EXPERIMENTAL ANALYSIS OF CI ENGINE PERFORMANCES AND EMISSIONS OPERATING WITH SYNTHETIC FUEL EXTRACTED FROM INDUSTRIAL OIL

Sofiane MIMOUN[1,2,]*, Mohamed BENCHERIF[1,3], Nasreddine LARBES[1,2], Tewfik LEFTAS[1,2] and Amel KACED[4]

[1] Department of Mechanical Engineering, USTO-MB, PO 1505, El Mnaouer, Oran, Algeria;
[2] LMA Laboratory, USTO-MB University, PO 1505, El Mnaouer, Oran, Algeria;
[3] LTE Laboratory, ENPO-MA University, PO 1523, El Mnaouer, Oran, Algeria;
[4] CRAPC Research Center, Tipaza, PO 384 Bousmail, Algeria;
* Corresponding author: sofiane.mimoun@univ-usto.dz; sofiane.31kristel@gmail.com

This paper deals with an experimental analysis of performance and emissions of a single cylinder, air cooled, direct injection, compression ignition engine using synthetic fuel extracted from Tilia B233 refrigerator lubricating oil and waste cooking oil biodiesel. Biodiesel and synthetic fuel are produced by transesterification process using methanol and potassium hydroxide. Physical properties as well as liquid density, liquid viscosity, total acidity number and flash point are measured. Physical properties and their blends are compared with conventional diesel fuel properties. A first insight to the results indicates that, unlike biodiesel, synthetic fuel which is distinguished by their its low acidity, which enables its storage. In addition, their viscosity is quite high and require the use of synthetic fuel blends with diesel fuel. A careful investigation according to current limitations and standards leads us to a direct engine test with a maximum blending rate of 50%. Thus, blends are achieved by mixing 15%, 30% and 45% of biodiesels with a complementary amount of commercial diesel fuel. The experimental results are obtained on single cylinder diesel engine operating at 1600 rpm for a wide range of loads. Brake specific fuel consumption, specific NOx and CO emissions are compared for each blend with those obtained by conventional diesel fuel.

Key words*: Tilia B233, Biodiesel, Physicochemical properties, Diesel engine, BSFC, NOx, CO.*

1. Introduction

If we refer to diesel engine history, the first compression ignition engine whose cycle was imagined and produced by Rudolf Diesel was powered by fuel extracted from peanut oil. In fact, diesel fuel did not exist at that time and Rudolf Diesel recommended plants providing fuels from for his new thermal engine [1, 2]. Indeed, for several years the use of biodiesels as alternative fuels has increased because the use of such biodiesels called biodiesels does not require modification of the engine or the injection system [3]. In addition, a major advantage lies in the fact that biodiesels are extracted from a set of oils from different sources:

1- Edibles (Soy, Peanuts, Nuts, etc.). This family includes so-called 1st generation biodiesels.

2- Non-edible (Frying, Palm, Eucalyptus, etc.). This family includes so-called 2nd generation biodiesels derived mainly from fast-growing plants. Used oils constitute a significant source for the manufacture of biodiesels. Thus, the recovery of biodiesels from this type of waste is part of their energy recovery and sustainable development while preserving nature. However, the use of biodiesels on thermal engines raises more than one question.

Namely, the acidity, viscosity and density of biodiesels are high compared to conventional fuel oil. In conjunction with this, the use of such biodiesels leads to high levels of NOx in the exhaust released by diesel engines, especially at low and medium loads [4]. Thus, several research paths are opening up on different topics related to biodiesel properties prediction or extraction process optimization and experimental analysis of operating performance on engine [4-6]. Tilia B233 is a dewaxed naphthenic mineral oil for refrigerating compressors.

The present paper is formed by two parts. The first part presents transesterification process details as well as physical and chemical characterization of biodiesel and synthetic fuel emanating from respectively waste cooking oil and Tilia B233 industrial oil. It consists furthermore on the thermal evolution of biodiesel and synthetic fuel liquid densities and viscosities. In addition, the total acidity number and flash point are measured as well. The chemical composition of the biodiesel is provided by the mean of gaseous chromatography coupled to mass spectroscopy. Synthetic fuel properties are compared to those of the biodiesel and the diesel fuel ones. Thus, according to current limitations and standards, different analysis deriving from the present work leads to a better clarity in terms of blending limitations and storage capabilities of both biodiesel and synthetic fuel.

In the second part, we present the experimental results that were obtained on a diesel engine test bench operating with biodiesel and synthetic fuel blends. According to the results obtained in the first part, blending limits are to be set under 50%. Moreover, we compare specific carbon monoxides and nitrous oxides besides brake fuel consumption obtained when the engine operates with biodiesel, synthetic fuel and conventional diesel fuel.

2. Extraction process

A multitude of transesterification experiments aiming to produce synthetic fuel from different oils is presented in Fig. 1. According the regular experimental plan, and as indicated in the specialized literature in order to have a high yield of transesterification the catalyst used is potassium hydroxide and the alcohol is methanol [7, 8]. Transesterification goes through the following steps:

1. Reactive masses and volume measurement. Fig. (1.a).
2. Dissolution of the catalyst in methanol. Fig. (1.b).
3. Oil preheating at 65 °C. Fig. (1.c).
4. Stirring the emulsion at 55 °C to 65 °C. Fig. (1.c).
5. Separation after 24 hours. Fig. (1.d).
6. Washing with water heated to 40 °C. Fig. (1.e).
7. Drying of biodiesel after 24 hours at 100 °C. Fig. (1.f).

