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Conference Paper

Diesel Internal Combustion Engine Emissions Measurements for Methanol-Based and Ethanol-Based Biodiesel Blends

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There is a recent interest for the utilisation of renewable and alternative fuel, which is regulated by the European Union, that currently imposes a lower limit of 7% by volume of biodiesel fuel blend in diesel fuel. The biodiesel physical characteristics, as well as the percentage of biodiesel blend in diesel fuel, affect the injector nozzle flow, the spray characteristics, the resulting air/fuel mixture, and subsequently the combustion quality and emissions, as well as the overall engine performance. In the present study, two different types of pure biodiesel fuel, namely, methanol-based biodiesel and ethanol-based biodiesel, were produced in the laboratory of Frederick University by chemical processing of raw materials. The two biodiesel fuels were used for blending pure diesel fuel at various percentages. The blends were used for smoke emissions measurements of a diesel internal combustion engine at increasing engine speed and for increasing engine temperatures. From the experimental investigations it was found that ethanol-based biodiesel blends result in higher smoke emissions than pure diesel fuel, while methanol-based biodiesel blends smoke emissions are lower compared to pure diesel fuel.

1. Introduction

There is recent interest for the utilisation of renewable and alternative fuels by the European Union (EU), which is regulated by Directive 2009/30/EC. For the usage of biodiesel blends, a lower limit of 7% by volume biodiesel fuel blend in diesel fuel is currently imposed. The specifications of biodiesel fuels which can be used for blending diesel fuel are defined by the European standard EN 14214 [1]. The physical properties of biodiesel affect the diesel blends, and the range of density, viscosity, and flash point of biodiesel are specified in EN 14214. However, other physical properties of diesel blends including the surface tension coefficient, the fuel vapour pressure, the boiling point, and the latent heat of evaporation also affect the injected fuel spray characteristics, the resulting air/fuel mixing, combustion, and the emissions of diesel internal combustion engines (ICE), as well as the engine overall performance.

Biodiesel is mainly produced from oilseed crops and other raw materials [2]. Biodiesel fuels can be produced from rapeseed via cold pressing/extraction and transesterification, known as fatty acid methyl ester (FAME) [3], and are known as first generation biofuels. For second generation biodiesel fuels known as hydrotreated biodiesel, hydrotreatment technologies are used for vegetable oils and animal fat materials [3].

Biodiesel fuel type and fuel physical properties, as well as the resulting physical properties of different blends of biodiesel in diesel fuel, are considered very important but were studied in a limited number of previous experimental and computational investigations. The biodiesel physical properties including density, dynamic viscosity, and surface tension coefficient have been investigated by [4] among others. At atmospheric conditions, the density of biodiesel compared to pure diesel fuel is around 5 to 10% higher, and the viscosity of biodiesel given at 40°C is higher by almost factor of two than the viscosity of pure diesel. Limited data was published for surface tension coefficient, which ranges from 0.025 to 0.03 N/m for biodiesel, while for diesel ranges approximately from 0.02 to 0.025 N/m. However, the different raw materials as well as the different production processes for biodiesel result in different physical properties of the produced biodiesel. The present work aims to examine the effect of different raw materials, namely, methanol and ethanol, used for the production of biodiesel in order to distinguish their effects on the exhausted emissions and engine performance.

Published experimental and computational studies dealt with diesel injector internal flow, cavitation phenomena and the resulting sprays for biodiesel fuel. The resulting sprays from diesel fuel and biodiesel blends were examined experimentally in [5, 6] among others. It was found that the spray cone angle decreases and spray penetration increases with increasing the blending percentage of biodiesel. Computational spray studies were performed in [7] among others, and it was found that spray cone angle decreases and spray penetration increases when the blending percentage of biodiesel is increasing.

