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 different 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). Over the different 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 over 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.

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 filter coated 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 [3-5], 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 [6-8] 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 different engine operating conditions (speed and load) or over various 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).

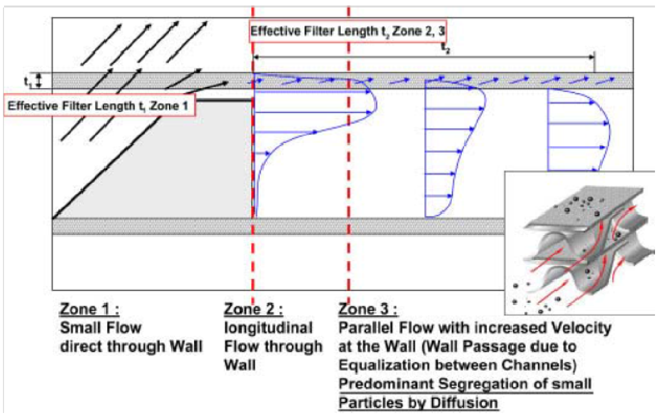


Figure 1. Schematic of the filtration mechanisms taking place within the PFF. Reproduction from [8].

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.

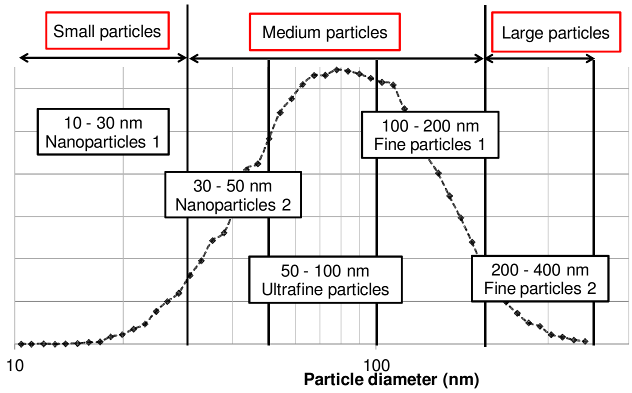


Figure 2. PM size classification used in this study.

Methodology

A single cylinder diesel research engine, set-up as described in the experimental setup section, was operated at different steady state conditions, to vary the filter gas hourly space velocity (GHSV or SV, defined as the ratio of exhaust gas flow rate on filter volume) and the engine-out soot profile (concentration and size). To study the effect of PM concentration on the filter 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 (#/cm^3) 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 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 operating condition. The measurement was repeated at least three times and averaged to allow a more representative recording of the actual soot concentration.
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 NO_2 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 cm x 60 cm). 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 tests (7 hours).

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).

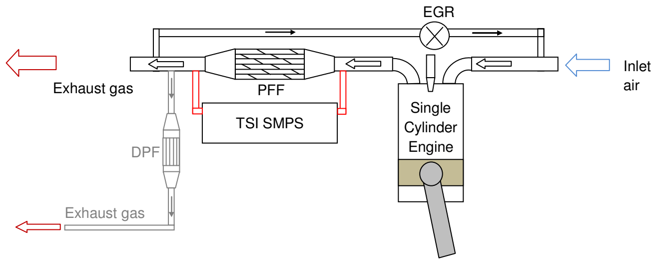


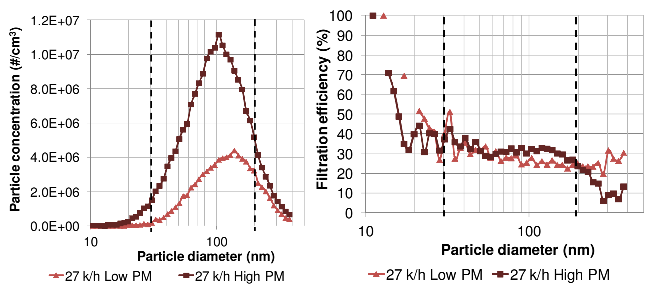
Figure 3. Schematic of the experimental setup used in this experiment.

Results and Discussion

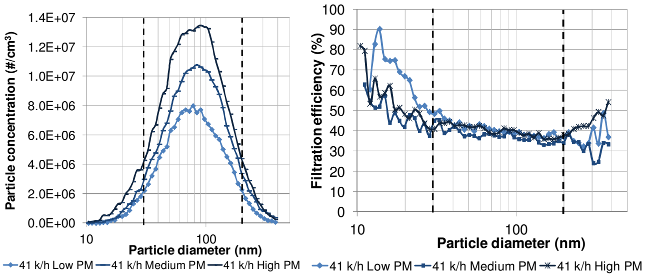
Effect of the PM Profile and Space Velocity on the Filtration Efficiency

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.