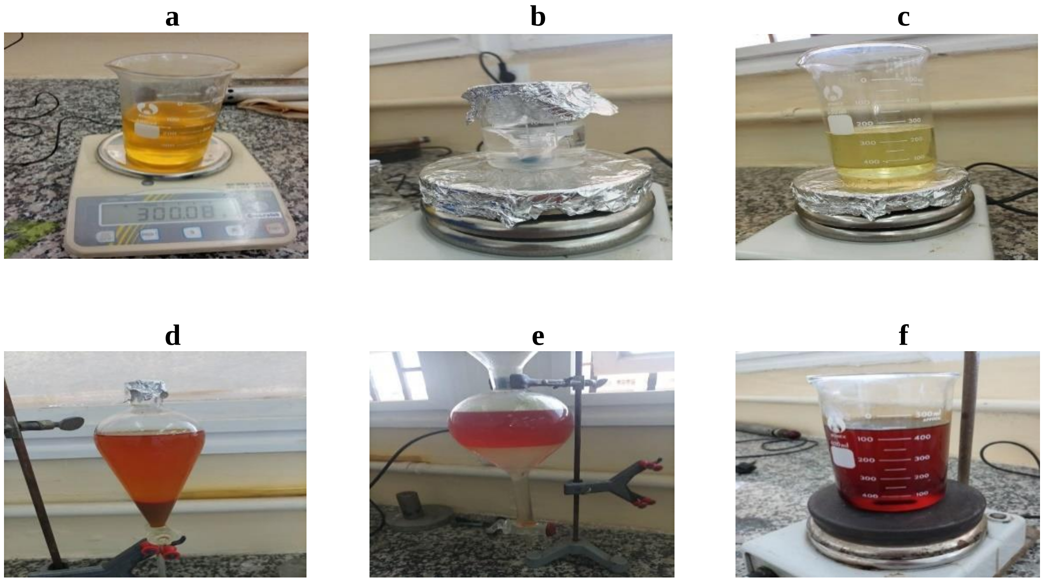


Figure 1. Transesterification steps.

3. Chemical and physical properties measurement

Biodiesel quality can be influenced by several factors that may be reflected in its chemical and physical properties [7-9]. Some physical and chemical specifications of the three industrial oils are shown in the Tab. 1. Tilia B233 Industrial crude oils used in the present study have low acidity number.

Table 1. Tilia B233 oil properties.

Property Specification	ASTM Test Methods	Tilia B233 Oil
Density @ 15 °C (kg/m^3)	D1298	898
Viscosity @ 40°C (mm²/s)	D445	32
Pour point (°C)	D97	-33
Total acidity number (mg KOH/g)	D664	< 0.05
Flash point (°C)	D92	154
Flocculation point (°C)	-	-60
Cooper corrosion 3h @ 100°C	D160	1
Water content (PPM)	D1533	< 30

To be commercialized, biodiesel has to comply to quality specifications established by institutions like the European Committee of Standardization (ISO) [10] and the American Energies Society for Testing and Materials (ASTM) [11] reported in Tab. 2 and Tab. 3. These regulations, which are dynamic and must be periodically reviewed, describe the quality requirements and the test methods employed [9].

Table 2. EN 14214 biodiesel specifications [9-11, 13].

Property Specification	EN 14214 Limit	Test Methods
Density @ 15 °C (kg/m^3)	860–900	EN ISO 3675/12185
Viscosity @ 40°C (mm²/s)	3.5–5.0	EN ISO 3104
Cetane number	Min. 51.0	EN ISO 5165

Acid value (mg KOH/g)	Max. 0.50	EN 14104
Flash point (°C)	Min. 101	D93
Sulfur (mg/kg)	Max. 10.0	EN ISO 20846/20884
Sulfated ash (% (m/m))	Max. 0.02	EN ISO 3987
Phosphorus content (mg/kg)	Max. 4.0	EN 14107/16294

Table 3. ASTM D6751 biodiesel Specifications [9, 11-13].

Property Specification	ASTM D6751 Limit	Test Methods
Density @ 15 °C (kg/m^3)	880	D1298
Viscosity @ 40°C (mm^2/s)	1.9–6.0	D445
Cetane number	Min. 47	D613
Acid value (mg KOH/g)	Max. 0.50	D664
Flash point (°C)	Min. 130	D93
Sulfur (mg/kg)	S15 Max. 15/ S500 Max. 500	D5453
Sulfated ash (% (m/m))	Max. 0.02	D874
Phosphorus content (mg/kg)	Max. 10	D4951

Fig. 2 illustrates the transesterification reaction efficiencies related to each type of fuel. Biodiesel transesterification process is more efficient compared to synthetic fuel one. Acceptable values are observed since the value obtained for Tilia B233 is over 70%.

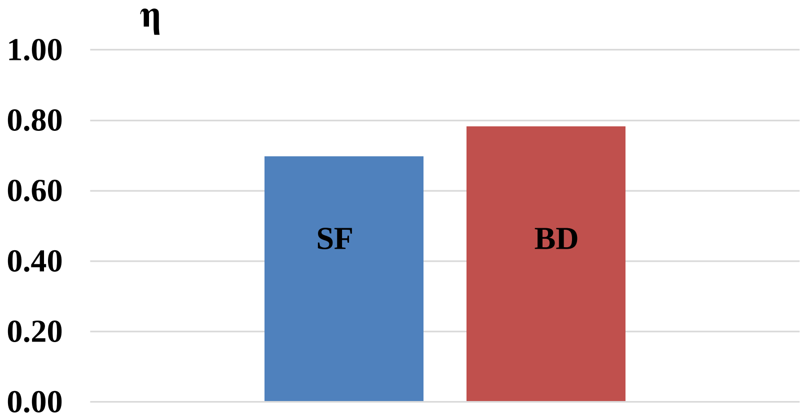


Figure 2. Transesterification reaction efficiencies comparison.

3.1 Physical properties

Now that biodiesel and synthetic fuel have been properly extracted by transesterification, starting the engine test campaign requires that main physical and chemical properties and thermal behavior have to be well known. In fact, such measurements can lead to a better understanding of an eventual blending ratios limitations. Complementary measurements of physical properties were carried out, such as liquid density, kinematic and dynamic viscosities of biodiesel and synthetic fuel oil, as well as their mixtures.

3.1.1 Liquid density measurement

Biodiesel and synthetic fuel liquid densities as well as their blends has been measured by Anton Paar DMA 35 densimeter shown in Fig. 3. With a measuring range from 0 to 3 g/cm3 and an accuracy of 0.001 g/cm3 at 0.2 °C. Resolution of density and temperature is on the order of 0.0001 g/cm3 and 0.1 °C respectively. Temperature of the sample varied from 0 to 100°C.

Figure 3. Anton Paar DMA 35 Densimeter, LTE laboratory/ENPO-MA.

Density variation versus temperature related to the biodiesel extracted from used cooking oil and its blends are illustrated in Fig. 4 and compared to commercial diesel fuel density evolution.