In published experiments the effects of different types of biodiesel blends on combustion and the exhaust emissions and performance of diesel ICE (see [8–11]) were studied. Anand et al. [8] used a nondispersive infrared analyser (NDIR) (AVL DiGas 444), gas analyser, and smoke meter (AVL437) and measured the emissions of blends of waste cooking oil methyl ester from B10 (10% by volume biodiesel in diesel) to B80 in a single-cylinder diesel engine. It was found that, with biofuel blends, the specific fuel consumption increased, the CO, CO_2, and HC emissions decreased, the smoke opacity decreased, while the NO emission slightly increased [8]. Guido et al. [9] employed a smoke meter (AVL415S) and studied biodiesel blends B20, B50, and B100 effects on the emissions of a General Motors 2-litre four-cylinder diesel engine. It was also found that the emitted smoke is reduced with increasing percentage of biodiesel blends [9]. Nabi and Hustad [10] employed a gravimetric method and examined the 20% in volume jatropha biodiesel blend in diesel in a six-cylinder turbocharged direct injection engine, and found that smoke decreased with the use of blended fuel. Zhang et al. [11] used a portable exhaust gas analyzer (FGA-4100) along with a smoke opacity meter (AVL 439) and investigated the combustion and emission characteristics of soybean methyl ester biodiesel blends in a single-cylinder direct injection engine at different loads and constant speed. It was found that smoke opacity decreases with higher percentage of biodiesel blends [11]. In a recent investigation [12], the effects of increasing blending percentage of biodiesel on the emitted smoke from the engine utilising gas analyser described in the present study were examined. It was found that the amount of emitted smoke decreases with increasing biodiesel blends, which agrees with the other published investigations.

However, further experimental investigations accompanied with computational studies should be carried out for better understanding of the quality of biodiesel and the various effects of biodiesel on emissions and performance of ICE. Particularly, the effect of different types of biodiesel fuels is required to be assessed.

The present study examines, experimentally, vehicle diesel internal combustion engines operating with blends of two different types of biodiesel fuels, namely, methanol-based and ethanol-based denoted MB and EB, respectively, in diesel fuel. The effects of different types of biodiesels blends on ICE emissions are identified. From the experimental results and discussion, conclusions and suggestions are provided regarding the adaptation of biodiesel in ICE. First, the experimental setup used for the measurements of the emissions is presented, including details for the production of the two different types of biodiesel fuels which were used for the blending of pure diesel fuel at increasing percentages. Then, the experimental results are discussed, followed by the conclusions of the present study.

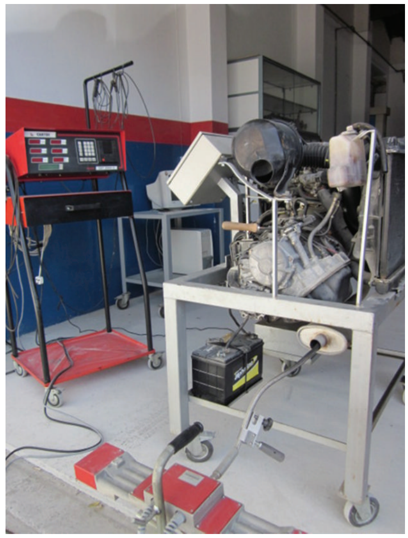

Figure 1: Diesel ICE on a frame, used for biodiesel blends testing.

2. Experimental Setup

The experimental setup used for the measurements includes the diesel internal combustion engine where the test fuels were examined and the exhaust emissions were measured, the exhaust gas analyser which was employed for the measurements, the laboratory production of the two types of biodiesel, and the preparation of blends at various percentages.

2.1. Diesel Internal Combustion Engine. The diesel ICE used for the measurements of emissions for pure diesel fuel (Eurodiesel) and different blends of biodiesel in Eurodiesel is shown in Figure 1. The diesel ICE is manufactured by Mitsubishi and is mounted on a special antishock frame. It is a four-cylinder engine with four valves per cylinder (2 inlet and 2 exhaust valves) with direct injection fuel system equipped with a turbocharger. Technical details of the engine are tabulated in Table 1.

2.2. Gas Analyser and Experimental Procedure. The gas analyser which was used for the exhaust emissions measurements from the diesel ICE is shown in Figure 2. The test fuels of various blends of the two different types of biodiesel fuels in diesel fuel were utilised for fuelling the ICE. The gas

Table 1: Technical specifications of the diesel ICE.

