

Properties of Partial-Flow and Coarse Pore Deep Bed Filters Proposed to Reduce Particle Emission of Vehicle Engines

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ABSTRACT

Four of these Particulate Reduction Systems (PMS) were tested on a passenger car and one of them on a HDV. Expectation of the research team was that they would reach at least a PM-reduction of 30% under all realistic operating conditions. The standard German filter test procedure for PMS was performed but moreover, the response to various operating conditions was tested including worst case situations. Besides the legislated CO, NO_x and PM exhaust-gas emissions, also the particle count and NO₂ were measured. The best filtration efficiency with one PMS was indeed 63%. However, under critical but realistic conditions filtration of 3 of 4 PMS was measured substantially lower than the expected 30 %, depending on operating conditions and prior history, and could even completely fail. Scatter between repeated cycles was very large and results were not reproducible. Even worse, with all 4 PMS deposited soot, stored in these systems during light load operation was intermittently blown-off. Due to these stochastic phenomena the behavior of these systems is hardly predictable. Furthermore the provision of NO₂, through catalysis ahead of the filter or in the filter matrix, is inherent in these systems. Some of this secondary NO₂ is emitted. Cost/benefit ratio is high compared to full-flow filters and Diesel engines equipped with partial-flow filters are inferior to SI engines regarding global warming potential. Based on these findings it is concluded that the sustainable performance of partial-flow filters is not yet determined.

INTRODUCTION

Full-flow filters (FFF) have become a standard. Wall flow honeycomb filter media, used in this concept are reaching filtration efficiencies exceeding 99.9% [1]. These are fitted ex-factory to European passenger cars and USA trucks [2,3]. Retrofitting onroad heavy-duty (HD) vehicles and offroad construction machines is also very successful [4]. Retrofit filter systems with active regeneration, a prerequisite for dependable operation, are however still rather complex, bulky and costly and therefore prohibitive for retrofitting in-use passenger cars. Nevertheless to diminish emissions, in countries with a high Diesel car population, environmental policy requires simpler and less costly retrofit systems. These shall enable at least 30% curtailment of the particle mass (PM) emission, and correspondingly benefit air quality in the Low Emission Zones. The German [5] specification, which the Netherlands and other countries have adopted, is based on a weighted average PM emission reduction measured over 3 New European Driving Cycles (NEDC) in the as new state, after 2000 km, and after 4000 km operation.

This paper describes the investigation of 4 commercially available partial-flow filters. These were tested according to the German NEDC based criteria. Moreover, since the NEDC is regarded as not reflecting real world city driving conditions [6], tests were performed in various other driving cycles and at other realistic operating conditions. In addition to PM, the investigation also measured the emission of solid nano-particles in the size range 10 nm – 400 nm, and of the systems inherent NO₂ emissions.

BASIC PROPERTIES OF FULL-FLOW (FFF) AND PARTIAL FLOW FILTERS (PFF)

The filtration response of the full-flow [7,11,21] filter and the partial-flow filter [8,9,10] is very extensively published. Fig. 1 shows schematically the basis concept of the full-flow filter and the partial-flow filter.

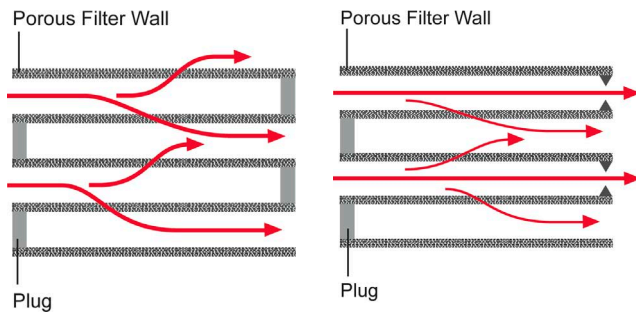


Fig. 1: Schematic of full-flow Filters FFF (left) and partial flow filters PFF (right).

Whereas in FFF [11] all exhaust gas has to pass through the fine porous walls of the filter, in the PFF [10] some flow is allowed to pass unfiltered. The ratio of the two flows PFF/FFF may be designed to be 0.5, when clean but will vary with soot deposition and may reach very low values when the filter wall gets plugged, resulting in corresponding low overall filtration.

