

Particulate matter emission characteristics for a compression ignition engine fueled with a blend of biodiesel and diesel

B M Jurchiș, N Burnete, N V Burnete and C D Iclodean

Department of Automotive Engineering and Transports, Technical University of Cluj-Napoca,
Cluj-Napoca, Romania

E-mail: jurchismanu21@gmail.com

Abstract. The particulate matter produced by diesel engines, also called PM, are solid particle formations of microscopic dimensions suspended in air. Their extremely small size is one of the problems. Many studies have shown that they can aggravate lung and heart problems and can cause eyes irritation of the human body, if exposed for longer periods of time. Diesel soot particles are toxic air contaminants, which contain toxic heavy metals and dangerous organic pollutants. In this paper, the authors present the particles emission for different blends of biofuel with diesel under different load and speed conditions. The simulation model was built in AVL BOOST based on the AVL 5402 single cylinder research diesel engine of the Testecocel laboratory, from The Department of Automotive Engineering and Transports, Faculty of Mechanics of Technical University of Cluj-Napoca. The biodiesel fuel used was palm oil methyl ester in different proportions, the purpose of the work was to highlight the particulate matter emission when running with a mix of biodiesel and diesel for different engine speeds. The tests have shown that biodiesel can be used in a blend with pure diesel to reduce the particulate matter.

1. Introduction

The continuous lowering of emission thresholds requires new and improved systems and strategies for reducing emissions resulting from diesel combustion. Compared to the legislation from 1992, when a particulate matter emission threshold was introduced for the first time, current legislation (Euro 6) requires a reduction of about 28 times (to 5 mg/km). To comply with the legislation in force, the automotive industry has introduced the diesel particulate filter for diesel engines. These diesel particulate filters are designed to capture solids particles generated by combustion. The efficiency of these filters ranges from 85 % up to 99 % but this efficiency is relative and depends on several factors. The efficiency of the filter is influenced by the driving style, the ambient temperature combined with the operation over short distances, which causes the particle filter to not reach the optimal operating temperature, thus leading to an increased particle emission. Another solution to lower the PM emission is to use fuels with a high oxygen content which favors the combustion, thus producing less smoke and consequently, lowering the PM emissions. Many studies have highlighted the benefits of using a blend of pure diesel and biodiesel in terms of reducing particulate emissions [1][2][3][4][5].

2. Particulate mater

Particulates are the result of incomplete combustion of fuel in fuel-rich regions. The formation of solid particles is mainly due to insufficient oxygen present in the mixing zone[1]. The particulate matter is made of mainly soot (approximately 50 %). Aldehydes, alkanes, alkenes, aliphatic hydrocarbons,



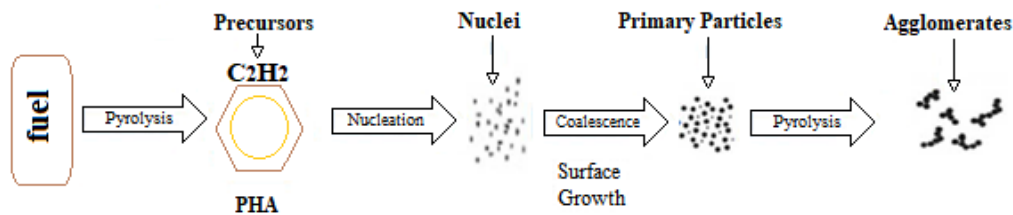


Figure 1. Particulate matter formation[6].

PAH's present in particulates represent the soluble fraction while the lubricating oil, partially oxidized fuel and oil represent the soluble organic fraction in the particulate matter. The process formation of soot includes 4 steps (figure 1). The first step is the pyrolysis process when the organic compounds like the fuels, suffer a change in the molecular structure at high temperatures in a process without sufficient oxygen. The second step is named nucleation and represent de phase where particles are formed from gas phase reactants. The process where the number of small particles is greatly increased is called surface growth. The last step, where the combination of particles takes place, is named the agglomeration. In this phase the interparticle collisions can lead to agglomeration. As a result, the number of particles decreases but the size of particles is increased in this step [6].