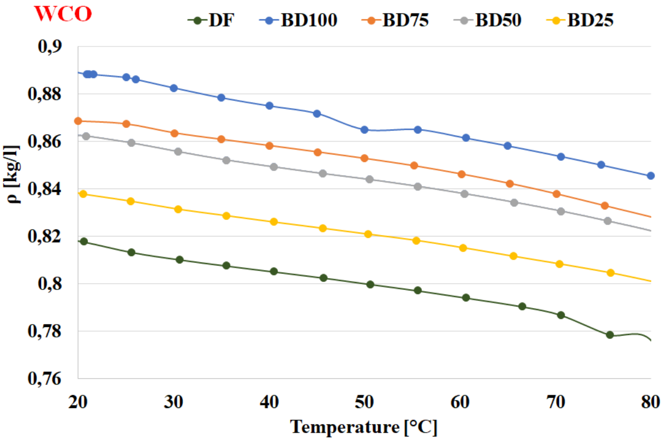


Figure 4. Measured densities of waste cooking oil and its blends versus temperature

Fig. 5 illustrates the liquid density evolution according to temperature growth related to the synthetic fuels extracted respectively from Tilia B233 oil and its blends compared to commercial diesel fuel density thermal evolution.

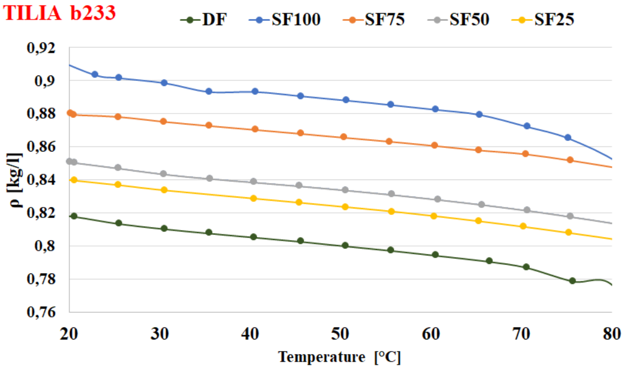


Figure 5. Measured densities of synthetic fuel and its blends versus temperature.

3.1.2 Liquid viscosity measurement

The thermal liquid viscosities of the biodiesel and synthetic fuel have been measured by Anton Paar RheolabQC Rheometer shown in Fig. 6.

Figure 6. Anton Paar RheolabQC Viscosimeter, LTE laboratory/ENPO-MA.

Liquid dynamic viscosities variation according to temperature variation related to commercial diesel fuel and waste cooking oil biodiesel can be shown in Fig. 7.

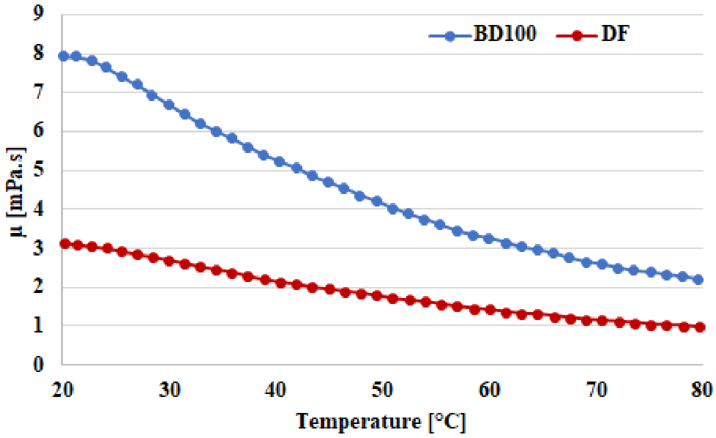


Figure 7. Measured dynamic viscosities of diesel fuel and biodiesel versus temperature.

Liquid dynamic viscosities variation according to temperature variation related to the synthetic fuel extracted from Tilia B233 oil is illustrated in Fig. 8. The kinematic viscosity of the biodiesel and synthetic fuel as well as their blends have been measured by RA1Z/SONATRACH laboratory Bain Marie Viscosimeter shown in Fig. 9.

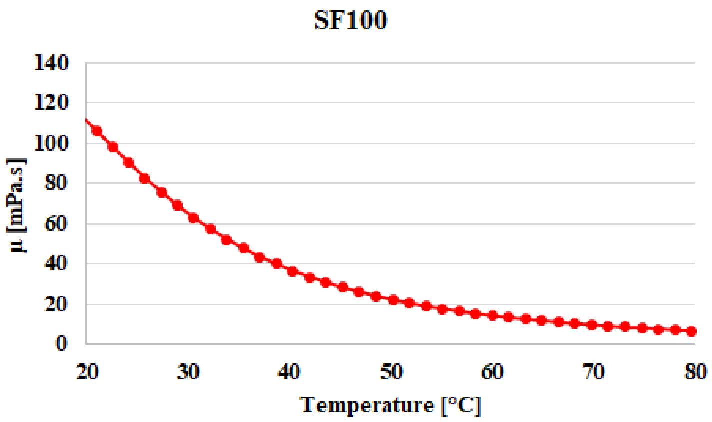


Figure 8. Measured dynamic viscosity of synthetic fuel versus temperature.

Figure 9. RA1Z/SONATRACH laboratory Bain Marie Viscosimeter.

Figs. 10 and 11 show the liquid kinematic viscosities at 40 °C variation versus blending ratio for respectively biodiesel and synthetic fuel. Commercial standard limitation is represented by a horizontal line. It can be shown that standard limitation level for viscosity of 6 mm²/s can be reached for synthetic fuel at blending ratio of 65%. Consequently, a set of three blending ratios have been chosen for both biodiesel and synthetic fuel. Explicitly, 15%, 30% and 45% blending ratios are to be explored on experimental diesel engine test bench.

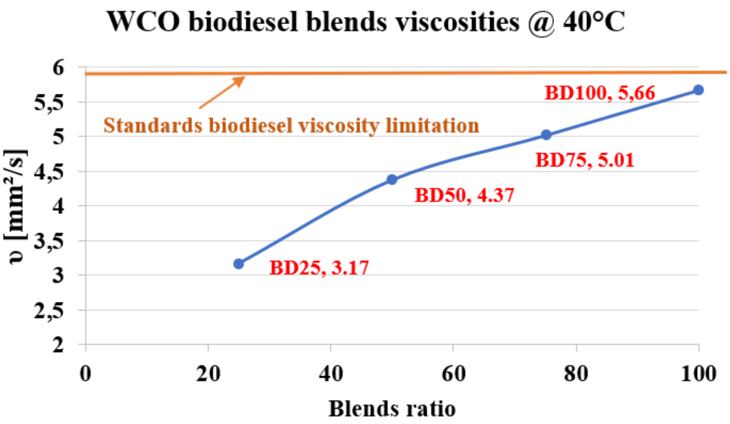


Figure 10. Kinematic viscosity of biodiesel blends @ 40 °C.