Figure 2 shows some of the basic characteristics of the FFF and PFF concepts. Figure 2a shows the characteristics of the FFF, with this design filtration is improved with soot loading, approaching nearly 100% after a few minutes of operation. Back-pressure also increases thus continuous or discontinuous regeneration is required. Figure 2b shows the characteristics of the PFF; these are clearly different. In the PFF design filtration efficiency decreases with soot loading and sudden blow off can happen where all stored material is lost. Backpressure however remains low.

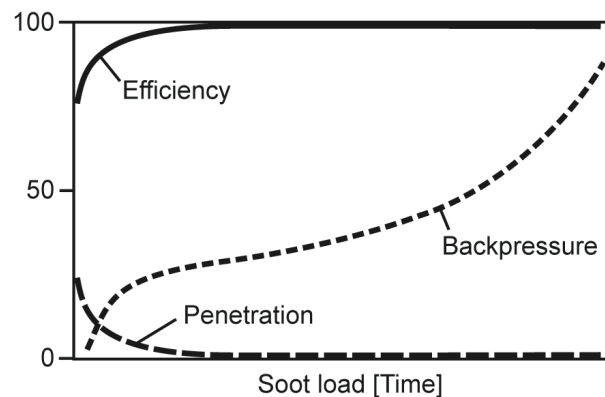


Fig. 2a Basic properties of full-flow filters (FFF)

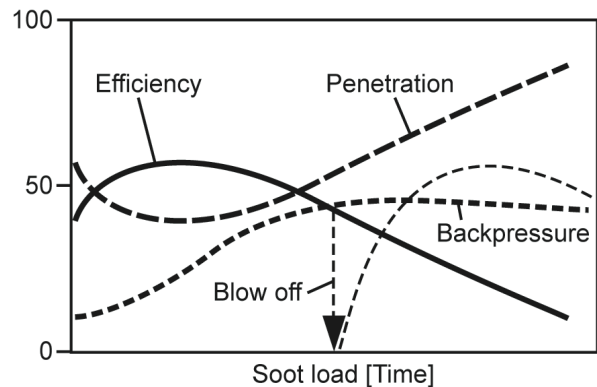


Fig. 2b Basic properties of partial flow filters (PFF)

With the FFF backpressure increases when soot loading and can become plugged if not regenerated properly while backpressure with PFF levels out with decreasing filtration efficiency. The PFF can clean itself by releasing stored soot to avoid plugging – which is undesirable from an environmental point of view.

The well-established full-flow filters, of the wall through-flow type, have porous cell walls, through which the exhaust gas passes at very low velocities (a few cm/s). Thus diffusion effects occur in the very small pores (about 10 μm). Such filters attain filtration efficiencies above 99.9% for all particle sizes prevalent in the exhaust-gas. The large surface area of these filters facilitates catalyst coating. The filtration efficiency of full-flow filters usually increases from 70-80%, in the new state, to the maximum value within minutes of engine operation. The maximum filtration rate is sustained during the filter life. The regeneration process periodically combusts the deposited soot particles. The full-flow filter also dependably intercepts incombustible ash particles from engine wear and combustion of lubricating oil. The back-pressure initially increases rapidly, due to particle deposition in the filter walls; the back-pressure then increases linearly during soot-cake build up and finally rises rapidly if the filter becomes fully loaded. The consequent high back-pressure is not permissible. Hence, the filter must be regenerated before the back-pressure exceeds about 200 mbar (approx. every 1,000 km). Subsequently, after 2 - 3,000 operating hours the filter must be cleaned of ash. The filter is then fully reusable.

Prerequisites for effective regeneration are monitoring the back-pressure and initiating the regeneration through raising the temperature until ignition of the deposited soot is triggered. Engine management (delayed fuel injection, diminishing air through-flow) can raise the exhaust temperature. Other possibilities are heating after the engine, e.g. burner, catalytic combustion or electrical heating. These methods are expensive and relatively complex but they are required unless the exhaust temperature is high enough to guarantee continuous regeneration supported by catalysis [11,35].

