# ANALYSIS OF NOx EMISSIONS AND SPECIFIC FUEL CONSUMPTION OF A DIESEL ENGINE OPERATING WITH DIESEL/BIODIESEL BLENDS

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***Abstract.*** *This study aims to examine experimentally the NOx emissions and the performance of a motor AGRALE M95, single cylinder, operating with diesel and biodiesel blends. The engine was linked to an electric generator, which provided 1500 W, 3000 W and 4500 W to an electrical system. The engine was tested with fuel blends containing different amounts of commercial diesel (B4) with palm biodiesel (B100). NOx emissions, as well as the specific fuel consumption of diesel, biodiesel and their mixtures were measured and analyzed. In this study, emissions of NOx have been prioritized over other pollutants by environmental issues and techniques. Air pollution by NOx causes serious respiratory problems. Furthermore, emissions of NOx enable a qualitative assessment of the combustion process. The results show that the commercial diesel has better performance in terms of energy efficiency and NOx emissions.*

***Keywords****: diesel, biodiesel, engine, emission.*

## 1. INTRODUCTION

Nowadays, biofuels are replacing fossil fuels in many engineering systems as engines, gas turbines and furnaces. This tendency takes account environmental, social and economical benefits. The main aspect associated to the biofuels is the fact that these ones are renewable fuels. In this context, the biodiesel and diesel/biodiesel blends became alternatives to diesel fuel. However, pure biodiesels can not be used in diesel engines, due to technical problems. To overcome these limitations, diesel/biodiesel blends have been employed in diesel engines. Studies show that diesel engines are only able to work, without modification, using diesel/biodiesel blends containing up to 20% biodiesel. Above this percentage there are technical problems that require more elaborate ratings on performance, the specific fuel consumption and engine emissions. Nevertheless, air pollution is an important environmental drawback in the adoption of the biodiesel instead of diesel. Some studies have shown that NOx emissions are greater using biodiesel than diesel in internal combustion engines. The other hand, the chemical element sulfur is not present in the biodiesel molecule. Then, the biodiesel does not contribute to the acid rain.

The fuel combustion process inside engines is responsible for most of the atmospheric pollution in the Brazilian big cities. These sources of pollution produce mainly hydrocarbon (HC), carbon monoxide (CO), carbon dioxide (CO2) and nitrogen oxides (NOx). However, NOx is extremely dangerous to the human healthy and to the environment. Moreover, NOx is relevant in the Ozone (O3) production, which is a high toxicity substance. A lot of respiratory, dermatologic and ophthalmologic diseases are caused by the NOx pollution.

The NOx production in an internal combustion engine is linked with complex mechanisms. “The formation of NOx in engines, are greatly influenced by the following factors. First of all, the combustion flame temperature; secondly, the duration of high temperature, and thirdly, the oxygen content in the flames. Among these factors, flame temperature is the key factor. The higher of combustion temperature of flame in the engine is, the higher NOx emission will be” (Wang et al., 2007).

There are two main strategies to reduce the NOx emissions: the first is to process the exhaust gas using catalysts to react with the NOx, the second is to prevent NOx formation in the cylinder of the engine. The first strategy is expensive and it consists in the introduction of a catalyst in the exhaust line. The second strategy is to prevent the NOx formation modifying the chamber conditions and the air-fuel mixture. One of the strategies to reduce NOx formation is the use of the Exhaust Gas Recirculation. “Exhaust gas recirculation (EGR) is effective to reduce NOx from diesel engines because it lowers the flame temperature and the oxygen concentration in the combustion chamber. However, EGR results in higher particulate matter (PM) emissions” (Agarwal et al., 2006).

There are other important aspects that should be taken in account in relation to biodiesel. The production process of biodiesel is very simple; consequently it is possible to be produced in small plants, using different vegetable oils. These characteristics are especially interesting to the Brazilian economy, reducing the diesel importation and creating jobs in Brazil. The biodiesel production can employ large quantities of manpower in the agriculture and in small industries. In this context, the biodiesel can contribute to mitigate the problems of the people migration from the field to the cities. Considering the logistical and infrastructure problems of the Amazon region, the biodiesel can be used to develop this region. Remote communities in the Amazon region can produce the biodiesel and use this fuel in small biodiesel power plants to furnish electricity to the community.

