

Partial Flow Sintered Metal Filter as Part of a Tier 4 Emission Reduction Strategy

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ABSTRACT

Full flow particulate filters are a state of the art solution for many serial production Diesel engine applications. They are very effective for removing > 90 % of particulate mass and > 99 % of the particulate number from the exhaust gas of Diesel engines. Many Diesel engines have to work at load profiles which necessitate active regeneration procedures to ensure continued engine operation and the reliability of the full flow particulate filter. Passive regeneration via NO₂, as a cost effective solution, can not be used as the sole method for all applications, due to restrictions such as, insufficient engine out NO_x/PM ratio, low exhaust gas temperature level or occasionally poor fuel quality. To meet the Tier 4 emission legislation casually partial flow particulate filters enable sufficient particulate reduction at boundary conditions where full flow DPF are not applicable.

This paper discusses the influences of boundary conditions on the performance of partial flow sintered metal particulate filters and their relevance for Tier 4 applications. The filtration efficiency is controlled via design of the filter in conjunction with the DOC layout. By means of NO₂ formed in the DOC the regeneration of the soot retained in the filter is carried out. Due to the increased variance sufficient filtration efficiency can be granted at NO_x/PM ratios partially less than 1/3 as required for full filter CRT applications and even at lower exhaust gas temperatures. Depending on soot loading variable efficiency, periods with very poor regeneration performance can be covered. The presented partial flow particulate filter gives almost equal reduction of PM and PN between 30 % and 70 %. Backpressure or filtration efficiency can be adjusted nearly independent from the substrate volume. Due to the special design the ash retention of the partial flow sintered metal filter is negligible. The realization of a stage / Euro 4 application, based on a stage 3 engine is shown by real applications.

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INTRODUCTION

With the growing demand for energy, primarily met through the combustion of fossil fuels, atmospheric pollution is one of the most serious challenges the world faces today. The quality of the air we breath is influenced by many different variables. Along with the emissions produced by industry, domestic households and power stations, the pollutants from road traffic are of major significance in this respect.

The combustion process produces water (H₂O), carbon dioxide (CO₂) and the pollutants carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), sulfur dioxides (SO₂) and - primarily in the case of diesel engines - particulate matter (PM). PM is a combination of soluble hydrocarbons (SOF), sulfur trioxides and soot particulates. The composition of PM depends on a range of variables,

including combustion temperature, the engine load, the type and consumption of lubrication oil and the sulfur content of the fuel.

As national and international regulations governing emissions and atmospheric pollution become even more stringent, to the point at which further optimization of in-engine and on-engine measures alone no longer suffices, exhaust gas aftertreatment systems emerge as absolutely essential.

Due to reasons as for example durability or fuel efficiency Diesel engines are the most used engines in a wide field of applications. They e. g. work in a lot of land based applications from small three-wheeled vehicles to locomotives or gensets with an output from near 5 kW up to more than a few thousand kW. Diesel engines are long-lived and dependable, which leads to long periods for the same engine construction to be in use. This guarantees the



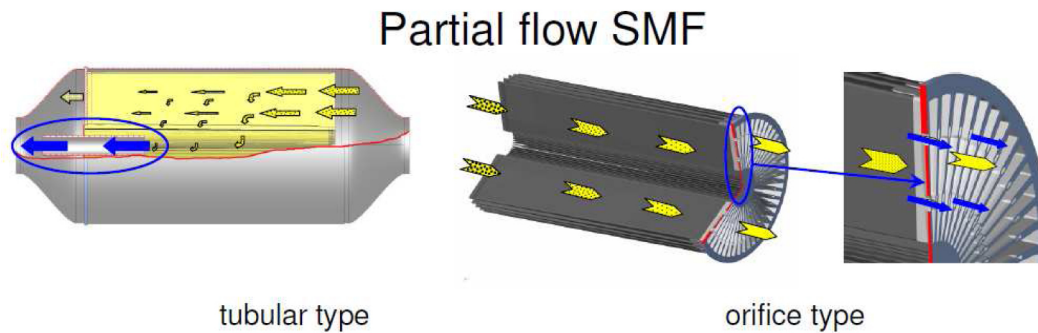


Figure 1. Different types of partial flow sintered metal particulate filters

customer a well known and easy to maintain power source for his daily work. By continuously becoming more and more stringent emission legislation demands on regulated engine emissions were increasing all the time. This leads to shorter cycles at the combustion side of the engine development and in the end effects probably more complex engines. At least with introduction of Tier 4 / Stage 4 it is necessary to introduce exhaust gas aftertreatment systems for nearly all engines. All harmful pollutants in the exhaust gas can be significantly reduced by certain exhaust gas aftertreatment technologies.