Partial-flow filters are essentially open cell systems, whose walls, too, are porous materials. Part of the inlet gas exits the system directly, without surrendering particles. The main channel flow has a very high velocity. The partial-flow through the filter walls is at a reduced flow rate, so that filtration can occur within the porous walls and on their surfaces. Here, too, soot deposition occurs that supports the filtration of ultrafine particles. The soot deposition in the filter medium however inevitably shifts the ratio of partial-flow to full-flow, i.e. more gas exits unfiltered. Thus the filtration efficiency decreases. The claimed advantage is that such a construction tends not to clog. Increasing soot deposits on the walls narrows the channels thereby raising the flow forces, until the deposited soot is blown off in a short but intensive smoke puff. That process then reiterates - an effect which is well known and described as store-and-release [12]. Any actual curtailment of particle emissions only occurs when the intercepted soot is converted to CO or CO₂. The temperature in a passenger car exhaust is too low for oxygen to react with the soot. The only possibility is to utilize NO₂ for regeneration, a process, which may start at temperatures as low as 230 °C if sufficient NO_x is available. Hence, a very effective oxidation catalytic converter, coated with platinum, must be mounted ahead of the filter. This oxidation catalyst converts part of the engine NO into NO₂. NO₂ will be decomposed again and will release an oxygen atom, which can combust soot above 230°C. This is a slow process and therefore only oxidizes deposited soot. The stoichiometric mass ratio of for this process is at NO₂/C = 7.6 if CO₂ shall be formed. Experience indicates a 2-3 times higher NO₂ production is necessary, since not all NO₂ can react with soot [35]. The four critical parameters of partial-flow filters therefore are: filtration response, NO₂ availability, adequate temperature and storage capacity.

ON-ROAD TEST

The German test procedure was performed as per Annex 26 [5] of the German traffic certification directive. The filtration performance is assessed during the NEDC test in the as new state, then after 2000 km of light load city operation and then again after further a 2,000 km. Depending on the emission level of the vehicle, the distance can be extended to 2,500 km. The mileage accumulation can be performed on the road, or on the chassis dynamometer. The average speed is between 25 and 35 km/h but never exceeding 70 km/h. The idling time is > 7% of operating time. The duration between 50 and 70 km/h is <10% of operating time. The highest exhaust temperature is < 300°C. The measurements on the chassis dynamometer are done after conditioning (2-3 times, Part 2 of the NEDC). A weighted average, which overweights the results after the city driving period, decides the approval. This value must be more than 30% filtration efficiency. After the actual test, a so-called worst-case test is performed at engine full load: as soon as exhaust temperature reaches values above 550 °C an oxygen regeneration is initiated. This fast regeneration with high heat release is used to verify the thermo-mechanical dependability of the system. The test

is supplemented with a smoke measurement during free acceleration.

This standard test was performed on two of the systems, here designated system A and system C, i.e. an actual partial-flow filter and a foam deep filter. Fig. 3 shows the results. In the figure "C" denotes the conditioning phase (3 times NEDC without measurement), "T" denotes the emissions testing phase (NEDC) and "WC" denotes the worst case test. How the system behaves in between the test points "T" is not known.

The baseline is the filtration efficiency in the as new state, which complies with the limits. Compared to the baseline, the filtration decreases substantially for both systems after the first city driving period. This deterioration continues in the second stage but is mostly corrected through regeneration during the so-called worst case test (WC). The weighted average filtration efficiencies are: system A 3.1%, and system C 8.2%. Both systems do not attain the objective.

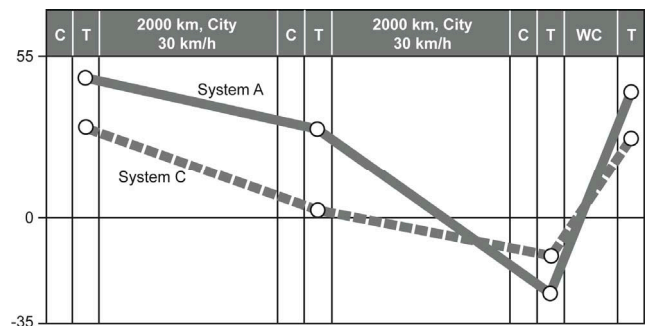


Fig. 3: Performance of system A and system C.

The soot puff, during free acceleration from idling engine speed to governed engine speed, was verified after the defined test runs. System B emitted 17% less soot than the base-line; system G emitted double the baseline value.

These tests clearly indicate the deficiency of these partial-flow filters. The filtration deteriorates, due to soot deposition, and thus the danger of soot puffs when the deposits are blown-off.

