FUEL CONSUMPTION, EMISSIONS AND PARTICLE SIZE DISTRIBUTION EVALUATION OF A DIESEL ENGINE OPERATING WITH BIODIESEL AND PERFORMANCE OPTIMIZING ADDITIVE AT PART LOAD

Pedro Bancillon Ventin Muniz[1,2], Felipe Andrade Torres[2,3], João Felipe Teixeira de Santana Freitas[2], Clara Rodrigues Pereira[1], Lílian Lefol nani Guarieiro[1], Ednildo Andrade Torres[2]
[1]SENAI CIMATEC, [2]PEI/UFBA, [3]UFRB.

ABSTRACT

Emissions from the exhaust gases of a diesel engine contain a large number of nanoparticles that are harmful to human health and the environment. The use of fuel optimizers, i.e. fuel additives, potentially reduce emissions, particulate matter (PM), and improve combustion characteristics. In this study, the engine-out exhaust emissions, fuel consumption and particle size distribution emitted from a diesel engine were evaluated using a mixture of 11% biodiesel and 89% mineral diesel (named B11), containing 10 ppm of sulfur; a second blend with an optimizer (called B11x) and a third fuel of 100% mineral diesel (named B0). The engine was kept at a constant load of 15 N.m at a speed of 1700 rpm (BMEP of 0.23 MPa) coupled with a dynamometer. A mobility nanoparticle spectrometer was used, as well as a gas analyzer and a dilution system type CVS (Constant Volume Sampling), which has been used to dilute the exhaust gas to collect the PM. In general, the results of the experiment indicated that the addition of biodiesel promoted an increase in fuel consumption; in the emission of emitted particles and no variations in gaseous emissions. The additive was effective only in reducing particulate emissions under the conditions and concentrations tested.

Keywords: diesel engine emissions, particle size distribution, fuel additive.

RESUMO

As emissões provenientes dos gases de escapamento de um motor ciclo diesel contém um grande número de nanopartículas, que são prejudiciais ao meio ambiente e à saúde humana. A utilização de otimizadores de combustível – aditivos – promete reduzir as emissões, o material particulado (MP) e melhorar à queima na combustão. Neste estudo, é observado o comportamento das emissões, consumo e da distribuição do tamanho de partículas emitidas por um motor diesel utilizando uma mistura de biodiesel e diesel mineral (B11) com 10 ppm de enxofre; esta mesma mistura aditivada de um otimizador (B11x); e o diesel puro (B0). O equipamento foi mantido a uma condição constante de 15 N.m de carga e 1700 rpm de rotação (BMEP de 0,23Mpa), acoplado a um dinamômetro do tipo estacionário. Além disto, foram utilizados um espectrômetro de partículas, um analisador de gases e um sistema de diluição tipo CVS, sendo este utilizado para diluir parte da exaustão proveniente do motor, na obtenção e contagem de MP. De forma geral, os resultados do experimento indicaram que a adição de biodiesel promoveu um aumento no consumo de combustível; na emissão de MP e nenhuma variações nas emissões gasosas. O aditivo mostrou-se eficaz apenas para a redução das emissões de MP nas condições e concentrações testadas.

Palavras-chaves: emissões, motor diesel, distribuição de tamanho de partículas, aditivos.

INTRODUCTION

Compression ignition engines are used on a large scale around the world as equipment for generating mechanical and or electrical energy. However, their exhaust gases contain a very large number of environmental pollutants and particles that are associated with respiratory diseases [1]. Between the main pollutants emitted are: carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x) and particulate matter (PM) [2]. The particles emitted by diesel oil are formed by volatile and non-volatile components generated from rich combustion regions and have a size range of 30 to 500 nm [1].

Carbon monoxide is a colorless and odorless venous gas, a product of incomplete combustion in the combustion chamber of an engine [3], due to a lack of oxygen capable of oxidizing the air/fuel mixture [4]. The inhalation of large concentrations of CO results in a reduction in the ability of the hemoglobin protein to transport oxygen within the cell and can even lead to death [5].

NO_x emissions are mainly composed of nitric oxide (NO) and nitrogen dioxide (NO_2), which are usually considered as the worst pollutants emitted by the diesel engine [3]. Diseases related to this pollutant include respiratory problems such as lung irritation, inflammation of the airways, and asthma [5]. NO_x formation is associated with the in-cylinder peak pressure and temperature inside the cylinder, the concentration of oxygen present in the air/fuel mixture, and the duration of combustion reaction [3].