Almeida et al. (2003) have used the diesel engine MWM - 229, 70 kW fueled with palm oil and fresh diesel to verify the concentration of exhaust gas emissions and the specific fuel consumption. The results showed that the palm oil specific consumption was approximately 10% higher than the diesel specific consumption. It was a consequence of the lower heat value of the palm oil in relation to the diesel heat value. Moreover, the emissions of diesel had lower concentration of the CO. However, emissions of $CO_2$ and $O_2$ were independent of the fuel, but it increased when power engine had been improved. Furthermore, NOx emissions were also increased with power engine, since in such conditions the temperature of the combustion chamber was improved.

Kalam and Masjuki (2002) studied the 4-cylinder Isuzu 4FB1, using three different fuels: 100% diesel (B0), 20% palm biodiesel (B20) and B20X, where X is the percentage of the additive 4-Nonyl phenoxy acetic acid (NPAA) in the B20 fuel. Higher power was obtained using B20X. This result can be attributed to the influence of the additive. Regarding the specific fuel consumption, the behavior of B20 and B20X were similar to the B0 until 2250 rpm, after this angular velocity, the B20 fuel consumption increases. The consumption of B20X remains similar to the B0 until 3500 rpm, but it was increased for greater values of angular velocity. Emissions of NOx, CO and HC are lower in fuel B20X, followed by B20, and finally the B0.

Kanok-On and Chinde (2004) studied diesel/ biodiesel blends fuels in a single cylinder Yanmar diesel engine - LM 85 TF. Diesel and biodiesel blends (B10, B50, B90 and B100) from palm oil and fresh coconut oil. After several experiments, they found that the power was reduced when the engine was fueled with biodiesel. Therefore, the specific fuel consumption was reduced when the percentage of diesel in the blend has been decreased.

Rakopoulos et al. (2006) conducted an experimental study to evaluate the performance and emission of gases from an engine fueled with different fuels: B10 and B20 blends of biodiesel from cotton, soybean, sunflower, rapeseed and palm. The tests were performed using a single cylinder diesel engine, working at an angular speed of 2000 rpm and subjected to medium and high loads. The results show that NOx emissions were reduced by using vegetable oil and biodiesel blends instead of diesel. CO emissions have shown the same behavior in relation to B10 and B20 blends of biodiesel, but exactly the opposite by using B10 and B20 blends of vegetable oils. HC emissions were shown independent of the fuel. Furthermore, the specific fuel consumption of B10 and B20 vegetable oils blends were greater than B10 and B20 biodiesel blends.

Agarwal et al. (2006) have investigated the NOx emissions of diesel and biodiesel blends fuels from a two cylinders engine. The main objective of this work is to verify the reduction of NOx emission by use of the Exhaust Gas Recirculation (EGR). “EGR involves replacement of oxygen and nitrogen of fresh air entering in the combustion chamber with the carbon dioxide and water vapor from the engine exhaust. The recirculation of part of exhaust gases into the engine intake air increases the specific heat capacity of the mixture and reduces the oxygen concentration of the intake mixture. These two factors combined lead to significant reduction in NOx emissions” (Agarwal et al., 2006). The results show that the EGR reduces NOx emissions using diesel and biodiesel fuels.

Kalam and Masjuki (2008) examined the performance and emissions of the gases in a 4-cylinder Isuzu 4FB1. They employed a dynamometer and a gas analyzer Bosch ETT 008.36. The study used three different fuels: diesel oil; 50 ppm + 7.5% additive biodiesel from palm oil + 92.5% diesel oil and 50 ppm + 15% additive biodiesel from palm oil + 85% diesel oil. The results show that the engine performance is improved, when the concentration of palm biodiesel increases. This was due to the additive IRGANOR NPA that influenced the transformation of thermal energy into mechanical energy by increasing efficiency during the combustion process. Furthermore, by increasing the palm biodiesel concentration, the emissions of NOx, CO and HC are reduced.

Dutra et al. (2009) have analyzed the emissions and the performance of the palm oil biodiesel and diesel blends. The experiments were conduct in a M95 Agrale engine linked to a dynamometer of induction model 66DG. The dynamometer was set to keep constant the load and the speed. The results show that the NOx emissions increases with the load and with the amount of biodiesel in the blend for 50% of the maximum load. However, for 75% of the maximum load the differences between the tested fuels were not relevant. Furthermore, the specific fuel consumption increased with the amount of biodiesel in the fuel mixture.