The filtration efficiency scatter indicates that conditions change from test to test. Possibly, other higher values might have been recorded, had the filter shed soot just before measurement, i.e. a stochastic phenomenon. These observations indicate that filter conditioning is unsuitable for system evaluation. During conditioning, deposits are removed. Thus the filter is restored to a more effective state than after the city driving period. Without assessing the conditioning phenomena, the results are unrealistically distorted. Hence, the results of this standard test are misleading, overestimating the real world efficacy of these devices.

In 2008 the German automobile club ADAC [13] tested 9 marketed partial-flow filters, types A and B. However, the city driving phase was only 1,500 km. The measurements before and after the city driving showed

an average deterioration of the filtration efficiency from 39% to 21% with individual cases of –51%, despite conditioning before measurement. During a so-called “ADAC Autobahn-cycle” 8 of 9 filters candidates showed blow-off, emitting on average 110% PM above engine baseline, in one case 370%.

CHASSIS DYNAMOMETER TESTS

In 2006 the Exhaust-Gas Test Center AFHB of the Swiss University of Applied Sciences, Biel investigated such devices. The tests comprised the following:

INFLUENCE OF SOOT BURDEN AND BLOW-OFF PHENOMENA

Constant speed 35 km/h from cold start
4th gear
Exhaust temperature < 200°C
Test duration: 210 minutes

Constant speed 65 km/h from warm start
4th gear
Exhaust temperature ≈ 300°C
Test duration: 210 minutes

Load variation to investigate temperature dependence
Constant speed 85 km/h in 6th gear
Wheel load incremented in 5 steps from 0 – 1600 N
chassis dynamometer setting i.e. until full load

EMISSIONS AT CONSTANT SPEED

Setting the chassis dynamometer, which simulates roll resistance on a horizontal road; driven in 5th gear at constant speeds of 45 – 120 km/h.

EMISSION FACTORS IN VARIOUS DRIVING CYCLES

The following driving cycles were tested twice on two different days:

- New European Driving Cycle NEDC, cold and warm
- Federal Test Procedure FTP75, warm
- CADC (so-called ARTEMIS cycle [6]) warm
- New York City Cycle NYCC, warm
- German Autobahn Cycle BAB, warm

This program is based on over 10 years experience in testing and certification of full-flow particle filters deployed in Switzerland. It also considers results of prior investigations [1, 14, 15, 16, 17]

The test vehicle details are given below.

VW Passat TDI (on the chassis dynamometer)

- Manufactured in year : 2005
- Vehicle type: 3BG
- Engine displacement : 1.9 dm³ (1896 cm³)
- Power rating: 96 kW at 4000 RPM
- Torque: 310 Nm at 1900 RPM
- Engine type: AVF
- Engine: TDI 2V VTG
- Injection system : Pump nozzle
- Exhaust after-treatment : DOC close coupled
- Emission level: EURO 3
- Gear box: 6 gear manual
- Odometer at start: 23,700 km

The test fuel used throughout this work was Shell Formula Diesel, compliant to EN-SN-590 with a sulfur content of less than 10 ppm. Details of the test lubricant are given below.

Lubrication oil: SAE OW/30
Sample analysis of fresh oil:
Sulfur: 5000 ppm
Calcium: 2847 ppm
Iron: 171 ppm
Phosphorous: 1078 ppm
Zinc: 1243 ppm

The baseline emissions results over the different test cycles are given in Table 1 and the baseline emissions values at the different load settings at 85km/h in 6th gear are given in Table 2.

Table 1: Emissions baseline of the test vehicle over the different driving cycles

g/km	Limit value EURO 3	NEDC cold	NEDC warm	FTP 75 warm	CADC urban warm	NYCC warm	BAB warm
CO	0.64	0.21	0.05	0.04	0.24	0.27	0.02
HC	-	0.06	0.02	0.03	0.02	0.03	0.02
NOx	0.5	0.35	0.35	0.40	0.72	0.75	0.8
PM	0.05	0.03	0.025	0.033	0.07	0.07	0.025

Table 2: Emissions baseline of the test vehicle in load steps at 85 km/h, 6th gear

Load	Exhaust Temp. °C	PM g/km	Particle Count x 10 ⁶ 10-400nm #/cm ³	P Ø nm	NOx ppm	NO ₂ / NOx %
3 N	230	0.007	35.7	60	50	41
400 N	330	0.019	21.1	70	196	39
800 N	390	0.033	10.6	80	461	23
1200 N	435	0.046	4.4	80	856	15
1600 N	465	0.055	4.5	80	1099	8

