An Experimental Study of Optimization of Biodiesel Synthesis from Waste Cooking Oil and Effect of the Combustion Duration on Engine Performance

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Abstract- The use of waste cooking oil (WCO) as a reagent for biodiesel synthesis ensures their transformation from harmful products into beneficial ones. The possibility of safe use as pure fuels or mixtures with diesel is a promoting and an environmental friendly alternative. This strategy is very encouraging especially for countries which have not enough space to produce vegetable oils. However, the researches in this field (WCO biodiesels) are still rare.

In this work, we have synthesized biodiesel from WCO using the transesterification technique, then experimental investigations have been carried out on a four cylinder-direct injection diesel, engine equipped with a turbocharger on a test bench, according to the International norm ISO 27.020. In a first time, effects of different blends of methyl-ester/diesel in different proportions (B00, B10, B20 and B30) on engine behavior were studied and compared with petroleum diesel. In a second time, B20 blend was investigated but with variation of injection timing compared to original settings (as set by the engine manufacturer), on the same engine and following the same testing procedure.

Experimental results showed that engine performances decreased with increasing amount of methyl ester in the fuel mixture. Moreover, it is found that advanced injecting B20 fuel by 2 crank angle degrees compared to that of the original injection timing, gives better performance without penalty on pollutant emissions (smoke opacity). The use of B20 accompanied with the advanced injection timing lead to a significant power increase (up to 4%) as well as an increase in torque (up to 2.8%) on conventional diesel engines compared to diesel. Emissions such as Smoke opacity remained close to the original values (without variation of injection timing).

Keywords Waste cooking oil, transesterification, Biodiesel, engine performances, advanced injection timing.

1. Introduction

Nowadays, the progressive depletion in petroleum resources in combination with environmental problems associated with the use of fossil fuels, in addition to stringent exhaust regulations, have prompted the development of new ecologically clean energy sources, at lower costs to meet the world's energy needs while preserving the environment [1, 2, 3]. In this regard, the use of biodiesel has emerged as the most feasible solution to accomplish this challenge [4, 5].

Such an alternative, which is cleaner than oil and is produced from biomass, ensures the reduction of oil consumption as well as greenhouse emissions [6, 7]. It can be used as alone or as mixed with fossil diesel fuel [8]. The most dominant feedstocks are soybean oil in the United States, rapeseed and sunflower oil in Europe in addition to algae and palm oil in South-east Asia [8, 9, 10]. Many countries, especially in North-Africa, Golf and Japan, have not enough spaces to produce vegetable oils like Colza and palm. Therefore, exploitation of frying oil has been proposed as an environmental friendly alternative to transform them from harmful materials to suitable ones.

Biodiesel, in particular methyl-ester, has several advantages especially its higher viscosity which is between 7 and 11 times lower than that of the original oil [5]. That had triggered many trends to improve the physico-chemical properties of methyl-ester especially viscosity and water content. Production of methyl-ester as fuel from frying oils signifies the transformation of a pollutant product into a beneficial one. Besides, that helps to ensure noticeable reduction in pollutant emissions: NOx, sulphur and carbon mono-oxide [11]. As an example, in Europe, biofules has been commercialized from the 90's, as part of a plan which has been focused on the improvement of physico-chemical characteristics of methyl-ester in order to reach better energy balances and reduce emissions (combustion studies). In addition to that, a main goal of this plan is to increase agricultural production of methyl-ester. For that, it started with an initial aim to replace 2% of the European Union (EU) diesel with biodiesel by the end of 2005. Then, that has been gradually increased to 5.75% by 2010 and is expected to increase to 10% by 2020 [12]. In parallel with the EU plan, several studies have been conducted to assist popularization of waste edible oil (WEO) like waste cooking oil (WCO) and frying oil, by improving their combustion characteristics.

Shahabuddin et al. [13] presented an exhaustive literature review about studies focusing on ignition delay (ID), emission characteristic and combustion of biodiesel-fuelled diesel engines. They reported a slight difference in combustion characteristics between bio-fuelled engine and petroleum diesel one. Compared to diesel, it has been reported that biodiesel has a shorter ID (0.25 to 1°) and an early start of combustion (SOC) which is between 1 and 5°. Moreover, they reported a lower compressibility, a higher cetane number and a fatty acid composition of biodiesel. In addition to that, biodiesels have a slightly lower heat release rate (HRR) than diesel. That could be explained by the lower volatility of biodiesel, higher viscosity, shorter ID and lower calorific value.

Can et al. [14] have conducted combustions studies, exhaust emission as well as performances of a diesel engine fuelled with WCO/Diesel blend. For that, they used 5% and 10% biodisel blends (B5 and B10 respectively). Here, Bxx is a blend diesel/biodisel where xx is the %vol of biodiesel. They found a slight increase (up to 4%) in break specific fuel consumption. Moreover, a reduction (up to 2.8%) in break thermal efficiency was revealed. The biodiesel additions also increased NOx emissions up to 8.7%. Smoke and total hydrocarbon emissions decreased for the all engine loads. Although there were no significant changes on CO emissions at the low and medium engine loads, some reductions were observed at full engine load. Also, CO2 emissions were found slightly increased, for the all engine loads.

