional electric filters also had high filter rates for small particle sizes.

2.1 Operating principles of particulate filters (depth filters)

For small particle diameters the separation of particles, solids or droplets is not based on a barrier effect (sieve effect) but on a combination of inertial separation (impaction) by interception from a limiting particle path (interception) or by molecular movement of extremely small particles (diffusion). Figure 2 shows the effective range of the filter mechanisms in relation to particle diameter.

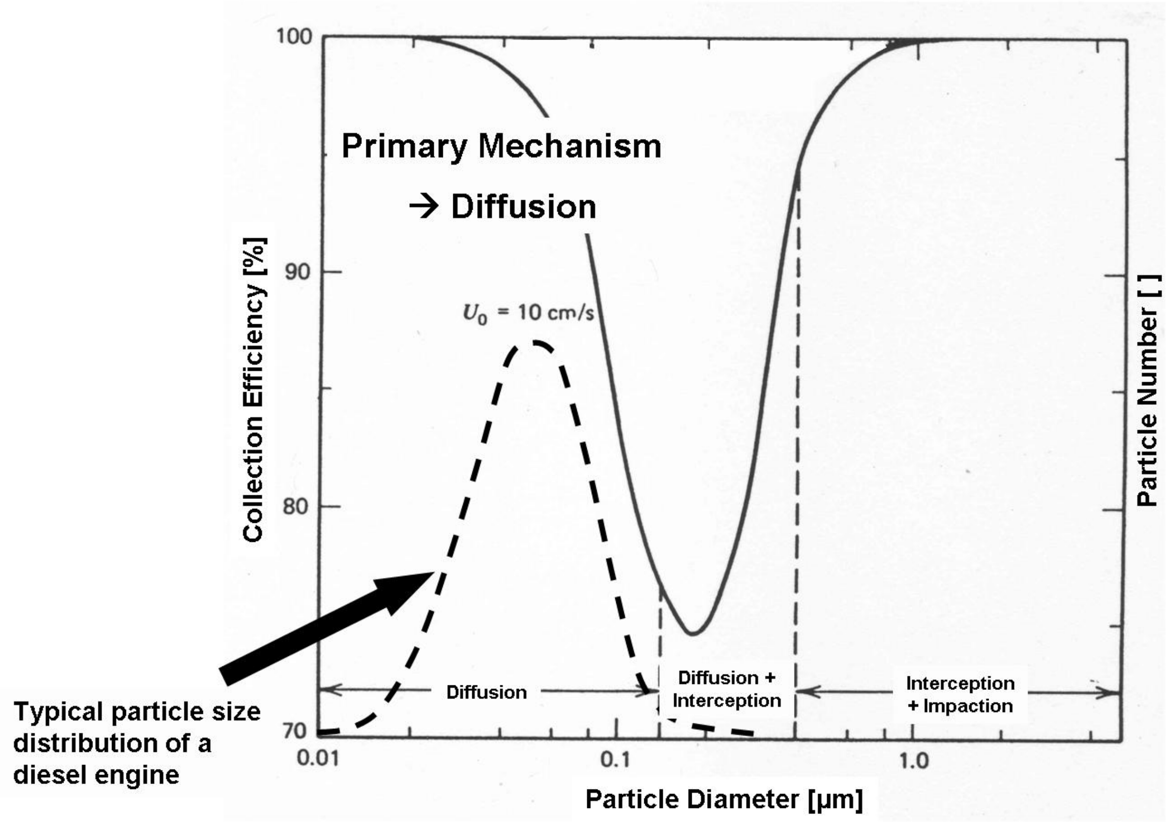

Figure 2: Filter efficiency of a depth filter as a function of particle diameter and filter mechanisms [7]

The probability of a particle being filtered depends on the filter structure, the pore size of the internal surface, the flow speed and the filter thickness and hence the retention time. Surface adhesion is generally due to van der Waals forces.

It is important that filters are not only able to separate but also retain the deposited particles.

Particles already deposited on filter surfaces agglomerate and form a filter cake. This filter cake, which consists of loosely deposited soot, increases the internal surface and thus improves the separation rate. Pressure loss rises simultaneously. As the soot is deposited the depth filter becomes a surface filter with increasing filter efficiency. Partial-flow filters take this fact into consideration by directing only part of the flow (=> lower speed => greater filter efficiency) through the filter medium and compensate for this by repeating the process several times.

2.2 Electric filters

Electric or electrostatic separators are systems that separate particles from gases on the basis of an electrostatic principle. Coulomb's law states that charges repel or attract each other. In 1906 tests carried out by F. Cottrell led to the first successful commercial application in the separation of sulphuric acid mist at the Pinole powder works and the Selby ironworks.

Separation in electric filters can be divided into 5 stages [4]:

1. Generation of electric charges

    Electric charges are generated in an electric field. An electric field is the space between two differently charged objects. Electric field strength is determined by the voltage and the distance between the objects. The electrostatic field does not change in time, so no magnetic field exists.

2. Charging particles in the electric field

    Particles are charged by negative charges that collide with and adhere to the particles as they enter the space through which the spray current flows. The process is based on field and diffusion charging; field charging primarily applies to particles > 1µm (figure 3).