The present work is devoted to NOx emissions and performance analysis of an engine operating with diesel and biodiesel blends. The engine was linked to an electric generator, which provided 1500 W, 3000 W and 4500 W to an electrical system. In such configuration, the electrical load determines the engine load. Such experimental apparatus shows to be very simple and cheaper than the traditional dynamometer experiments.

## 2. METODOLOGY

The proposed experiment consists of an M90 AGRALE engine linked to a KOHLBACK electric generator that provides power to an electrical system with nine lamps. The lamps were grouped into three separate arrays, each one with three 500 W lamps. The schematic organization of the experimental system is shown in Figure 1.

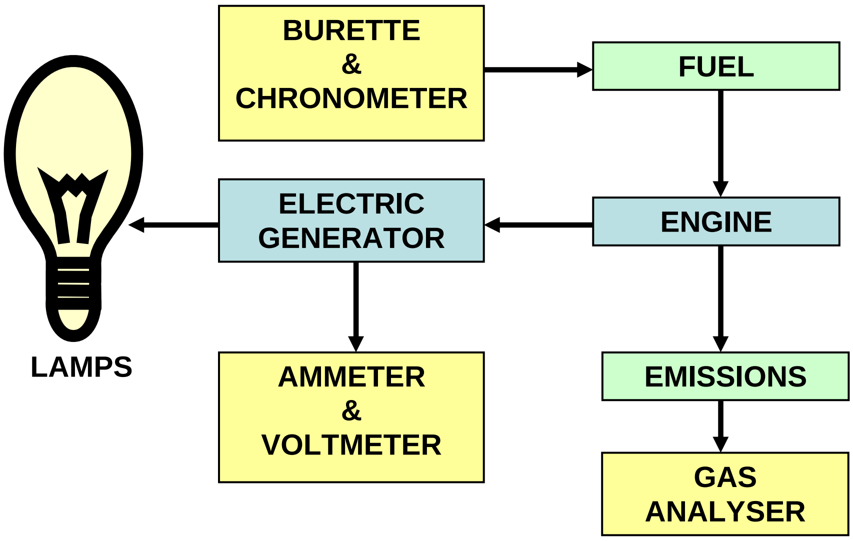


Figure 1. Experimental system.

The experimental equipments: engine, electrical generator and gas analyzer are, respectively, presented in Tabs. 1, 2 and 3. Besides the performance evaluation, this experimental setup reveals the engine behavior in relation to NOx emissions.

Table 1. Engine data sheet

| ENGINE | AGRALE M90 |
|---|---|
| Power CV / kW / rpm | 12 / 8.8 / 2400 |
| Max. Torque daNm / rpm | 3.9 / 2350 |
| Cylinder | 1 |
| Compression ratio | 20:1 |
| Injection System | Direct Injection |

Table 2. Generator data sheet

| GENERATOR | KOHLBACK |
|---|---|
| Power kVA | 7.5 |
| Voltage | 220/117 V |
| Frequency | 60 Hz |

Eleven fuel types were studied in this work: commercial diesel (B4); palm oil biodiesel (B100), obtained by the esterification process; and blends (B10, B20, B30, B40, B50, B60, B70, B80 and B90) of these fuels. Moreover, the engine operated at 1800 rpm during all of the experiments.

The measuring instruments used to perform the tests were: opacimeter NA-9000 analyzer and gas MODAL 2010-AO. Furthermore, to control the generator, it was used a system composed of: ammeter Hartmann & Braun scaled from 5 to 20 A with a sensitivity of 0.5 A, Hartmann & Braun voltmeter with a scale from 100 to 250 V and a sensitivity of 5 V. The partial or full activation of lamps allowed the variation of the load applied to the engine.

Therefore, the experimental apparatus is a low cost experiment which, in some cases, can replace a dynamometer. Furthermore, the proposed setup represents a real application of biodiesel in small electric power generation. These systems have become relevant, mainly in the Amazon region, due to the difficulties in supplying the most remote communities.

The experiment could be run with three different electrical power loads provided by three, six or nine lamps turned on. In other words, the experiments can be executed for 1500 W, 3000 W and 4500 W of electrical power, which is furnished by the electric generator. Since the electric generator is linked to the engine, the mechanical power provided by the engine is controlled by the electrical load. Noteworthy, the measurements were conducted after engine stabilization.