Particulate materials (PM) are emitted by the engine exhaust through the combination of components from the incomplete combustion of the mixture, lubricating oil, and equipment wear. They are formed by large concentrations of carbon nucleus particles containing several organic compounds, HCs, grease aerosols, and are commonly related to cancer [6]. The emitted particles are commonly classified through their aerodynamic diameter (d_p): nanoparticles (d_p < 50 nm); ultrafine particles (50 nm < d_p > 100nm); fine particles (100 nm < d_p > 1µm) and coarse particles (d_p > 1 µm). Ultrafine particles and nanoparticles can penetrate through the alveoli, into the lymphatic vessels and deposit themselves in human blood [4], developing other cardiovascular diseases.

The use of biofuels as an alternative fuel can contribute to the preservation of the atmosphere, as well as reduce fossil fuel dependence. Among the most used biofuels, biodiesel stands out for compression combustion engines. The term biodiesel is commonly associated with a fuel originated from methyl fatty acids or ethyl esters based on vegetable oils and animal fat [4]. Biodiesel utilization is related to positive factors such as the reduction of CO emissions, due to increased oxygen content in the fuel molecules, which results in more complete combustion [7]. Previous studies have reported similar findings and justified these results through higher cetane number that enhanced a reduction in the formation of fuel-rich zones [4]. Some parameters may affect these indexes, such as biodiesel raw material, fuel viscosity, fuel injection type, and strategy [6].

Biodiesel can increase the levels of NO_x due to higher temperatures and pressure peaks in the combustion chamber [4]. Previous studies have reported that these increases may be associated with the previous factors mentioned, in addition to an early fuel injection, due to as a result of its increased volumetric compressibility [2] and higher oxygen content [7].

The concentration and size distribution of particles (PSD) emitted by the diesel cycle engine may vary according to the type of engine, operational conditions (speed and load), and fuel type during operation [1]. There is a trend evaluated by several researchers in the reduction of particulate matter emitted by the diesel engine when using biodiesel, due to the longer oxidation time of the gases generated by combustion [4]. However, in a particle size distribution (PSD) analysis, it is noticeable that biodiesel enhances the reduction of coarse particles, promoting an increase in fine and nanoparticles [2, 8, 9].

The specific fuel consumption (BSFC) of diesel engines fueled with biodiesel shows a slight increase in comparison with diesel fuel [2]. This may be explained due to higher viscosity of the biofuel, lower calorific value, higher cetane number, and flash point [7], which result in an increased amount of fuel injection [1, 4].

When using biodiesel, there are some disadvantages, such as higher density, high fuel consumption, and high nitrogen oxides. To avoid the above disadvantages, fuel additives promote a significant role in minimizing the drawbacks of biodiesel and maintaining fuel characteristics standards. Additives can be considered to improve combustion, fuel economy, and reduce emissions. Many different types of additives are added to biodiesel in order to meet specification standards and restore the quality of biodiesel. Several additives have been studied. Furthermore, it is possible to classify them according to their chemical characteristics [10]. Metal-based additives promote an improvement in the flashpoint, reducing the fluidity and viscosity of biodiesel; besides reducing fuel consumption. Moreover, they are the most effective in reducing smoke opacity. Oxygen-based additives increase the oxygen content in the fuel mixture and reduce its viscosity and density. The addition of antioxidants increases the flashpoint, cetane number, and the specific power of the equipment, in addition to being the most indicated in decreasing the emitted NO_x rates [3].

Nano additives are a favorable solution for use in diesel engine fuel systems [11], mostly due to the impact that these additive promote in reducing the peak temperature inside the combustion chamber and contributing to the reduction of HC, CO, NO_x, and PM. Some additives promote an increase in the fuel atomization rate, which facilitates the complete combustion process [12]. It is possible to find in the literature that the use of ethanol as an additive, contributes mainly to the amount of heat released during the combustion [2]. Cerium-based additives are usually reported as reducing the concentrations of coarse particles in comparison with mineral diesel [13].

Studies around the world are being carried out to verify ways to reduce engine-out exhaust emissions and particle matter, with the addition of biodiesel, ethanol, or fuel additives. Therefore, this study aimed to investigate the effect of a new soluble catalyst on the performance and emission characteristics of a CI diesel engine fueled with a diesel-biodiesel blend.