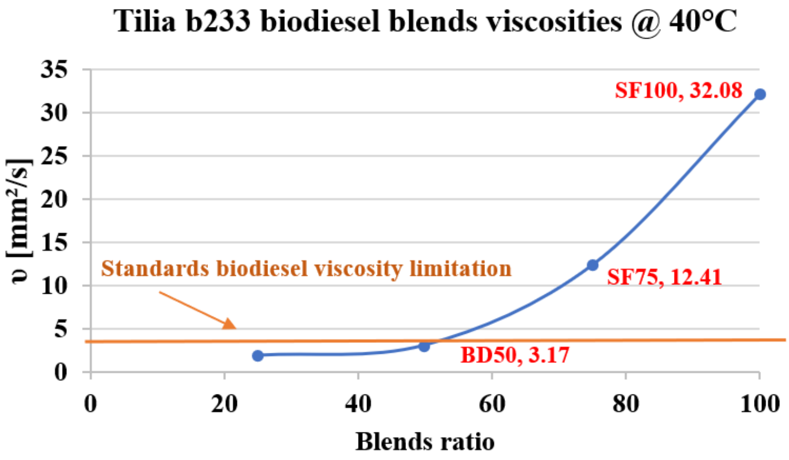


Figure 11. Kinematic viscosity of synthetic fuel blends @ 40 °C.

3.2 Chemical properties

In order to thoroughly analyze the synthetic fuel properties a set of complementary chemical properties measurements have been done.

3.2.1 Flash Point

Measured flash point related to biodiesel and synthetic fuel and their blends are regrouped in Fig. 12. It can be easily shown that all values related to both neat biodiesel BD100 and synthetic fuel SF100 are above the minimum value indicated by ISO and ASTM standard limitations which is represented by horizontal red line for ISO standard and dashed red line for ASTM standard.

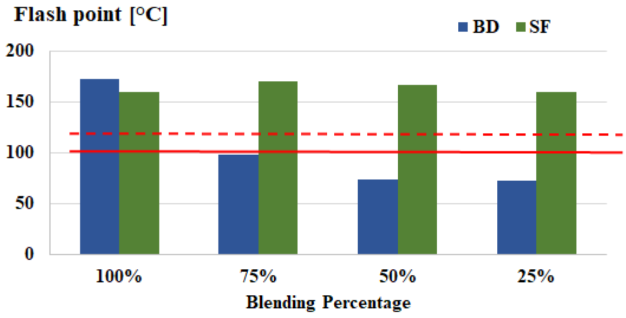


Figure 12. Measured flash point related to biodiesel and synthetic fuel and their blends.

3.2.2 Total Acidity Number

It must be noted that total acidity number have been measured twice for waste cooking oil biodiesel as well as synthetic fuel. Measurement interval for the same samples is about six months. Measured total acidity number related to biodiesel and synthetic fuel are regrouped in Tab. 4. Taking into account standards and limitations (less than 0.5 mg KOH/g), it can be concluded that for used domestic oil, biodiesel, although its low viscosity, cannot be stored beyond 6 months, in contrast biodiesel must be consumed instantly because of its acidity (over than 0.5 mg KOH/g). Inversely and despite of that, synthetic fuel cannot be used without blending with commercial diesel fuel. It offers the capability of being stored after their production for periods exceeding six months.

Table 4. Total acidity number measurements

Property	Total Acidity Number 1	Total Acidity Number 2
SF100	0.04	0.22
BD100	0.16	0.58

3.2.3. Gaseous chromatography-Mass Spectroscopy

A Hewlett Packard Agilent 6890 plus Gaseous Chromatograph associated with a Hewlett Packard Agilent 5973 mass Spectrometer were used to define chemical species components. The experimental setup can be shown in Fig. 13. Samples were prepared by injecting into the upper phase a mixture composed of 1g of the substances.

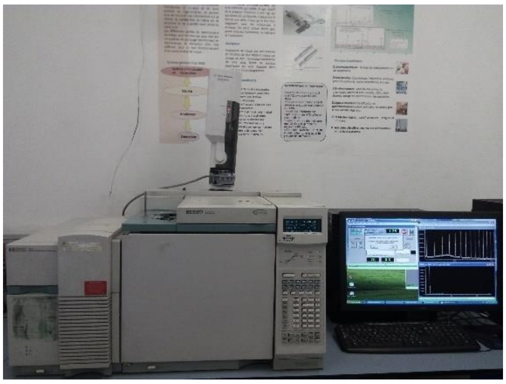


Figure 13. HP GCMS device, CRAPC/ Tipaza.

The sample volume of 01 µl is injected at 280 °C in a Column type HP-5MS with the dimensions: length 30 m, internal diameter 0.25 mm and film thickness 0.25 µm. Stationary phase parameters were: 5% Phenyl 95% dimethylpolysiloxane. The oven temperature is set at 42 °C for 5 min and rises 10 °C/min up to 300 °C. Then an isothermal interval of 20 min is observed. The analysis time is fixed at 50.8 min. Carrier gas chromatograph is pure helium 6.0 with a flow rate of 02 ml/min. For mass detector solvent delay is set to 3.5 min, the interface temperature is 270 °C, the mass analyzer type is a Quadripoles and the source temperature is set to 230 °C. Spectrums resulting from the Chromatography characterization of biodiesel is shown in Fig. 14.

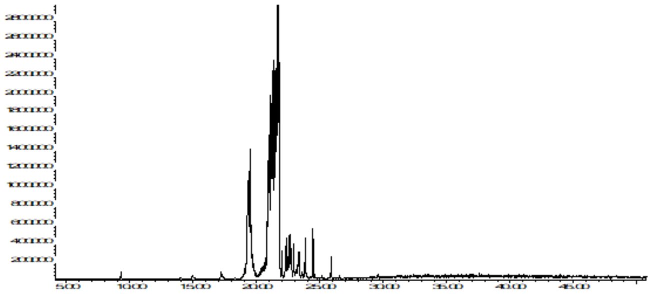


Figure 14. Waste cooking oil biodiesel GC-MS spectrum.

The chemical composition of the analyzed substance and their fraction can be obtained using the GCMS. Fatty acids methyl esters found in the biodiesel are shown in Tab. 5. The protocol used for mineral oils was unfortunately inadequate to found synthetic fuel composition.