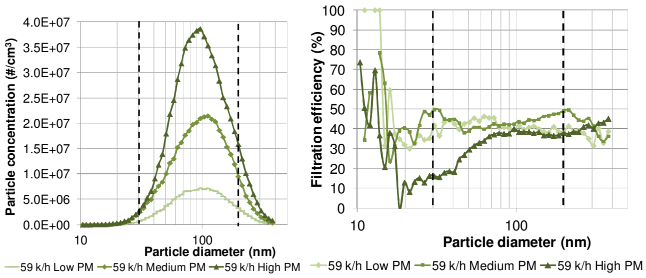
PM Concentration and Profile



(a) (b)



(c) (d)



(e) (f)

Figure 4. a) Particle size distribution at the PFF inlet and filtration efficiency for the low (a)-(b), medium (c)-(d) and high (e)-(f) space velocity conditions, respectively 27, 41 and 59k/h, at different PM concentration.

Small Particulates

For all three space velocities (Figure 4), an increase in PM concentration at the PFF inlet greatly 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 particle concentration gradients. This could justify the higher small PM filtration efficiency found for the medium space velocity condition (Figure 4 (c)-(d)).

Medium-Large Particulates

For medium-large particulates, the filtration remains similar for the different filter inlet PM concentration profiles. Medium-large particulate filtration mainly relies on the portion of flow diverted towards the fleece which is not much affected by the concentration of PM in the exhaust.

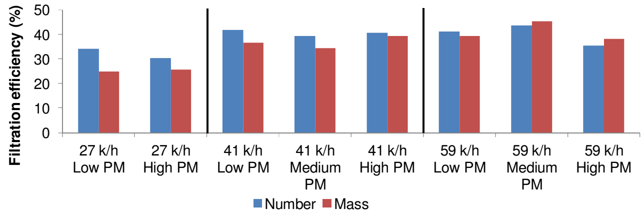
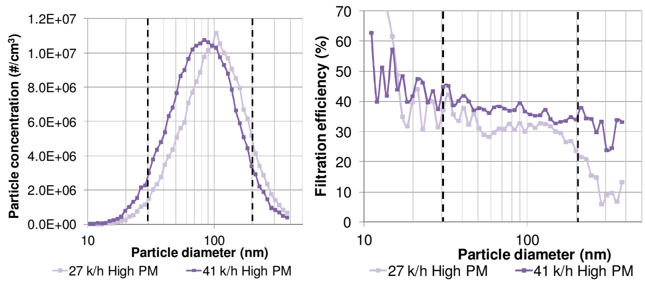


Figure 5. Total average mass and number filtration efficiency for the different PFF inlet PM concentration and space velocities.

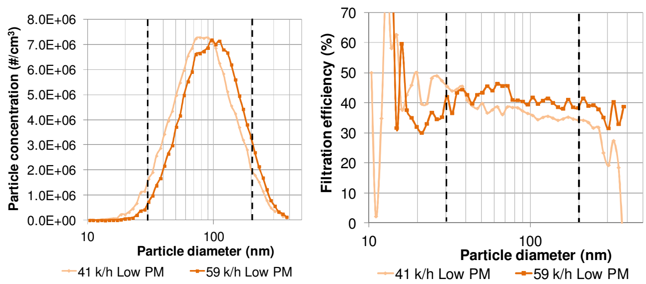
Figure 5 shows that the PFF is able to maintain an average total filtration efficiency of over 25% over the different engine operating conditions. While the different PM concentrations do not affect much the total efficiency, an increase in space velocity seems to be promoting the PFF filtration efficiency.

Space Velocity

The following section investigates the effects of space velocity on the filtration efficiency at comparable PM concentration at the PFF inlet.



(a) (b)



(c) (d)

Figure 6. Particle size distribution at the PFF inlet and filtration efficiency when varying the space velocity at similar inlet PM concentration (high PM concentration for (a)-(b) and low PM concentration for (c)-(d)).