METHODOLOGY

The experiments in this study were carried out using a naturally aspirated diesel engine, coupled to a Schenck dynamometer, model D - 210/1-E. The equipment has been tested with all original parts and components assembled by the manufacturer. This equipment uses a mechanical injection pump model Bosch PFR 2K 80A393. The main characteristics are shown in Table 1.

The engine was maintained at a constant speed and load (T) regime of 1700 rpm ($\pm$ 10) and 15 N.m ($\pm$ 1) of load, resulting in total output power (W) of 2.7 kW, according to equation 1. This same regime corresponds to a BMEP of 0.23 MPa and was selected simulating a constant speed and load regime, similar to that used in engines that operate as generators, field tractors or mechanical pumps.

Table 1. Engine specification

Model	Agrale M-790
Swept volume (cm³)	1272 cm³
Number of cylinders	2
Fuel injection system	Direct
Max torque	70 N.m @ 2250 rpm
Max power	24 cv/ 17.6 kW @ 3000 rpm
Engine cooling system	Air

$$\boldsymbol{W = T \times RPM \times \left(\frac{2\times\pi}{60000}\right)} \quad \textbf{(Equation 1)}$$

The engine tests followed a standard procedure for testing the three fuels. First, the engine was stabilized for about 30 minutes with the fuel to be tested. After this period, the test conditions were fixed on the engine. Variables such as ambient temperature, exhaust gas temperature, as well as ambient air humidity were also measured by appropriate sensors.

Three fuel mixtures were tested, being B0 (0% biodiesel with 10 ppm sulfur), B11 (11% biodiesel with 10 ppm sulfur), and B11 with a nanocatalyst. This nano-particle catalyst was added to an 89% diesel and 11% biodiesel fuel blend (B11 with 10 ppm of sulfur) at a concentration of 10 ppm for the evaluation of specific consumption parameters and exhaust emissions (O_2, CO, NO_x) and particle size distribution. This catalyst consists of 20 different types of enzymes that, when dissolved, create a chain of biochemical reactions in the fuel. The concentration used was adopted to the detriment of the manufacturer's recommendation. To ensure a 10 ppm concentration, a graduated pipette was used in order to reduce supply errors. The additive mixture underwent a manual stirring process for about 20 minutes and remained in storage for 24 hours before use. The main fuel specifications are shown in table 2.

Table 2. Fuel Specifications

Fuel Property	Unit	Method	B0	B11	B11x
Biodiesel concentration	Volume %	-	0	11	11
Additive concentration	ppm	-	0	0	10
Density	kg/m³	NBR 7148	833.1	839.1	839.3
Kinematic viscosity	cSt	NBR 10441	3.63	3.84	3.68
Water content	mg/kg	KF	433.3	333.3	500

The assessment of specific fuel consumption was performed using the gravimetric method. A container containing one fuel at a time was placed on an electronic scale. As the fuel mass was consumed, the time of this consumption was recorded on a digital timer. The verification of specific consumption occurred in triplicate, and each verification counted with the performance of 5 measurements of time for each mass of 50g of fuel consumed. Thus, BSFC was calculated by mass consumption, converted into hours, and by engine power, according to equation 2. The sensitivity of the scale used was 1g.

$$\boldsymbol{BSFC = \dot{m} \times \left(\frac{1000}{W}\right)} \quad \textbf{(Equation 2)}$$

The measurement of O_2, CO and NO_x was performed according to NBR 14489. For the collection of these data, a gas analyzer of MRU Instruments brand, model Optima 7 Biogas, was used, installed in the exhaust manifold of the diesel engine. The oxygen concentration of the emissions was measured in order to be related to the results of CO and NO_x. The main analyzer specifications are shown in table 3.

Table 3. Analyzer Specifications

Components	Measuring range	Accuracy
Operation temperature	5 a 45 ºC	-
Carbon dioxide	0 ... 100%	$\pm$ 3% reading
Oxygen	0 ... 25 Vol. (%)	$\pm$ 0.2 Vol. (%)
CO (H_2 compensated)	0 ...4000 ppm	$\pm$ 10 ppm
CO (low)	0 ... 500 ppm	$\pm$ 2 ppm
NO	0 ... 1000 ppm	$\pm$ 5 ppm
NO (low)	0 ... 300 ppm	$\pm$ 2 ppm
NO_2	0 ... 200 ppm	$\pm$ 5 ppm

NO_2 (low)	0 … 100 ppm	± 5 ppm
Gas temperature	-17.7 … 648 ºC	± 1% reading

The particle size distribution (PSD) was performed by a TSI spectrometer, model nanoScam 3910. A dilution tunnel of the CVS type was used as a partial gas dilution system at a rate of 24 (flow of atmospheric air/flow of gases exhaust) to collect the PM. The tests were carried out with the engine at working temperature, informed by the manufacturer. O_2, CO and NO_x measurements were carried out in triplicate, to improve test reliability and error bars were added to all graphs. The PSD measurement was performed in 10 collections of 1 min each, the last 5 with the engine off, and the CVS running to collect the particles from the ambient, which were subsequently subtracted from those previously collected. A schematic diagram of the experimental set up is shown in Figure 1.

