

The Use of a Partial Flow Filter to Assist the Diesel Particulate Filter and Reduce Active Regeneration Events

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ABSTRACT

This study investigates the potential of using a partial flow filter (PFF) to assist a wall flow diesel particulate filter (DPF) and reduce the need for active regeneration phases that increase engine fuel consumption. First, the filtration efficiency of the PFF was studied at several engine operating conditions, varying the filter space velocity (SV), through modification of the exhaust gas flow rate, and engine-out particulate matter (PM) concentration. The effects of these parameters were studied for the filtration of different particle size ranges (10-30 nm, 30-200 nm and 200-400 nm). For the various engine operating conditions, the PFF showed filtration efficiency over 25% in terms of PM number and mass. The PFF filtration behaviour was also investigated at idle engine operation producing a high concentration of nuclei particulates for which the filter was able to maintain 60% filtration efficiency. After a 14 hour soot loading phase, the filter trapping efficiency remained over 20% and showed unexpectedly high small PM filtration efficiency. Finally, a system composed of a PFF placed upstream of a DPF was studied and the filtration efficiency, soot mass accumulated, as well as the pressure increase during a loading period of 7 hours were compared to the ones from a standalone DPF, in order to estimate the beneficial effects of using a PFF to assist the main DPF and reduce the regeneration duration and/or frequency.

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INTRODUCTION

The use of wall flow particulate filters in diesel engine exhaust for controlling soot emissions requires complex engine calibration strategies for active regeneration phases to oxidise the accumulated particulates and limit any pressure build-up in the filter that would lead to an increase in engine fuel consumption. The active regeneration, whether through late cycle post-injection or fuel injection upstream of the diesel oxidation catalyst (DOC), also affects the vehicle fuel consumption [1, 2]. A strategy to reduce the frequency and/or duration of these regenerative events, and therefore their impact on the engine fuel consumption, could be to extend the DPF loading period before an active regeneration becomes necessary. This could be allowed through the use of an aftertreatment component located upstream of the DPF that would "pre-filter" a portion of exhaust particulate matter (PM) and assist the main DPF. An upstream pre-filter could also be beneficial for an oxidation or selective catalytic reduction (SCR) coated DPF to limit soot accumulation on the coated filter walls and maintain its optimum activity over time. The requirements for this "pre-filter" would be a limited pressure increase during PM accumulation and continuous passive regeneration, as an active regeneration would bring more complexity to the whole system. An interesting candidate that could be considered as a potential "pre-filter" is the partial flow filter.

Due to its limited filtration efficiency [3,4,5], the PFF cannot be used as a replacement to the wall flow filter in diesel exhaust as the tailpipe PM emissions would be over the limit imposed by the emission legislation. Nevertheless, these filters still present some advantages over their wall flow counterparts [3] such as lower backpressure increase, no requirement for active regeneration and lower tendency to significantly accumulate lubrication oil ashes. These characteristics lead to less constraints and complexity in terms of filter maintenance and usage which make the PFF an attractive solution to complement and assist the main DPF. Partial flow filters have already been studied as a retrofit solution for heavy duty vehicles [6,7,8] or possibly fitted in gasoline direct injection (GDI) engine exhaust as a solution for future legislations that impose a limit on particulate mass and number [3, 9]. It was also presented as a possible hydrolysis catalyst, positioned upstream of an SCR catalyst [10, 11]. Most of these studies investigate the PFF behaviour in terms of total filtration during various engine operating conditions (speed and load) or over different driving cycles. Fewer studies have analysed in detail the effect of independently varying some exhaust gas properties on the PFF filtration efficiency for different PM size classes, to provide a clearer understanding of the filtration mechanisms and how they can be affected by changing engine operating conditions. This study investigates the PFF filtration behaviour in terms of particulate mass and number, as well as

for different particle size ranges at various filter space velocities and inlet PM profiles (concentration and size). The effect of the filter state (clean or loaded) was also studied to analyse its filtration behaviour after 14 hours of operation without any regenerative events. Finally, a combination PFF/DPF was investigated to assess the effect of an upstream PFF on the filtration and loading time of a wall flow filter. This eventually provides a first insight on the possibility of increasing the DPF loading time and therefore, reducing the need for active regeneration events.

