



Full Length Article

An experimental study of the role of biodiesel on the performance of diesel particulate filters



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ABSTRACT

The study investigates the impact of the physical properties of biodiesel particulate matter on the performance of diesel particulate filters (DPF). Filtration efficiency (FE) and pressure drop (PD), as a function of loading time, were studied on a DPF for a range of biodiesel fuels with varying fuel molecular oxygen content from 0% (diesel) to 14%. The change in the oxygen content of the fuel resulted in diesel particle matter (DPM) with significantly different physical properties. FE and PD were investigated during the deep bed filtration stage, chosen because it presents the start of the loading process, which is a crucial step for high performance filtration. Firstly, we investigated the influence of the size distribution of various particles on the deep bed filtration, wherein size distributions of PM were measured before and after the DPF. The results show that for all fuels the FE is higher for smaller particles, as diffusion is the dominant process governing the filtration in tested conditions. Further we found that FE for biodiesel particles were up to 10% lower than for diesel particles at the beginning of the loading process, but with that difference diminishing as the filter fully loads. This result is attributed to the increase in the particulate fractal dimension with a higher biodiesel fraction resulting in more compact particles with lower diffusion coefficients. In addition, the study also demonstrated that the change of FE during the loading process is dependent on the physical properties of DPM. DPF performs differently for biodiesel soot as compared to diesel soot, with biodiesel soot causing higher PD for the same mass of the soot loaded on the DPF. This effect was attributed to the smaller primary particulate size of the biodiesel particles. The results presented in this study will further facilitate understanding of the filtration processes of particulate matter and validate detailed filtration models for the prediction of the filtration efficiency (FE) and pressure drop (PD) depending on the particle morphological properties.

1. Introduction

Due to their high energy output and fuel economy, diesel engines take a major role in the transport and other energy transformation areas [1]. However, combustion of diesel is associated with high pollutant emissions, especially the carcinogenic diesel particulate matter (DPM) [2–4]. As a result, stringent emission regulations have been introduced [5]. The two main approaches used to meet the set criteria are continuous improvement of the after-treatment devices (ATDs) and the

introduction of clean alternative fuels [6].

Biodiesels are considered as a potentially good diesel replacement due to their lower emissions and renewability [7–9]. A number of countries around the world have already mandated the use of renewable fuels such as biodiesel [10], and the corresponding infrastructure supporting the transition to renewable fuels will be increasingly built up in the future [11]. As Euro 6 standards have already introduced higher biodiesel percentages, there is an urgent need to explore the compatibility and efficiency of current after-treatment devices with the

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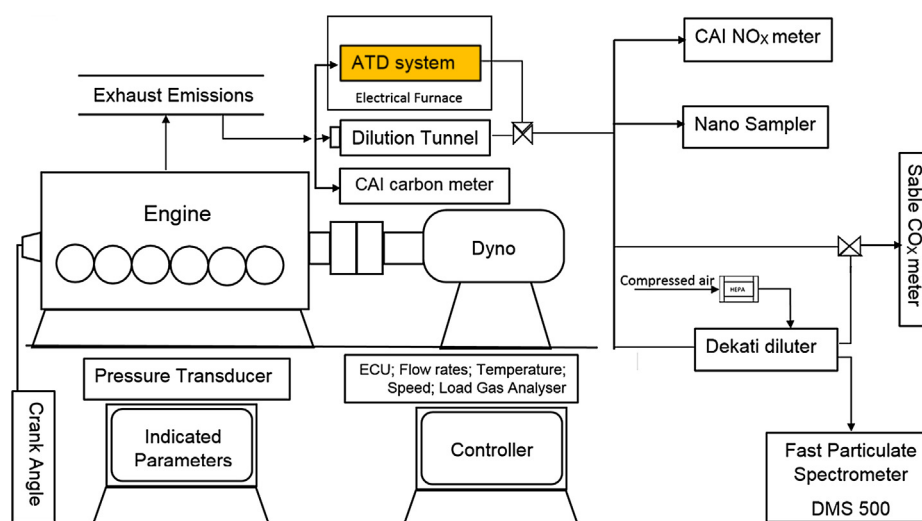


Fig. 1. Experimental setup.

emissions coming from the combustion of blended and neat biodiesels [12–14]. Following this concern, this research aimed to test and investigate the compatibility of a DPF system with biodiesel particulate matter (PM).

Some work has been done on the compatibility of after-treatment devices (diesel oxidation catalyst (DOC) + diesel particulate filter (DPF)) used to meet the Euro 5 and 6 emission standards with biodiesels [13]. The DPF's performance is dependent on two processes: soot loading and regeneration. Most of the research focus has been on the regeneration rate and strategies introduced to deal with the different reactivity of biodiesel soot [15,16]. Only a few publications have investigated the loading process [17–22].

Williams et al. investigated the amount of ash remaining within the filter in the loading process [17]. Another study, by Rose et al. [18], reported preliminary tests of loading ratio for different biodiesel blends, while in other studies particle number (PN) and/or particle mass concentration was monitored after the DPF system [16,19–22]. There are no publications on FE and PD changes during the loading process with biodiesel soot coming from blends with controlled composition such as fuel molecular oxygen content. Therefore, from the diesel engine emission measurement standpoint, there is a significant research gap in the investigation of the role of biodiesel particles on the FE and PD of the DPF.

From the filtration mechanism point of view, research has been conducted on the DPF loading process, which resulted in a better understanding of the evolution of FE and PD. Some literature highlights the features of soot deposition inside the wall-flow DPF by using electron microscopy [23,24]. Sandeep et al. [25,26] carried out the measurement on the FE, PD and most penetration particle size versus time in order to investigate the evolution of the deep-bed filtration of DPF with diesel particles. In addition, other groups tested the performance of different DPFs to characterise the DPF including the FE and PD versus time [27]. To test the filters for different particle sizes, all of the above studies have used diesel fuels, but run the engine at different conditions.

