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Metal Supported Flow-Through Particulate Trap; a Non-Blocking Solution

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1. Introduction

In 2000 about one third of all newly registered vehicles in Germany were equipped with a diesel engine. By tradition, this share is even higher in countries such as France and Austria. The sharp increase in the number of diesel vehicles on the one hand is due to the low fuel consumption - applicable in particular to engines with direct injection - in conjunction with relatively favourable diesel fuel prices, but is on the other hand related to the “fun factor” also. Today’s diesel vehicles with their performance, impressive torque characteristics and comfort can hardly be told apart from comparable spark ignition engine vehicles.It is above all the lower specific fuel consumption (Fig. 1) and consequently the emission of the supposed greenhouse gas CO_2 – currently a hotly debated political issue, which evoke the interest of the automobile industry for the diesel engine. In view of the stronger appearance of diesel vehicles on the market, there is the possibility to come a great deal closer to the average fleet consumption values agreed in the “voluntary restriction on the part of the German automobile industry” for the year 2008. This results in a fleet average of 140 g of CO_2 in the new European test cycle.

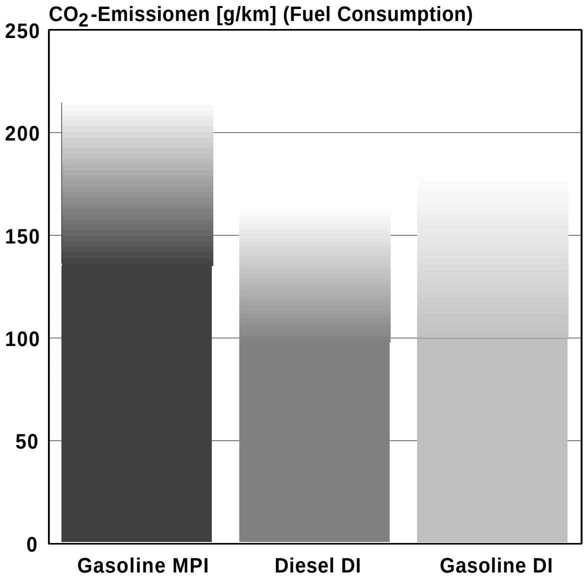


Fig. 1: Specific fuel consumption of several powertrain concepts

The look on world-wide exhaust legislation leads to the conclusion that the diesel engine has always been considered separately because of its lower fuel consumption as well as its lower raw emissions compared to spark ignition engines.

This is particularly true in the case of particle emissions, which are considerably higher than those from spark ignition engines. Fig. 2 describes the world-wide development of exhaust gas standards including particle emissions. Independent from the test cycle all values are shown in g/km.

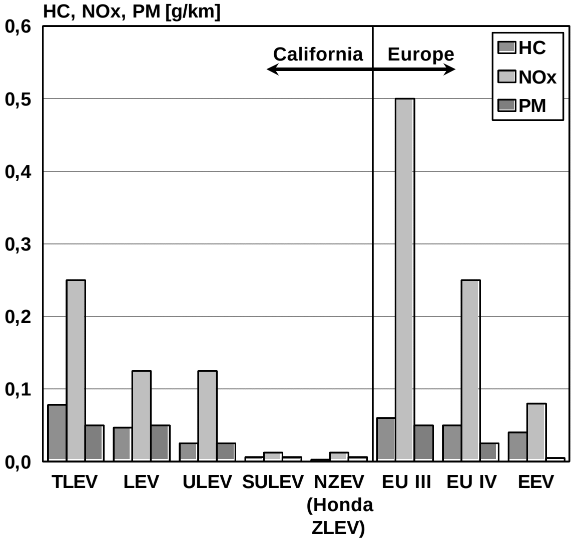


Fig. 2: Development of exhaust gas standards in the US/California and in Europe

HC as well as CO emissions from diesel engines can be oxidised by means of an oxidation catalyst similar to those used on an otto engine. However, the reduction of nitrogen oxides under lean (oxygen rich) conditions is more problematic. The three-way catalyst used in otto engines fails here. Technologies for the reduction of nitrogen oxides such as Selective Catalytic Reduction (SCR) with the addition of a reducing agent [1, 2, 3] or NOx Adsorbers used in otto DI [4, 5] could – in principle – also be applied here. Their utilisation has, however, not been required yet since up to today engine out emissions have always been reduced by means of further improved engine technology. The same applies to particle emissions.

The discussion whether particles and here specially the ultra fine sizes or the adsorbed polycyclic hydrocarbons have a negative effect on human health - and if so in what concentrations - has been going on for decades and no final conclusions have yet been reached. The legislator took precautionary measures and clearly reduced the value of permitted particle emissions (s. Fig. 2). New injection systems such as common rail with an increased injection pressure and related improved atomisation of fuel spray in the cylinder have resulted in a reduction of particle emissions so that until now no additional exhaust gas after-treatment by means of filter technologies has been required. Any further, major, engine-related reductions in nitrogen oxides or particle emissions from diesel engines can only be achieved, based on today’s combustion processes, to the detriment of one of both components. This means that either nitrogen oxides would have to be after-treated or a particle trap would have to be installed [6, 7].