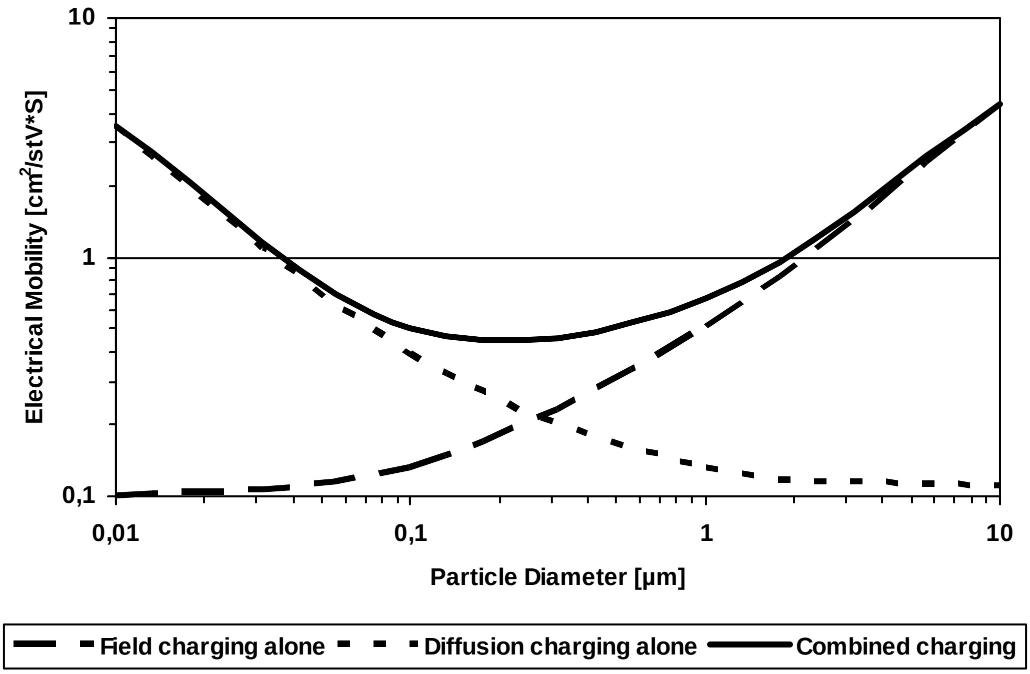

Figure 3: Charging process of a particle in an electric field as a function of particle diameter [4]

3. Transport of charged particles to the collecting electrode

    Stokes' law states that charged particles travel to the collecting electrode where they discharge their energy.

4. Particle adhesion to the collecting electrode

    After the particles have discharged their energy they adhere due to adhesive forces generated by the electric field strength in the deposited particle layer and the adhesive forces acting between the particles themselves and between the particles and the filter wall. Particles are considered to have been separated when the adhesive forces are stronger than the flow forces.

5. Particle removal

> Industrial electric filters are usually cleaned by brushing the particles from the collecting electrode. The removed particles fall into a bunker from where they can be disposed of. In automotive applications electric filters will have to be continuously regenerated.

Flue gas cleaning in power stations is known to achieve filter efficiencies of up to 99.9%.

2.3 Electric filters for automotive applications

Automotive applications are primarily concerned with the separation of soot particles. Electric filter processes have been used by the automotive industry in the past. One of these processes involves what is referred to as a soot deflector, where particles are separated, but not regenerated, in an electrostatic separator. After reaching a critical size the agglomerated particles are removed by the gas forces. Under the influence of inertia the agglomerated particles can be separated into a clean and a particle-rich partial flow. The particle-rich flow can be filtered by a particulate filter in the conventional manner and regenerated discontinuously – similar to the process taking place in a wall-flow filter – or separated in a cyclone.

Electric filters for mobile applications should aim for continuous regeneration on the precipitation electrode. Continuous regeneration uses the NO_2 contained in the exhaust gas. Large surfaces are required to make sure that the reaction continues to the point of completion, particularly at low temperatures, and to guarantee and achieve interaction between the NO_2 and the particles. This means that it is necessary to distribute the particles across the largest possible separation surface to facilitate the reaction with NO_2.

Due to the general increase of the particle diameter particular attention must be paid to particle measurements because the permeability of the sampling points, for example, can increase with expanding particle diameters.

3. Calculation of electrostatic soot particle separation [5] [6]

A corona discharge consists of an active and a passive field. Electrons are released in the active field.