To further investigate the factors impacting the FE and PD, a number of modelling studies have been conducted [24,28–31]. By applying relevant parameters (e.g. local porosity, porous size distribution, permeability etc.) governing the deposition, the models were built up and the modelled results compared with the experimental results. The studies showed that the models were in a good agreement with the experimental results, demonstrating the ability to predict the FE and PD during the loading process. However, the particles employed were only from the combustion of diesel fuel. Similar to the above studies, in

order to test the models for different particle sizes, different engine operation conditions were used [25,26]. As biodiesel particles differ from diesel particles intrinsically, not only in the primary particulate size, but also in the fractal dimension [32–34] and other physical properties [35], the FE and PD of the DPF loaded with biodiesel particles need to be characterised. Only with these results can the modelling proceed to bridge the macroscopic (FE, PD, most penetrating particle size) and microscopic properties (porosity, porous size, deposition mechanism), in aiming to build up a tool for analysing and designing particulate filters for biodiesel particles with specific physical properties. This manuscript holistically investigated the evolution of filtration efficiency and pressure drop for different biodiesel blends with varying oxygen content from 0 to 14%. It also shows how the size distribution of particles changed after they passed through the ATD, and how physical properties of biodiesel particles impacted the performance of the DPF. Findings from this research could be used to update the existing models and optimise them for the prediction of emissions coming from a variety of blends and alternative fuels. It is also anticipated that this study can be used as an initial step towards optimised DPF systems, and as a reference for the optimal chemical composition of alternative fuels that will yield a reduction in primary vehicle particulate emissions.

2. Methodology

2.1. Experimental setup

The performance of the DPF with diesel and biodiesel particles was investigated using the setup as shown in Fig. 1.

The ATD system (DOC + DPF system) was placed inside an electrical furnace to maintain a stable temperature (180 °C) for the DOC. A three-way valve enabled the monitoring of the particulate properties, including mass and number concentrations, as well as size distribution before and after the ATD system from which the filtration efficiency was then calculated. During the DPF loading process, all instruments were monitoring the emissions after the ATD system. Once the emissions became stable, primary emissions were measured before the ATD system by placing the equipment after the dilution system and before the ATD. For each fuel, the same test condition (setup, flowrate etc.) and loading time were applied, to ensure comparable results for the different fuels.

2.2. Facilities and instruments

This experimental study was performed on a Euro 3 Cummins diesel

Table 1
Test engine specifications.

Model	Cummins ISBe220 31
Cylinders	6 in-line
Capacity (L)	5.9
Bore × Stroke (mm)	102 × 120
Maximum power (kW/rpm)	162/2500
Maximum torque (Nm/rpm)	820/1500
Compression ratio	17.3
Aspiration	Turbo-charged & after-cooled
Fuel injection	Common rail
After-treatment devices	None
Emissions certification	Euro 3

engine coupled to a water brake dynamometer, both of which were connected to an electronic control unit (ECU). Table 1 shows the specifications of the test engine. The engine was operated at 1500 rpm with 75% load for the deep bed filtration test.

The tested DPF in the study is a passive ceramic wall-flow filter. A Diesel Oxidation Catalyst was installed in front of the DPF, so the whole system is a Continuous Regeneration Technology (CRT) system. The DOC and DPF media are housed in a stainless-steel system holder. The components of the after-treatment system are shown in Appendix 1.

In the experiment, the filter system was placed inside an electrical furnace to keep an appropriately high temperature for the DOC to be operational, while at the same time remaining low enough to prevent regeneration from occurring in the DPF. The system was connected to the engine exhaust via a half-inch stainless-steel tube. The outlet of the filter system was connected to the measurement system, which includes a number of instruments for particle and gaseous characterisation. The flow rate through the ATD system was kept constant at 17 lpm for every test to ensure that the results are comparable. To monitor the performance of the DPF during the loading test, the PD over the ATD system was continuously measured. The monotonous increase in PD is a typical sign of the accumulation of soot inside the DPF. During the filter loading engine performance was continuously monitored with the electronically controlled dynamometer. Engine exhaust emissions were also continuously measured with a set of laboratory grade gas meters (CAI series 600, NOx and CO₂ meters) to monitor any variations in the engine combustion. This was done to ensure that the engine operating conditions were the same for each fuel tested and to minimise any system errors.

After each measurement, for one type of fuel, the DPF was cleaned by ramping the temperature in the furnace from 150 °C to 600 °C, while blowing HEPA filtered lab air at 17 lpm through it. CO₂ and particle number concentration were monitored downstream of the filters. Both are produced during the filter regeneration process as they are both products of burning the soot captured in the DPF. Once the soot burning is initiated a spike in both CO₂ and particles is observed that lasts until all of the soot has been burned out. After the two monitored parameters came back to stable background levels the furnace was run for an additional 30 min to ensure any remnants of the soot from the previous fuel were removed. The results from the regeneration experiments will be presented in a coming manuscript.

As shown in Fig. 1, the particle number concentration and size distribution were measured with the Fast Particulate Spectrometer DMS 500 (Cambustion Ltd., Cambridge, UK) at 2 Hz. The DMS 500 first stage hot dilution was removed, and instead a dilution tunnel was used as the first stage dilution to dilute the raw exhaust with HEPA-filtered laboratory air. A second diluter (Dekati) was connected in series with the first stage dilution to further increase the dilution ratio and decrease the particulate concentrations. The purpose of the dilution was to bring down the temperature as well as the concentration of gases, and to make sure particle concentration is within the measuring range of the instruments. Diluted exhaust was then sent to different gaseous and particle-measuring instruments. A CAI 600 series CO₂ analyser was

used to measure the CO₂ concentration directly from the raw exhaust. A second CO₂ meter (SABLE, CA-10) connected via a three-way valve between the two diluters was used to record the CO₂ concentration from the diluted exhaust.

For the particle morphology analysis, the particles on the TEM grids were collected by employing the Nanometer Aerosol Sampler (TSI 3089). Joel 2100 High Resolution Transmission Electron Microscopy (HRTEM) was employed to capture the images for the data analysis.

Conventional diesel was used as the baseline fuel, along with coconut biodiesel. This particular biodiesel was chosen due to its dominance in the feedstock of the Pacific Islands. Also, in Europe, around 11% of biodiesel is sourced from coconut feedstock. Coconut biodiesel shares some common FAMES with other biodiesels, however its distinctive composition is that it contains 50% methyl laurate and it is around 90% saturated.

In the experiment, the biodiesel was blended with diesel in serial percentages to make different blends of fuel. The B20 blend contains 20% biodiesel and 80% diesel, and B50 is 50% biodiesel blended with 50% diesel, while the B100 is pure biodiesel. In addition, to improve the combustion, triacetin was added to the pure coconut biodiesel to form two other blends (B96T4 and B90T10). B96T4 is a blend of 96% biodiesel and 4% triacetin, and B90T10 is a blend of 90% biodiesel and 10% triacetin. Due to the different percentages of the fuel constituents, all the blends contain varying percentages of oxygen, which is shown in Table 2.