2. Particle trap

"Wall flow" particle traps [8, 9] consisting of ceramic substrates with alternately sealed channels have been available for a number of years and have already been installed in mass-produced vehicles [10].

Such a filter can achieve an efficiency of more than 95% over the total range of particle sizes. In addition to chemical interactions with additives and special coatings, the safe regeneration, i.e. combustion of soot in all sorts of vehicle operation, still cause problems. With excessive amounts of deposited soot the exhaust gas back-pressure increases and during the soot incineration process, temperature peaks develop in the filter leading to mechanical damage. Therefore, silicon carbide is used in modern applications in view of its high temperature stability. In addition to the honeycomb filter, there are also filter candles with a carrier tube wrapped with ceramic or metal yarn [11] as well as plate filters made of sintered materials in the market [12, 13].

In order to circumvent the disadvantage of discontinuous regeneration, continuously regenerating filter systems CRT were developed. In such a system particles are incinerated at temperatures above 200°C via oxidation by NO_2. The NO_2 often is generated in oxidation catalysts upstream of the particle trap. The exhaust gas temperatures of a diesel engine, especially in low-load operation, are so low, however, that only an insufficient amount of NO is oxidised to NO_2. The oxidation behaviour can be improved by means of oxidation catalysts extremely close to the engine or even upstream of the turbo charger [14]. A truly continuous regeneration process, however, can only be achieved if the filter itself is also close to the engine.

Since in addition to incinerable particles all engines also generate oil and additive ashes which cannot be regenerated, the traps in long term become clogged. Filters must therefore be exchanged and washed on a regular basis. Plate filter structures attempt to solve this problem by using vibrations in the exhaust system enabled by the design so that the ashes fall from the filters.

The question arises which filter efficiencies are really required to meet future particulate emission standards. Fig. 3 is a comparison of German certification data of diesel passenger vehicles in the model year 1999 and European EU IV limit values.

The results of the model year 2000 (introduction of the EU III standards) are not available until today. But it can be expected that there will be a greater step of improvement compared to those of recent years.

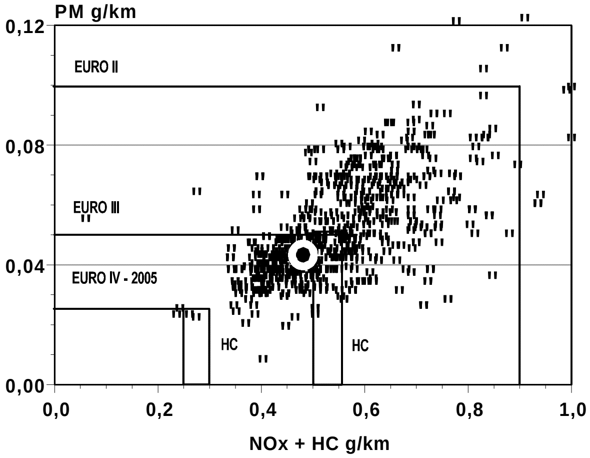


Fig. 3: German certification data of passenger vehicles in 1999

The graph shows that even in 1999 lots of the cars certified according to EU III legislation would be able to meet the EU IV limits with a filter efficiency of 30-40%.

3. Flow-through particulate trap

In addition to a minimum reaction temperature and a specific dwell time, the continuous regeneration of particles with NO_2 requires a sufficient amount of this component. Examining the dynamic NO and particle emissions in the European test cycle it becomes clear that particles are usually emitted when no or only little NO is contained in the exhaust gas and vice versa (Fig. 4).

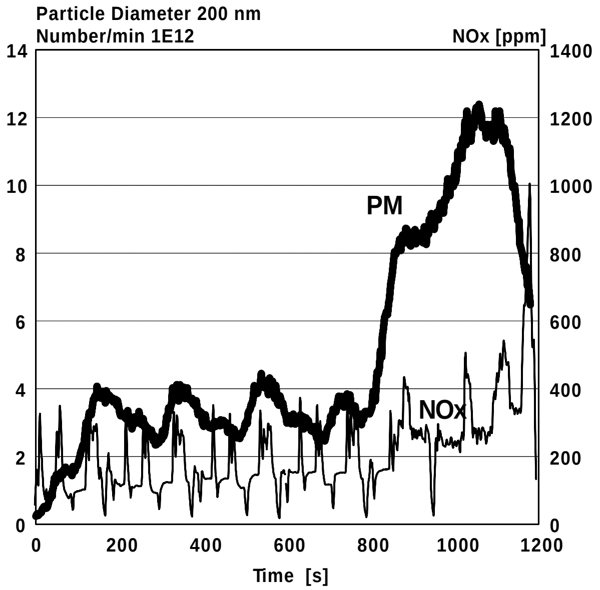


Fig. 4: Dynamic particle and NO emissions in the European exhaust gas test

The conclusion would be that a filter with real continuous regeneration would only have to compensate for “missing dwell times”. In addition, such a trap would have to be installed close to the engine to guarantee the highest possible exhaust gas temperature. Upstream of the filter an oxidation catalyst which oxidises CO and HC and subsequently NO into NO_2 has to be installed. Since even in such a position the temperature is the decisive parameter for converting diesel exhaust gas [14] it would make sense to split the volume of the oxidation catalyst. One part can be installed upstream of the exhaust gas turbine in a position with higher exhaust gas temperatures, that means the introduction of a pre-turbo catalyst.