The particulate matter is divided into 2 categories in terms of size. The first category refers to solid particles which are smaller than $2.5\ \mu\text{m}$, the so-called fine particles and the second category the particles smaller than $10\ \mu\text{m}$ but larger than $2.5\ \mu\text{m}$, called "coarse particles" [7]. Due to their extremely small size, these particles have harmful effects on human health. These particles can be studied only in specialized laboratories due to their extremely small size. The risk to inhale and access into the human respiratory system is very big. To understand the size of particulate matter, in comparison, the human hair has a diameter of about 30 times larger than $\text{PM}_{2.5}$ particles (figure 2)[8].

Harrison et al [9] conducted a study and measured during all four seasons, in seven different parts of Jeddah, Saudi Arabia, the human exposure to solid particles and they reported that the premature mortality is associated with chronic exposure to $\text{PM}_{2.5}$, the total deaths associated with particulate matter exposure being over 1100 for the 2014 population of Jeddah. Brook et al [10] reported that the exposure to $\text{PM}_{2.5}$ for a few hours to weeks, is associated with cardiovascular disease risk, while a greater exposure for few years increases the risk for cardiovascular mortality. The European Environment Agency argues that human exposure to particulate matter can cause premature death, also increasing incidence of a wide range of diseases, such as respiratory diseases, diabetes, cardiovascular disease and even cancer. The International Agency for Research on Cancer categorized particulate matter (PM) as a carcinogenic component of pollution. The Ambient Air Quality Directive set the exposure limit to PM_{10} at $40\ \mu\text{g}/\text{m}^3$ and for $\text{PM}_{2.5}$ to $20\ \mu\text{g}/\text{m}^3$. As it can be seen in figure 3, most EU countries reach the maximum exposure limit for solid particles[11].

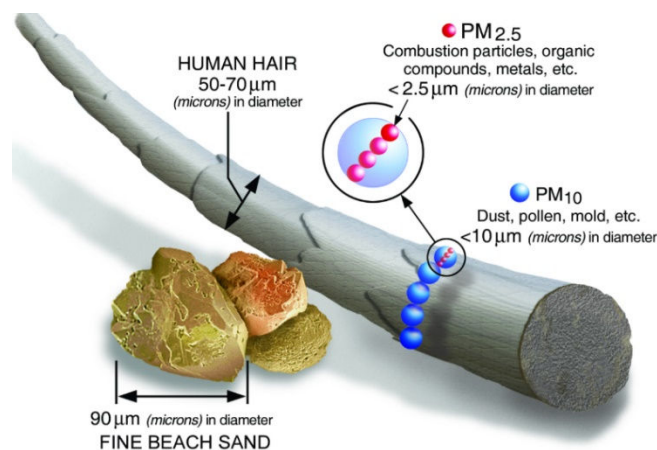


Figure 2. Size comparisons for PM particles [8].

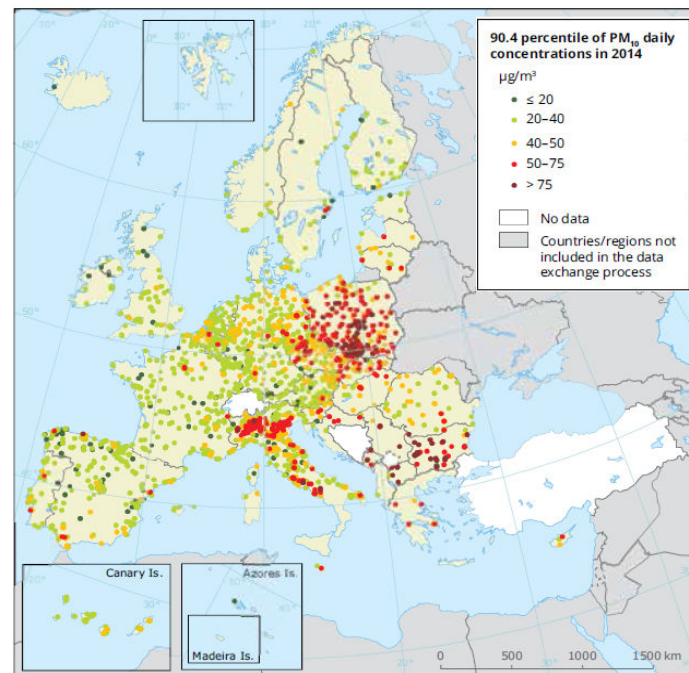


Figure 3. Concentration of PM_{10} in 2014 in European Union [11].

