IOP Conf. Series: Materials Science and Engineering **421** (2018) 042019 doi:10.1088/1757-899X/421/4/042019

Analysis of particle mass and number emission from an SI engine with direct fuel injection and a particulate filter

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Abstract. Direct fuel injection engines have dominated the market for passenger cars powered with gasoline. They are characterized by reduced fuel consumption and higher unit power and torque. The reduction of the time needed for fuel evaporation is associated with an increase in mass emission, and above all the number of solid particles in comparison to systems in which a multipoint injection is used. To minimize the negative effects of the applied solution, in September 2017 the EURO 6c standard was introduced, which apart from the mass also limited the road emission of the particle number. The article presents the mass and number emission and particle size distribution tests results for an engine with and without a particulate filter. The tests were carried out in simulated real conditions on a dynamic engine dynamometer station.

1. Introduction

Spark-ignition engines with direct fuel injection dominate the PC market (Passenger Car). The structural solution presented by the Mitsubishi company in 1996 involving the placement of injectors in the combustion chamber is associated with many advantages [1,2]. The most important of these is the possibility of more precise fuel dosing, which results in a fuel consumption reduction and greater control in shaping the characteristics, above all general and full power [3,4,5]. Unfortunately, it has some disadvantages. Shortening the fuel evaporation time causes intensified soot production, and as a result emits particulate matter, especially those of the smallest diameters up to several nanometers [6,7]. These particles are particularly dangerous to human health, because they can penetrate into the pulmonary alveoli, which is the reason for the increased incidence of upper respiratory tract diseases in societies exposed to air pollution [8,9].

For this reason, with the entry of the EURO 6c standard into force, same as it was with diesel engines, where it occurred in the EURO 5 standard [10], besides the limit of the road particle mass emission (PM), a limit in the number of particulate matter at the level of $6x10^{11}$/km was also introduced [11]. It is connected with the necessity to limit them by means of engine aftertreatment systems. One of which is the particulate filter used on a large scale in compression-ignition engines [12,13]. Its task is to accumulate solid particles and burning them when conditions are suitable (mainly related to the temperature of the filter) [14,15]. The second method used by manufacturers is the use of two injection systems, i.e. at the same time MPI (used at low engine loads), and direct gasoline injection for heavier loads. An example of such construction is the group of the third generation of VAG EA888 concern engines.

As part of the discussions conducted in the article, the influence of particulate filter use in the exhaust system of a spark-ignition engine and direct fuel injection was subjected to analysis. Engine operating points used for tests were recorded during the actual drive of the vehicle with the engine of the same technical parameters, in accordance with the RDE (*Real Driving Emission*) guidelines. These guidelines define primarily the vehicle speed and the distance the vehicle should travel in the urban cycle (speed from 0 to 60 km/h), extra-urban (speed over 60km/h, up to 90 km/h) and motorway (speed above 90 km/h up to 120 km/h) [16]. The engine's operating points have been simulated on a dynamic engine dynamometer to reflect determined conditions of the engine. A series of PEMS (*Portable Emission Measurement System*) analysers were used for measurements, which by measuring the concentration of harmful compounds and determining the instantaneous flow rate of exhaust gases is able to determine their emission per second [17]. What's more, by registering the instantaneous power generated by the engine by connecting to the diagnostic system, it is possible to determine the specific emission. The measured components were the gaseous compounds: carbon dioxide, carbon monoxide, hydrocarbons and nitrogen oxides, but the most important aspect was the analysis of solid particles. This analysis was carried out in three ways. The mass of the particulates, their number, as well as their size distribution were measured and then compared.

2. Research objects

The test object was a spark ignition engine with direct fuel injection and a displacement volume of 1.2 dm^3. The basic technical data of the engine is presented in Table 1. The test object was technically fully functional at the time of the test, and during the test it was loaded with an engine brake. The engine exhaust system contained a factory-installed three-way catalytic reactor.

Table 1. Test engine technical data

Engine type	SI
Number of cylinders, and number of valves	4 cylinders, 4 valves per cylinder
Arrangement of cylinders	in-line
Displacement	1.2 dm^3
Maximum power	77 kW/105 KM
Maximum torque	160 Nm
Fuel injection	GDI

Laboratory tests were carried out on a dynamic test bench designed by AUTOMEX company (Figure 1). These type of brakes allow for the mapping of real drives through a short time of engine overdriving as well as the possibility of simulating engine braking [18]. The technical parameters of the dynamic brake are shown in Table 2.