Small Particulates

Increasing space velocity can have an indirect effect on small PM filtration by increasing the portion of exhaust gas diverted in zone 1 (Figure 1) and therefore reducing the portion of exhaust gas in zone 2 and 3, promoting small PM filtration by reducing the velocity in this filtering zone. Nevertheless, further increase of the space velocity would eventually affect the exhaust gas residence time within the filter and therefore reduce small PM filtration efficiency. This could explain why higher filtration efficiency is recorded at medium space velocity (filtration efficiency at 41k/h > 27k/h > 59k/h). The effect of increasing the exhaust gas flow rate on, on one hand, the portion of flow diverted in zone 1 and on the other hand, the velocity recorded in zone 2-3 needs to be further assessed in order to define where the balance between the two effects is. Moreover, as explained previously, higher small particle concentration for a similar medium-large PM concentration could enhance the diffusion mechanisms through which small PM filtration takes place, therefore showing better filtration in the case of 41k/h for both graphs, due to higher small PM concentration at this condition.

Medium-Large Particulates

As the space velocity increases, medium-large PM filtration is promoted (Figure 6), due to a greater portion of exhaust gas diverted towards the fleece in zone 1 of the filter (Figure 1), where medium-large PM filtration takes place. Nevertheless, it can be though that as the exhaust flow rate further increases, the residence time within the filter would be reduced which could eventually affect the filtration at greater space velocities.

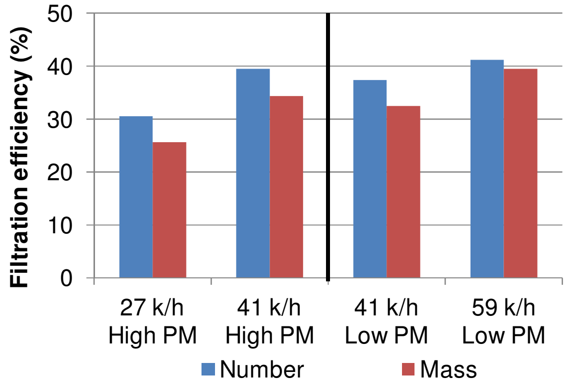


Figure 7. Total mass and number filtration efficiency at similar PM concentration for the different space velocities.

For the different set of conditions, the total filtration in terms of mass and number (Figure 7) is always greater at higher space velocity, independently of the PM concentration at the PFF inlet, due to the promotion of medium-large PM filtration.

Evaluation at Idle Operation

At idle and low speed engine operation, the space velocity within the filter is 15k/h. A lower concentration of large particulates (mainly soot) is also produced in the combustion chamber due to a reduction of the quantity of fuel injected at this engine condition (no load). Furthermore, the exhaust gas temperature is low (100℃) and allows water and some hydrocarbons to condense in the exhaust. Due to the lower soot concentration, it is more difficult for these condensates to adsorb onto solid particulates so they form small liquid droplets on their own, constituting most of the nuclei particulates measured in the engine exhaust gas at this operating condition. This PM distribution composed of a higher portion of nuclei particulates and fewer accumulated ones, makes idle a relevant condition to study the PFF filtration efficiency compared to the previous engine operating conditions where most of the particulates were soot contained in the accumulation mode.

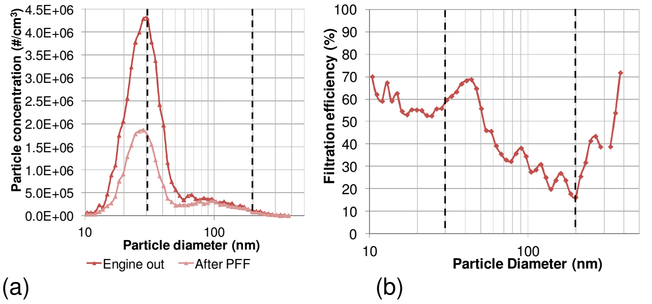


Figure 8. a) Particulate size distribution at the PFF inlet and b) filtration efficiency at idle operating condition.

Small Particulates

The 60% filtration efficiency recorded for the small PM (Figure 8) shows that the PFF can cope with high small PM concentration when medium-large PM concentration is limited. The PFF being non-coated, this high filtration efficiency cannot be accounted for by the oxidation of some of the hydrocarbons forming the nuclei particulates. The lower exhaust gas flow rate at this condition also allows an increased residence time enhancing the small PM filtration within the PFF.

Medium-Large Particulates

Filtration efficiency for this range of PM decreases from 60% for the 30 nm diameter PM to 20% at 200 nm diameter. The low space velocity at this condition reduces the portion of exhaust gas diverted towards the fleece in zone 1 of the filter (Figure 1), dramatically decreasing medium-large PM filtration at this condition.