Table 3. Gas analyzer MODAL 2010-AO

| Type | Resolution | Accuracy | Scale |
|---|---|---|---|
| HC | 1 ppm | 12 ppm or 5% of the maximum value | 0 - 2000 ppm |
| $CO_2$ | 0.01% | 0.06% CO or 5% of the maximum value | 0 - 20% |
| CO | 0.1% | 0.5% $CO_2$ or 5% of the maximum value | 0 - 15% |
| $O_2$ | 0.01% | 0.1% $O_2$ or 5% of the maximum value | 0 - 25% |
| NOx | 1 ppm | 32 ppm NOx in range from 0 to 1000 ppm | 0 - 5000 ppm |
| | | 60 ppm NOx in range from 1001 to 2000 ppm | |
| | | 120 ppm NOx in range from 2001 to 5000 ppm | |

## 3. RESULTS

Figure 2 illustrates the engine NOx emissions. It can be noticed by improving the engine electrical load, NOx emissions are also improved. It is a consequence of the high temperature level achieved inside the engine cylinder during the combustion process. The NOx formation in the combustion engine is proportional to the flame temperature and, by increasing the load, the temperature inside the cylinder is also increased. In addition, considering the accuracy of the experiments, NOx emissions were independent of the tested diesel/ biodiesel blends. However, the results in Fig. 2 show a tendency of the NOx emissions to increase with the amount of the palm oil in the blended fuel, when the 4500 W of electrical load is considered.

In Tab. 5, it is possible to observe that the cetane number increases with the quantity of biodiesel in the fuel mixture. The centane number is inversely proportional to the ignition delay and the ignition delay influences the NOx emissions. When the ignition delay is increased, the temperature and pressure inside the engine chamber of combustion increases and consequently more NOx is formed. Thus, the expected result is that reducing the cetane number, the NOx formation will be improved. Nevertheless, the results in Fig. 2 show a different behavior. The biodiesel of palm oil (B100) produces more NOx than the commercial diesel (B4) for high engine loads and the same tendency was found in the Agarwal et al., (2006) results. Moreover, Basshuysen and Schaefer (2004) explain that the biodiesel has greater viscosity than diesel, creating problems during the fuel injection and atomization. Such problems entail poor combustion, causing more NOx formation. Consequently, the cetane number is not a good parameter to analyze the NOx formation in comparative studies of different fuels as diesel and biodiesel.

The nitrogen present in the biodiesel molecules does not contribute to the NOx formation, but the nitrogen present in air does. The Tab. 5 shows the quantity of nitrogen present in the diesel/biodiesel blends.

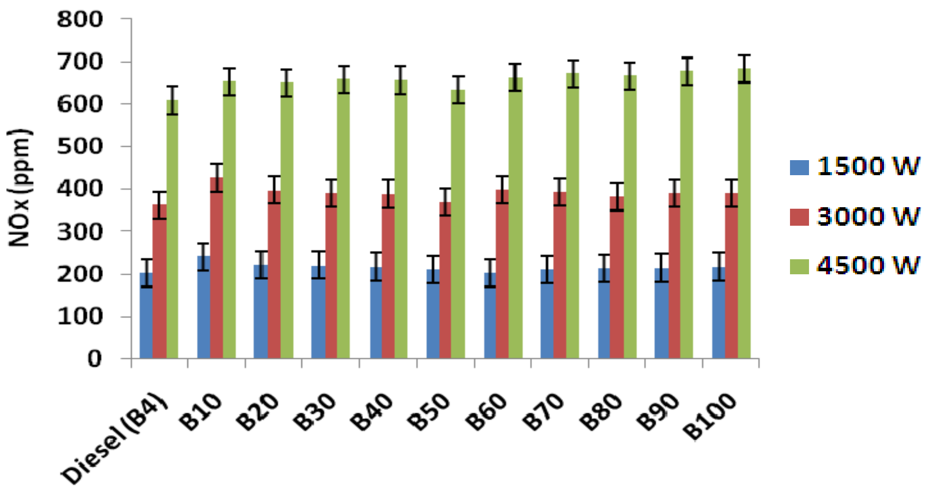


Figure 2. NOx emissions.

During each test, the time required to drain 100 ml of fuel from a burette, in the fuel supply line of the engine, was measured to evaluate the volumetric consumption of fuel (VCF). The VCF multiplied by the density furnishes the fuel mass flux. The densities of various fuel types used in this study are shown in Table 4. The uncertainty of these measurements is ± 0.005 g/cm$^3$.