In the passive field of the corona discharge the particles are charged by negative ions. This process is based on two mechanisms. The first mechanism is field charging where the particles are charged by ions that move in the direction of the electric field. The charge of the particles depends on the electric field strength E. In diffusion charging, the second mechanism, particles are charged by random collisions with thermally moved charge carriers (cf. figure 3)

The electric field strength E for a wire/cylinder electric filter is calculated on the basis of the following formula.

$$E = \frac{U}{r \cdot \ln\left(\frac{r_T}{r_W}\right)} \qquad (1)$$

E = electric field strength [V/m]
U = voltage [V]
r = radial position of particle [m]
r_t = tube diameter [m]
r_w = diameter of wire electrode [m]

Particles that move through the electric field become charged.
The saturation charge of the particles, taking account of both charging mechanisms, can be calculated according to Cochet.

$$q_{sat} = \left[\left(1 + \frac{2 \cdot \lambda}{d_p}\right)^2 + \left(\frac{2}{\left(1 + \frac{2 \cdot \lambda}{d_p}\right)} \right) \cdot \left(\frac{\varepsilon_r - 1}{\varepsilon_r + 2} \right) \right] \cdot \pi \cdot \varepsilon_0 \cdot {d_p}^2 \cdot E \qquad (2)$$

q_{sat} = saturation charge [C]
λ = free path of gas molecules [m]
d_p = particle diameter [m]
ε_r = relative dielectric constant of particles [-]
ε_0 = dielectric constant of the free space [C/Vm]

The division of q_{sat} by the elementary charge e gives the number of charge carriers $n_{e, sat}$.

$$n_{e,sat} = \frac{q_{sat}}{e} \qquad (3)$$

$n_{e, sat}$ = number of absorbed charge [-]
e = $1.6 * 10^{-19}$ [C]

Figure 4 shows how the charge depends on electric field strength and particle diameter for typical voltages.

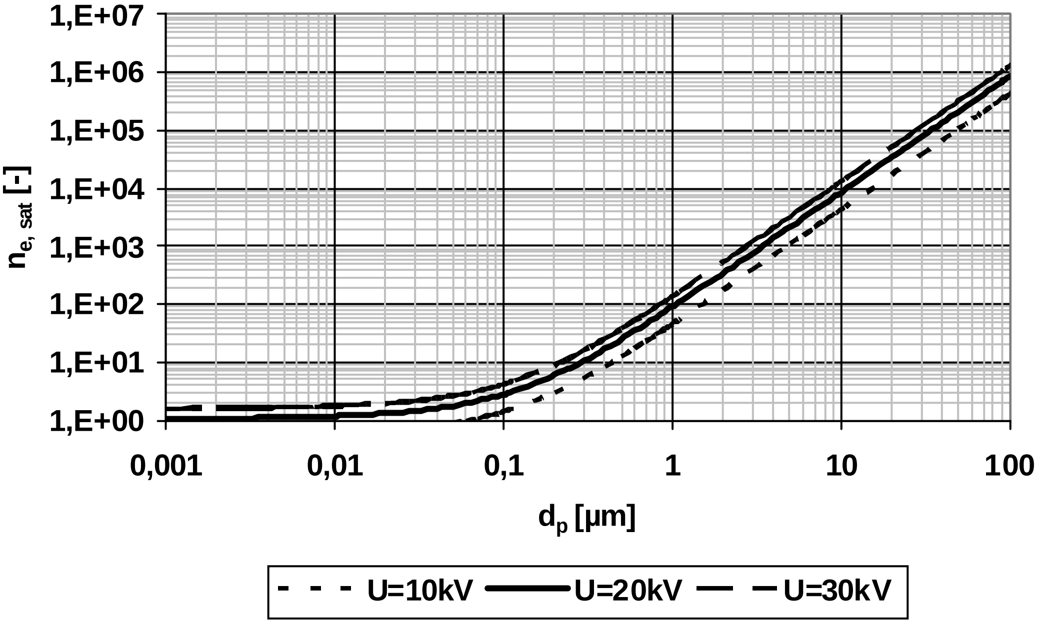

Figure 4: Correlation between electric charge and particle diameter for different voltages

The actual charge applied to a particle in relation to time and time constants can be calculated as follows.

$$q_p(t) = q_{sat} \cdot \frac{t}{t + \tau_Q} \tag{4}$$

$$\tau_Q \approx \frac{4 \cdot \varepsilon_0}{j_{NE}/E} \tag{5}$$

$q_p(t)$	=	charge as a function of time	[C]
t	=	time	[ms]
τ_Q	=	time constant	[ms]
j_{NE}	=	current density	[A/m^2]

The migration speed can be determined on the basis of the calculated particle charge. A charged particle is subject to an electrostatic force F_{el} and an opposing resisting force F_w. A speed component exists as soon as the electric force is greater than the resisting force. The migration speed w_p can be calculated on the basis of this correlation.

$$F_{el} = q \cdot E \tag{6}$$

$$F_w = 3 \cdot \pi \cdot d_p \cdot \eta_F \cdot w_p \tag{7}$$

$$0 = q \cdot E - 3 \cdot \pi \cdot d_p \cdot \eta_F \cdot w_p \tag{8}$$

$$w_p = \frac{q \cdot E}{3 \cdot \pi \cdot d_p \cdot \eta_F} \qquad (9)$$

F_{el} = electrostatic force [N]
F_w = resisting force [N]
η_F = dynamic viscosity [Ns/m^2]
w_p = drift velocity [m/s]

The resisting force of particles in the free path of gas molecules 1 decreases and has to be corrected by applying the Cunningham factor Cu.