It is well known [15, 16, 17] that the share of NO_2 is of greatest importance for both the oxidation of soot particles and the reduction of NO_x by selective catalytic processes. It is an established fact that a share of about 50 % NO_2 is desirable. It could be shown [18] that it is possible to almost achieve this 50 % and above 30% at least in a wide engine operating range by using a preturbocharger catalyst in combination with an oxydation catalyst behind the turbine.

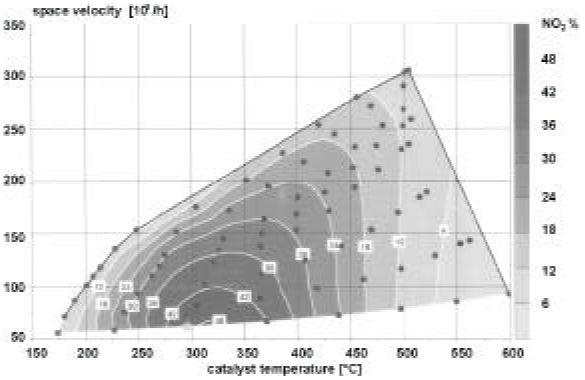


Fig. 5: Percentage NO_2 of nitrogen oxides provided by the combination of an oxidation catalyst with a pre-turbo-cat [18]

The encouraging spread of relatively high nitrogen dioxide shares rouses great expectations regarding emission control devices such as continuous regenerating flow-through particle trap systems.

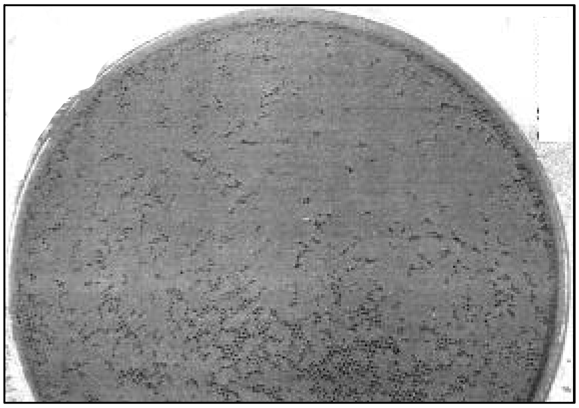
The objective for the development of the flow-through particle filter system was to install the filter directly downstream from the oxidation catalyst in a close-coupled position. Since unlike the classical filter in an under-floor position longer filling times without regeneration of particles are avoided due to higher temperatures, it is possible to achieve a very small filter volume in conjunction with splitting the oxidation catalyst.

3.1 General principle

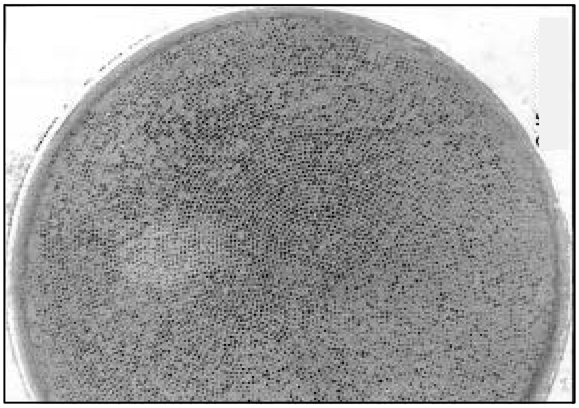
It is well known that soot is deposited at the gas inlet front face of the catalyst in the diesel exhaust gas pipe which partially reacts with NO_2. Fig. 6 shows the front face of catalytic carriers after low load operation and various concentrations of NO_2 in the exhaust gas. With very low NO_2 concentration in the exhaust gas the total front face is blocked by soot, with 5 % NO_2 a part of the soot already can be burnt. With 40 % of NO_2 no soot can be recognized on the front face.

In view of the laminar flow hardly any particles are deposited in the channels of the catalyst itself.

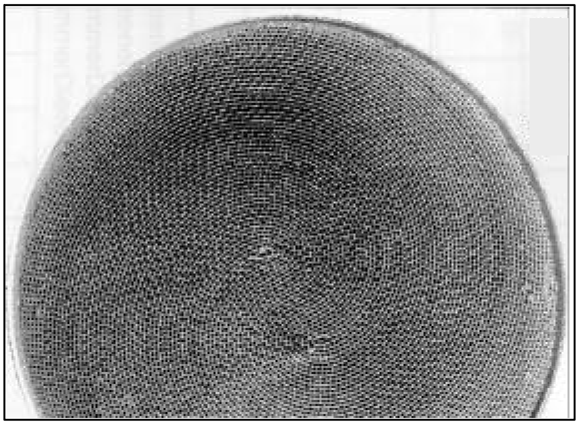
It was the task of the developers to ensure that the filtering efficiency of the catalytic carrier was increased and that deposited particles would not be blown out again by a sudden increase of the mass flow and the resulting aerodynamic forces.