Fuel lines were flushed after changing the fuels by running the engine for 30 min. Additionally, for each fuel blend and engine load/speed, at least one hour was allocated to warm the engine, ensuring the reliability of the results.

2.3. Data analysis

2.3.1. DPF particle loading

Particle mass concentrations were calculated from the particle size distributions measured by the DMS500. The inversion procedure as recommended by the manufacturer was used [36]. A key parameter needed to convert the total volume, as calculated from the size distributions, to total mass is the effective density. Although the authors are aware that the effective density of diesel and biodiesel particles are most likely not the same due to the lack of empirical data for biodiesel particles, we have used the same effective density, as recommended by the manufacturer [37], for all of the fuels. This may introduce some errors, but it is believed to be insignificant.

The total particle mass trapped (M_{trapped}) inside the DPF after n seconds was calculated by integrating the trapped particle mass at the DMS 500 sampling frequency of every half-second, as shown in the following formula:

$$M_{\text{trapped}}(n) = \sum_{t=1}^{t=n} (C_{\text{mass(pre-DPF)}}(t) - C_{\text{mass(post-DPF)}}(t)) \times 2 \times 60s \times 17\text{lpm} \quad (1)$$

$C_{\text{mass(pre-DPF)}}(t)$ is the particulate mass concentration of the exhaust before the DPF system at the loading time t , and $C_{\text{mass(post-DPF)}}(t)$ is the particulate mass concentration of the exhaust after the DPF system at the same time t . The difference in the concentrations was first multiplied by 2, to take into account the sampling frequency of 2 samples per second, then by the flow rate through the filter of 17 lpm.

Table 2
Fuel molecular oxygen content of the tested fuel blends.

Fuel blends	Diesel	B20	B50	B100	B96T4	B90T10
Oxygen content (%)	0	2.19	5.51	11.01	12.02	14.00

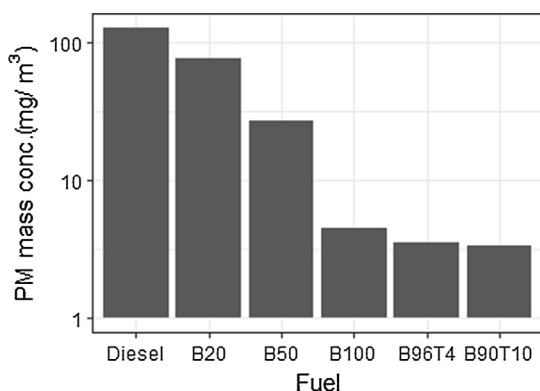


Fig. 2. Comparison of Particulate Matter mass concentration before the DPF from different fuels. Engine conditions were 1500 rpm with 75% load.

2.3.2. TEM analysis and image post processing

For the determination of morphology of DPM agglomerates, low resolution images were taken at 30,000 times magnification for TEM micrographs with a resolution of 200. Approximately 40 images per sample were taken from different positions. A MATLAB-based code was developed based on algorithms reported in the literature [38,39] to analyse the TEM images and calculate the morphology characteristics of the DPM. A detailed analysis of the morphology of particles has been explained in another paper [40].

3. Results and discussion

3.1. Exhaust characterisation

3.1.1. Particulate mass concentration

Fig. 2 shows the mass concentration of the particles before the DPF for all fuels used in this study. The fuels were sorted according to their oxygen content, with diesel having 0% and B90T10 having 14% oxygen.

From the figure, we can see that with higher oxygen content in the fuel, the particle mass concentration significantly reduced. This is a well-known effect and has been observed in the literature [41]. Diesel particulate mass concentration was the highest at 126.33 mg/m^3 , followed by B20 at 76.33 mg/m^3 , B50 at 26.77 mg/m^3 , B100 at 4.51 mg/m^3 , B96 at 3.51 mg/m^3 and B90 at only 3.32 mg/m^3 . A very low mass concentration observed with the addition of triacetin is due to the improvement in the combustion [42]. The total mass delivered to the DPF with the biofuels was smaller than for diesel, and therefore the loading times were significantly longer.

3.1.2. Particulate number concentration (PN) and particle size distribution (PSD)

After the dilution correction, the DMS measured PSD before the DPF as shown in Fig. 3. From Fig. 3, we can see that from diesel to B90T10, the particle number concentrations significantly decreased with diesel being $5.22 \times 10^7 \text{ cm}^{-3}$, and B90T10 $8.4 \times 10^6 \text{ cm}^{-3}$.

What is also clear is that the accumulation mode reduced with an increase in the fuel oxygen. For diesel, the accumulation mode was at 115.5 nm , while for B20 it was at 100 nm , B50 at 86.6 nm , B100 at 64.9 nm , B96T4 also at 64.9 nm also, and B90T10 at 56.23 nm .

All of the PSDs show a bimodal distribution with a smaller nucleation mode. The appearance of the nucleation mode may be due to the condensation of the volatiles inside the sampling line, as we did not use the inbuilt DMS first-stage hot dilution.

3.2. Estimation of the deep bed filtration stage

The test DPF is a ceramic wall-flow filter, with a pore structure

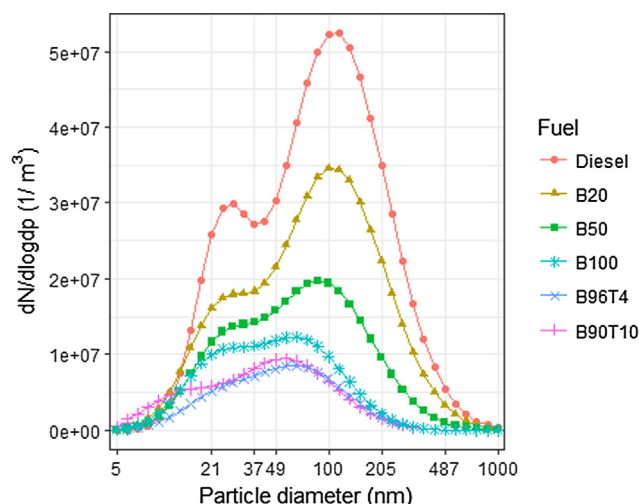


Fig. 3. Particle size distribution for the tested fuels.

inside the wall. For the test filter, there are three main filtration stages [23,24]: deep bed filtration (DBF), transient filtration (TF) and “cake” layer filtration (CLF). During the DBF stage, the particles deposit on the surface of the pores, forming a soot layer. As this filtration starts with the unloaded filter when the pores are clean, filtration merely depends on the filter media (e.g. porosity, pore size distribution etc.) and properties of depositing particles. With the particles depositing on the surface of the pores, a non-uniform soot layer was formed on the surface of the pores. After this, the filtration entered the transient filtration stage. In this stage, the incoming particles deposited on the top of the soot layer, forming particle trees. With the particles accumulating on the trees, the trees grow and connect with each other until the space among the trees is filled up. After all the porosity is filled up, the subsequent effluent particles are detained on the outside of the wall, forming a “cake” layer on the filter wall. When the cake layer is formed, it adds to the filtration process as well. This latter stage is termed as “cake” layer filtration.