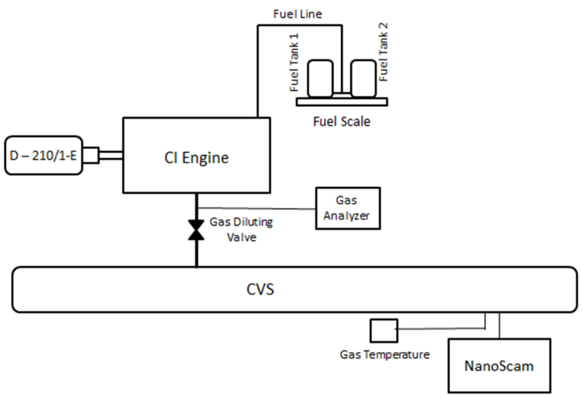

Figure 1. Scheme of the sampling system for particle matter and exhaust gases.

RESULTS AND DISCUSSIONS

Analyzing the BSFC, it was possible to notice that the addition of biodiesel promotes an increase in fuel consumption. This behavior is in agreement with previous experiments carried out other researchers [4, 10]. The addition of biodiesel increased the fuel's viscosity index, which can reduce the fuel return flow through the injection pump and contribute to an increase in the injected volume. The addition of the fuel additive did not result in significant variations in consumption, being considered statistically equal to the B11 mixture and slightly higher than pure diesel (Figure 2).

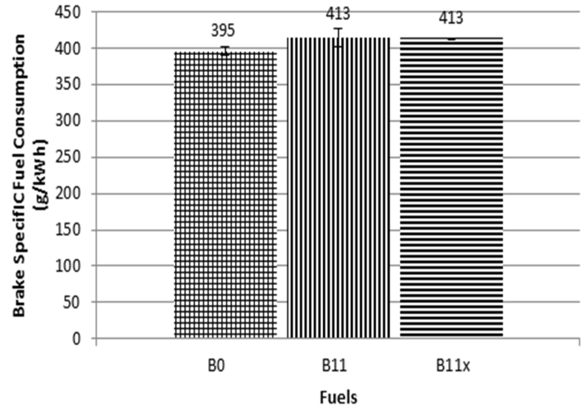

Figure 2. Brake specific fuel consumption of different fuels.

Figure 3 shows that the O_2 emissions resulting from the combustion of the biofuel had a similar compared to diesel and blend with additive. The values fluctuate around 16%, since this engine does not have electronic fuel injection, and the load imposed in the tests was the same.

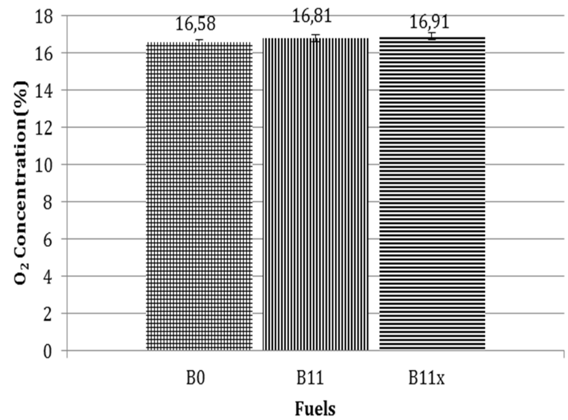

Figure 3. Oxygen concentration of different fuels.

Figure 4 shows that the CO emissions resulting from the combustion of the biofuel had a similar compared to diesel. It is expected that the higher oxygen content of the biofuel will lead to an improvement in combustion, reducing emissions. However, these results were also found by other researchers in their literary reviews [4, 6, 7]. The use of the catalyst did not reproduce the effects of increasing or decreasing the CO content in the B11 mixture, being considered statistically equal to diesel oil.