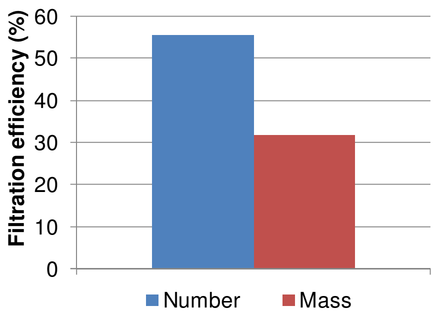


Figure 9. Total mass and number filtration efficiency at idle operating condition.

The total filtration (Figure 9) shows greater efficiency in terms of number compared to mass due to the filter being more efficient at trapping small PM (high number but low mass) while having a reduced efficiency for medium-large PM (low number but high mass) for this operating condition.

Partial Flow Filter Performances at Loaded Conditions

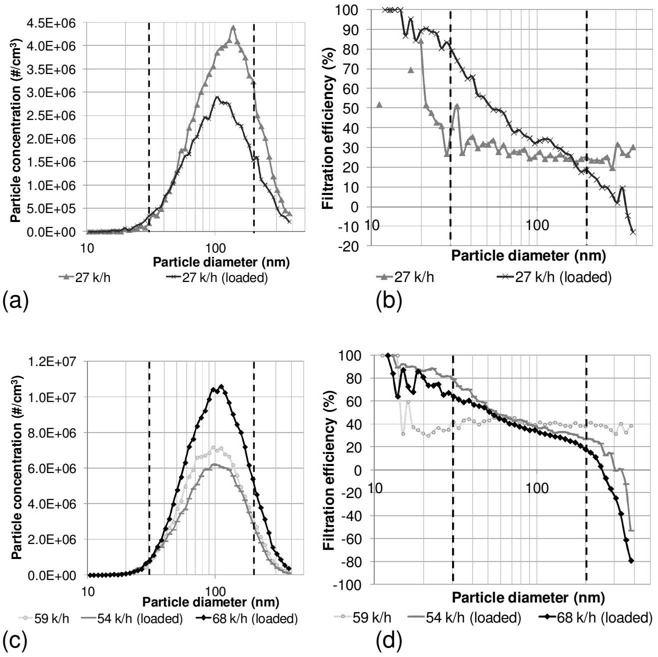


Figure 10. Particle size distribution at the PFF inlet and filtration efficiency for a clean and a loaded filter at low (a)-(b) and high space velocities (c)-(d).

Once the PFF becomes loaded with soot, different filtration patterns are observed compared to the clean PFF. Figure 10 shows that the general trend of filtration for the loaded state remains the same when varying the space velocities and PM concentrations.

Small Particulates

At the loaded condition, high filtration efficiency of up to 90% is recorded for small particles. The filtration mechanisms taking place here are thought to be specific to the loaded state as such a high filtration was not encountered at any other engine conditions during this study. The accumulation of soot within the filter could create a soot cake on the surface of the membrane, which would promote small PM filtration, similarly to a wall flow filter.

Medium-Large Particulates

After hours of filtration, the membrane saturated with soot, especially in zone 1 (Figure 1) and the possible formation of a soot cake layer on the fleece would lead to a greater portion of exhaust gas by-passing the filtration zone for medium-large PM, decreasing their filtration. The apparent negative value recorded for the largest PM filtration efficiency in Figure 16 (b) also highlights a possible blow-off of some particulates previously trapped in zone 1 or formed from smaller particle accumulation within the membrane and blown away with the increased exhaust flow in zone 2 and 3. The opposite filtration behaviour for small PM compared to medium-large ones needs further investigations to highlight the specific filtration mechanisms taking place once the filter is loaded and to explain the origin of such a high small PM filtration capacity.

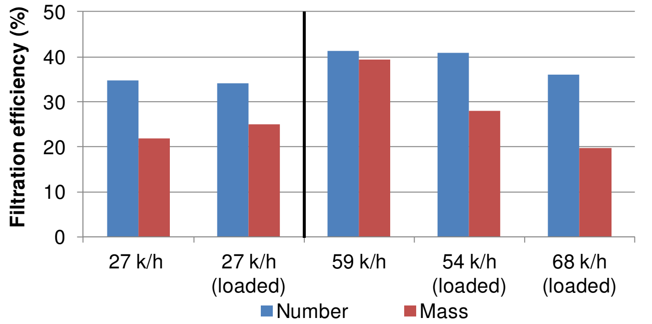


Figure 11. Total mass and number filtration efficiency for a clean and loaded filter at low and high space velocity.