Table 2. Dynamic brake technical data

Contained power	up to 200 kW
Weight	400 kg
Cooling agent	air
Maximum rotational speed	6000-1800 [rpm]
Revolution direction	any
Maximum torque	18-2000 [Nm]
Modules	ATMX2090, ATMX2040, ATMX2400, ATMX2080, EOBD, open engine driver

Figure 1. Dynamic test bench

3. Research methodology

The equipment from the PEMS group was used for the tests. The apparatus was connected to the engine exhaust system from which the sample was taken. The AVL MOVE analyser (Figure 2a) was used to measure the mass concentration of particulate matter. The concentration combination with the instantaneous volumetric flow of exhaust allowed to determine the solid particles mass emission during the test cycle. The analyser operates using the photoacoustic method, subjecting the particles to a permanent action of modulated radiation, under the influence of which they start to act like an acoustic wave. These vibrations are captured by sensitive microphones and the value of their sound signal is proportional to the mass of soot particles in the gas. The particulate size distribution of the number of particles was obtained using the Engine Exhaust Particulate Sizer (EEPS 3090) analyser, measuring the particle size distribution in the range from 5.6 to 560 nm (Figure 2b). In the analyser, the particles are charged with an electric charge and then captured by electrodes, which allows to determine their number and mass (related to the diameter).

a) b)

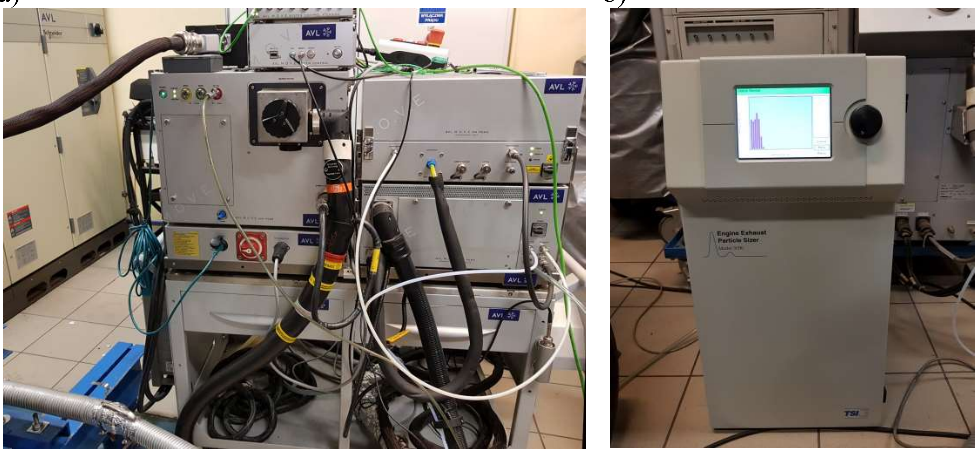

Figure 2 a) AVL MOVE MSS device; b) EEPS TSI device

The cycle simulated on the dynamic engine dynamometer was a fragment of the vehicle drive with the same engine, in accordance with the RDE requirements. During the tests, the vehicle was loaded with two people and test equipment including power generators (about 200 kg). The tested vehicle had an automatic transmission, which resulted in low crankshaft speed values. During the tests the start stop system remained disabled (figure 3).

The driving cycle was obtained during the tests in line with the RDE procedure, in which only the engine operating points and gas components were recorded. Operating points data have been transferred to the engine test bench. The time reduction in relation to the actual measurement was dictated by the temperature setting behind the TWC reactor at an approximately constant level.