Boubahri et al. [15] studied combustion, performance and exhaust emissions of different WCO blends comparatively to diesel fuel, at full load for various speed conditions, in a gas-oil engine. Biodiesel blends were varied from 15% to 40% (B15 to B40) by a step of 5%. Engine experiment results revealed a decrease in power and torque by 5%, for each addition of 10 % in biodiesel to the blend. In addition to that, fuel consumption was slightly increased (up to 6% for each 10% of biodiesel blend added) compared to pure diesel fuel. With regards to engine emissions (HC, CO and smoke), they were found relatively lower than that of a diesel-fuelled engine. That was due to the higher oxygen content of biodiesel.

As continuation to these previous work, in particular that of Boubahri et al. [15], we have first investigated the possibility of optimizing the properties of methyl-ester obtained from transesterification of waste cooking oils. Besides, we have focused on the effect of various blends of methyl-ester/diesel on the behavior and performances of a four cylinder-direct injection diesel engine equipped with a turbocharger. The impact of the variation of the ID, as an alternative to increase combustion duration, on the engine performances were then carefully investigated.

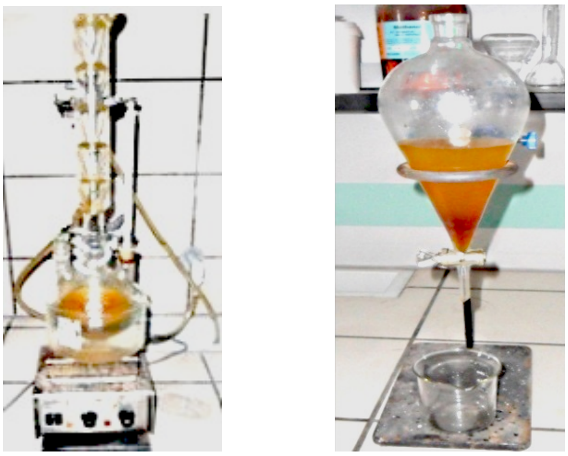
2. Experimental Setup and Procedure

2.1 Optimization of the physico-chemical properties of methyl ester

WCO are obtained from restaurants. They were collected from various sources then mixed. First, a gas chromatography analysis was performed in order to establish fatty acid composition. Results are then shown in Table 1.

Table 1. Fatty acid composition of Waste Cooking Oil used in this research

Fatty acid	Palmitic C16 :0	Stéaric C18 :0	Oléic C18 :1	Linoléic C18 :2	Linolénic C18 :3
Content (wt.%)	11.19	4.48	37.13	46.59	0



(a) (b)

Figure 1. The experimental setup for the biodiesel production (a) and the technique of separation between the biodiesel and the glycerol (b)

After being collected, used oils were first washed using hot distilled water in order to remove salt and other soluble materials. Then, they were decanted and filtered using a fine filter paper to eliminate all insoluble impurities. A solution was prepared by mixing methanol and sodium hydroxide, which were place on a hot plate and then had been stirred using a magnetic stirrer (Fig.1a), until the catalyst was totally dissolved. After 5 minutes in an Erlenmeyer glass, WCO was added to the solution.

Then, the reaction mixture was vigorously stirred and heated (using a hot plate) under a temperature ranging from 45 up to 60°C. The reaction mixture was stirred for 2 h to remove water used during washing. It was initially marked by a rapid change in color to become clearer after 5 minutes, then was continuing all along the stirring duration. At the end of reaction (about 120 minutes), the product was put in a separator funnel (Fig.1b) [16].

The reaction produced two distinct liquid phases: methyl-ester in the upper part and glycerol below [16].

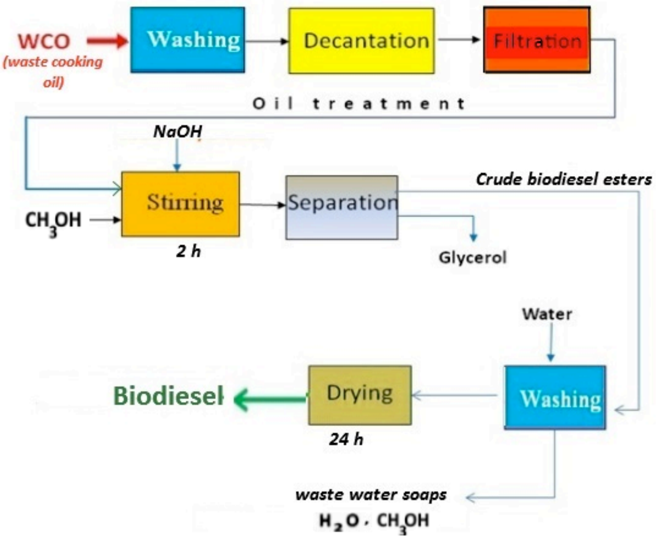


Figure 2. A schematic illustration of the procedure of production of biodiesel used in this research

Methyl-ester was collected carefully, then was introduced into a second separating funnel and washed several times using distilled water to remove soap and other contaminants. Finally, the washed methyl-ester was dried at room temperature for approximately 24 hours in order to potentially reduce water content. Thus, it would be ready to characterization tests. A schematic illustration of the adopted procedure is proposed in Fig.2.