Unlike the DBF, the TF and the CLF depend on the formed layer either on the pores and or on the wall. Due to this, the filtration in the latter two stages is different, and it evolves differently as well. According to the literature [23,24,27,43,44], the PD and FE rising ratio are different in these three stages. In the DBF, the PD increased with an increasing gradient, and the FE also steeply increased to become more stable later in the process. In the transient filtration stage, the PD kept increasing but at a lower rate, and therefore the gradient went down. After the cake layer was formed, the PD increased linearly, so the PD gradient became constant.

Based on these differences, the filtration stages are identified by applying this method to characterise the filtration stages on the test DPF as shown in the following figure.

As shown in Fig. 4a, during the entire experiment the PD was continuously rising with varied gradients. As the data was fairly noisy due to the pulsating engine flow it had to be smoothed. This was done by applying a 3rd order polynomial fit to the raw PD data ($R^2 = 0.5682$). Based on the values obtained from the fitting procedure we found the first derivative of the fitted polynomial function and that enabled us to obtain the inflection point, which can be seen in Fig. 4(b). To be noted is that the 3rd order polynomial function does not truly represent the change in the PD especially at the tails of the data, but is a good representation in the middle, around the inflection point. As such the curve representing the first derivative, as shown in Fig. 4(b), is merely used to estimate the position of the inflection point and does not truly represent the change in the PD gradient at the beginning and end of the measurements. It is clear that the filter is far from the cake filtration phase, as in the cake filtration phase the increase of the pressure drop is

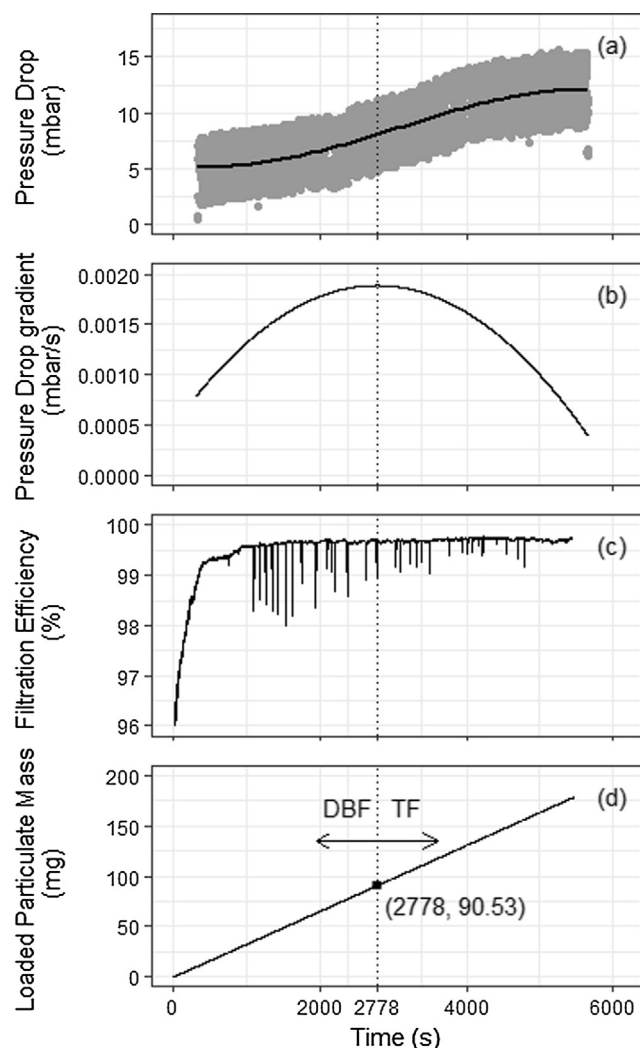


Fig. 4. Estimating the Deep Bed Filtration (DBF) stage from pressure drop gradient for diesel fuel. ((a) The time-resolved pressure drop; (b) the pressure drop gradient; (c) filtration efficiency; (d) the time-resolved loaded soot mass).

linear and therefore the pressure drop gradient constant. On the other side at the beginning of the filtration process the DPF is in the DBF phase. In this stage, the filtration efficiency of the DPF increased sharply over the first few minutes of the filtration process, after which it experienced a steady increase (Fig. 4c). We assume that the DBF stage ended when the PD gradient reached its maximum value. The calculated mass of particles loaded on the DPF, after the DBF stage ended, at approximately 2778 s, was 90.5 mg of diesel soot (Fig. 4d).

For all other fuels the total amount of mass loaded was significantly smaller therefore we can be sure that for all of the fuels the filter was in the DBF phase. During the DBF stage, two sampling points were chosen as of importance for the filtration efficiency of the DPF. One corresponded to the beginning of the loading process (when the filter was clean), while the other one was chosen to be in the middle of the DBF stage, when the filter was loaded with 3.98 mg of soot. The second point was also chosen as this was the maximum amount of mass loaded for the fuel with least PM emissions (B90T10).

3.3. Particle size distribution change

To investigate how the DPF influenced the particle size distribution, the pre-DPF and post-DPF particle size distributions were compared in Fig. 5 for all the fuels tested. Note that the post-DPF data is on the right-side scale due to significantly lower concentrations. Particle size

distributions are presented at the beginning of the DBF (yellow) and at the end of the DBF phase.

During the deep bed filtration stage, the smaller particles were more effectively removed, resulting in a different particle size distribution after the filter.

For most of the fuels, the nucleation mode was still observed after the DPF. This could be an artifact of the cold dilution used. The very sharp nucleation mode observed for B50, as well as for some other fuels, after the DPF could be an artefact of the DMS 500 inversion procedure. In general, for all of the fuels it is clear that the particle size post DPF has increased. The accumulation mode for diesel and B20, both changed from 154 nm into 178 nm, and for B50, B90, B96 and B100, the mode moved from 133.4 to 154.0 nm, 75.0 to 86.6 nm, 64.9 to 100 nm and 75.0 to 86.6 nm respectively.

To have more insight into the reason for the PSD change, the size-dependent FE for different filtration stages is discussed in the next section.