$$Cu = 1 + 2{,}429 \cdot \frac{\lambda}{d_p} + 0{,}84 \cdot \frac{\lambda}{d_p} \cdot e^{\left[-0{,}435 \cdot \frac{d_p}{\lambda}\right]} \qquad (10)$$

$$w_p = \frac{q \cdot E}{3 \cdot \pi \cdot d_p \cdot \eta_F} \cdot Cu \qquad (11)$$

Cu = Cunningham factor [-]

The deposition effectiveness of the particles can be calculated by using the drift velocity. This is based on the Deutsch formula.

$$T = 1 - e^{\left(-\frac{w_p \cdot A_T}{\dot{V}}\right)} \qquad (12)$$

T = separation effectiveness [-]
A_T = separation surface [m^2]
V = gas flow rate [m^3/s]

Figure 5 shows the separation effectiveness in relation to particle diameter and electric field strength in turbulent gas flow.

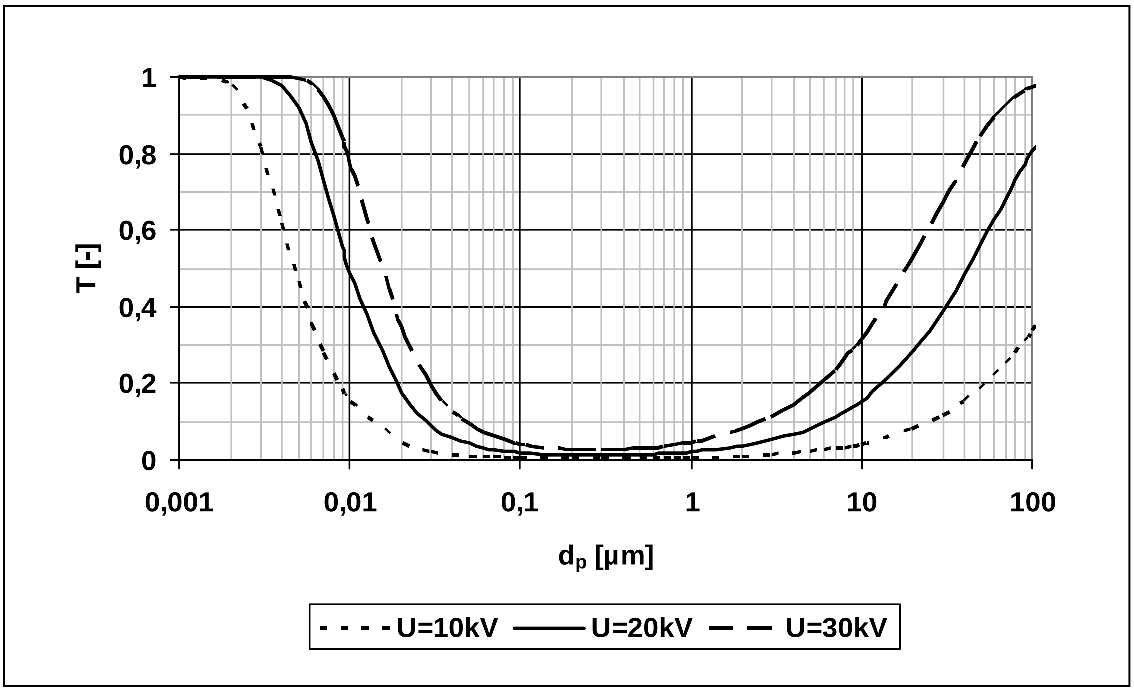

Figure 5: Separation effectiveness in relation to particle diameter and electric field strength in turbulent flow

The electric field strength and the particle diameter can be seen to have a great effect on the saturation charge and the separation probability. The separation probability, especially of small particles, also depends on the free path of the gas molecules and hence the temperature.

On the basis of the calculated force that acts on a particle via the electric field, separation can be simulated using CFD programs. Figure 6 shows one such example. The equations had to be adapted to the specific application, that is, separation in a channel with laminar flow. The less effective separation of larger particles highlights the need for flow modifiers inside the channels.

4. PM-Metalit Advanced

The development of electric filters, electrostatic agglomerators and soot deflectors with cyclone separators was started several times over the past 25 years. The trials failed because of the relatively high complexity of the equipment needed to generate high voltages in the exhaust system and particularly because of durability issues with the electric high voltage feedthrough in the exhaust system. In some cases soiling caused short circuits and electric flashovers after short operating periods. Due to high soot raw emissions in relation to NO_2 and the relatively small filter surfaces soot could not be regenerated passively and therefore had to be collected.
Modern high-voltage power supplies are only marginally larger than a mobile phone and include highly dynamic controls.