3. Particulate emission standards

The emission limit for particulate matter is very low (figure 4). Comparing the maximum admissible limits set by EU, it can be remarked the extremely high reduction emission limit during 26 years, decreasing from 0.36 [g / kWh] for Euro 1 to 0.01 [g / kWh] for Euro 6, which has a direct impact on the production costs so that the car manufacturers can be able to achieve these limits. As it can be seen in figure 5, the public transport sector together with the agricultural sector, produce an important percentage of particulate emissions. This can be improved by using alternative solutions for the after-treatment system of exhaust gases. The biggest step adopted by the automotive industry in terms of reducing soot emissions, was the diesel particulate filter. Besides the extremely high cost of the filter, another problem it is also the efficiency of these filter for all operating conditions. The major problems are the emissions of PM is when starting the engine at -25 C or when driving distances under 5 km during winter, when the diesel particulate filter does not have the capacity to reach the optimum

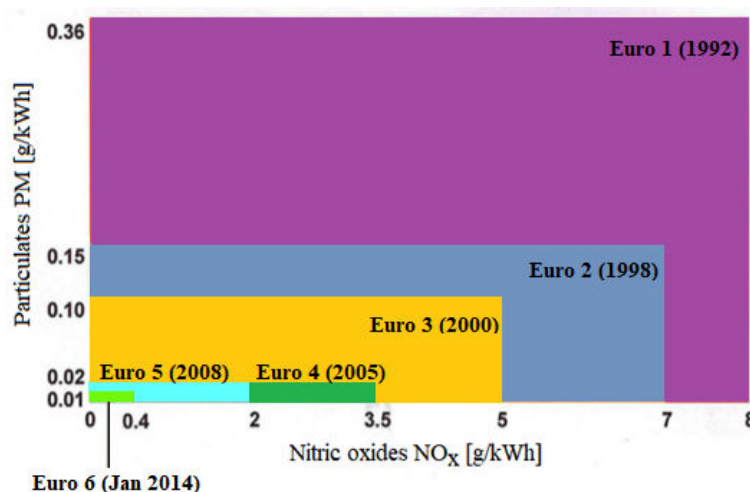


Figure 4. EURO 1-6 emissions standards for PM/ NO_x [15].

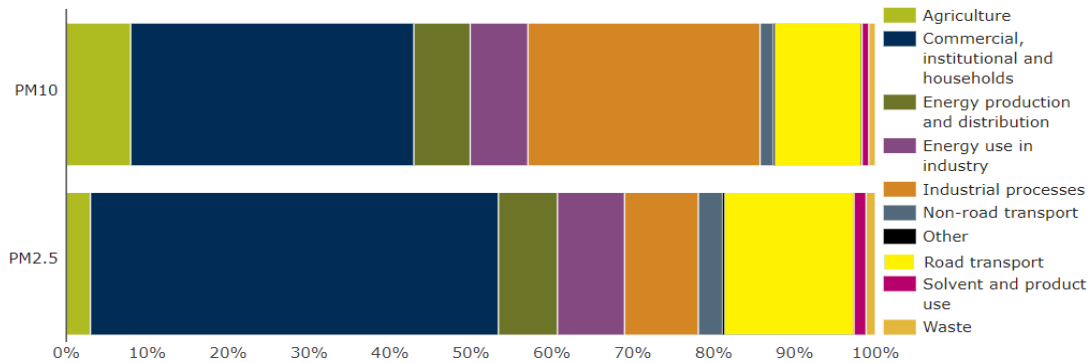


Figure 5. PM₁₀ and PM_{2.5} emissions sectors [11].

temperature for a good efficiency of filtering these solid particles. That's why more studies are based on using so-called green fuels which can be taken into account to reduce particulate emissions.

4. Methodology

One of the biggest advantages of biodiesel is the proportion of oxygen contained in the structure, which differs between 10% and 13% depending on the type of raw material used. The lubricity of biodiesel is very good being suitable to blend with diesel in an important proportion. In table 1 is presented the C/H ratio, the oxygen content and the chemical composition of pure diesel and palm oil methyl ester [12].

Table 1. Elemental composition of diesel fuel and biodiesel (% m/m) [12].

Fuel	C	H	O	C/H	Empirical formula
Diesel	86.5	13.5	0	6.24	C _{15.05} H _{27.94}
PME	76.35	11.26	12.39	6.16	C _{18.07} H _{34.93} O ₂

In this paper, the authors focused on the use of biodiesel produced from PME-palm oil methyl ester which has a 12.39 % of oxygen in his composition in a blend with diesel in terms of lowering emissions. The main input data for the simulation is presented in table 2. The engine used for the simulation model is based on the AVL 5402 single cylinder research diesel engine, from the Testecocel laboratory, from The Department of Automotive Engineering and Transports, Faculty of Mechanics of Technical University of Cluj-Napoca.