3.4. Filtration efficiency

Fig. 6 shows the FE for different particle sizes for all the tested fuels. Fig. 6a shows the data for the first two minutes of the filtration process. In this process, the filtration is referred to the beginning of the DBF. In this stage the deposition is due to interaction of the filter substrate and particle motion, so apart from particulate mobility, it only depends on filter properties such as the pore size, porosity and substrate material etc. Thus, it is a critical stage to evaluate the DPF performance. Fig. 6(b) shows the intermediate stage (when the filter is loaded with 3.98 mg of soot) of the DBF.

In both stages, the FE is higher for smaller particles and that is obvious for all of the fuels tested. It drops down as the particle size increases. For diesel, B20 and B50, the FE drops from 98% (for $d_p \leq 21$ nm) to 94%, 90% and 88% respectively (for $487 \text{ nm} \leq d_p \leq 1000$ nm) in the first two minutes of filtration, and FE drops from 99% (for $d_p \leq 21$ nm) to 97%, 96%, and 95% respectively (for $487 \text{ nm} \leq d_p \leq 1000$ nm) in the intermediate DBF stage. Although for B100, B96T4 and B90T10, the FE is not monotonically decreasing, the overall tendency of the FE is that it decreased with the size of the particles' increase. The increase observed during the TF stage for larger sizes could be a computational error as there were few particles larger than 500 nm in our sample.

The overall decreasing trend of the FE with particle diameter indicates that diffusion plays the dominant role in the deposition mechanism during DBF under the present experimental condition, as the diffusion is the only deposition mechanism which has larger influence over the smaller particles rather than the bigger particles [25–27].

More importantly, there is also a trend in the change of the FE versus particle size for various fuels. The trend is more obvious during the TF stage than during the DBF stage. The general trend is that the FE, for all particle sizes, is lower for fuels with a larger fuel oxygen content. While fuel oxygen content has little to do with the FE per se, it strongly influences the total particle mass emitted from the engine as well as the soot particle morphological properties, which on the other hand can influence the FE.

Particle fractal dimension is one important morphological property that quantifies the structure of the soot particles. It represents a measure of how compact and/or branched the particles are. An illustration of the shape of a soot particle for different fractal dimensions is shown on the insert above Fig. 7. One can see that the larger the fractal dimension, the more compact the particles are and more primary particles they will have for the same size, with particles having a fractal dimension closest to the value of 3 being almost compact spheres. Fig. 7 further shows the increase of the particle fractal dimension for fuels with a larger oxygen content (note that the oxygen content of the fuel increases for fuels going from left to right).

This means that diesel particles have a more linear shape than

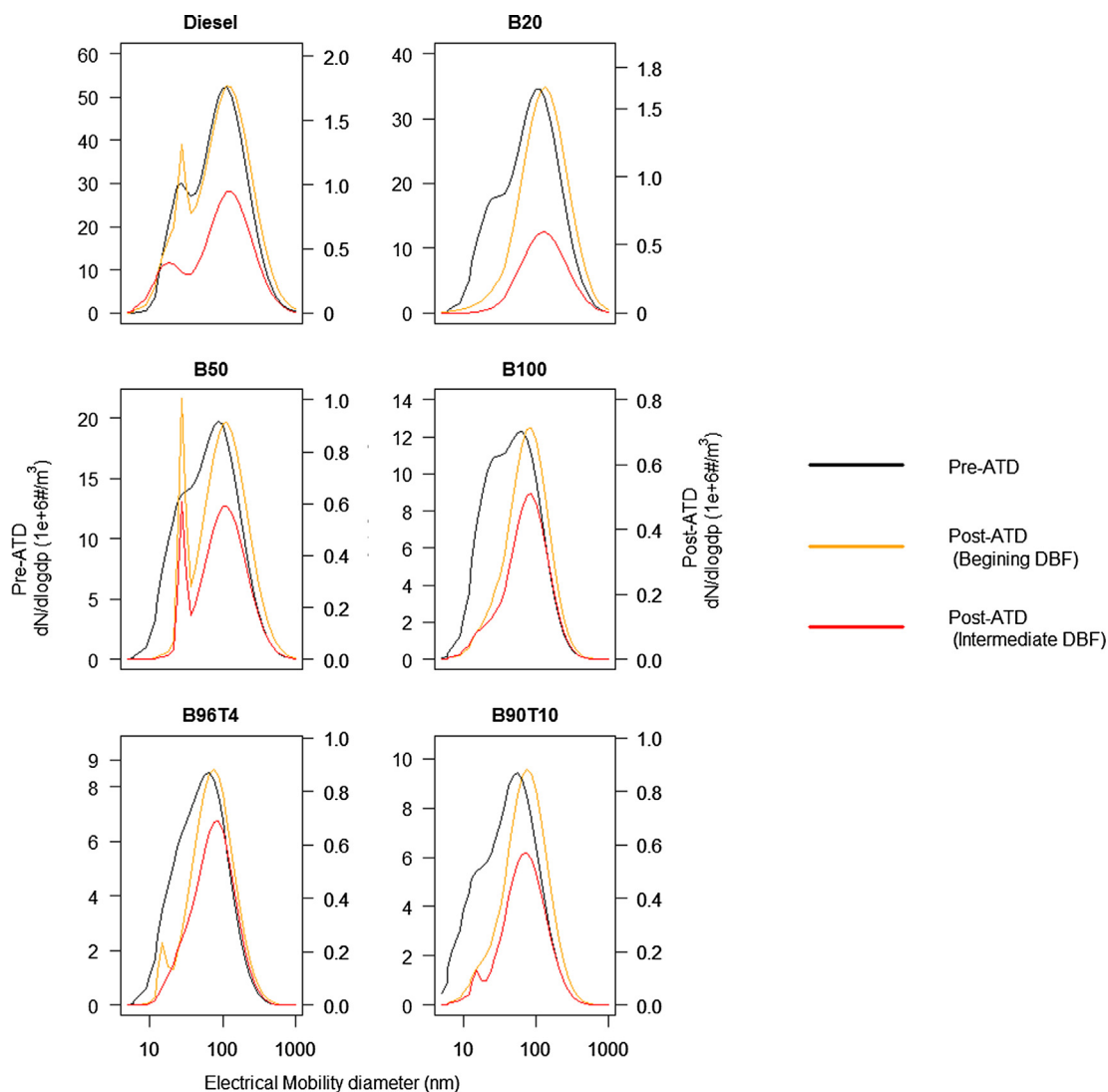


Fig. 5. Particle size distribution comparison before the DPF (Primary y Axis) and after DPF (Secondary y Axis) at two DBF stages.