DOCs reduce CO and HC significantly and in some way partially the SOF of the PM emissions as well. SCR technology and EGR or a combination of both is used to minimize NO_x emissions. Particulate Filters are common to reduce PM emissions of combustion engines. Full flow Diesel particulate filter (DPF) reduce the particulate mass (PM) for more than 90 % and the particulate number (PN) emission for more than 99 %. All these aftertreatment technologies have boundary conditions which describe their reliable and efficient operation. One main effort in the development and application process for an aftertreatment system for a new Tier 4 / Stage 4 Diesel engine is to guarantee reliable operation of the system under all operational conditions of the engine.

Especially for the DPF application a no fault strategy has to be applied. If the regeneration of the DPF can not be guaranteed in almost all engine operation points this may cause filter blocking and due to this filter or even engine damage. A passive regeneration of the DPF via NO₂ is well known [1] but seldom applicable as solely measure, because exhaust gas temperature distribution may not be sufficient in every user profile of the engine. That can lead to quite laborious engine measures to ensure right boundary conditions even for passive regeneration e. g. exhaust gas temperature, NO_x / PM ratio etc. to enable the exhaust system to work properly. In some applications even this may not work, so that active regeneration measures as late post-injection or HCI systems are necessary to grant reliable DPF regeneration.

Engines fitted with EGR + DOC + Partial Flow Filter are capable to fulfill Tier 4 emission regulations. Exhaust gas

recirculation (EGR) systems reduce NO_x, while the diesel oxidation catalyst (DOC) converts more than 90% of the gaseous emission components - such as hydrocarbons (HC) and carbon monoxides (CO) - from diesel exhaust gas. Besides cutting harmful HC and CO emissions, the DOC also converts nitrogen oxide (NO) from the diesel exhaust into nitrogen dioxide (NO₂), which is required for filter regeneration as described. Such passive regenerated partial flow particulate filters give the advantage of a recent PM and PN reduction at much wider boundary conditions than a full flow DPF. For example partial flow filters can be applied, combined with a DOC, as a retrofit solution to Euro 2 to Euro 4 passenger cars although the exhaust gas of their engines provides an NO_x/PM ratio which is less than half the value which is feasible and exhaust gas temperatures at urban operation are much too low for proper CRT functionality.

This paper describes the theoretical background of particulate filtration and regeneration of this type of filter and shows its performance at realized serial applications. Examples for partial flow particulate filters using sintered metal and their flow through passes of the exhaust gas (blue arrows) are shown in [figure 1](#). This paper focuses on partial flow SMF of the orifice type.

PARTIAL FLOW PARTICULATE FILTRATION WITH SMF

A partial flow SMF is a combination of a full flow filter with small orifices at the down stream side of the filter substrate. The opening area of the orifices is in the range of less than 1/1000 to the filter material surface. For the following fundamental explanation particulate filtration without any consideration of regeneration of soot is considered. The functional principle is based on the balance between the differential pressures of the orifices and the filter material.

The differential pressure of the filter material is described by Darcy [2] as

$$\Delta p_F = (B_F + B_C \cdot \frac{m_F}{\rho_S \cdot A_F}) \cdot \eta \cdot u_F \quad (1)$$