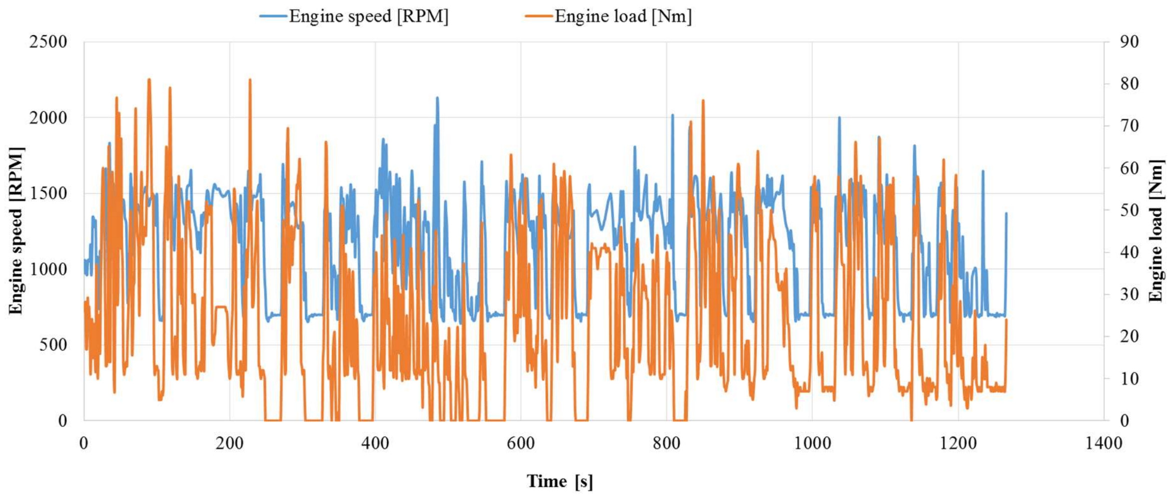

Figure 3. Engine operating points in test cycle

A prototype particulate filter with a metal carrier was used for the tests (Figure 4). It is made from a rolled sheet of heat-resistant steel. After cleaning, it was covered with a bottom layer in the form of Al_2O_3-γ. This is designed to increase the surface area of the carrier and, as a result, to influence the flow of exhaust gases in a more significant way [19]. On the bottom layer, an active layer consisting of noble elements belonging to the platinum group (including Platinum and Palladium) which was applied in order to catalyse the oxidation reaction of the particles accumulated in the particulate filter. The volume of the particle filter carrier was selected based on the engine's stroke volume and was 0.8 of this value. The pre-test filter was brand new and placed approximately 30 cm from the TWC reactor, which was dictated by the geometry of the standard exhaust system.

a) b)

Figure 4 a) Carrier used in particulate filter; b) Particulate filter used for the test

4. Results

During the tests, the temperature before and after the TWC reactor (at the inlet to the particle filter used (Figure 5)) was measured using thermocouples.

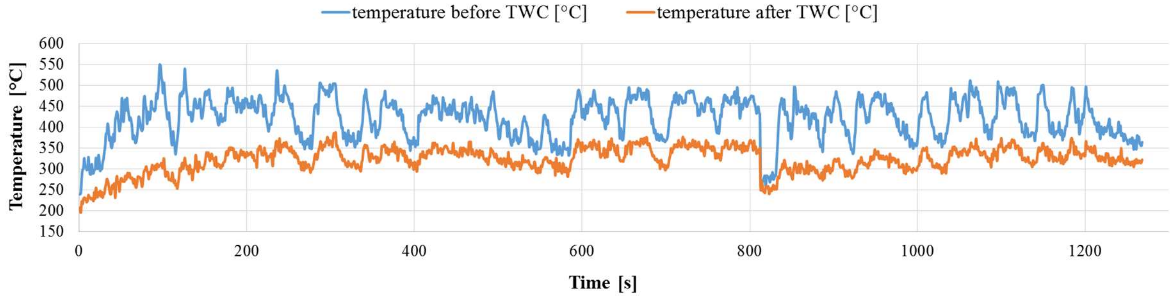

Figure 5. Temperature of the exhaust gases at two points of the exhaust system during the tests

The recorded temperature values are directly related to the engine load, the temperature drop in the TWC reactor is noticeable. It can also be stated that it does not have a large thermal capacity, i.e. after reducing the temperature of the exhaust gases, the temperature of the carrier changes after approx. 2-3 seconds, but after it increases, the reaction lasts longer, causing the temperature difference to reach over 200 °C. This is also related to the cooling function of the engine exhaust system walls.
The obtained result allows to conclude that the use of a catalytically coated filter in the given operation would enable its regeneration without forcing this process by additional heating of the exhaust gases using an excess fuel dose, which is burnt in the exhaust system. The results are shown below (Figure 6,7,8).