NO_2 Concentration < 2%



NO_2 Concentration 5%



NO_2 Concentration 40%

Fig. 6: Deposition of soot at the catalyst front face in relation to the NO_2 content of the exhaust gas

The development is based on a mixing catalyst support originally used for the distribution of urea in SCR systems (Fig. 7)

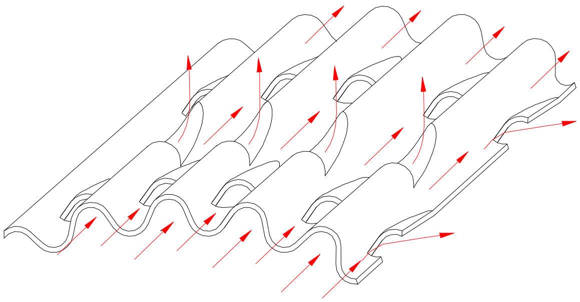
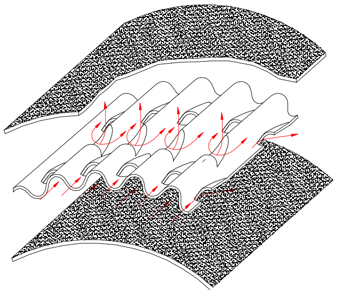


Fig. 7: Mixing section for monolithic metal honeycomb substrates

The vanes of the mixing section pass part of the exhaust gas of each cell into a neighbouring channel. The construction of the mixing honeycomb substrate is identical to the standard metal honeycomb substrate.



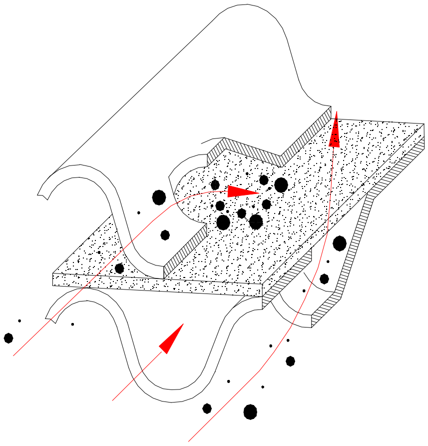


Fig. 8: Principle of particle depositing in a porous smooth section of the mixing section

But there are no flat foils or these are replaced by highly-perforated ones so that gasses can pass from one channel into the neighbouring channel. If a porous flat foil of wire mesh, fibre material or stretch material is used, some of the particles which are in the exhaust gas passing the porous foil are trapped (Fig. 8).
The design of the porous flat foil with respect to porosity, pressure loss and thickness was determined by means of a simulation programme at the University of Rome.

4. Flow simulation in an flow-through particle filter system

The simulation was conducted by means of a two-dimensional model for several parallel channels. The following set of equations is solved for each mesh of the 2D-grid in the CFD model:

- ***Continuity***

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

- ***Navier-Stokes equations***

x direction

$$r\,\frac{Du}{Dt} = \frac{\partial(-p + t_{xx})}{\partial x} + \frac{\partial t_{yx}}{\partial y} + S_{Mx}$$

y direction

$$r\,\frac{Dv}{Dt} = \frac{\partial(-p + t_{yy})}{\partial y} + \frac{\partial t_{xy}}{\partial x} + S_{My}$$

- ***Energy balance***

$$r\,\frac{DE}{Dt} = -\nabla\,(r\,u) + \left[\frac{\P u t_{xx}}{\P x} + \frac{\P u t_{yx}}{\P y} + \frac{\P v t_{xy}}{\P x} + \frac{\P v t_{yy}}{\P y}\right] + S_E$$

where

$$E = \frac{1}{2}\mathbf{u} \cdot \mathbf{u} + I\,;$$

For the calibration of the programe the flow distribution of two channels connected to each other via a porous foil was first measured. The gas stream was injected in one channel only. Because of the channel back-pressure a part of the gas stream passes through the porous foil into the second channel. The speed of the flow and the flow distribution was measured with the help of a hot-wire sensor behind the channels. The channel size chosen corresponded to that of a catalyst with a cell density of 31 cells/cm² and a length of 74,5 mm.

The comparison between measurements and calculations is shown in Fig. 9.