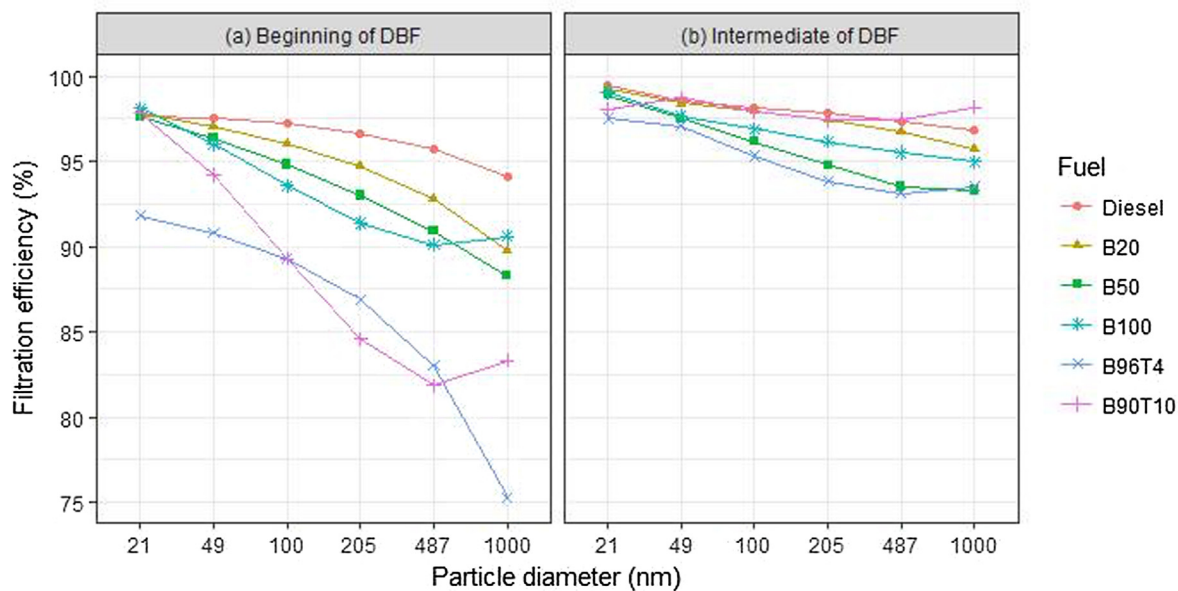


Fig. 6. Filtration efficiency versus particle diameter during deep bed filtration at (a) the beginning of the DBF, (b) the intermediate stage of the DBF.

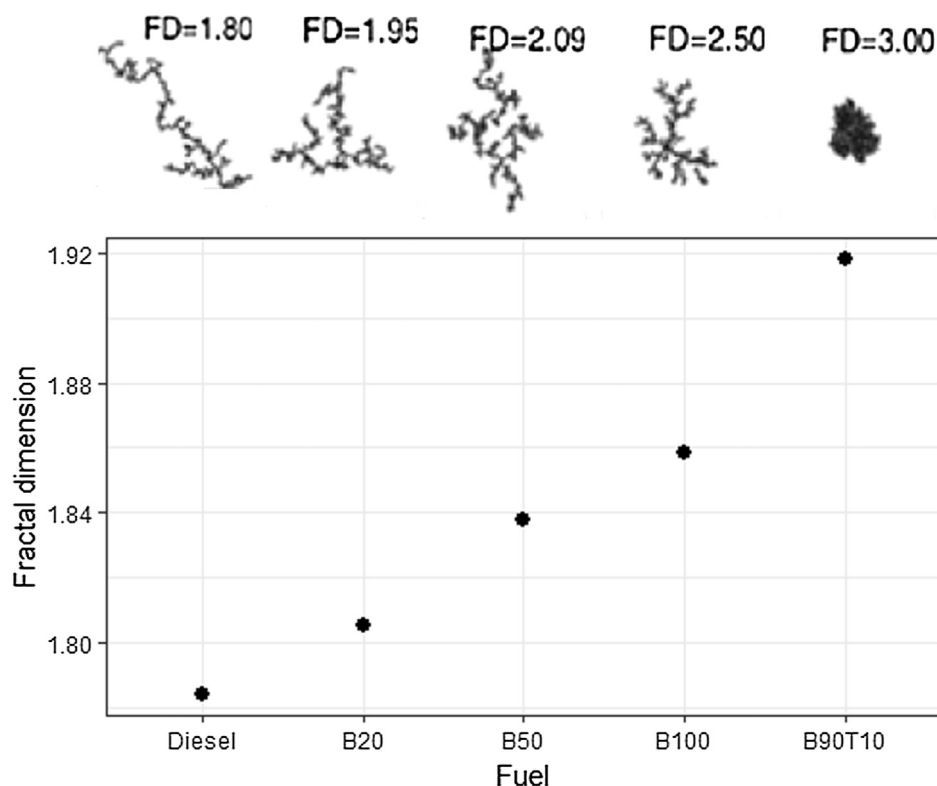


Fig. 7. Fractal dimension of the soot particles coming from the combustion of the fuels used.

biodiesel particles [45]. Consequently, diesel soot aggregates have a smaller number of primary particles than biodiesel aggregates with the same diameter. Likewise, diesel particles have a smaller mass than the biodiesel particle with the same diameter, assuming the bulk densities of the primary particles are equal. This results in particulate effective density being proportional to the fractal dimension, so the biodiesel particle with higher fractal dimension has higher effective density than the diesel particle of the same size [36]. Furthermore, according to the Brownian motion theory, which is the underlying mechanism for diffusion, momentum transfer is inversely proportional to the mass of the particle. Thus, a diesel particle of the same size will have a larger diffusion coefficient than a biodiesel particle. The higher diffusion coefficient will mean that the deposition occurs more frequently, so the FE is higher for the same particle size.

By comparing Fig. 6a and b, we can observe an increase in FE for all fuels from when the intermediate DBF staged has been reached. This effect is more pronounced for B90T10 and B100. The improvement of the FE mainly depends on the reduction of the porosity and permeability of the filter, which requires further investigation and was not the focus of this study. As DPM mass emissions are vastly different for the different fuels used in this study, the amount of soot deposited in the DPF for the same time would be significantly different. Therefore, to investigate the time evolution of the FE for different fuels during the loading process, we studied the FE as a function of the trapped soot mass instead of the loading time. In this way, the FE differences would not be due to the amount of soot loaded but could be attributed to the difference in the soot (particle) properties other than the mass concentration in the exhaust (Fig. 2). Fig. 8 is the dependence of the FE on the total trapped particle mass.