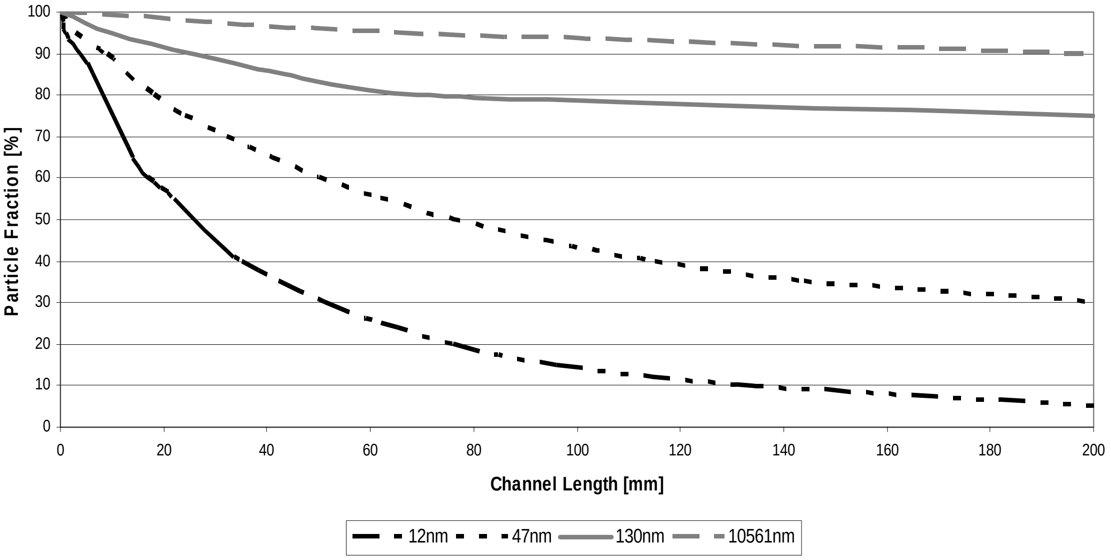

Figure 6: Calculated particle separation in a channel

Although an electric feedthrough is still required soot emissions from the engine are now significantly lower than in the past, which reduces the soiling tendency, and modern high-voltage power supplies can be controlled in a way that prevents short circuits.

As described in 2.3 electrostatic filters in cars must aim to oxidise the filtered soot by passive regeneration alone. This requires the soot to be distributed across a large surface to facilitate a reaction with the NO_2 contained in the exhaust gas. Plate electric filters provide large surfaces but are not mechanically suitable for use in an exhaust system.

Metal honeycombs have been used in catalytic converters of cars and two-wheelers for a long time and combine the advantages of mechanical/thermal durability, low pressure loss, large surfaces and electrical conductivity.

Therefore a metal honeycomb was developed that also functioned as a precipitation electrode. The design was based on the PM-Metalit partial-flow deep-bed filter and was particularly efficient at preventing deposited soot from being blown out during dynamic operations. The blades installed in the channels disrupt laminar flow and improve the electrostatic separation of larger particles. The PM-Metalit has already been put into large-scale production and proven itself in commercial vehicles and non-road applications for many years.

For maximum effectiveness the electric field has to be built up over the entire cross-section in front of the honeycomb as uniformly as possible (figure 7).

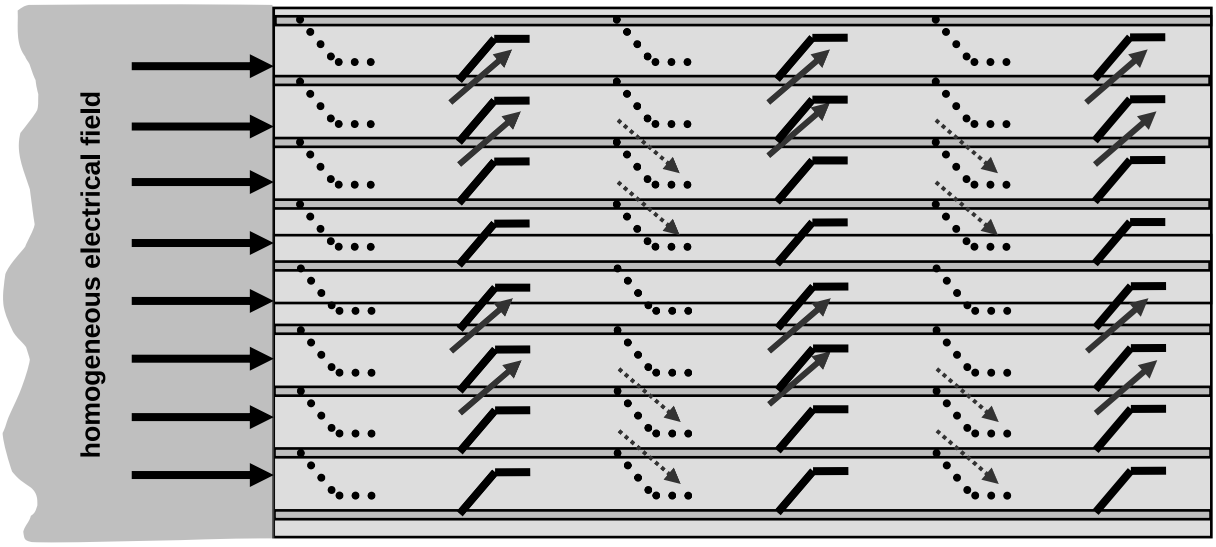

Figure 7: PM-Metalit partial-flow deep-bed metal filter as a precipitation electrode with guide blades in the channels

It is difficult to build up an electric field with just a single emission electrode, especially in case of large catalyst cross-sections. Several electrodes increase the complexity of the construction and would have to be electrically interconnected. Therefore a second metal honeycomb was designed to act as a current distributor. The electrodes can be soldered into the honeycomb. The number and form of the electrodes can be adapted to the specific basic conditions (figure 8).