Table 2. AVL 5402 Engine Technical Data [13].

Parameter	Value	M.U.
Number of cylinders	1	[-]
Bore x Stroke	85 x 90	[mm] x [mm]
Maximum power	6	[kW]
Rated speed	4200	[min ⁻¹]
Combustion system	4 valve	[-]
Displacement	510.7	[cm ³]
Compression ratio	17.1	[-]

The cases simulated on the single cylinder engine were at 3 different engine speeds as shown in the table 3. The blend used in this paper was 30 % biodiesel obtained from palm oil and 70 % pure diesel. The simulation process started by defining the injection parameters. Values used for injection parameters were extracted from the technical data, offered by the manufacturer for AVL 5402 engine

presented in table 3. The pre-injection and the main injection advance to TDC was defined by the following parameters[14]: delay TS - represents the start of the injection delay; delay TU - represents the injector opening delay; delay TD - represents the delay of the end of injection; delay TE - represents the delay of the injector closure; SON_pre injection – represents the beginning of the pilot injection; SOFF_pre injection – represents the end of the pilot injection; SON_main injection - the beginning of the main injection; SOFF_main injection - the end of the main injection.

Table 3. Injection parameters used for the simulation cases

Parameters	M.U.	Value		
Speed	[min ⁻¹]	1500	2000	2500
Fuel mass/cycle	[mg]	22	25	23
Delay TS	[μs]	450	225	285
Delay TU	[μs]	275	250	125
Delay TD	[μs]	225	175	125
Delay TE	[μs]	450	300	275
SON_pre injection	[deg]	-20.625	-22.125	-23.250
SOFF_pre injection	[deg]	-18.625	-20.125	-21.250
SON_main injection	[deg]	-5.625	-8.625	-10.500
SOFF_main injection	[deg]	7.375	4.375	2.5

The injection time was divided into two injection phases, namely in the pre-injection phase and the main injection phase as it can be seen in figure 6. The diagrams and the experimental data was stored with the aid of the post-processing software AVL CONCERTO, the combustion model used for simulation was the AVL MCC Model (Mixing Controlled Combustion), a model which can predict the accumulated SOOT emissions in respect with the quantity of fuel injected per cycle. To determine the

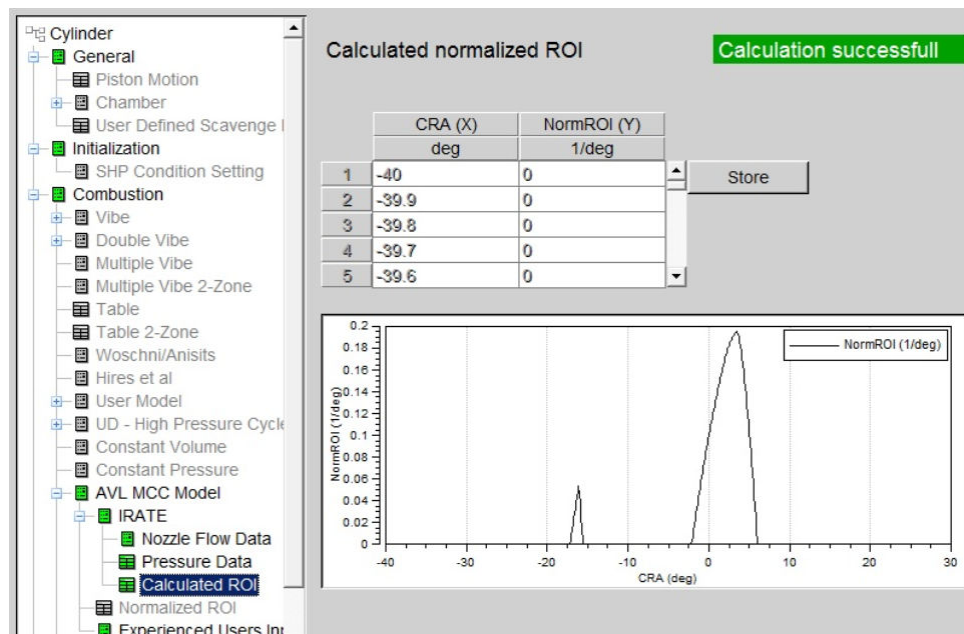


Figure 6. The pre-injection and main injection sequences used.

injection rate of the combustion process for the AVL MCC model, the normal injection rate (ROI) was used[13].