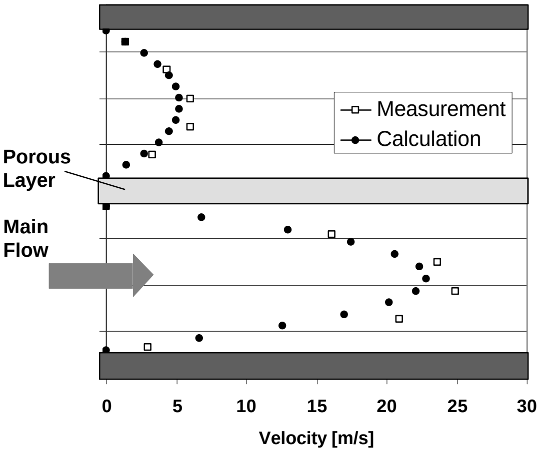


Fig. 9: Comparison of measured and calculated flow distribution between two neighbouring ducts

There was a good correlation between measurements and calculations. In a second step the percentage of exhaust gas flowing through the porous foil in relation to the foil porosity was calculated (Fig. 10), assuming that a higher amount of exhaust gas passing the porous foil will increase the trap efficiency. The “true porosity” relates to the porosity of the fibre mat which was used in figure 9. The fibre mat had a thickness of 0,5 mm with a porosity of 85% and a fibre diameter of 0,012 mm.

Under real driving conditions the trap has to work with different engine out mass-flows. The influence of the mass flow rate on the flow in the channels is shown in Fig. 11.

The share of cross-flows through porous foil increases with the flow rate in the channels (brighter means higher mass flow) center, leading to the conclusion that with continuos regeneration the trapping efficiency increases with higher mass flow rates.

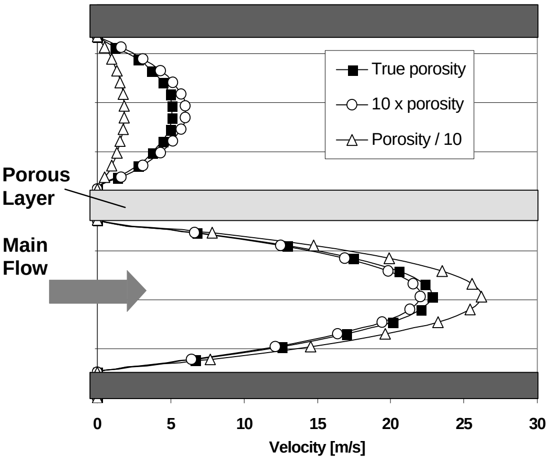
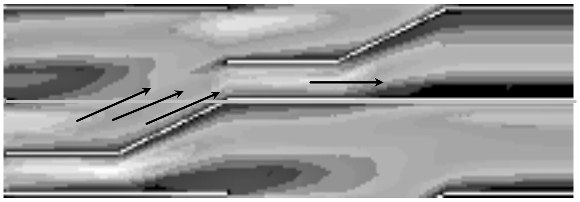
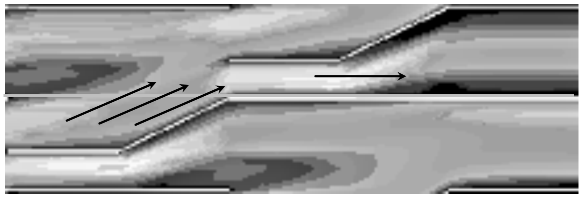


Fig. 10: Percentage of exhaust gas flowing through porous smooth sections in relation to porosity



mass flow 125 kg/h



mass flow 250 kg/h

Fig. 11: Duct flow in an open particle trap in relation to mass flow rate

In order to determine a theoretical filter efficiency under ideal conditions and assuming that most of the particles of the exhaust gas passing the porous foil are trapped, the number of aligned vanes and the percentage of the separated flow can be multiplied.

5. Efficiency evaluation in a laboratory test arrangement with synthetic soot-like particles

A sample of a flow-through particle trap with a cell density of 31 cells/cm² was used in a laboratory test arrangement with synthetic soot-like particles. The particle flow was produced via spark discharge between graphite electrodes in a nitrogen carrier gas stream as described in principle in the literature [19]. The microstructures of the obtained particles are very similar to those in the soot of diesel engines, as well as their size distributions. The aerosol containing the carbon particles is mixed with the other gaseous components like oxygen and nitrogen dioxide, than heated to different set temperatures before introduction to the model filter elements. Downstream of the model filter element various analytical techniques were applied to describe the influence on the particles and the gaseous components. The particles were characterized by SMPS and gravimetric analysis. The concentrations of the nitrogen oxides were measured by CLD, the carbon balance was calculated based on CO_2 - measurement via a NDIR-instrument (CO after catalytic oxidation to CO_2) and the oxygen is measured with a paramagnetic analyzer.

Test conditions:

- Volume Flow: 335 l/h (at room temp.)
- Temperature: 350 °C
- Concentration O_2: 10 Vol.-%
- Concentration NO_2: 300 ppm
- Particle Mass: 3,5 – 3,9 mg/m^3 (at room temperature)
- Filter Size: Ø 10x45 mm; 31 cells/cm^2
- Porosity Flat Foil: 85 %
- Thickness Flat Foil: 0,5 mm

At the tested load point with a space velocity of 95.000 h^{-1} a filter efficiency of 14 % could be obtained. The results were influenced by particle accumulation within the test set-up. Because of the relatively high temperature even this particles did react with the NO_2, so that a total particle removement of up to 50 % could be found. Further tests with an optimized test set-up and different space velocities and temperatures has to be done.