Figure 8: Metal honeycomb as a current distributor with installed electrodes

High voltage insulation and mounting extends across the circumference of the honeycomb. Specially developed deflecting structures are used to prevent impurities. The electric field builds up between the tips of the electrodes and the precipitation substrate. Both the current distribution substrate and the precipitation substrate can be catalytically coated. Figure 9 shows the assembly and the electric field between the two metal substrates.

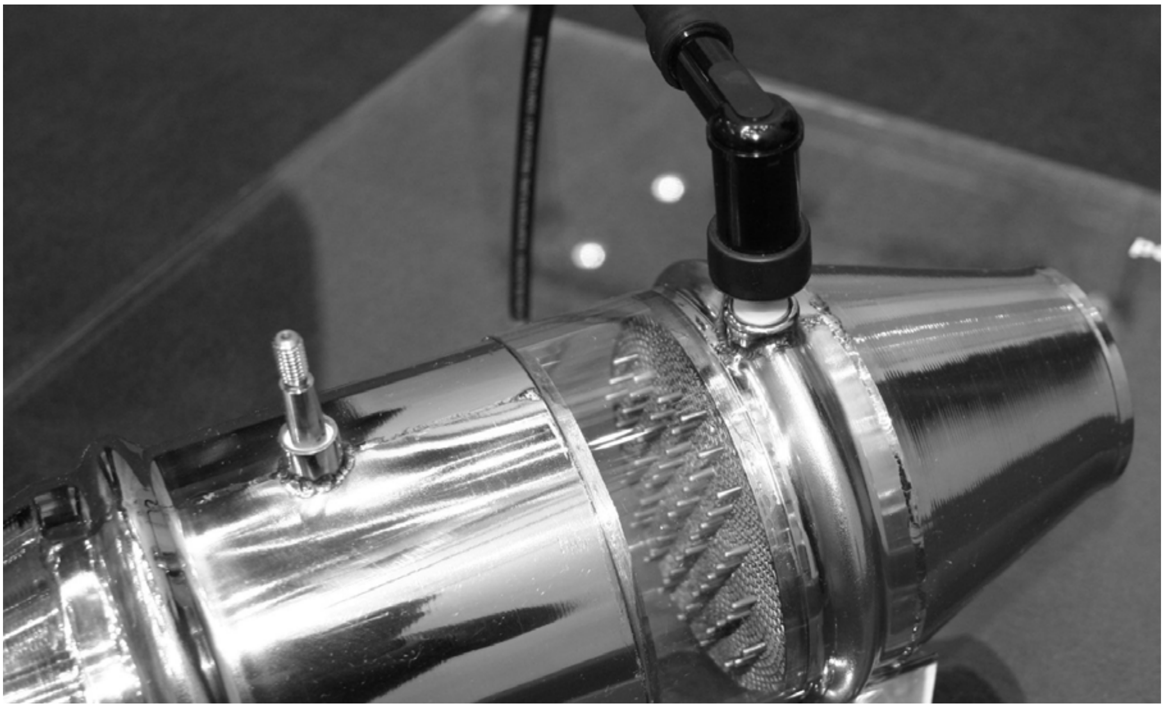

Figure 9: PM-Metalit Advanced consisting of a current distribution substrate with soldered electrodes and a precipitation substrate

This construction charges the particles electrostatically and thus increases the efficiency of the existing PM-Metalit filter. The electrostatic forces intensify the diffusion separation by adding another force component.

5. Test results

The PM-Metalit Advanced is currently in the predevelopment phase. First trials were carried out on a dynamic test bench using an EU IV car diesel engine. A distributor, which allows part of the exhaust gas to flow through a bypass, if required, was installed behind the exhaust gas turbine to perform mass flow variation regardless of engine operations.

The aim of the initial tests was to determine whether the soot deposits only formed on the end faces of the precipitation substrate or across the entire substrate. Therefore a metal substrate was eroded to form discs and fitted to the exhaust system with an air gap of 2 mm (figure 10).