Effect of the temperature reaction was investigated by choosing a temperature range from 30 to 70°C. The highest biodiesel yield was found 78% between 45 and 60°C, which is similar to that of H. Venkatesan et al. [17]. The physical characteristics of produced biodiesel from waste cooking oil were determined experimentally, following standard test methods as illustrated in Table 2.

As the viscosity slightly exceeds the requirement of the pure diesel standard (EN ISO 3104), it is proposed to run engine tests with different blends of the synthesized methyl-ester and pure diesel.

Table 2. Characteristics of the produced Methyl-ester and fuels used in this work

Analyses		Method	Unit	Limits of diesel		Limits of biodiesel		Results			
				Min	Max	min	Max	Methyl ester	B10	B20	B30
Density at 15°C		EN ISO 3675	Kg/m^3	820	860	860	900	890	936.8	837.3	837.3
Flash point		EN 22719	°C	55	-	101	-	66	64	62	58
Acid value		ASTM D6751	%	-	0,5	-		0,42	-	-	-
Distillation	250 °C	Pr EN ISO 3405	% Vol	-	65	-	-	-	31.6	31.6	32.0
	350° C			85	-	-	-	-	87.4	88.2	90.0
Calculated cetane number		EN ISO 4265	N	46.0	-	51	-	-	53.4	53.3	53.2
Water content		Pr EN ISO 12937	Mg/Kg	-	200	-	500	550	114.3	163.5	238
Sulphur content %		EN ISO 8754	m/m	-	0.3	-	1	00	0.12	0.12	0.12
Kinematic viscosity at 40° C		EN ISO 3104	Cst	2.00	4.50	3.50	5	4.6	2.4	3.1	3.7

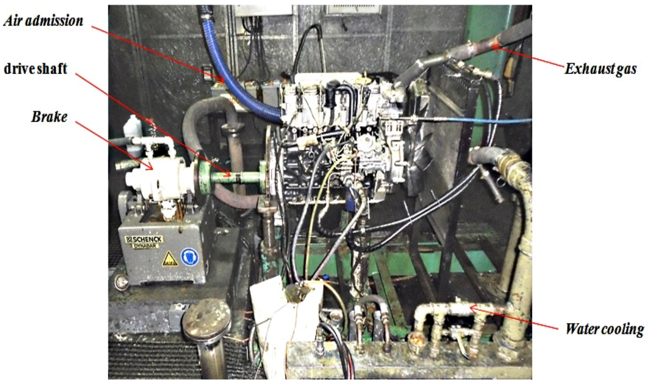


Figure 3. Photographic view of the experimental setup of the diesel engine test stand

2.2 The procedure of engine tests

Tests were performed on an engine test bench equipped with a brake type SCHENCK D600 (Fig.3). The main characteristics of the diesel test engine are listed in Table 3.

The engine was first fuelled by a pure diesel, in order to determine its reference point. Then, it was fuelled by different diesel/biodiesel blends. Tests were conducted using four different fuels: pure diesel fuel (B0) and biodiesels (B10, B20 and B30). Properties of the different blends are also illustrated in Table 2.

Measurements of engine performances were carried out, according to ISO 27.020 standards, under full load. Therefore, different blends were tested at six engine speeds: 3800, 3600, 3200, 2400, 2200 and 1600 rpm. Indeed, the engine was first run without load. Then, it was gradually loaded by a hydraulic break until the predefined engine speed levels were observed. It should be noted that the accelerator was always set in his maximum position. Once the engine reached a steady state operation at the desired speed, engine performance data were then recorded.

Calibration of advancements of the start of combustion timings, for a diesel-fuelled engine, differs from that running on biodiesel. A main goal was then to determine the “ideal” settings for the use of the chosen mixture (B20), in order to find the best behavior of the engine. Therefore, we have repeated the engine test procedure, explained above, for different injection advance angles.