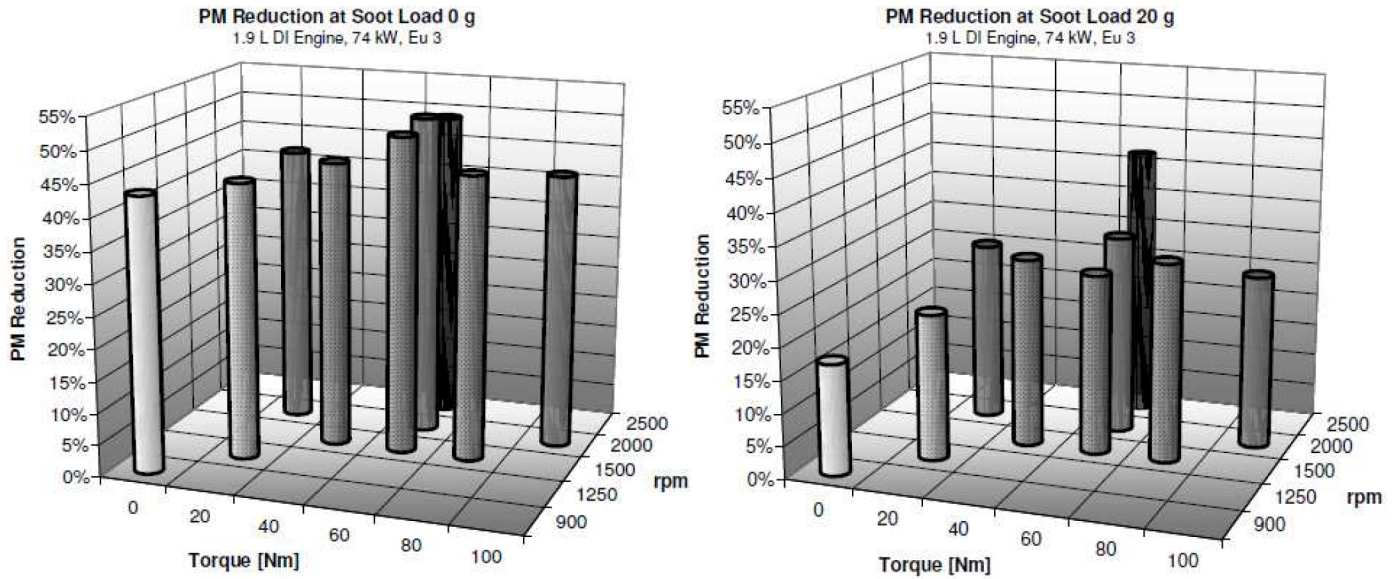


Figure 2. PM reduction of partial flow SMF (1 m² filtration surface) at common soot loads

Converting the flow velocity u_F to mass flow $\dot{m}_F$ using filtration area A_F and the ideal gas equation gives (2):

$$\Delta p_F = \left(B_F + B_C \cdot \frac{m_F}{\rho_S \cdot A_F} \right) \cdot \eta \cdot \frac{\dot{m}_F \cdot R \cdot T}{A_F \cdot p} \quad (2)$$

Δp_F : pressure drop filter; B_F : resistance coefficient filter material; B_C : resistance coefficient soot layer; ρ_S : soot density; A_F : filtration area; η : viscosity; u_F : flow velocity filter; m_F : soot mass filter; T : temperature [K]; p : pressure; R : gas constant of air; $\dot{m}_F$: exhaust gas mass flow filter; p : total pressure upstream filter

Equation (2) shows linear influence of flow resistance through the soot loaded filter material, exhaust gas mass flow and the filtration area.

On the other hand the pressure drop for orifices is defined by Darcy-Weisbach as (3):

$$\Delta p_B = 0.5 \cdot \zeta_B \cdot \rho \cdot u_B^2 \quad (3)$$

Converting the flow velocity u_B to mass flow $\dot{m}_B$ using orifice area A_B and the ideal gas equation gives (4):

$$\Delta p_B = 0.5 \cdot \zeta_B \cdot \frac{R \cdot T}{p} \cdot \frac{\dot{m}_B^2}{A_B^2} \quad (4)$$

Δp_B : pressure drop orifice; ζ_B : resistance coefficient orifice; A_B : total area orifices; u_B : gas velocity through orifice; $\dot{m}_B$: mass flow orifices. $\dot{m}_{AG}$: total exhaust gas mass flow.

By combination of the pressure drop model equations (2) and (4), the exhaust gas mass flow through orifices $\dot{m}_B$ and filter $\dot{m}_F$ can be estimated depending on the soot loading with following assumptions

$$\Delta p_B = \Delta p_F \quad (5)$$

and

$$\dot{m}_{AG} = \dot{m}_B + \dot{m}_F \quad (6)$$

A linear influence of flow resistance through the orifices and quadratic effect of exhaust gas mass flow or the filtration area is described by equation (4).

The test results of different flow resistances through certain soot loads and various exhaust gas mass flows on the PM reduction of partial flow SMF are shown for one filter type in the following diagrams. For these tests the engine was operated in stationary points derived from the NEDC for a European lower mid class passenger car equipped with this engine. Tests were carried out on an engine test bench at a filter type with a quite low nominal PM reduction between 30 % and 45 %. The named variance in PM reduction is depending on the particular engine application and the included DOC. To demonstrate only the influences of exhaust gas mass flow and soot load on PM reduction the filter was mounted to the engine without DOC upstream.

These results in figure 2 demonstrate, that the PM reduction is only slightly affected by exhaust gas mass flow, if the soot layer on the sintered metal filter material is very low. The tendency of higher PM reduction with higher gas velocity in the filter becomes more evident with a total soot load of 20 grams. If the filter is soot free, the effect of the orifices with quadratic influence of the gas mass flow see