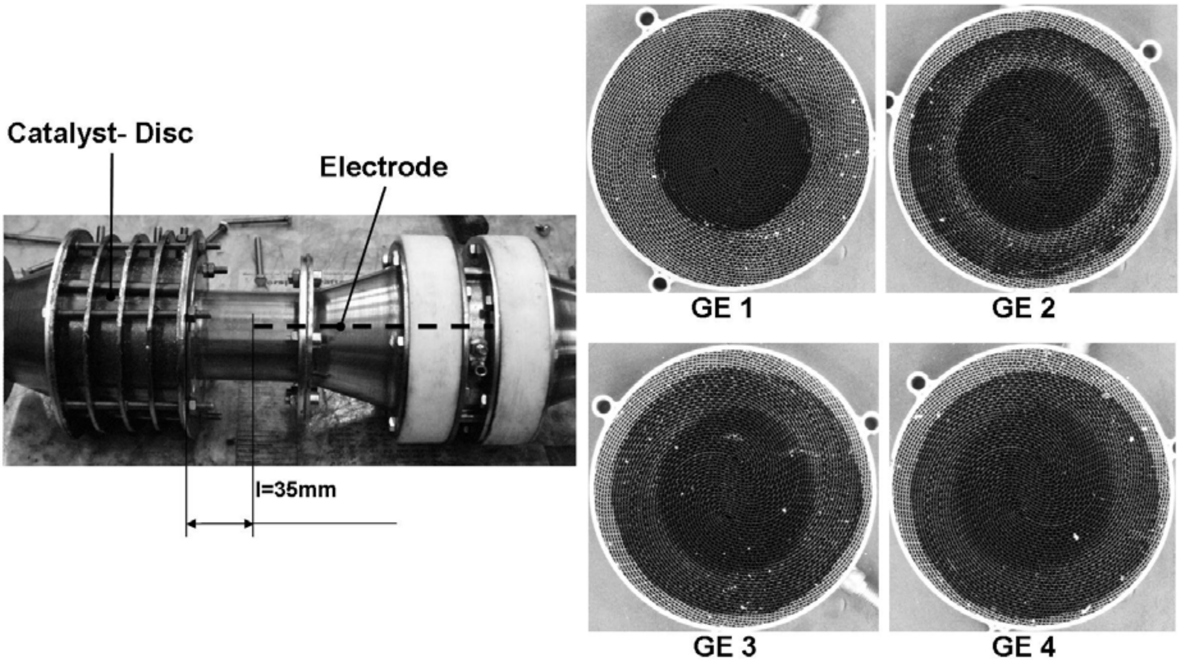

Figure 10: Test setup: Precipitation substrate in four discs with upstream single rod electrode

A single electrode was positioned at a distance of 35 mm in front of the separator. The design of the electrode and the distance were chosen so that the electric field would build up only across part of the substrate diameter allowing areas inside the electric field to be clearly distinguished from adjacent areas.
Figure 11 shows the rear sides of the catalyst discs.

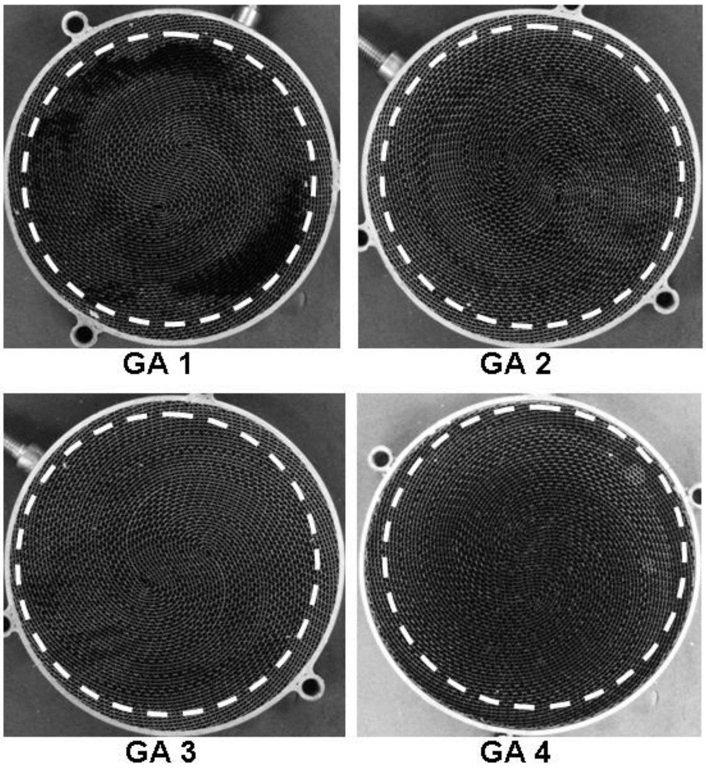

Figure 11: Rear sides of catalyst discs 1 – 4 (in flow direction)

Soot is clearly visible in the channels of the first disc. However, the deposits cover only the area inside the electric field. The gap between the discs allowed the gas and particles to exchange across the cross-section, resulting in a much larger deposition zone in discs 2 to 4. The fact that soot is visible also at the end of the last disc confirms the complete utilisation of the separation surface, which creates ideal conditions for passive regeneration.

The same test setup was used to measure particle mass reduction and number reduction at varying mass flows and constant voltage. Figure 12 shows the results.