Table 5. Biodiesel composition.

Name	*Formula*	*ICAS*
Octanoic acid, methyl ester	$C_9H_{18}O_2$	000111-11-5
Nonanoic acid, methyl ester	$C_{10}H_{20}O_2$	001731-84-6
Tetradecanoic acid, methyl ester	$C_{15}H_{30}O_2$	000124-10-7
Pentadecanoic acid, methyl ester	$C_{16}H_{32}O_2$	007132-64-1

4. Engine test bench

A single cylinder air cooled Kipor 178FWX diesel engine with output power of 4.5 kW at 3600 rpm is used to carry out engine tests. The basic data of this engine are given in Tab. 6. The experimental setup of the engine bench with the test engine, the dynamometer and the exhaust gases analyzer, the measurement chain, the sensors and regulator are shown in Fig. 15.

Table 6. Engine Specifications.

Designation	Value
Model	Kipor 178FWX
Type	1 cylinder, 4-stroke, air-cooled, direct injection
Bore	78 mm
Stroke	62 mm
Compression ratio	20 : 1
Volumetric capacity	296 cm^3
Power output	4.5 kW at 3600 rpm
Fuel temperature	40 °C
Fuel injection timing	18° BTDC

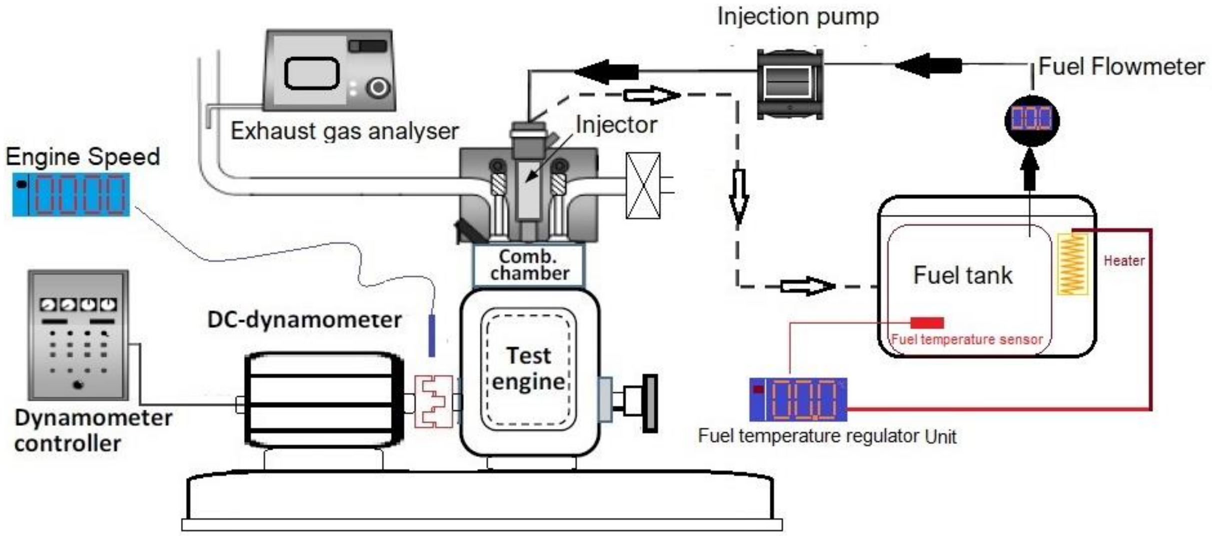


Figure 15. Experimental setup.

5. Results and discussion

In this study, a set of measurements on the engine test bench have been done. In order to get a better understanding of the engine performances and emissions the results obtained by biodiesel and synthetic fuel blends are to be compared with those obtained by diesel fuel oil. The experimental results are obtained when diesel engine is operating at 1600 rpm from engine braking to full load. A particular focus has been done with CO and NOx concentrations emitted by the engine as well as its brake specific fuel consumption when the engine operates with biodiesel and synthetic fuel 15%, 30% and 45% blends referenced as BD15, BD30 and BD45 for the biodiesel and SF15, SF30 and SF45 for the synthetic fuel. Figs. 16a, 17a and 18a show normalized carbon monoxide emissions variation versus brake mean effective pressure for both biodiesel and synthetic fuel blends at 1600 rpm. Normalized carbon monoxide emissions are calculated as indicated by the following equation:

$$Normalized\ [CO]_i = \frac{[CO]_i - [CO]_{DF}}{[CO]_{DF}} \qquad (1)$$

with I = BD or SF blend.

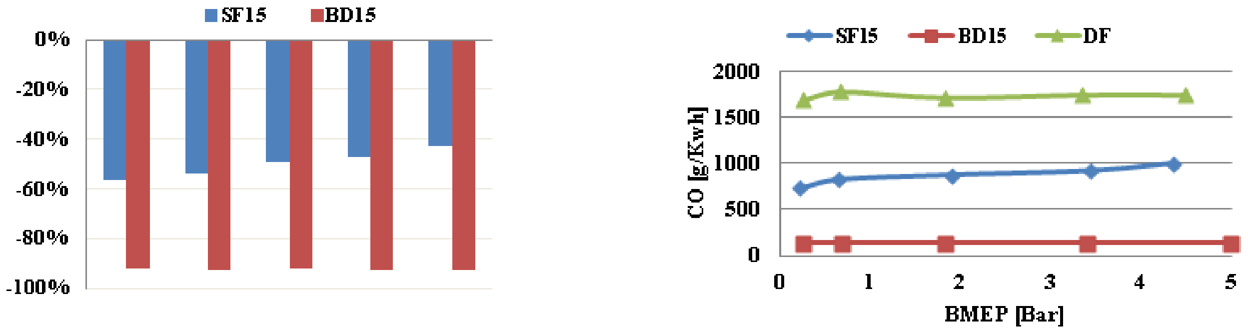
Figs. 16b, 17b and 18b show specific carbon monoxide emissions variation versus brake mean effective pressure for both biodiesel, synthetic fuel blends and diesel fuel at 1600 rpm. It can be clearly shown that for higher blending ratios, lower carbon monoxide is emitted when the engine operates with synthetic fuel oil. At 15% blending ratio lower carbon monoxide is emitted when biodiesel is used. Figs. 19a, 20a and 21a show normalized nitrous oxide emissions variation versus brake mean effective pressure for both biodiesel and synthetic fuel blends at 1600 rpm. Normalized nitrous oxide emissions are calculated as indicated in the following equation:

$$Normalized\ [NOx]_i = \frac{[NOx]_i - [NOx]_{DF}}{[NOx]_{DF}} \qquad (2)$$

with i=BD or SF blend.