Table 3. Technical specifications of the test engine

Specifications	**Diesel Engine TDI 300**
Engine type	Direct injection, turbocharged
Cylinder number	Four
Bore	90.47 mm
Stroke	97.00 mm
Total cylinder volume	2495 cm^3
Compression ratio	19.5:1 ± 0.5 :1
Original injection timing	Lifting 1.54 mm BTDC
Injection pressure	280 bar
Cooling system	Water cooled

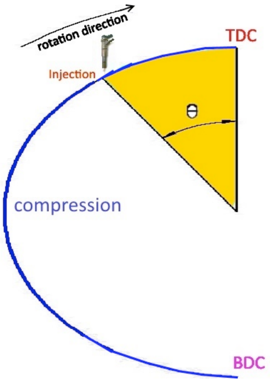


Figure 4. Schematic illustration of the angle of advance to admission

For that, we choose the following angles: -2°, 2° and 4°, compared to original settings. It is here recalled that the advance to injection is the angle θ between the beginning of injection and the top dead center (TDC) during the compression phase, as illustrated in Fig.4.

The soot opacity of the exhaust gas was measured with a TEXA opacity meter, mounted on the exhaust line.

3. Results and Discussion

3.1 Physico-chemical properties of the synthesized methyl esters

WCO used in this research proves similar performances as rapeseed, sunflower soybean or jatropha oils, that makes it good candidate to be upgraded into fuels, because they are rich in triglycerides and fatty acids. The chosen parameters of the procedure (in particular stirring and drying durations) of transesterification allow us to refine vegetable oil by synthesizing a methyl-ester whose properties are close to or fulfill biodiesel standards. Similar observations are revealed for the different blends (B10, B20 and B30), when compared to diesel norms. An improvement in physico-chemical properties was observed compared to the results obtained by Boubahri et al [15], especially in kinematic viscosity. A slight decrease in density compared to the work of Tarabet et al. [18] has also been revealed in this work. That increases the efficiency of the pulverization during injection. From an ecological point of view, frying oils have been successfully transformed into a beneficial product (biofuel).

Therefore, we can ensure engine tests to evaluate the performances and engine behavior when being fuelled by the different blends thus prepared.

3.2 Impact of the synthesized blends on the engine performances

Properties of methyl-ester could be improved when mixed with diesel fuel in different concentrations. First, densities of B10, B20 and B30 were found respectively 837.3, 837.3 and 836.8 kg/m^3, so within EN ISO 3675 requirements. Moreover, flash point values of B10, B20 and B30 were found 64, 62 and 58°C respectively. These values exceed the minimum limit of 55°C set by EN 22719. That allows a safe storage and handling of biodiesel.

Then, calculated cetane numbers for all mixtures are between 53.2 and 53.4, which fulfills the EN ISO 4265 specifications (a minimum value of 46 is required for biodiesel). This criteria has a direct impact on combustion. Indeed, the higher is the cetane number, the higher is the speed of propagation of the flame during combustion. That leads to a more complete combustion. Thus, we will have an improvement of the effective yield of the engine. Moving to water content, it was found within pr EN ISO 12937 exigencies for B10 and B20, but a relative exceeding was marked by B30 blend (238 mg/kg against a maximum limit of 200). A higher water content causes incomplete combustion and triggers corrosion of engine parts, especially injector nozzle. That's why, we choose 30% as maximum ratio of methyl-ester in the fuel blend in this work. If water has a harmful effect on engine performances, oxygen, in contrast, improves efficiency of combustion. Indeed, methyl-ester, by containing about 3% of oxygen [15], contributes in improving combustion.

In order to provide more definite information about the behavior and performance of the engine to biofuel users, it is essential to focus on the study of variation of engine torque and power, as well as pollutant emissions as a function of engine speed.

For each blend (B0, B10, B20 and B30), variations in engine torque and power, with speed, were measured. Obtained curves are then illustrated in Figs.5 and 6. Here, curves of torque and power versus speed have the same form for all blends, which demonstrates that the engine keeps his behavior even when changing fuel type.