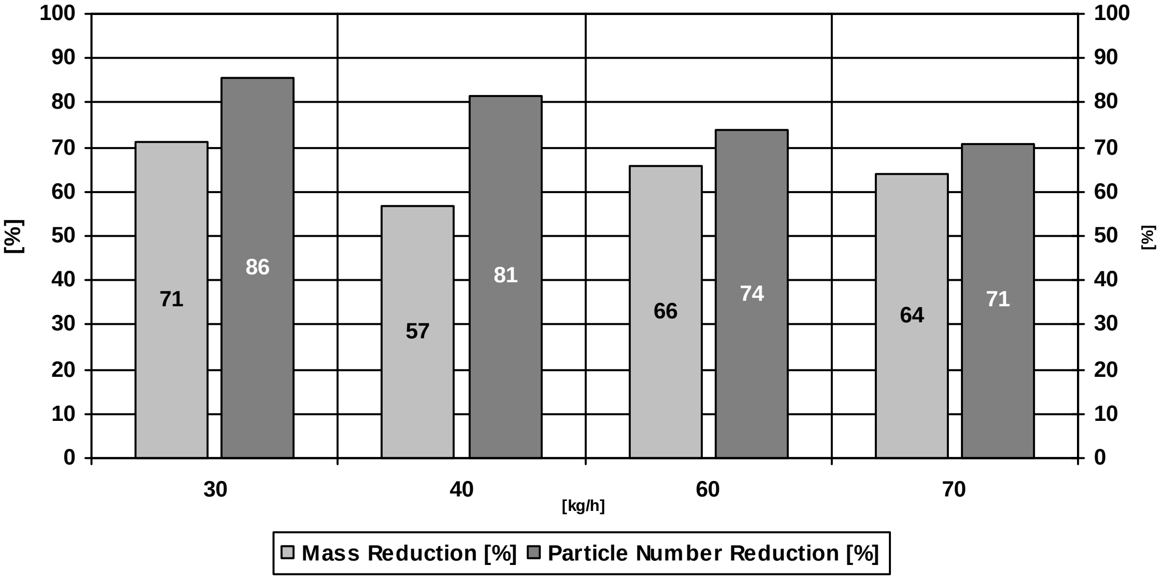

Figure 12: Particle mass and number reduction in relation to exhaust gas mass flow at constant voltage

At a constant voltage of 16kV particle mass was reduced by 60 – 70% and particle number by 70 – 85% depending on the exhaust gas mass flow. The result is even more surprising because the electric field as revealed by the results shown in figure 11 builds up only across part of the cross-section of the precipitation substrate.

A system with a multi-electrode similar to the setup in figure 9 was measured in a further test. Both particle number and particle mass effectiveness were measured. Particle mass and number were reduced by over 95% in the NEDC. For clarification particle number effectiveness was determined via particle size at a medium load point.

Figure 13 shows number effectiveness as a function of particle diameter.

According to the theory, number effectiveness depends on particle diameter and is over 95% in the 50 – 300 nm range. The result makes it clear that the electrostatic separation of soot particles in the channels of honeycombs with guide blades works successfully across the entire particle size range.

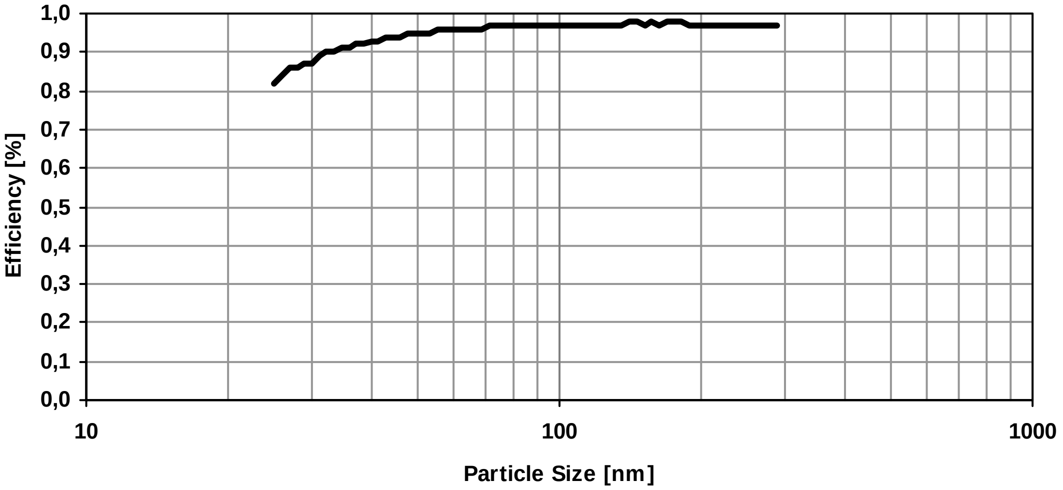

Figure 13: Number effectiveness in relation to particle diameter

6. Summary / outlook

The PM-Metalit Advanced electrostatic particulate filter for mobile applications represents a completely new development that is able to meet particle number limits with minimum pressure loss. First results indicate that the innovative use of metal substrates as current distributors and separators present a new method of particulate filtration. When used as a separator PM-Metalit substrates with small channels and guide blades achieve good separation rates for all particle sizes.
As a next step, both the power supply and the PM-Metalit Advanced will undergo further development with the aim of creating a durable solution for passenger car and commercial vehicle applications.
Apart from this development work it is crucial that policymakers restrict themselves to defining new limits and do not directly or indirectly express a preference for, or even prescribe, particular technologies. Such prescriptive legislation would put an end to innovation and place Europe at a disadvantage in international competition.

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