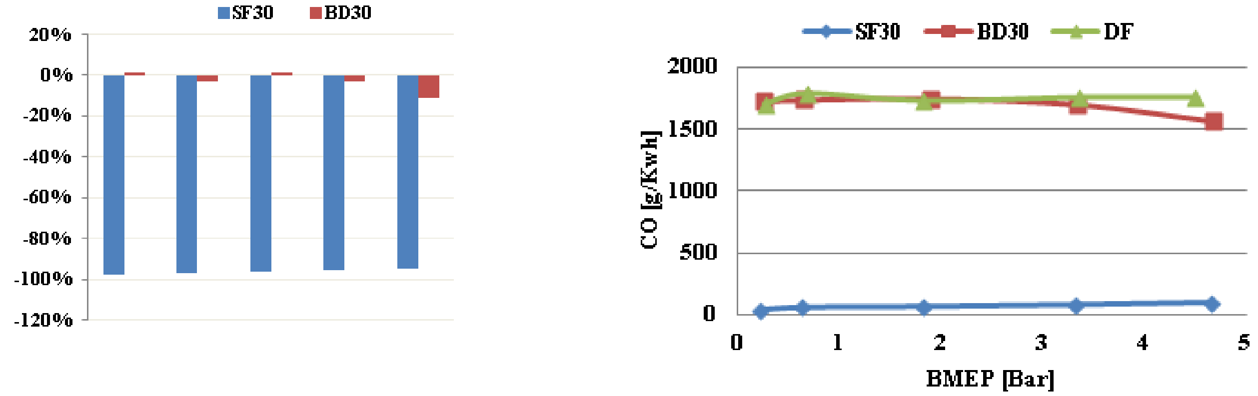
All figures with normalized CO and NOx emissions have been obtained for engine load increasing form IDLE to full load and reported in the figures from left to right.

Figs. 19b, 20b and 21b show specific nitrous oxide emissions variation versus brake mean effective pressure for both biodiesel, synthetic fuel blends and diesel fuel at 1600 rpm. It can be shown that for higher blending ratios, lower nitrous oxide emissions are to be observed when the engine operates with synthetic fuel oil. Whatever is the blending ration lower nitrous oxide is emitted when biodiesel is used. Fig. 22, shows brake specific fuel consumption variation versus brake mean effective pressure for both biodiesel, synthetic fuel blends and diesel fuel at 1600 rpm. It can be shown that for over all cases, BSFC are similar at lower at middle and full engine loads. BSFC are excessive at low engine load and the engine seems to consumes more when fed with both biodiesel and synthetic fuel oil.



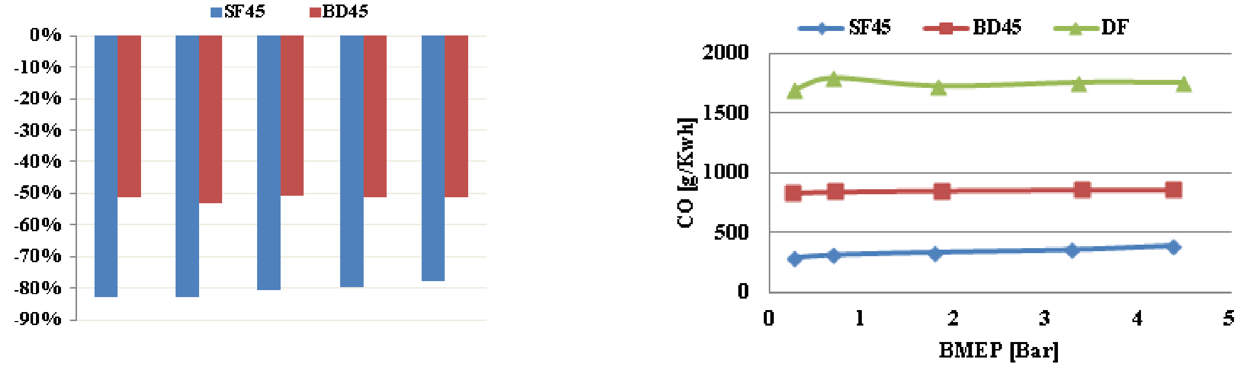
a b

Figure 16. Measured normalized and Specific CO emissions for BD15 and SF15 at 1600 rpm.



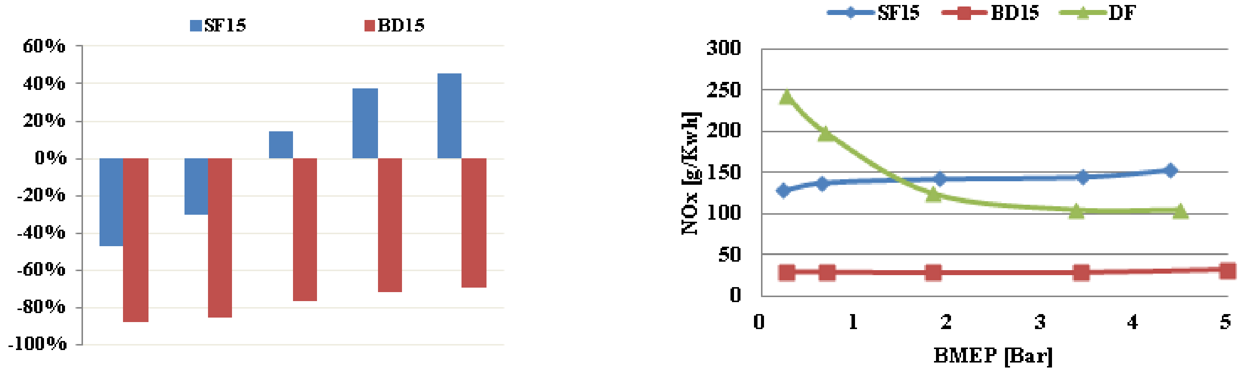
a b

Figure 17. Measured normalized and Specific CO emissions for BD30 and SF30 at 1600 rpm.