5. Results and discussions

The aim of this paper was to highlight the benefits of using biodiesel in a blend with pure diesel in terms of particulate emissions. It can be noticed that the oxygen content of biodiesel has a direct impact on decreasing the particulate emissions due to the fact that higher oxygen favors the

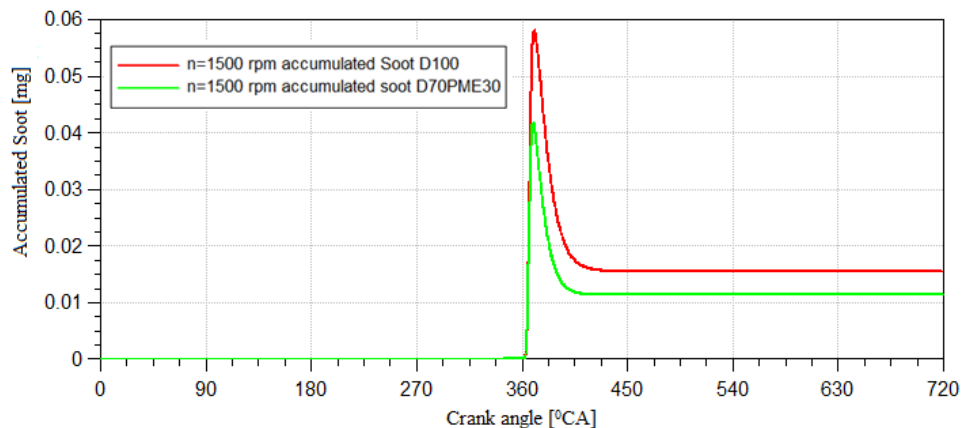


Figure 7. Accumulated soot $n=1500 \text{ min}^{-1}$.

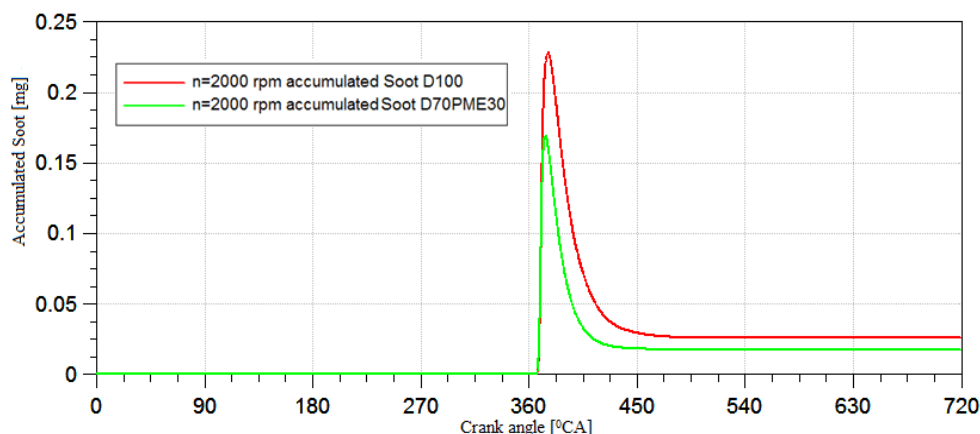


Figure 8. Accumulated soot $n=2000 \text{ min}^{-1}$.

combustion. The cases simulated on the single cylinder engine AVL 5402, were at 3 different engine speeds as shown in the figure 7 at 1500 min^{-1} , figure 8 at 2000 min^{-1} and figure 9 at 2500 min^{-1} . In figure 7 the emission of soot was lower with approximately 12.8 % with the addition of 30 % biodiesel