Table 4. Fuel density at 26°C

| FUEL | B4 | B10 | B20 | B30 | B40 | B50 | B60 | B70 | B80 | B90 | B100 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ρ (g/cm$^3$) | 0,832 | 0,834 | 0,835 | 0,835 | 0,836 | 0,841 | 0,847 | 0,849 | 0,853 | 0,855 | 0,856 |

The specific fuel consumption (SFC) is an important parameter to verify the system efficiency. This parameter is defined dividing the fuel mass flux by the power of the engine. To compute the SFC, some measurements should be done. The voltage (V) and the amperage (i) of the electric generator were measured to evaluate the electric power (P) of the generator. Besides, the present work considers that 81% of the engine power is furnished to the electric generator.

The results in Fig. 3 show the SFC for the tested fuels. In this figure, it is observed that increasing the amount of the palm oil on the blended fuel, the SFC also increases. It could be explained taken in account the heating values of the fuels presented in Tab. 5. The high heating value (HHV) and the lower heating value (LHV) of the commercial diesel (CD) are greater than the ones of the palm oil biodiesel blends. So, it is necessary more biodiesel than diesel to make the same work. It is important to note that the SFC were not evaluated for 1500 W of electrical load, because the amperage of the generator were minor than the ammeter accuracy. Nevertheless, improving the electric power of the system, the SFC is reduced. This result could be explained by the engine efficiency curve, since the engine was working in a low load. From the Tab.1 the maximum load of the engine is 8.8 kW, but in the present work the maximum operation load is approximately 5.5 kW. Then, it is possible that in this low load condition, the specific fuel consumption increases when the electrical load is reduced.

Table 5. Fuel specification (Teixeira, 2010)

| Fuel | CD | B20 | B50 | B100 | METOD |
|---|---|---|---|---|---|
| Nitrogen (% m/m) | 0.09 | 0.04 | 0.07 | 0.07 | ASTM D 5291 |
| High Heating Value (Kcal/kg) | 10765 ±23 | 10536 ± 1 | 10144.5 ± 18.5 | 9460.2 ± 5.0 | ASTM D 4809 |
| Lower Heating Value (Kcal/kg) | 10068 ± 23 | 9819.6 ± 0.7 | 9448.5 ± 18.7 | 8784.0 ± 5.0 | ASTM D 4809 |
| Cetane number | 48.8 | 49.7 | 56.1 | 59.3 | ASTM D 613-01 |

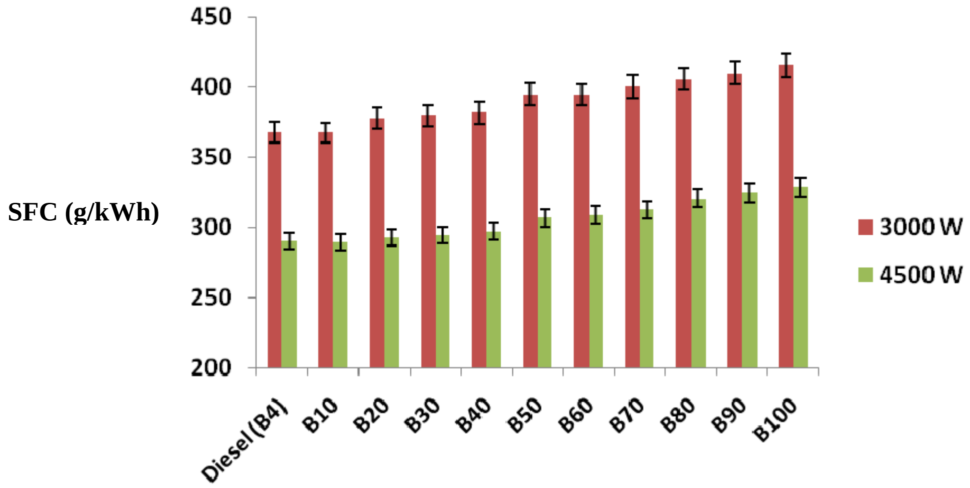


Figure 3. Specific fuel consumption (SFC).

## 4. CONCLUSION

The present experimental work has analyzed the NOx emissions and the performance of an internal combustion engine fuelled with eleven different diesel/biodiesel blends. The proposed experimental apparatus used an electric generator instead of a dynamometer to control the load on the engine. This alternative shows to be very simple and cheaper than the traditional dynamometer experiments. Besides, the engine linked to an electric generator is a more realistic application than the engine linked to a dynamometer. Otherwise, the electrical load is the unique parameter used to control the proposed experimental apparatus. The angular velocity of the engine is not controlled. This limitation is usually not found when a dynamometer is employed.