The limited filtration of large PM when the filter is loaded translates into low mass filtration efficiency while number filtration efficiency remains similar or slightly lower compared to the clean filter. The filtration profile of the loaded PFF presents an attractive trapping efficiency for small-medium PM that are the most harmful for humans and for which the filtration can be limited in DPFs. The reduced large PM filtration efficiency for the loaded state can be considered as a limited drawback as the downstream DPF would take care of filtering the particulates that by-passed the membrane in the PFF.

Partial Flow Filter/ Diesel Particulate Filter Combination

This section presents the filtration efficiency, soot accumulation and pressure increase of a system composed of a PFF placed upstream of a wall flow DPF and compares these results with those from a standalone DPF (Figure 12), in order to evaluate the capacity of the PFF to assist the DPF and reduce the needs for active regenerative events.

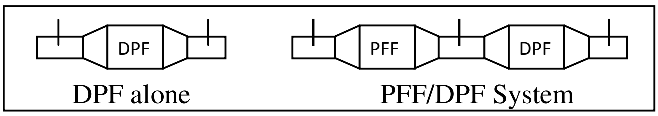


Figure 12. Schematic representation of the two different configurations studied.

Filtration Efficiency

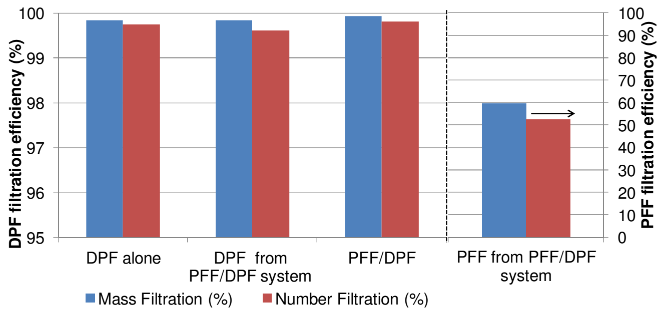


Figure 13. Number and mass filtration efficiency for the different components and configurations studied.

Figure 13 shows that the addition of an upstream PFF does not improve the total filtration of the system much in terms of both mass and number. This is due to the fact that the DPF on its own already shows high filtration efficiency of over 99%. A slightly lower total filtration can be noticed for the DPF when it is part of the PFF/DPF system compared to the standalone DPF.

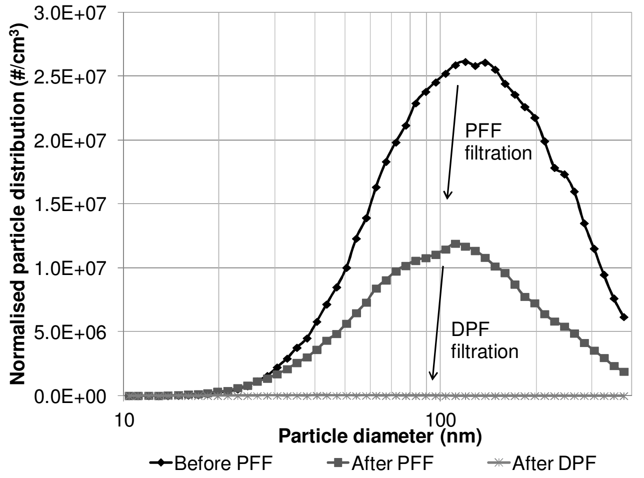


Figure 14. PM profile at the PFF inlet, outlet and DPF outlet.

The PM concentration supplied to the DPF is reduced by 50% on average due to the presence of the upstream PFF (Figure 14). This can affect the soot cake accumulation on the channel walls acting as a filter medium in the DPF and therefore reduce the filter trapping efficiency.

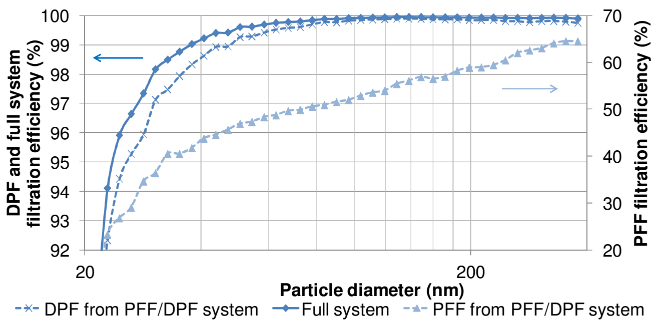


Figure 15. Particle size related filtration efficiency for the DPF, PFF and PFF/DPF system.