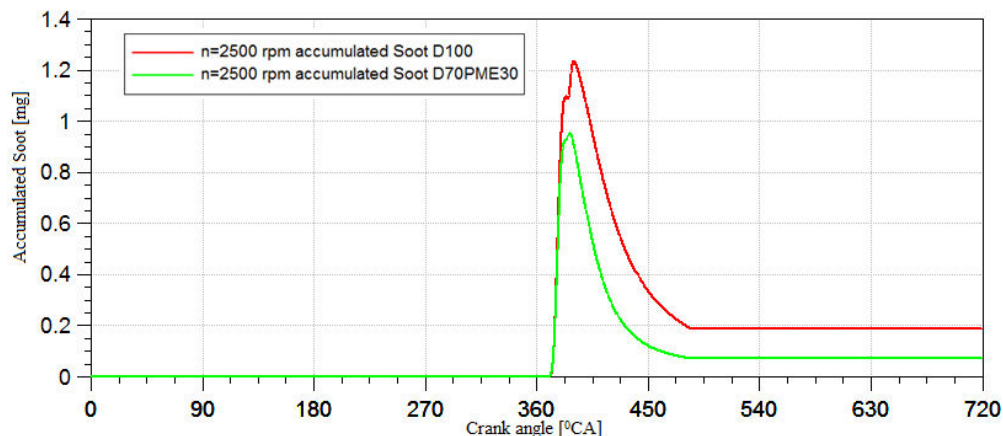


Figure 9. Accumulated soot $n=2500 \text{ min}^{-1}$.

in blend. In figure 8 the emission of soot retained a relatively constant decrease compared to figure 7, about 13.8 % the emission of soot was lower. The largest decrease in emissions can be seen in figure 9 where emissions dropped by about 42 %. Particulate emissions were reduced for all engine speeds using a blend of biodiesel with diesel compared to pure diesel. As can be seen in the figure 9, the most

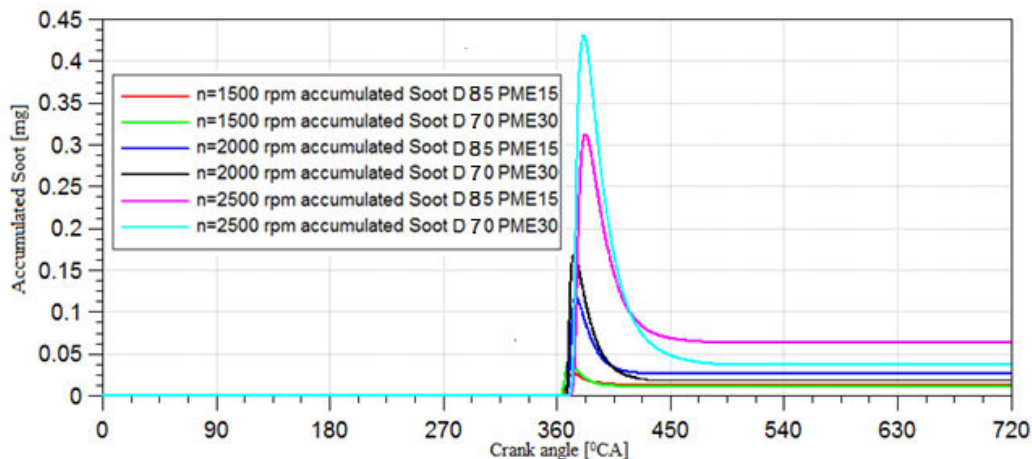


Figure 10. Soot emissions for D85PME15 and D70PME30.

notable soot emission drop was at the engine speed of 2500 min^{-1} for using a blend of biodiesel and diesel compared to pure diesel. An interesting aspect has been highlighted in figure 10, where 2 different proportion of biodiesel were used respectively 15 % and 30 %. It has been observed that increasing the amount of biodiesel in the mixture decreases the particulate emission, D70PME30 producing less soot than D85PME15 and this trend has been maintained for all three engine speeds used for the simulation.

6. Conclusions

Based on the simulations, the conclusions that can be drawn are :

- Due to the oxygen content, the use of biodiesel leads to a reduction of particulate emissions for all engine speeds;
- The most notable soot emission drop when using D70PME30 was at 2500 min^{-1} ;
- By comparing the two cases where 2 different percentages of biodiesel have been used, it was observed that increasing the biodiesel concentration leads to a decrease in particulate emissions;
- Biodiesel can be considered as a sootless fuel which can be taken into account to reduce the emission of particulate matter of diesel engines;
- For the combustion process to be complete, it is necessary that the ratio between fuel and air to be ideal, but this fact is impossible so ensuring a greater amount of oxygen favors the combustion process resulting in lower particulate matter emission;
- With an increased oxygen content of the mixture, the reduction of particulate emissions is justified by a better oxidation of the fuel even in the rich mixture zones, where soot particulates form;
- Changing the injection rate did not cause any significant improvement in terms of decreasing particulate matter emissions

7. References

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