6. Loss of pressure in the flow-through particle trap

The pressure loss in “unloaded” and “loaded” conditions was examined in a flow test bench in relation to the mass flow rate at room temperature. In loaded condition about 0,5 g soot was stored in the porous flat foils of the trap by running it for a long time at low temperature in the exhaust line of a diesel engine. In “unloaded” condition no soot at all was stored in the trap. The flow distribution upstream of the filter is deemed to be homogeneous. The particle trap was tested in the size of Ø 118 x 74,5 mm with a cell density of 31 cells/cm^2. Results are presented in Fig. 12.

It becomes quite clear that at “loaded” condition the pressure-loss was only influenced by 15 % in relation to the “unloaded” trap, in comparison to a traditional wall flow filter system where the soot increases the back pressure in the range of a factor of 5 – 8.

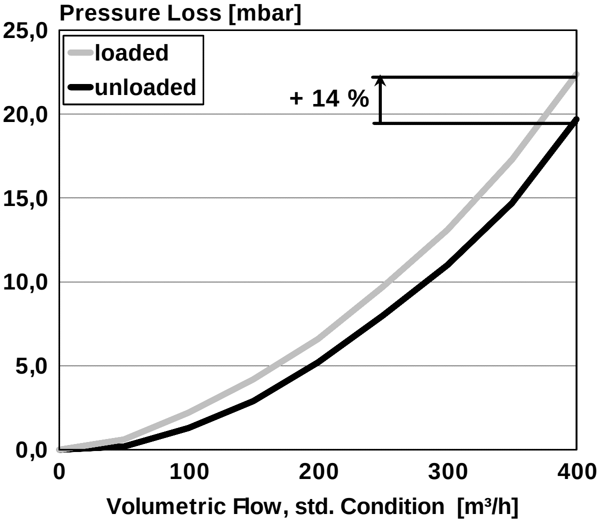


Fig. 12: Pressure loss of open particle trap in unloaded and loaded condition and in relation to the air flow rate (cold gas flow)

Because the calculation (chapter 4) shows in principle higher trapping rates at higher flow speed (higher massflow) a support with Ø 90 x 74,5 mm; 31 cells/cm^2 was tested in the following dynamic test bench for engines. The same porous flat foil as described in chapter 5 was used.

7. Exhaust gas measurements in a dynamic engine test bench

A modern 3 litre 6-cylinder in-line engine with common-rail injection and inter-cooled turbo-charging (turbine with variable geometry) on a test bench was used for laboratory testing. During all experiments the engine setting was unchanged. Two quick response analysing systems were installed for modal analysis of the gaseous concentrations in the raw exhaust and behind the catalyst. The exhaust system was original equipment from a medium-sized passenger car. The sequence of engine speed and torque was set according to measured values during EU III test runs on a chassis dynamometer. The exhaust mass flow was calculated by measuring the fuel consumption and the mass flow of the combustion air on a modal basis. Two systems with identical coatings were compared: The original catalyst system was equipped with a ceramic, close coupled catalyst (oval shape, 90 mm x 185 mm, length 114 mm, volume 1492 cm³, 62 cells/cm², wall thickness 0,165 mm), and two metallic under-floor catalysts (volume 762 cm³ each, 62 cells/cm², foil thickness 0,040 mm). As a second system the flow-through particle trap (diameter 90 mm x 74,5 mm, 31 cells/cm²) with an oxidation catalyst diameter 98,4 x 120 mm, 62 cells/cm² mounted in front of the particle trap was tested.The tests were carried out with sulphur-free diesel fuel (S < 10 ppm). All exhaust gas results are the mean value of at least three measurements.

Fig. 13 shows the HC, CO and NOx emissions in comparison to the standard exhaust gas system. The modified system with particle trap was measured without standard under-floor catalyst. The extremly small volume of the oxydation catalyst compared to the production catalyst results in higher CO and HC emissions.

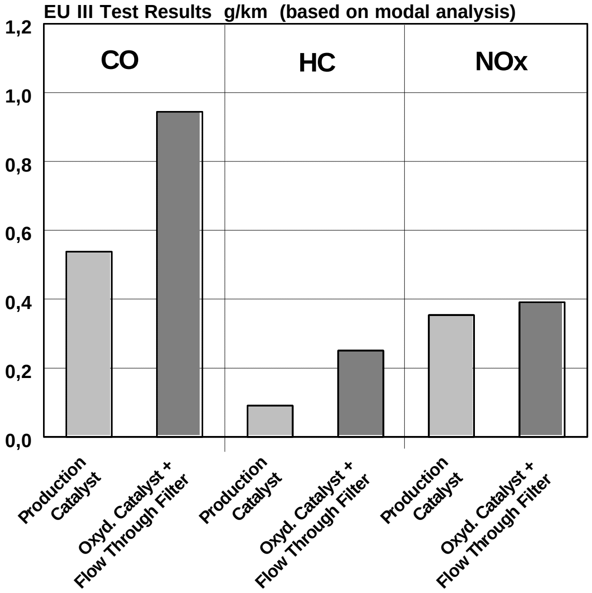


Fig. 13: HC, CO and NOx emissions in the European EU III test cycle

It can be expected that the installation of a pre-turbo catalyst reduces the CO and HC emissions significantly as it was shown by a former project without having a negative influence on engine power and fuel consumption [14]. Particle emissions were measured in parallel (Fig. 14).