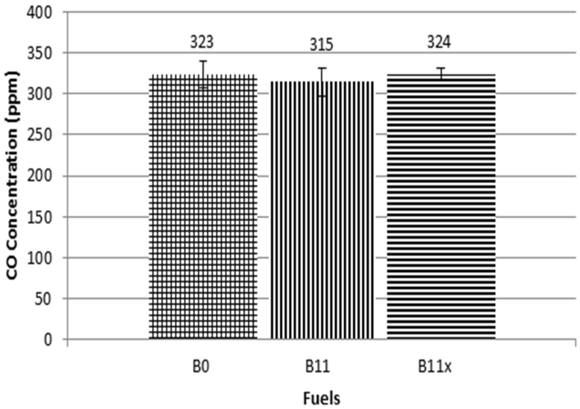

Figure 4. Carbon monoxide concentration of different fuels.

NO_x emissions had a similar behavior in nitrogen oxide emissions (Figure 5), as the results are considered statistically equal. It was expected that the use of biodiesel would provide a slight increase in the rates due to the higher viscosity and density of the biofuel. The higher oxygen content is also identified as one of the precursors to this increase in NO_x emissions, as the combustion temperature increases, increasing NO_x levels [1, 4]. However, some researchers have identified results similar to those presented and indicated that these values may vary according to the operating conditions of the engine and the source of biodiesel [4]. Others indicate that the use of up to 20% of biodiesel provides similar NO_x emissions [6]. The additive added to the B11 mixture did not promote significant changes in these emissions.

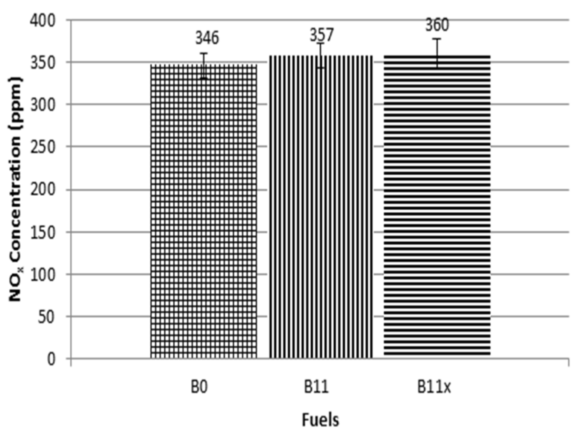

Figure 5. NO_x concentration of fuels

PSD analysis was performed comparing mineral diesel (B0) with the mixture without additive (B11) and with the mixture with additive (B11x). The results of the analyzed data present a characteristic form of PM emissions from diesel and its mixtures, with the highest emissions occurring around 65 nm (figure 6). In this diameter it is possible to notice an increase in the number of particles caused by the addition of biodiesel to mineral diesel. A similar behavior occurs from 110 nm, until the end of the measurement range. These results are similar to those analyzed by some researchers [2, 6]. The use of the additive was able to reduce the particles emitted by biodiesel, providing a reduction in peak emissions by approximately 25% compared to the B11 mixture.

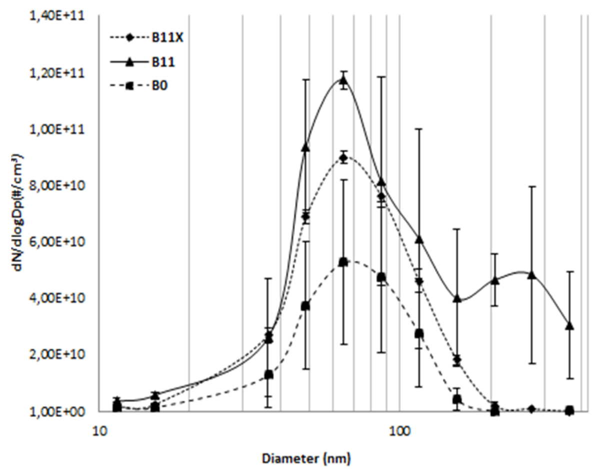

Figure 6. Particles Size Distribution of tested fuels

CONCLUSION

From the data analyzed in the experiment, it was possible to conclude that the use of biodiesel in relation to mineral diesel promoted a slight increase in the BSFC content, but without statistical variations in the levels of CO and NO_x. The addition of a catalyst additive to the B11 mixture proved to be ineffective in reducing the parameters indicated above. The analysis of the excess oxygen emission showed that the values are statistically equal. Mineral diesel (B0) proved to be more efficient in BSFC, factors already expected in the literature. Regarding the PSD study, B0 had the lowest peak values of PM emitted for the conditions tested. The addition of biodiesel caused an increase in the peak PM emission and an increase in fine particle emissions (d_p> 100 nm). The catalyst showed satisfactory yield, reducing the peak values of B11, bringing them closer to those generated by B0.