METHODOLOGY AND EXPERIMENTAL SET-UP

Partial Flow Filter

The partial flow filter used in this study is a PM-Metalit® manufactured by Emitec. It is composed of thin stainless steel foils folded to form sinusoidally shaped channels. Along the length of the channels, the exhaust flow encounters metallic shovels forcing a change of direction of the flow and guiding it towards a porous sintered metal fleece layer located on top of the channels. Part of the exhaust gas flows through the fleece, depositing medium and large particulates through deep-bed filtration and reaches the top-neighbouring channel (zone 1 in Figure 1). Due to their higher momentum, the largest particulates are also trapped in this zone through impaction. The remaining portion of exhaust gas by-passes the fleece and travels either along or within the fleece in the direction of the flow, as the channels are not completely blocked by the shovel structure. This portion of exhaust gas contains on average smaller particulates, depending on the medium-large PM filtration efficiency taking place previously in zone 1. At that stage, the filtration takes place through diffusion mechanisms with the exhaust gas depositing small particulates along the fleece (zones 2 and 3 in Figure 1).

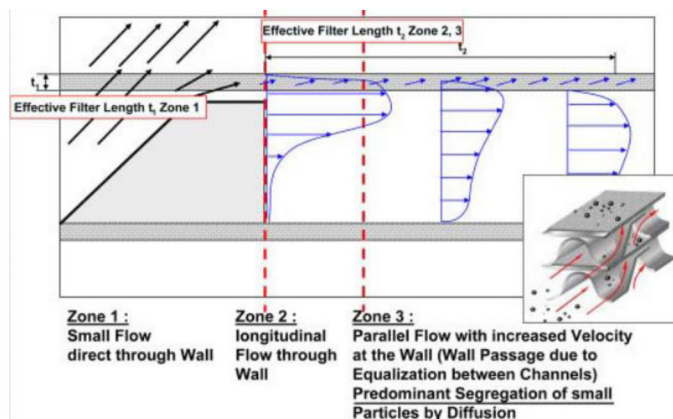


Figure 1. Schematic of the filtration mechanisms taking place within the PFF. Reproduction from [8].

In this study, small particulates will refer to nanoparticles 1 (diameter between 10 nm - 30 nm), medium particulates comprise nanoparticles 2, ultrafine particles and fine particles 1

(diameter from 30 nm - 200 nm) and the large particulates denomination includes fine particles 2, with a diameter from 200 nm - 400 nm, as shown in Figure 2.

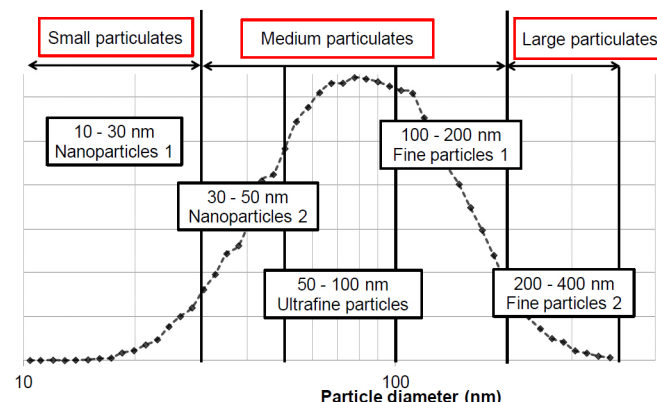


Figure 2. PM size classification used in this study.

Methodology

A single cylinder diesel research engine, set-up as described in the experimental setup section, was operated at several steady state conditions, to vary the engine-out soot profile (concentration and size) and the filter gas hourly space velocity (GHSV or SV, defined as the ratio of exhaust gas flow rate on filter volume). To study the effect of PM concentration on the filtration efficiency, different exhaust gas recirculation (EGR) rates were used while adjusting the engine speed to maintain a constant filter space velocity. Comparable soot profiles were recorded at different engine speed to allow the investigation of the space velocity effect on the filtration, independently from the PM concentration (Table 1).

Table 1. PM concentration in number (#/cm³) for the different operating conditions and space velocities considered in this study.

Parameter Considered	Space velocity	Low PM	Medium PM	High PM
PM Concentration	27k /h	2.51e ⁶		6.49e ⁶
	41k /h	5.01e ⁶	7.07e ⁶	9.32e ⁶
	59k /h	4.31e ⁶	1.26e ⁷	2.15e ⁷
Space Velocity	27k /h			6.49e ⁶
	41k /h	4.46e ⁶		7.07e ⁶
	59k /h	4.31e ⁶		
Idle	15k /h	1.55e ⁶		
Loaded State	27k /h (clean)	2.51e ⁶		
	27k /h (loaded)	1.73e ⁶		
	54k /h (loaded)	3.75e ⁶		
	59k /h (clean)	4.31e ⁶		
	68k /h (loaded)	6.21e ⁶		

The PFF used in this study, which properties can be found in Table 2, was not coated, as the washcoat could block the fleece layer, resulting in a possible reduced porosity and

filtration efficiency [12]. As the aim of this study was to investigate the filtration mechanisms and efficiency of the PFF, an uncoated component was better suited to estimate its behaviour relative to filtration.