The results show that the B100 NOx emissions are greater than B4 for 4500 W of electrical load. But, for small electrical loads meaningless discrepancies was observed between the fuel blends. In this study, NOx emissions could be considered independent of the diesel/biodiesel blends. In addition, the results show that improving the electrical load, the NOx emissions were also increased for all of the tested fuel mixtures. This is due to high temperature levels achieved inside the engine cylinder when electrical load increases.

Furthermore, it was observed that the cetane number of the biodiesel is greater than the cetane number of the diesel. However, wrong conclusions could be done if the cetane number was used to analyze the NOx emissions. The biodiesel has greater viscosity than diesel, creating problems during the fuel injection and atomization. These problems entail poor combustion increasing the ignition delay. Consequently, the temperature and pressure in the combustion chamber increases, causing more NOx formation.

Despite of the fuel studied in the present work, the temperature is the main factor responsible for the NOx formation. In this sense, NOx emissions increase when the electrical load also increase, because the temperature inside the combustion chamber reaches high levels.

The specific fuel consumption increases with the amount of the palm oil on the blended fuel. It could be explained by the heating values of the fuels. The high heating value and the lower heating value of the commercial diesel are greater than the ones of the palm oil biodiesel blends. Then, it is necessary more biodiesel than diesel to make the same work.

The specific fuel consumption results show that improving the electrical load, the SFC reduces. It is a consequence of the engine efficiency under different conditions.

## 5. ACKNOWLEDGEMENTS

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## 6. REFERENCES

Agarwal, D., Sinhab, S., Agarwal, A.K., 2006, “Experimental investigation of control of NOx emissions in biodiesel-fueled compression ignition engine”, Renewable Energy, Vol. 31, pp. 2356–2369.

Almeida, S.C.A., Belchior, C.R., Pimentel, V.S.B., Nascimento, M.V.G., Vieira, L.S.R., Fleury, G. 2003, “Performance of a diesel generator fuelled with palm oil”, Fuel (Guildford), USA, Vol. 81, pp. 2097-2102.

Basshuysen, R. V., Schaefer, F., 2004, Internal Combustion Engine Handbook, SAE, Warrendale, USA, p.868.

Dutra, L.M., Teixeira, C.V, Colaço, M.J., Alves, L.S.B., Caldeira, A.B., 2009, “Comparative Performance and Emissions of an Engine Operating with Palm Oil and Ethyl Esters and Their Blends with Diesel”, Proceedings of the 20th International Congress of Mechanical Engineering, CD ROM.

Kalam, M.A., Masjuki, H.H., 2002, “Biodiesel from Palm oil - An Analysis of its Properties and Potential”, Biomass and Bioenergy, Vol. 23, pp. 471-479.

Kalam, M.A., Masjuki, H.H., 2008, **“**Testing palm biodiesel and NPAA additives to control NOx and CO while improving efficiency in diesel engines”, Biomass and Bioenergy, Vol. 32, pp. 1116-1122.

Kanok-On, R., Chinda, C., 2004, “Performance of an Engine Using Biodiesel from Refined Palm Oil Stearin and Biodiesel from Crude Coconut Oil”, Proceedings of The Joint International Conference On Sustainable Energy And Environment, Hua Hin, Thailand. p. 30-44.

Rakopoulos, C.D., Antonopoulos, K.A., Rakopoulos, D.C., Hountalas, D.T., Giakoumis, E.G., 2006, “Comparative performance and emissions study of a direct injection Diesel engine using blends of Diesel fuel with vegetable oils or bio-diesels for various origins”, Energy Conversion and Management, Vol. 47, pp. 3272–3287.

Teixeira, C.V., 2010, “Análise de Emissões e Desempenho de Motores Diesel Utilizando Óleo Diesel Comercial, Biodiesel de Palma (B100) e Misturas (Bx)”, M.Sc. dissertation, Instituto Militar de Engenharia, Rio de Janeiro, Brazil.

Wang, Y., Lin, L., Roskilly, A.P., Zeng, S., Huang, J., He, Y., Huang, X., Huang, H., Wei, H., Li, S., Yang, J., 2007, “An analytic study of applying Miller cycle to reduce NOx emission from petrol engine”, Applied Thermal Engineering, Vol. 27, pp. 1779–1789.

## 5. RESPONSIBILITY NOTICE