In view of the tests applied, it is recommended to carry out new experiments varying the load imposed by the dynamometer by 50 and 75%, in addition to considering higher concentrations of catalyst, such as 100 ppm and 500 ppm, to verify the behavior of the additive.

REFERENCES

[1] YOUNG, Li-Hao; LIOU, Yi-Jyun; CHENG, Man-Ting; LU, Jau-Huai; YANG, Hsi-Hsien; TSAI, Ying I; WANG, Lin-Chi; CHEN, Chung-Bang; LAI, Jim-Shoung. Effects of biodiesel, engine load and diesel particulate filter on non-volatile particle number size distributions in heavy-duty diesel engine exhaust. Journal of Hazardous Materials 199– 200 (2012) 282– 289.

[2] GUARIEIRO, L.L.N.; GUERREIRO, E.T.A.; AMPARO, K.K.S.; MANERA, V.B.; REGIS, A.C.D.; SANTOS, A.G.; FERREIRA, V.P.; LEÃO, D.J.; TORRES, E.A.; ANDRADE, J.B. Assessment of the use of oxygenated fuels on emissions and performance of a diesel engine. Microchemical Journal 117 (2014) 94–99.

[3] RASHEDUL, H.K.; MASJUKI, H.H.; KALAM, M.A.; ASHRAFUL, A.M.; ASHRAFUL RAHMAN, S.M.; SHAHIR, S.A. The effect of additives on properties, performance and emission of biodiesel fuelled compression ignition engine. Energy Conversion and Management, v. 88, p. 348-364, 2014.

[4] LAPUERTA, Magin. ARMAS, Octavio. RODRÍGUEZ-FERNÁNDEZ, José. Effect of biodiesel fuels on diesel engine emissions. Progress in Energy and Combustion Science 34 (2008) 198–223.

[5] VALLERO, D. Fundamentals of Air Pollution. Elsevier Inc, 5th Edition. 2014.

[6] AGARWAL, A.K.; GUPTA, J.G.; DHAR, A. Potential and challenges for large-scale application of biodiesel in automotive sector. Progress in Energy and Combustion Science 61(2017)113-149.

[7] PATEL, P.D.; LAKDAWALA, A.; CHOURASIA, S.; PATEL, R.N. Bio fuels for compression ignition engine: A review on engine performance, emission and life cycle analysis. Renewable and Sustainable Energy Reviews, 65(2016)24–43.

[8] ZHANG. Y.; LOU, D.; HU, Z.; TAN, P. Particle number, size distribution, carbons, polycyclic aromatic hydrocarbons and inorganic ions of exhaust particles from a diesel bus fueled with biodiesel blends. Journal of Cleaner Production 225 (2019) 627e636.

[9] SUN, W.; WANG, Q.; GUO, L.; CHENG, P.; LI, D.; YAN, Y. Influence of biodiesel/diesel blends on particle size distribution of CI engine under steady/transient conditions. Fuel 245 (2019) 336–344.

[10] VIJAY KUMAR, M.; VEERESH BABU, A.; RAVI KUMAR, P. The impacts on combustion, performance and emissions of biodiesel by using additives in direct injection diesel engine. Alexandria Engineering Journal (2018) 57, 509–516.

[11] MIRZAJANZADEH, M.; TABATABAEI, M.; ARDJMAND, M.; RASHIDI, A.; GHOBADIAN, B.; BARKHI, M.; PAZOUKI, M. A novel soluble nano-catalysts in diesel– biodiesel fuel blends to improve diesel engines performance and reduce exhaust emissions. Fuel, v. 139, p. 374-382, 2015.

[12] SHAAFI, T.; VELRAJ, R. Influence of alumina nanoparticles, ethanol and isopropanol blend as additive with diesel–soybean biodiesel blend fuel: Combustion, engine performance and emissions. Renewable Energy, v. 80, p. 655-663, 2015.

[13] SHAAFI, T.; SAIRAM, K.; GOPINATH, A.; KUMARESAN, G.; VELRAJ, R. Effect of dispersion of various nanoadditives on the performance and emission characteristics of a CI engine fuelled with diesel, biodiesel and blends—A review. Renewable and Sustainable Energy Reviews, v. 49, p. 563- 573, 2015.