The flow-through particle filter system with a filter size of 0,47 l was able to reduce particle emissions by 24 % in the European Drive Cycle.

Examinations on the influence of the efficiency in relation to particle diameter will be carried out in the near future.

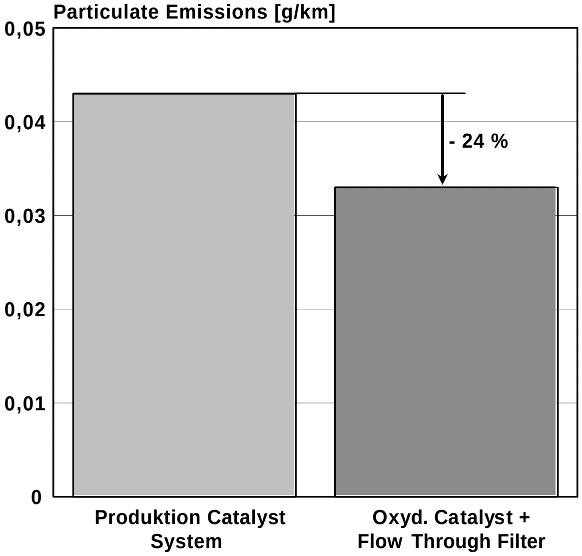


Fig. 14: Particle emissions of the standard exhaust gas system in comparison with the flow-through particle filter system and upstream oxidation catalyst

In addition to the European Test Cycle the following 4 constant load points were driven in order to see if there is an influence of the mass-flow on the trap efficiency.

Table 1: Torque and engine speed of tested constant load points

Engine Speed [rpm]	1200	2000	3000	4000
Torque [Nm]	150	195	194	155

The results are shown in figure 15.

A trapping efficiency between 12 and 31 % can be seen. The best result was found with an engine speed of 3000 min^{-1} and a torque of 194 Nm. This result indicates that a further improvement of the total efficiency in the test cycle and under real driving conditions can be achieved by adapting the diameter/length ratio of the flow-through trap.

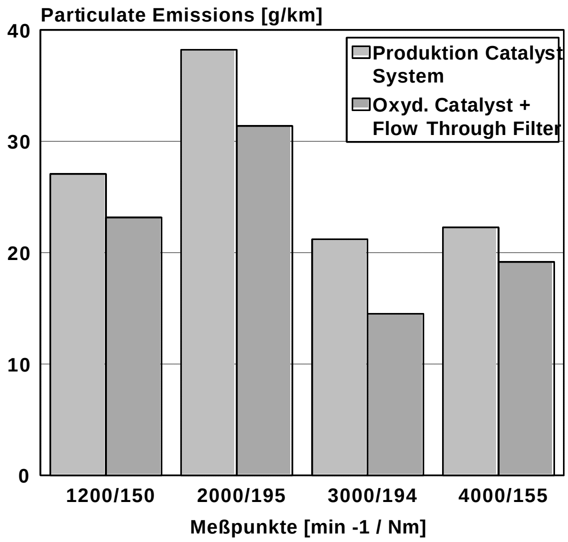


Fig. 15: Particle emissions in different constant load points with and without the Flow Through Filter

8. Summary

An open particle filter system was developed in order to reduce particle emissions of diesel engines with load-independent pressure loss and without long-term clogging features.

In combination with an upstream oxidation catalyst first emission tests with a small open trap (Ø 90 x 74,5 mm; 200 cpsi) achieved particle reductions of 24 % in a passenger car equipped with a 6 cylinder 3.0 l diesel engine in the European Stage III Drive Cycle. The open trap would therefore be an opportunity to adhere to future exhaust gas limit values for particles without any negative long-term impact.

In order to increase the trapping efficiency more test work with different kinds of porous flat foils, optimized diameter/length ratio of the trap and increased fliter length has to be done.

Results on the efficiency with respect to particle sizes are being developed by means of calculations as well as laboratory tests.

The mechanical durability of the system is examined in test benches for components as well as engines.