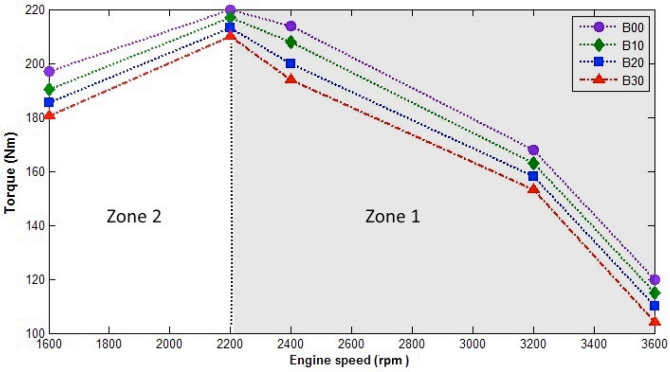


Figure 5. Engine torque versus engine speed measured for fuels tested

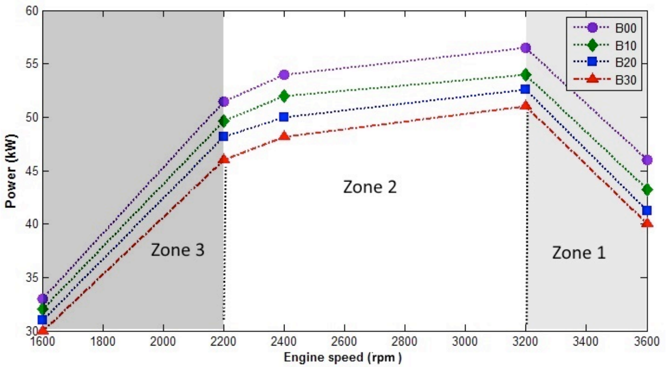


Figure 6. Engine power versus engine speed measured for fuels tested

From all speeds, a slight decrease was revealed for both power and torque. Similar results were found by P. Verma [19]. This little decrease was evaluated to be about 3 to 4 % in torque and about 5% in power, for every addition by 10% of methyl-ester. That traduces the efficiency of the procedure of preparation of methyl-ester.

According to the test protocol complying with ISO 27.020 standards at full load, it is recalled here that the engine was first turned without load until reaching its maximum speed (3600 rpm), then a resistive torque was applied through the intermediate SCHENCK brake.

Variation of torque with engine speed is marked by two zones (Fig.5). Zone 1 (from 3600 to 2200 rpm) corresponds to a decrease in engine speed on the one hand and an increase in the torque delivered by the engine on the other hand. This is valid for all blends. With regards to zone 2 (from 2200 to 1600 rpm), there is a decrease in speed, as well as a reduction in engine torque. This is also true for all blends.

Regarding power versus speed, we distinguish three different zones as illustrated in Fig.6. It is recalled that the power P is linked to the torque C by the relation P = C ω, when ω is the engine speed. To begin with zone 3, which corresponds to speeds from 1600 to 2200 rpm, torque increases as well as engine speed. Thus, power has trend to increase too. With regards to zone 2, torque decreases while engine speed decreases. The increase of the regime would then overcome the decrease of the torque. We would thus have an increase in power with an increasing slope but less than that of zone 3. Finally, in zone 1 (from 3200 to 3600 rpm), the decrease in torque would overcome the increase in ω, resulting in a decrease in P.

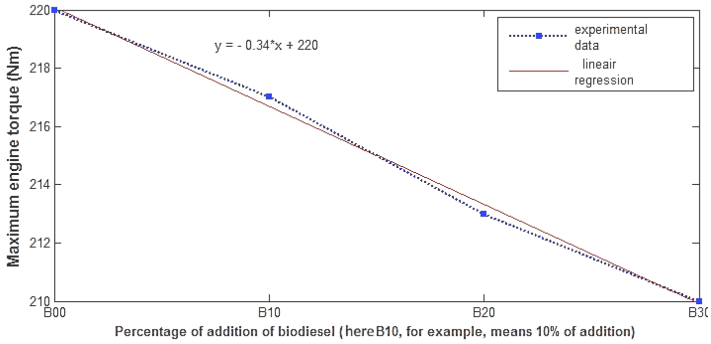


Figure 7. Variation of maximum engine torque (obtained at 2200 rpm) with increasing methyl-ester addition to the blend

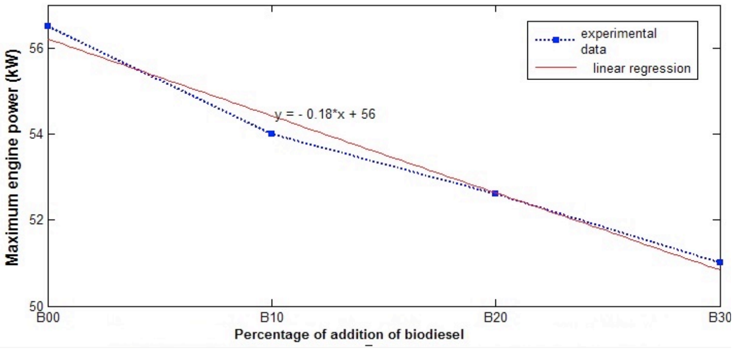


Figure 8. Variation of maximum engine powers (obtained at 3200 rpm) with increasing methyl-ester addition to the blend

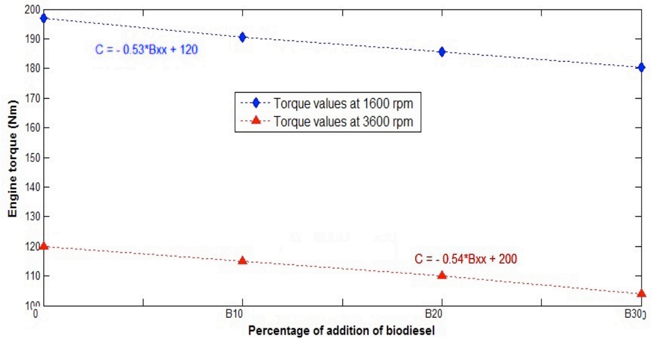


Figure 9. Variation of engine torques (obtained at 1600 and 3600 rpm) with increasing methyl-ester addition to the blend