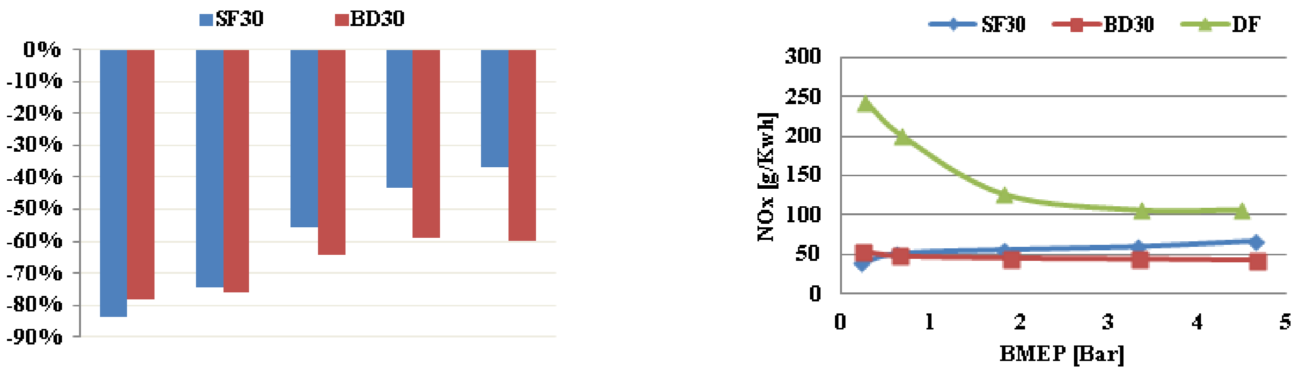
a b

Figure 18. Measured normalized and Specific CO emissions for BD45 and SF45 at 1600 rpm.



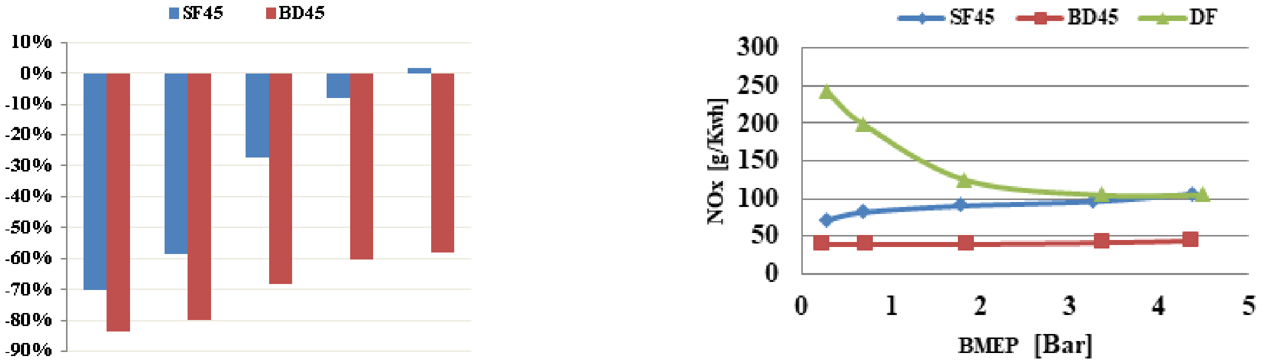
a b

Figure 19. Measured normalized and Specific NOx emissions for BD15 and SF15 at 1600 rpm.



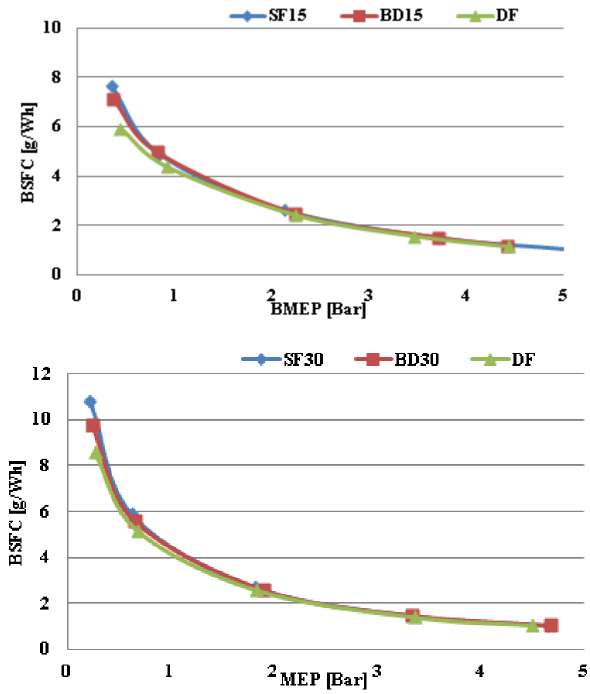
a b

Figure 20. Measured normalized and Specific NOx emissions for BD30 and SF30 at 1600 rpm.



a b

Figure 21. Measured normalized and Specific NOx emissions for BD45 and SF45 at 1600 rpm.



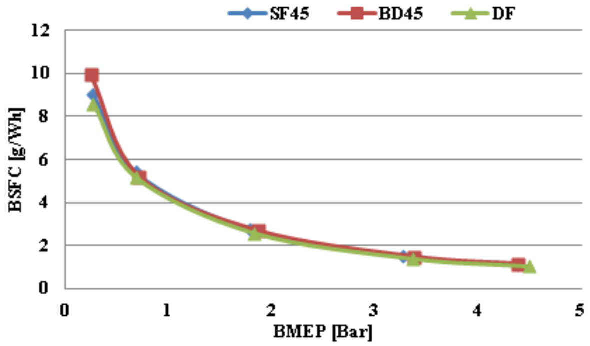


Figure 22. Measured brake specific fuel consumption at 1600 rpm.