9. References

[1] H. Lüders, R. Backes, G. Hüthwohl, D. A.Ketcher, R. W. Horrocks, R. G. Hurley, R. H. ammerle: “An Urea NOx Catalyst System for Light Duty Diesel Vehicles”, SAE 952493, 1995

[2] S. Fischer, L. Hofmann, J. Zürbig: „The Development of the SINOx System for Commercial Vehicles for Serial Applications“, 20th Vienna Motor Symposium, May 6-7, 1999

[3] J. Gieshoff, A. Schäfer-Sindlinger, P. C. Spurk, J. A. A. van den Tillart, G. Garr: „Improved SCR Systems for Heavy Duty Applications“, SAE 2000-01-0189, 2000

[4] N. Miyoshi, S. Matsumoto, K. Katoh, T. Tanaka, J. Harada, N. Takahashi, K. Yokota, M. Sugiura, K. Kasahara: “Development of New Concept Three-Way Catalyst for Automotive Lean-Burn Engines”, SAE 950809, 1995

[5] U. Dahle, T. Beutel, A. Punke: „Euro 4-Abgasnachbehandlungstechnologien für Magermotoren (Otto/Diesel)“, Technischer Kongress VDA, 20.-21. September 1999, Frankfurt

[6] H. Lüders, P. Stommel, M. Hernier: „Neue dieselmotorische Abgasnachbehandlungskon-zepte für Niedrigstemissions-Fahrzeuge“, Kolloqium „Abgasreinigung bei mageren Dieselmotoren“, 15.-16. Juni 1999, HdT Essen

[7] A. G. Konstandopoulos, M. Kostoglou, E. Skaperdas, E. Papaioannou, D. Zarvalis, E. Klado-p oulou: „Fundamental Studies of Diesel Particulate Filters: Transient Loading, Regeneration and Aging“, SAE 2000-01-1016, 2000

[8] W. A. Cuttler, G. A. Merkel: „A New High Temperature Ceramic Material for Diesel Particulate Filter Applications“, SAE 2000-01-2844, 2000

[9] N. Zhi, Z. Xinyun, Y. He: “Development and Experimental Study of a New Diesel Exhaust Particulate Trap System”, SAE 2000-01-2846, 2000

[10] O. Salvat, P. Marez, G. Belot: “Passenger Car Serial Application of a Particulate Filter System on a Common Rail Direct Injection Diesel Engine”, SAE 2000-01-0473, 2000

[11] R. L. Bloom, N. R. Brunner, S. C. Schroer: “Fiber-Wound Diesel Particulate Filter Durability. Experience with Metal-Based Additives”, SAE 970180, 1997

[12] K. Matsunuma, T. Ihara, Y. Hanamoto, S. Nakajima, S. Okamoto: “Development of Diesel Particulate Filter Made of Porous metal”, SAE 690132, 1996

[13] P. Zelenka, W. Reczek, W. Mustel, P. Rouveirolles: „Towards Securing the Particulate Trap Regeneration: a System Combining a Sintered Metal Filter and Cerium Fuel Additive”, SAE 982598, 1998

[14] M. Reizig, R. Brück, R. Konieczny, P. Treiber: „New Approaches to Catalyst Substrate Application for Diesel Engines”, SAE 2001-01-0189, 2001

[15] L. Hofmann, S. Fischer, W. Mathes, J. Zürbig: „Das SINOx-System zur Stickoxidreduktion von Nutzfahrzeugmotoren“, Kolloqium „Abgasreinigung bei mageren Dieselmotoren“, 15.-16. Juni 1999, HdT Essen

[16] S. E. Thomas, A. R. Martin, D. Raybone, J. T. Shawcross, K. L. Ng, P. Beech, J. C. Whitehead: “Non Thermal Plasma Aftertreatment of Particulates – Theoretical Limits and Impact on Reactor Design”, SAE 2000-01-1926, 2000

[17] R. Allansson, P. Blakemen, G. Chandler, C. Maloney, A. Walker, J. Thoss: “Einsatz von selbstregenerierenden Partikelfiltersystemen (CRT – Continuously Regenerating Trap) sowie SCRT (CRT + SCR – Selective Catalytic Reduction) zur Einhaltung künftiger Emissions-grenzen”, 21st Vienna Motor Symposium, May 4-5, 2000

[18] E. Jacob, A. Döring: “GD-Kat: Abgasnachbehandlungssystem zur simultanen Kohlenstoffpar-tikeloxidation und NOx-Reduktion für Euro4/5-Nfz-Dieselmotoren“, 21st Vienna Motor Symposium, May 4-5, 2000

[19] H. Hackfort, E. Hünnekes, J. Dornseiffer: „Fundamental Investigations of Continuous Regeneration of Carbon Particle Traps with Oxygen“, SAE 2000-01-2984

10. Abbreviations

CLD:	Chemiluminescence detector
NDIR:	Non dispersive infrared absorption analyser
SMPS:	Scanning mobility particle sizer

Abbreviations in formula

ρ = density

t = time

$\mathbf{u}$ = velocity vector

u = velocity in x-direction

v = velocity in v-direction

p = pressure

τ_{ij} = ij-component of stress tensor

S_{Mi} = i-component of momentum source term

μ = dynamic viscosity

α = permeability of porous media

v_i = velocity in i-direction

E = energy

S_E = source term of energy

I = specific internal energy