The filtration efficiency for the different particulate size (Figure 15) confirms the limited improvement from using the PFF/DPF combination. Due to the engine condition used for this experiment producing a high medium-large PM concentration, the PFF filtration efficiency in the 20-30 nm particle range remained limited. Nevertheless, the filtration is still slightly enhanced when using the PFF/DPF system for PM between 20 and 50 nm due to the partial flow filter filtration efficiency.

Soot Accumulation and Pressure Increase

The reduced PM concentration supplied to the filter (Figure 14) resulted in the DPF accumulating 0.22 g of soot when fitted with an upstream PFF compared to 0.31 g for the standalone DPF over the 7 hour test. This 30% lower soot accumulation translated into a lower pressure increase over the loading time (Figure 16). Moreover, the increase in DPF pressure from the PFF/DPF configuration was steadier than in the case of the DPF alone, which reduced the engine power loss created by the higher backpressure.

Due to the differences in terms of flow rate (over 14 times more for the PFF), the pressure increase over the full size PFF could not be directly compared with the pressure recorded over the 1 inch diameter DPF. Nevertheless, a limited pressure increase was recorded over the tests, which is in agreement with other studies that recorded small pressure increases during the use of a PFF [14-16].

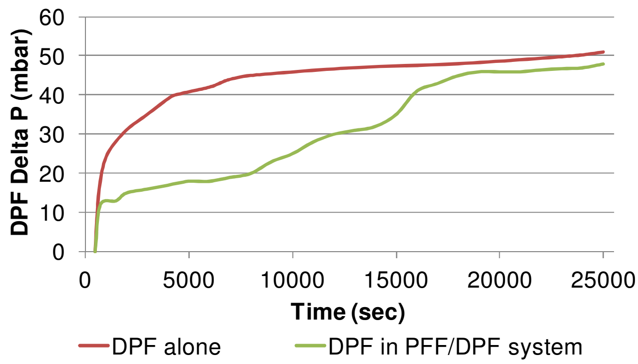


Figure 16. Pressure increase over the DPF during the loading process when alone and when fitted with the upstream PFF.

The reduced soot mass loading, associated with lower pressure increase, show the potential of the PFF/DPF combination to reduce the duration and/or frequency of active regenerations, allowing either a loading time a third longer or a shorter regenerative event to oxidize the lower mass of soot accumulated within the DPF.

Conclusion

This study investigates the use of a partial flow filter (PM-Metalit) as a pre-filter component located upstream of a DPF in order to reduce the frequency and/or duration of the required active regeneration phases. The investigation of the PFF capacity in filtering PM at various engine operating conditions (space velocity and PM concentration at the filter inlet) showed that filtration of small PM is affected by the presence of a high filter inlet concentration of larger particulates, while medium-large PM filtration is enhanced at higher space velocity. A different filtering pattern was recorded once the PFF was soot loaded, with 80-90% filtration efficiency for small PM which decreases with increased particulate size, down to zero or even negative filtration efficiency, showing a possible blow-off phenomenon in the filter. A system composed of a PFF located upstream of a DPF showed limited improvement of the total filtration efficiency of the system but allowed 30% less soot mass accumulation within the DPF compared to a standalone DPF. This translated into a lower and steadier pressure increase over the loading time.

More investigations are required to allow a fuller understanding of the effectiveness of the PFF/DPF combination. The requirements in terms of NO_2 concentration and temperature to favour an effective and continuous regeneration of the PFF need to be estimated. Moreover, during active regeneration

events, the effect of the PFF on the temperature profile supplied to the downstream DPF needs to be assessed as it could possibly reduce the effectiveness of the regeneration. Finally, the reactivity of the soot at the outlet of the PFF could also be investigated in order to estimate the oxidation capacity of the soot profile supplied to the DPF.
Eventually, a system composed of a coated PFF combining both pre-filtration and oxidative functions could be investigated to further enhance the effectiveness of a PFF/DPF combination which already proven some interesting results in relieving the main DPF from a portion of particulate concentration.

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Abbreviations

DOC	diesel oxidation catalyst
DPF	diesel particulate filter
EGR	exhaust gas recirculation
GDI	gasoline direct injection
GHSV	gas hourly space velocity
IMEP	indicative mean effective pressure
NO_2	nitrogen dioxide
PFF	partial flow filter
PM	particulate matter
SCR	selective catalytic reduction
SV	space velocity