Before the experiments, the PFF was completely regenerated at 600°C for 6 hours to eliminate any soot previously accumulated.

Table 2. Partial flow filter characteristics.

PM-Metalit® properties	
Brick dimensions	118.4 x 123 mm
Cell density	200 cpsi
Flat/Corrugated foil thickness	0.3/0.065 mm
Fleece properties	
Thickness	22 µm
Porosity	85%

Exhaust gas PM concentration and size distribution were measured before and after the filter at each engine operating condition. The measurement was repeated at least three times and averaged to allow a more representative recording of the actual soot concentration. The graphs representing the total filtration efficiency in terms of mass and number were fitted with error bars, based on the standard deviation of the three measurements and a 95% confidence level.

Furthermore, in order to study the filtration behaviour of a loaded PFF, the filter was loaded with soot for 14 hours before analysing its filtration efficiency. During this phase, the exhaust temperature was kept at a level limiting any passive regeneration using NO₂ from the engine exhaust gas.

The last part of this study investigated the use of a PFF to assist a downstream wall flow DPF. For this experiment, various parameters were recorded (filtration efficiency, pressure and soot mass accumulation) to understand the benefits of a PFF/DPF configuration. For this experiment, the engine was operated at a steady-state condition (1500 rpm and 5 bar IMEP) producing a significant concentration of PM. The DPF used in this experiment was a non-coated cordierite honeycomb wall flow filter (25.4 mm × 60 mm). At first, the experiment was realised with the DPF on its own. It was then repeated with the PFF placed upstream of the DPF. Prior to both loading sessions, the DPF was regenerated in a furnace at 600°C for 6 hours in order to remove any soot residual and volatile organic compounds accumulated during the experiment. Moreover, the filter was weighted before and after the loading session, in order to compare the total soot mass accumulated over the 7 hour tests.

Experimental Setup

The engine used in this study is a single cylinder, direct injection diesel engine, the properties of which can be found in [13].

The test rig is composed of a DC motor-generator dynamometer coupled to a load cell used to load and motor the engine. Standard engine test rig instrumentation is used to monitor intake air flow, temperatures and pressures (air, oil, inlet manifold and exhaust system). The EGR system is externally cooled and its flow is controlled by a valve. The EGR level is determined volumetrically as the percentage reduction in volume flow rate of inlet air at a fixed engine operating point. The fuel used in the study is a ULSD fuel supplied by Shell Global Solutions UK and its properties can be found in [13].

A TSI SMPS 3080 particle number and size classifier was used to measure the PM concentration and size distribution. The dilution ratio was 1 part exhaust to 36 air at a dilution temperature of 150°C. A schematic of the experimental setup used in this study is shown in Figure 3. When investigating the PFF/DPF configuration, the DPF was fitted in a small reactor placed into a furnace which temperature was externally controlled. A portion of exhaust gas (70 L/min) was by-passed and directed to the reactor to load the filter (shown in grey in Figure 3).

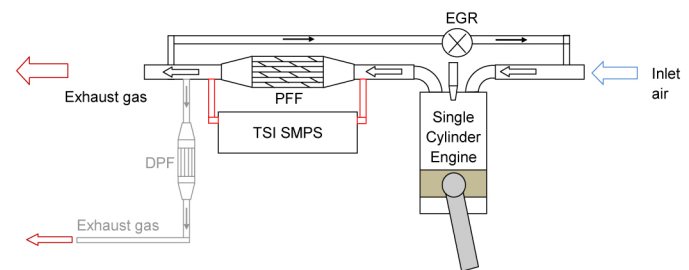


Figure 3. Schematic of the experimental setup used in this experiment.

RESULTS AND DISCUSSION

Effect of the PM Profile and Space Velocity on the Filtration Efficiency

Varying the PM concentration at the filter inlet and the space velocity affects differently the filtration efficiency depending on the size of the particulates considered.

PM Concentration and Profile

Small Particulates

For all three space velocities (Figure 4), an increase in PM concentration at the PFF inlet affects small particulate filtration. First, the presence of a higher concentration of medium-large particulates in the flow by-passing the membrane could limit the access of small PM to the filtering medium. Nevertheless, it also seems that a higher small PM concentration without excessive medium-large particulate concentration could, on the contrary, enhance the filtration through diffusion as it relies on small particulate concentration gradients. This could justify the higher small PM filtration efficiency found for the intermediate PM concentrations measured at the medium space velocity condition (Figure 4 (c)-(d)).