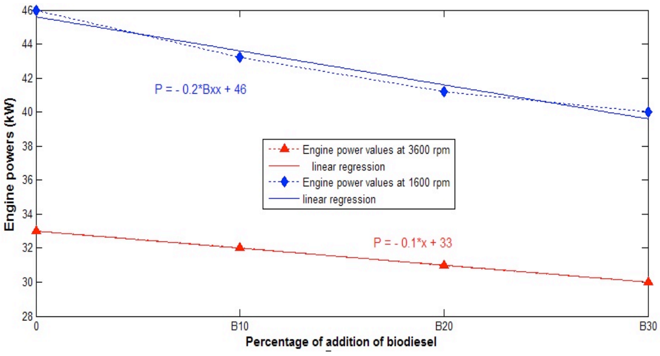


Figure 10. Variation of engine powers (obtained at 1600 and 3600 rpm) with increasing methyl-ester addition to the blend

Variation of maximum engine torque (obtained at 2200 RPM) with increasing methyl-ester addition to the blend are illustrated in Fig.7. Each 10% of increase of methyl-ester in the blend, induces a decrease of 1% of the maximum torque. In the same way, variation of maximum engine power (found at 3200 rpm) with increasing methyl-ester addition to the blend are illustrated in Fig.8. Each 10% of increase of methyl-ester in the blend, induces a decrease of about 3% of the maximum power.

It is interesting to study the behavior of the engine torque for the speed corresponding to maximum resistant torque (applied by the brake on the engine) → 1600 rpm, as well as for the idle speed (without load) → 3600rpm.

Thus, Fig.9 illustrates the variation in torque with the percentage of methyl-ester in the blend for these two regimes. Torques decrease linearly with methyl-ester content, with almost the same decrease rate (the slopes are respectively -0.53 and 0. 54 for speeds 1600 and 3600 rpm).

We now repeat the same study but we focuses on the variation of the power instead of the couple. While increasing the level of methyl ester in the mixture, there is a higher decrease in power for 3600 rpm (idle speed) compared to 1600 rpm. Indeed, as illustrated in Fig.10 the slope of the curve P= f(% methyl ester) for 3600 rpm is twice that of 1600 rpm. It is thus recommended that the exploitation of biodiesel is more efficient (higher yields) for engines operating with high resistant torques, such as agricultural machinery and heavy equipment vehicles.

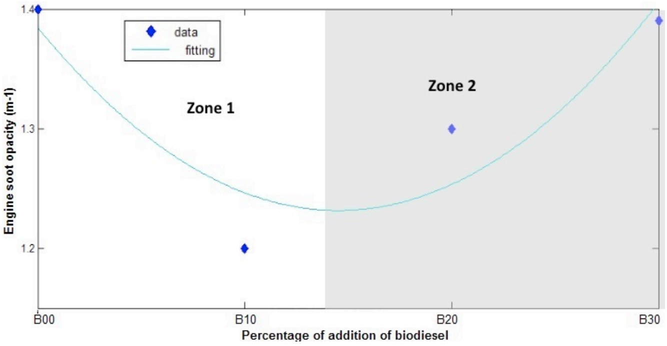


Figure 11. Engine soot opacity measured for various blends

The effects of different biodiesel blends on smoke opacity are shown in Fig.11. Here, two different zones could be distinguished. In zone 1, it is noticed that the higher is the methyl-ester content in the fuel blend, the lower is the exhaust emissions. The soot opacity thus decreases with addition of biodiesel. That could be explained by the presence of oxygen which leads to more complete combustion processes [20]. Opacity reaches a minimum value of about 1.2 m^{-1}, that corresponds to a decrease by 15% compared to pure diesel. However, in zone 2, it increases with biodiesel content due to the higher viscosity, which causes incomplete combustion.

In both zone 1 and 2, biodiesel opacity still less than that of diesel. That confirms that the exploitation of biodiesel from B0 to B30 is favorable for the environment and life of the engine; reduction of fouling of the intake and exhaust valves as well as pistons and bearings. The interval [B10-B17] is thus proposed as the most favorable (encouraging opacity values are here found).

Results obtained in the previous parts prove that mechanical performance of the engine decreased by about 3 to 4% in torque and about 5% in power. To fix these losses, different alternatives could be proposed:

- Increasing injection pressure to ensure better blend pulverization during injection.
- Increasing air filling rate by improving air supercharging system
- Heating the blend before injection to decrease its kinematic viscosity
- Increasing the duration allowed for combustion by varying the angle of injection advance and so the ignition delay.

In the following part of this work, we choose to focus on the last alternative (variation of ignition delay).