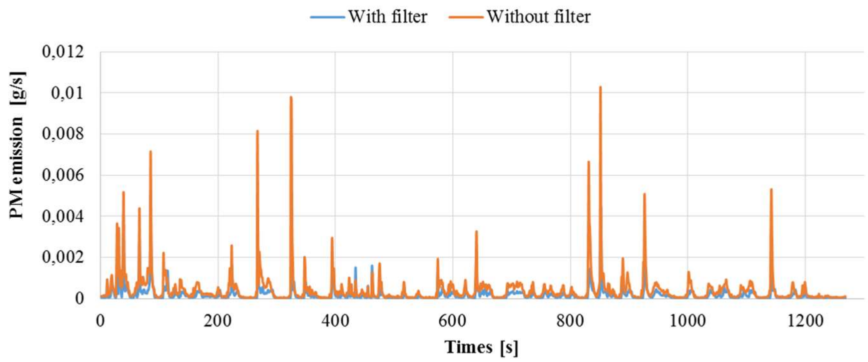

Figure 6. Particulate matter emission over time measured by AVL MSS

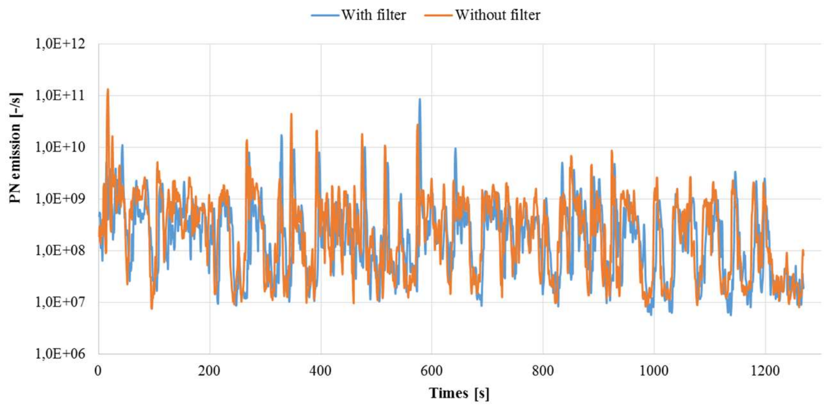

Figure 7. Patriculate matter emission over time measured by EEPS TSI

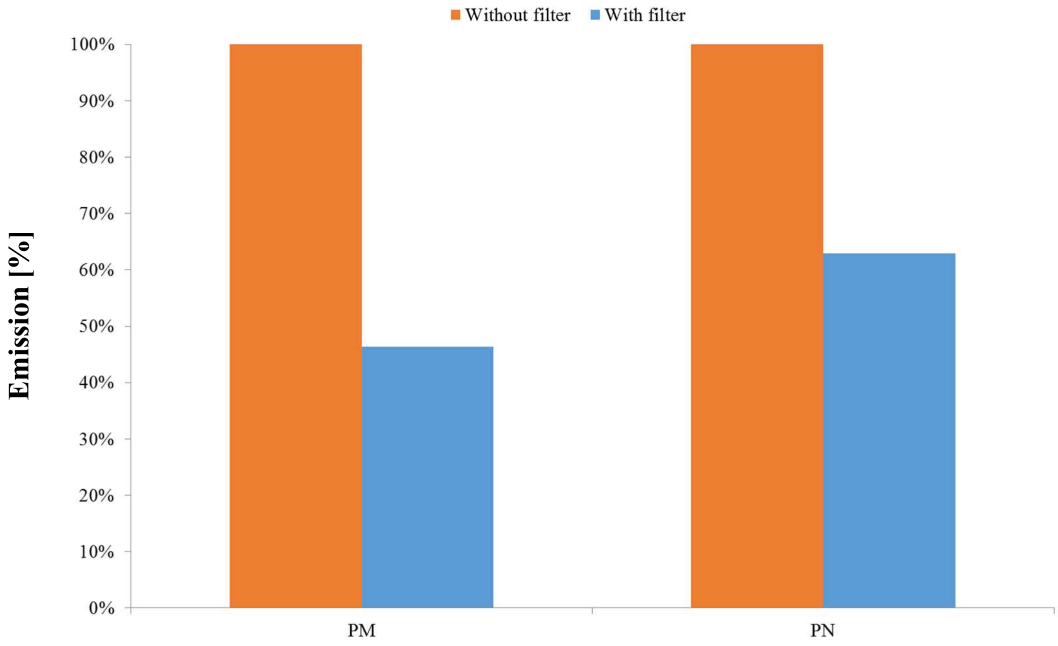

Figure 8. Relative emission of mass and number of particulates with and without filter

The use of a diesel particulate filter reduced the particle mass by 54% and their number by 37%. The emission diagrams indicate a very similar nature of the emission, i.e. the overlap of local maxima, especially noticeable for PM emissions. The obtained particle mass values are smaller, this is less noticeable for the number. Due to the comparative nature of the study, the specific emission value was not used, only the cumulative mass and number of particles. In relation to the solutions dedicated to the diesel engine, the obtained efficiency is lower, but this may be caused by relatively small engine loads during tests and as a result of a small amount of generated exhaust gases. Particle sizes were shown on Figure 9.

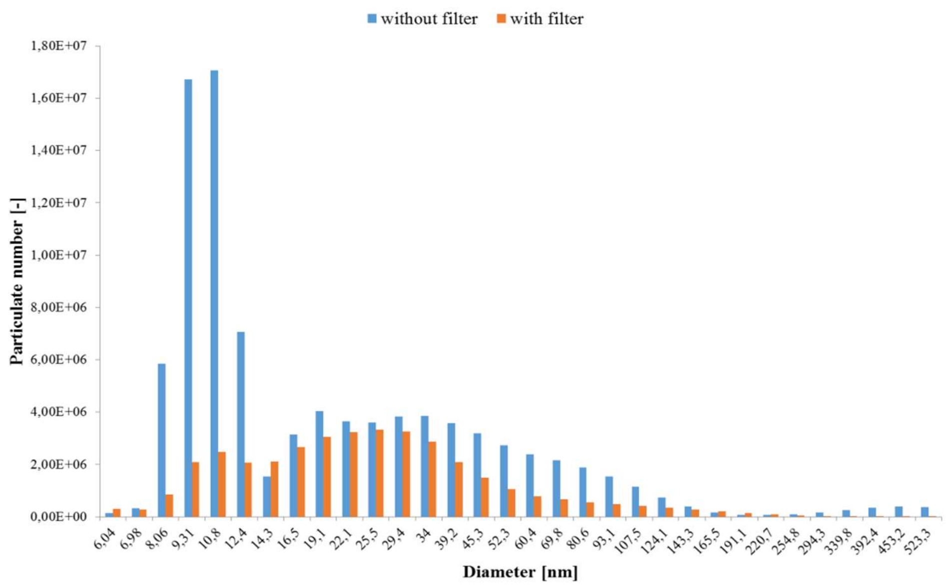

Figure 9. Average particulate size distributions measured in the transient test

In the case of the particles diameters particulate size distribution analysis it should be noted that the largest differences were obtained in the number of particles with the smallest diameters, i.e. those most dangerous for human health. In their case, almost a 10-fold reduction in the number was measured. A reduction in number was recorded for most of the measured diameters.
The used GPF is in fact with a very low filtration efficiency reduced the PN approximately 20% due to diffusion losses.

5. Conclusions

Using a filter is one of the potential solutions for reducing PM and PN from spark-ignition engines, which is necessary from the perspective of human health especially in urban areas. The research carried out in the article, done on a prototype filter originally designed for a CI engine, proved the effectiveness in particle mass (by 54%) and number (by 37%) reduction. The particulate size distribution analysis also shows the elimination of the majority of particles with the smallest diameters. The exhaust gas temperature test, which in the case of SI engines is higher than in diesel engines, allows to conclude that using the vehicle in the urban and extra-urban cycle may generate sufficient conditions for burning the particles accumulated in the filter. The weak filtration efficiency of GPF, the soot loading and regeneration, but first of all the ash loading merit further research.

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