From this figure, it is clear that the FE abruptly increases for every fuel during the DBF filtration stage. If we compare the performance for the different fuels, we can see that the FE started at different levels and increased at a different rate, with B90T10, B96T4 and B100 increasing faster than other fuels.

According to the experimental research on the DBF process on the

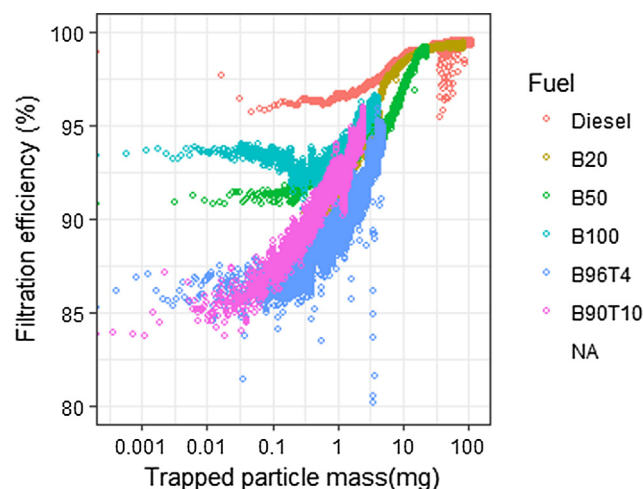


Fig. 8. Loaded particle mass inside the filter versus filtration efficiency (FE) during DBF stage.

pores of the filter, when the soot layer is formed (fully or partially), properties of particles deposited within the layer will influence the subsequent deposition of the new particles and the pore will turn into the substrate [24,46]. Therefore, the difference in the FE among particles from different fuels in the middle of the DBF stage, when part of the layer is formed, is linked to the particle layer's property. The observation of a faster increasing rate of the FE for particles coming from combustion of higher oxygen content fuels, suggests that the oxygen content dominates the soot's layer functionality and that it ultimately influences the FE during DBF.

To illustrate the importance of the initial loading, where the FE is significantly changing, on the performance of the filter we have plotted the cumulative post DPF particle mass and number emissions as a function of time for all the fuels tested on Fig. 9. We can clearly see that

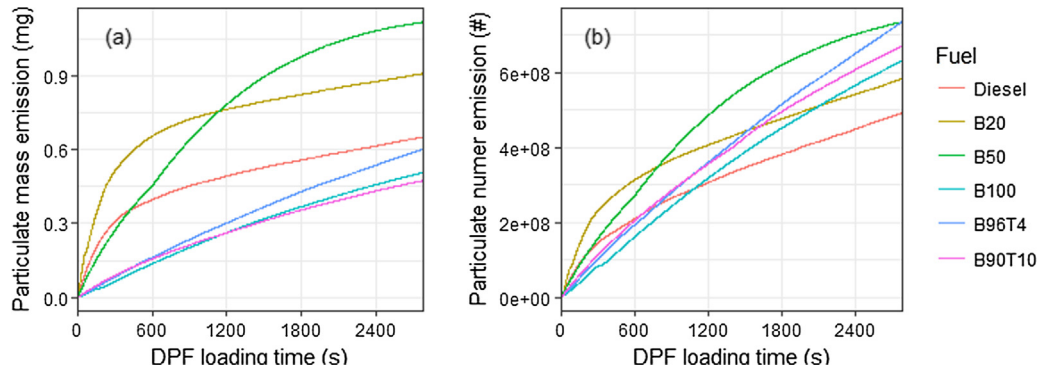


Fig. 9. Cumulative emissions post DPF over the DBF phase (a) particulate mass emission, (b) particulate number emission.

the amount of PM (either mass or number) that is not filtered presents a complex interplay between the concentration of PM coming from the raw exhaust that is loading the filter, particle properties that influence FE, and the change of the FE over time. For particle mass, diesel fuel seems to be in the middle with the 2 biodiesel blends B20 and B50 having an overall higher post DPF cumulative mass emissions. The 3 other biodiesel fuels (B100, B96T4 and B90T10) have a significantly smaller raw exhaust concentrations than diesel therefore while the efficiency of the DPF's is smaller than for diesel the total mass post DPF is smaller. Nevertheless it is interesting to observe that B20 and B50 will allow more PM mass to pass through the DPF than diesel will although the PM mass emissions for the 2 fuels are smaller.

The situation with the particle number emissions post DPF is somewhat different with diesel having the smallest cumulative particle number emissions. This is due to the total particle number emissions not being as different for different fuels as the mass emission. While the largest mass reduction, from diesel to B90T10, was almost 40-fold the largest particle number reduction was 6-fold. Therefore, the reduction in the filtration efficiency, and the longer time needed for FE to reach higher values, was not compensated by the reduction in number emissions as it was for the mass emission. This resulted in diesel having the lowest cumulative particle number emissions.

It is also important to observe that the cumulative mass emitted is significantly smaller than the mass trapped in the DPF (see Fig. 8). The difference increases as the filter efficiency reaches its maximum of over 99% and most of the DPM is trapped.

3.5. Pressure drop

When the exhaust passes through the DPF, due to the pores inside of the filter, back pressure is generated which is referred to as PD quantitatively. PD is an important aspect to evaluate the performance of DPF, therefore we compare the PD caused by particles originating from different fuels. In Fig. 10, the correlation between the PD and the loaded

mass is presented. Note that fuels with higher oxygen content have much smaller mass emissions, therefore for the same maximum loading time of 2772 s the loaded mass was much smaller.

From Fig. 10, we can see that the PD increased linearly with the increase of the mass of trapped soot. The initial increment rate of the PD ($d\Delta P/dt$) is proportional to the average pore diameter D_p , the pore size distribution range 3σ , the exhaust dynamic viscosity μ , exhaust velocity u , and inversely proportional to the porosity ε_w :

$$(d\Delta P/dt)_{\text{deep}} \propto \mu u 23\sigma D_p / \varepsilon \quad (2)$$

Thus, with the particles accumulating in the filter, the porosity decreases, so the PD increases. Also, from the graph, we can see that on the condition of the same mass loaded, higher biodiesel blends create higher back pressures than lower biodiesel-containing blends. This indicates that when using biodiesels in diesel engines, a higher PD will be generated for the same amount of soot loaded.