3.3 Effect of variation of ignition delay on engine performances

Differences in physical properties between diesel and biodiesel fuels affect the combustion characteristics. Biodiesel have a higher density and viscosity than conventional diesel fuel which leads the injectors to inject a higher mass of fuel. A higher duration of combustion is then required to completely burn the fuel during combustion. A way to increase the burning time is to increase the injection advance angle (inject in advance). By literature, few works have been focusing on the effect of variation of the injection timing on engine performances.

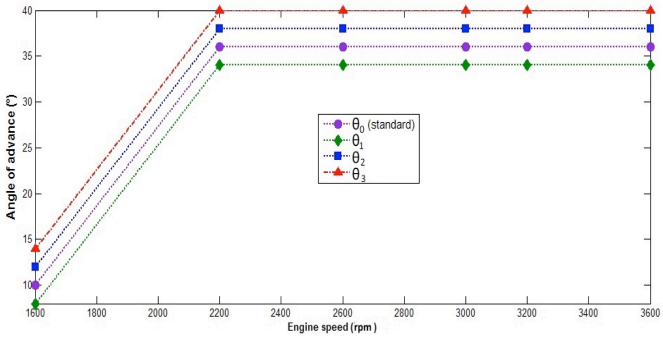


Figure 12. Behavior of the unit of the automatic advance according to the engine speed

In this part, we were interested only on the blend B20 because of the satisfactory results obtained in the previous part, particularly in performances and opacity.
Fig.12 shows the variation of the injection advance angle as a function of the engine speed:

- Curve (θ_0) corresponds to the original settings made by the engine manufacturer, adapted to diesel.

- Curve (θ_1) → an injection advance delay of 2°compared to the original settings. That results in an angle of 8° in advance to injection at 1600 rpm and 34° at 2200 rpm or above (instead of the 10° and 34° respectively ; the manufacturer settings).

- Curve (θ_2) → an injection advance by 2° compared to the original settings.

- Curve (θ_3) → an injection advance by 4° compared to the original settings.

Figs.13 and 14 show the effect of advanced injection timing on combustion characteristics of B20 blend compared to that of the original injection timing. These curves lead to determine the start of injection timing corresponding to the maximum torque as well as the maximum power and minimum soot opacity.

By varying the injection advance angle, we found similar curves (in appearance). Thus, the engine hasn't changed its operating mode. The changes in torque are directly related to the combustion time, so to the angle of advance. If we compare the measured torques with the advances θ_1 and θ_0 for example, the decrease in combustion time generated by θ_1 correction explains the reduction in the engine torque.

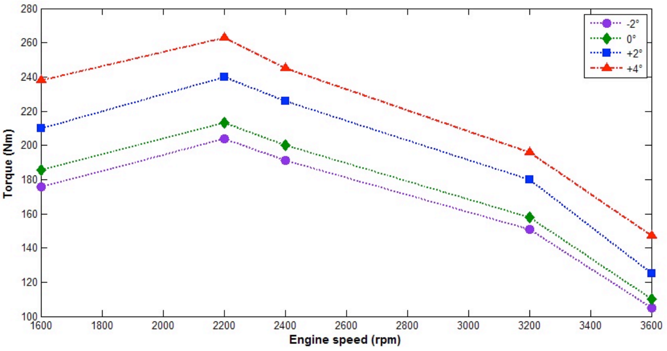


Figure 13. Engine torque vs. engine speed measured for fuels tested, with variation of advanced injection timing

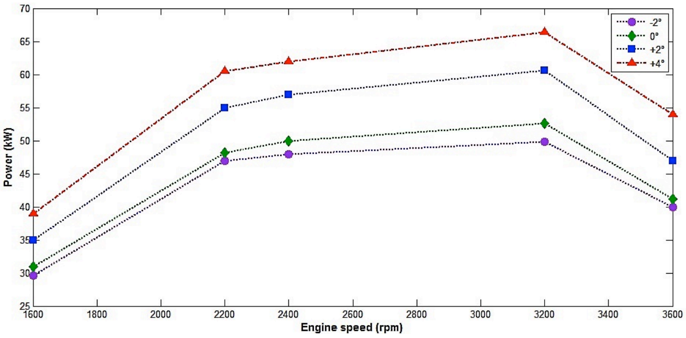


Figure 14. Engine power vs. engine speed measured for fuels tested, with variation of advanced injection timing

However, for θ_2 and θ_3 corrections, there is an improvement in the mechanical performance of the engine (torque and power). That could be explained by the increase in the time reserved for combustion (there is a tendency to a more complete combustion). With regards to opacity, there is an increase for θ_1 (compared to θ_0). That could be explained by the reduction of the time reserved for combustion. Indeed, they are more unburned hydrocarbons (HC) in the exhaust gas, thus causing an increase in opacity. Opacity is significantly improved for θ_2, that is explained to a more complete combustion.
By applying this correction, the maximum amount of unburned HC in the exhaust gases was increased. If we continue to increase the time reserved for combustion (θ_3); although mechanical performance is improved, there would be a formation of soot due to the thermal cracking of unburned hydrocarbons. That causes an increase in opacity.