7. Conclusion

The present paper reveals the complete procedure required for the extraction of biodiesel from waste cooking oil and a synthetic fuel from Tilia B233 industrial oil. The paper focuses firstly on the main physicochemical properties of each fuel. Indeed, liquid densities and liquid kinematic viscosities thermal evolutions, total acidity number, flash point of both fuels have been measured. It can be concluded that industrial and domestic oils transesterification lead to substances with physical properties matching perfectly with ASTM D6751 and EN 14214 standards and limitations for commercial biodiesel. According to measured acidity numbers, the synthetic fuel extracted from Tilia B233 offers the advantage of long-term storage capacity which can exceed 6 months after its production. In contrast, biodiesel extracted from domestic waste oils cannot be stored but offers a low acidity number and can consequently be used directly after its production in diesel engines with or without blending. Because of its high viscosity, synthetic fuel extracted from Tilia B233 cannot be used directly on diesel without blending with commercial diesel fuel. As mentioned previously, 15%, 30% and 45% blending ratios have been explored on experimental diesel engine test bench with both biodiesel and synthetic fuel extracted from Tilia B233 oil. Three blends are realized by mixing 15%, 30% and 45% of biodiesels with respectively 85%, 70% and 55% of commercial diesel fuel. The experimental results are obtained on an engine test benchmark on single cylinder diesel engine coupled with DC dynamometer operating at 1600 rpm for a range of loads from engine braking to full load. Brake specific fuel consumption, specific NOx and CO emissions for all blends of biodiesel and synthetic fuel have been compared with those obtained by conventional diesel fuel. According to normalized carbon monoxide and nitric oxides graphs, it can be noted the following remarks:

1- For all studied cases higher CO emissions are obtained when the engine operates with conventional diesel fuel.

2- Increasing blending ratio for synthetic fuel extracted from the Tilia B233 leads to lower CO emission levels.

3- Increasing blending ratio for biodiesel extracted from the WCO leads to higher CO emission levels.

4- For all studied cases higher NOx emissions are obtained when the engine operates with conventional diesel fuel.

5- Increasing blending ratio for synthetic fuel extracted from the Tilia B233 leads to lower NOx emission levels.

6- Increasing blending ratio for biodiesel extracted from the WCO leads to lower NOx emission levels.

7- Increasing engine load leads to increasing NOx levels at the exhaust gases for both synthetic fuels.

In addition, it was shown that for all studied cases BSFC has the same tendency. According to specialized literature and due to the engine type and the dynamometer limitations BSFC do not exceed the acceptable value of 200 g/kWh for medium and high loads.

The present work can be improved along the following lines:

1- Start an experimental campaign on an engine test bench recording high and low frequency quantities.
2- Investigating deeply unburned hydrocarbons and NOx emissions at nominal and critical engine speeds.
3- Investigating fuel temperature effect on the engine performances and emissions.

Nomenclature

CI – Compression Ignition

ABDC – After Bottom Dead Center, [CAD]

ASTM – American Society for Testing and Materials

ATDC – After Top Dead Center, [CAD]

BBDC – Before Bottom Dead Center, [CAD]

BD – Biodiesel

BSFC – Brake Specific Fuel Consumption, [g/Wh]

BTDC – Before Top Dead Center, [CAD]

CAD – Crank Angle Degree

CO – Carbon monoxide

DF – Diesel Fuel

EN – European Norms

EVC – Exhaust Valve Closure, [CAD]

EVO – Exhaust Valve Opening, [CAD]

ISO – European Committee of Standardization

IVC – Intake Valve Closure, [CAD]

IVO – Intake Valve Opening, [CAD]

NOx – Nitrous oxide

RPM – Revolution per Minute

SF – Synthetic fuel

WCO – Waste Cooking Oil

Greek letters

η – Transesterification reaction efficiency

μ – Liquid dynamic viscosity, [mPa.s]

υ – Liquid kinematic viscosity, [mm^2/s]

ρ – Liquid density, [kg/l]

Acknowledgments

This paper is the result of a scientific cooperation between LCGE/USTO-MB laboratory, LTE/ENPO-MA laboratory and RA1Z/SONATRACH (Oran, Algeria) supervised by Development department of SOMIZ-SPA/SONATRACH (Oran, Algeria).

References

[1] Lienhard, J.H., *The Engines of Our Ingenuity*, An Engineer Looks at Technology and Culture", Oxford University Press, Oxford, UK , 2000

[2] Mollenhauer, K., H. Tschöke, *Handbook of Diesel Engines,* Springer Verag, Berlin, 2010.

[3] Van Gerpen, J. et al, *Biodiesel Production Technology,* Subcontractor Report NREL/SR-510-36244, Subcontract No. ACO-2-35016-01, 2004.

[4] Brakora, J., L., RA, Youngchul, Reitz, R., D., et al. Development and validation of a reduced reaction mechanism for biodiesel-fueled engine simulations. *SAE International Journal of Fuels and Lubricants,* 2009, vol. 1, no 1, p. 675-702.

[5] Brakora, J., L., Reitz R., D., Investigation of NOx Predictions from Biodiesel-fueled HCCI Engine Simulations Using a Reduced Kinetic Mechanism, April 2010, *SAE Technical Papers, Conference,* SAE 2010 World Congress & Exhibition.

[6] Brakora, J., L., Reitz R., D., A Comprehensive Combustion Model for Biodiesel-Fueled Engine Simulations, SAE International, Conference Proceedings, 2013-01-1099, SN 0148-7191.

[7] Leftas T., Bencherif A, Larbes N., Benzerdjeb A., Valorisation énergétique par extraction d'huiles usagées industrielles et domestiques. Partie I : extraction et caractérisation de biodiesels', 1st National Day on Renewable Energy in Mechanics, JNERM 2022, Oran, Algeria.

[8] Leftas T., Bencherif A, Kaced A., Larbes N., Benzerdjeb A., Abed B., 'Chemical & Physical Characterization And Selection Criteria Of Oxygented Fuels Extracted From Lubricating Torba Oil.' International Conference on Renewable Energies and Power Systems, ICREPS2024, May 13-14 2024, Salhi Ahmed University center of Naama, Algeria.

[9] Ramos, M., dias, A., P. S., puna, J., F., et al., Biodiesel production processes and sustainable raw materials. *Energies,* 2019, vol. 12, no 23, p. 4408.

[10] European Committee for Standardization. European Standard EN 14214: 2012+A1; European Committee for Standardization: Brussels, Belgium, 2014; pp. 1–21.

[11] Nikolić, B., D., kegl, B., milanović, S. M., *et al.* Effect of biodiesel on diesel engine emissions. *Thermal Science,* 2018, vol. 22, no Suppl. 5, p. 1483-1498.

[12] U.S. Department of Energy. ASTM Biodiesel Specifications. Available online: https://afdc.eenergy.gov/fuels/ biodiesel_specifications.html (accessed on 5 November 2018).

[13] Yasar, F., et Altun, Sehmus., The effect of microalgae biodiesel on combustion, performance and emission characteristics of a diesel power generator. *Thermal Science*, 2018, vol. 22, no 3, p. 1481-1492.

Submitted: 07.09.2024
Revised: 06.11.2024
Accepted: 11.11.2024