From the linear regression fittings, we can observe that the PD increment rate is different among the different fuels. Fig. 11 shows the gradients of the PD versus loaded mass as a function of the blend percentages, together with the primary particle size for each of the blends. It is clear that the $d\Delta P/d_{\text{Mass}}$ differs among different fuels, and it shows inverse proportionality to the primary particle size.

This is in agreement with S. Bensaid's study [23]. In this publication, it is reported that the contribution of the soot layer to the PD is inversely proportional to the permeability which the soot causes. On the other hand, the permeability is proportional to the collected particulate primary particle size. Because of the different primary particle sizes, the loaded particle layer formed on the surface of the pores has different permeability. The smaller the primary particles, the less permeability. Therefore, the permeability directly affects the PD value, with lower permeability producing a higher PD. In our case, the biodiesel particles have smaller primary particle sizes, and thus they cause higher back pressure.

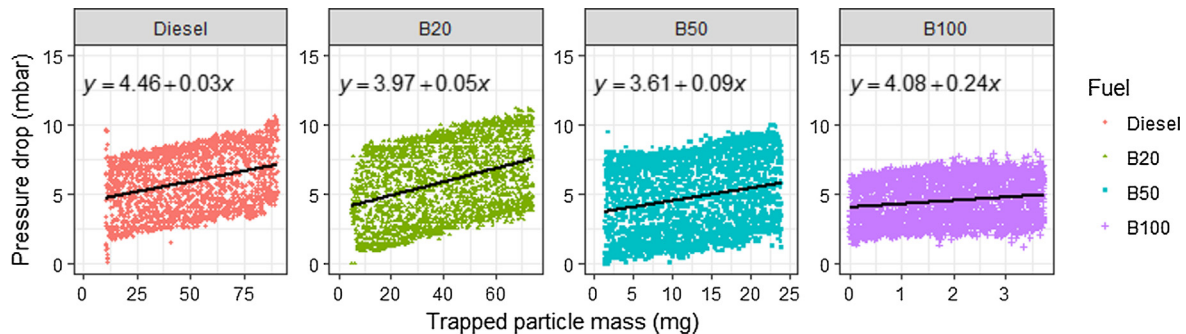


Fig. 10. Pressure drop as the function of the total mass trapped in the filter for various biodiesel blends (the linear regression for each blend is also shown on the graph).

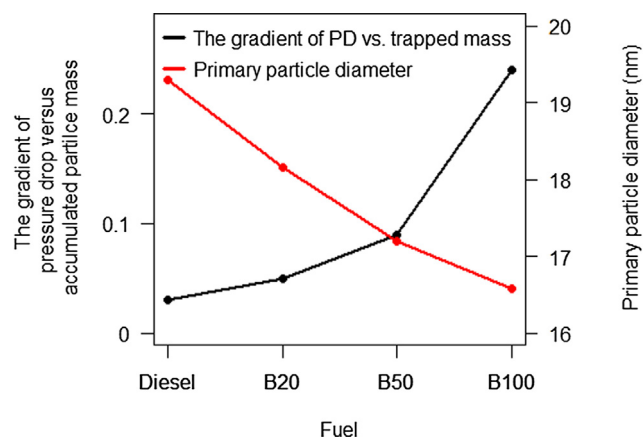


Fig. 11. The gradients of pressure drop as function of loaded particle mass (Primary Y axis) with primary particle diameter (Secondary Y axis) as a function of biodiesel blend percentages.

4. Conclusions

This paper investigates the performance of the DPF for particles generated from fuels with scaling value of the fuel molecular oxygen content. The performance of DPF varied for different fuels. It was shown that the increase in oxygen content of the fuel led to the emission of lower mass and particle number and changed size distribution as compared to diesel. Whilst biodiesel particles still contained small nucleation mode peaks, accumulation mode peaks were shifted towards smaller sizes with the increase of oxygen in the fuel. Also, emitted particles, originating from different fuels, were having different morphology, particularly fractal dimensions. Biodiesel particles and particles originating from the combustion of more oxygenated fuels, were found to be more compact, which further means that for the same size, more primary particles were contained within more compact biodiesel particles, when compared to diesel particles. Consequently, biodiesel particles were having larger mass for the same size when compared to diesel particles – higher effective density. This important morphological characteristic had an impact on the FE and the overall dynamics of filtration. Efficiency of filtration was found to be higher for smaller particles and mainly driven by diffusion. Taking into account the fractal

dimensions and effective density, owing to its larger diffusion coefficient, FE was higher for diesel particles for the same particle size.

It was also found that the FE for different particles evolved differently with time. To highlight the influence of the soot properties on the FE, FE was investigated as a function of mass deposited on the filter. It was observed that at the start of the filtration, the efficiency was much lower for biodiesel particles as compared to diesel. Yet, after formation of the soot layer, FE increase was much higher for biodiesel particles, ultimately reaching similar values when 10 mg of particles were deposited on the filter. This mechanistic difference in the process of filtration is attributed to the property of the formed layer that then influences the deposition of new particles. Combustion of oxygenated fuels forms soot with different properties that enable easier packing of incoming particles.

Pressure drop is a very important parameter used for the estimation of efficiency of DPFs, commonly used as a measure of quality and cost-effectiveness of filters. PD increases as the porosity of the filter decreases, thus being inversely proportional to the permeability altered by the soot layer. Smaller particles are decreasing the permeability, so biodiesel particles, due to their smaller sizes, caused higher back pressure.

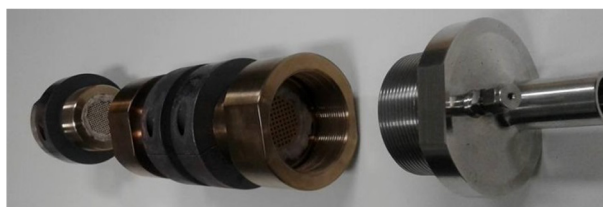
This work has demonstrated that conventional DPF systems are suitable to be used for the filtration of particles generated by combustion of alternative fuels. It was demonstrated that the efficiency of DPF systems strongly depends on properties of PM, that mainly depend on the chemical composition of biodiesel fuels, where oxygen content has been recognised as one of the most important parameters. Still, conventional DPFs will work longer with diesel particles, whilst the filtration may be more efficient with biofuels. It is anticipated that the performance of DPFs with biodiesel particles can be significantly improved with some modifications of porosity and permeability of the medium.

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Appendix A

Diesel Particulate Filter assembly (Left: inflow with the DOC, Mid-section: wall-flow substrates DPF; Right: outflow with cap).



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