To summarize, significant improvements were observed by the application of advanced injection timing by 2 crank angle degrees in BTDC (before top dead center). The use of B20 accompanied with the advanced injection timing leads to a significant power increase (up to 4%) as well as an increase in torque (up to 2.8%) of conventional diesel engines compared to diesel. It is therefore allowed to advance the injection of few degrees before TDC and therefore maximize engine performance without penalty on pollution emissions (soot opacity), as illustrated in Figs 15 and 16.

An optimized timing has to be found for any fuel to strike a balance between reducing emissions and improve the performance of the engine [21].

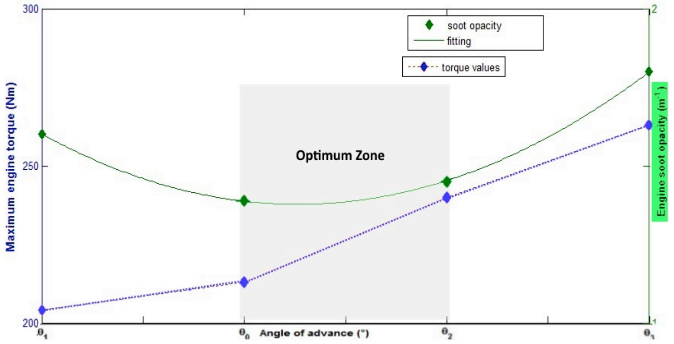


Figure 15. Variation of maximum engine torque (obtained at 2200 rpm) and soot opacity measured for B20 Blend, with variation of advanced injection timing

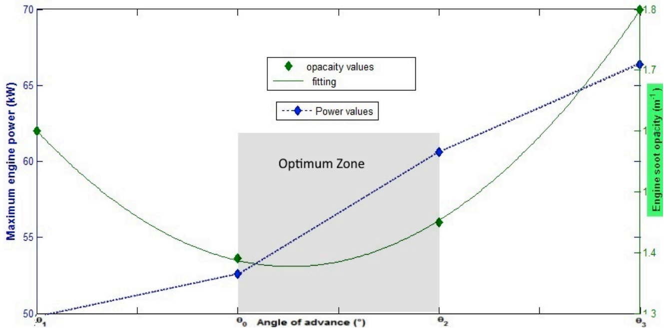


Figure 16. Variation of maximum engine power (obtained at 3200 rpm) and soot opacity measured for B20 Blend, with variation of advanced injection timing

By literature, various works have been focused on the effect of injection timing on engine performances. Most of these works showed that the use of biodiesel blends, with variation of injection timing, could reduce CO and HC emissions as well as smoke on the one hand, and improve the combustion process on the other hand. Gumus et al. [22], in contrary, found that original settings give optimum results compared to retarded and advanced injection timing. They reported that good results could be obtained with the strategy of timing variation in order to ensure a balance between performance and emissions.

Previous studies mostly focused on biodiesels obtained from vegetable oils. In our work, we have presented new and rare experimental results about the use of WCO methyl-ester and the effect of the advance in injection timing on engine behavior.

We found that at the optimum injection timing (from θ_0 to θ_2), significant reductions in smoke emissions and maximum performance (torque and power) of a engine fuelled with of the B20 blends were observed. It was noted that after an optimum advancement of injection timing, the efficiency decreased (high smoke and poor performance).

4. Conclusion

In this work, we succeeded to produce biodiesel from waste cooking oil by transesterification process, and then we have investigated their effects on engine performances and emissions. A mixture of biodiesel fuels produced was blended in 10%, 20 and 30% with diesel fuel. The methyl ester/diesel fuel blends were tested in a four cylinder diesel engine. Results obtained demonstrate that the use of the blends of WCO biodiesel with small contents (from B10 up to B20) leads to slightly decrease power performances of conventional diesel engines, compared to diesel.

These blends could be used in all diesel equipment and could replace the petroleum-based fuel. That helps in controlling air pollution and encourages collection and recycling of edible oil waste in order to produce biodiesels. It is worth noting that these low-level blends generally do not require any engine modifications. However, biodiesel blends higher than B20 require special handling and engine modifications to fix performance problems.

Finally, this study demonstrates that the use of these biofuels is recommended for engines operating at a low speed especially stationary engines and construction vehicles. The use of WCO biodiesels accompanied with the advanced injection timing leads to a significant power increase and a substantial reduction in soot opacity emissions, as well as the transformation of products with detrimental effects into beneficial ones.

Use of up to 20% methyl ester biodiesel blends accompanied with an advancement of injection timing by 2 crank angle degrees in a engine gives better engine performance and emits less emissions (opacity) compared to the standard injection timing.

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