Description	Details
Engine code	4D68
Engine type	Inline 4 cylinders, turbocharged diesel
Displacement (cm^3)	1998
Bore (mm)	82.7
Stroke (mm)	93
Compression ratio	22.4

Figure 2: Gas analyser with exhaust emissions probe.

analyser model is CARTEC CET 2000 [13], and it has various sensors and probes for measurements of exhaust emissions and monitoring of engine speeds in revolutions per minute (rpm).

The gas analyser can measure gasoline ICE emissions and diesel ICE emissions [13]. The absorption method utilising turbidity meter (opacimeter) is used for the diesel engine emissions ([13, 14]). For diesel ICE, the measured emitted smoke is given by the coefficient of light obscuration (CLO) which is analogous to the mass concentration of unburned carbon particles contained in the exhaust gases. The corresponding values of smoke as mass concentration to the CLO are given by the manufacturer in tables. The measurement of CLO as function of engine speed and engine temperature is used in the presentation of the experimental results.

2.3. Methanol-Based Biodiesel Production and Preparation of Blends with Pure Diesel. The methanol-based biodiesel was produced in the Materials Process Laboratory of Frederick University and was used for the preparation of blends of biodiesel in conventional diesel fuel. The biodiesel production and the preparation of blends with conventional diesel are described below.

The raw materials included the corn oil, methanol, and sodium hydroxide (NaOH) ([15, 16]). For every 1 liter of corn oil, 250 mL of methanol and 3.5 g of NaOH were used.

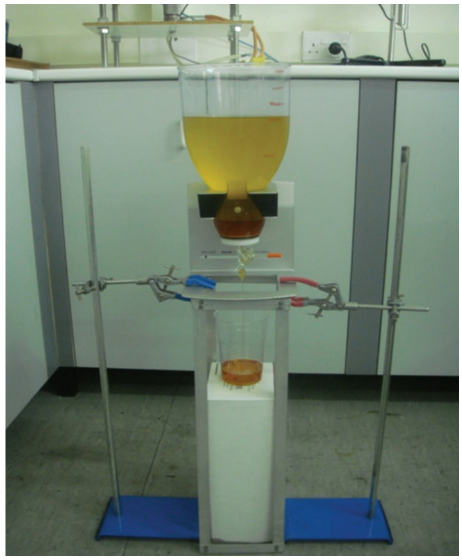

Figure 3: Photograph of the experimental apparatus for the production of methanol-based biodiesel, separation of glycerine and other by-products, and collection of biodiesel.

The production process involves heating of the corn oil at around 50–60°C and adding of methanol with dissolved NaOH by constant stirring for a period of about 20 minutes. The mixture was left overnight for liquid phase separation. Biodiesel is the lighter liquid phase, whereas the heavier liquid is the biowaste containing glycerine and other by-products (mainly, NaOH and moisture). The biowaste was emptied by draining, while biodiesel was left in the container as shown in Figure 3.

The methanol-based biodiesel blends with conventional diesel were prepared in the ICE laboratory with mixing of the produced methanol-based biodiesel in various percentages with conventional diesel fuel obtained from local market [17], traded as "Eurodiesel." The test fuels were pure Eurodiesel, denoted "diesel," and 25, 50, and 75% percentage of methanol-based biodiesel volume in the total volume of blended diesel, denoted "MB25, MB50" and "MB75", respectively.

2.4. Ethanol-Based Biodiesel Production and Preparation of Blends with Pure Diesel. The ethanol-based biodiesel was also produced in the Material Process Laboratory of Frederick University and was used for the preparation of blends of ethanol-based biodiesel in conventional diesel fuel. For the ethanol-based biodiesel production, ethanol was used instead of methanol. For every one liter of corn-oil, 350 mL of ethanol was used, while the same amount of NaOH was used. The processing of ethanol-based biodiesel resulted in increased amount of produced biowaste as shown in Figure 4.

The ethanol-based biodiesel biowaste depicted in Figure 4 was thicker and different in colour than the biowaste of the methanol-based biodiesel shown in Figure 3. Thus, the production process of ethanol-based biodiesel required washing of biodiesel with water and infiltration in order to improve the production and quality of the produced biodiesel.

FIGURE 4: Photograph of the experimental apparatus for the production of ethanol-based biodiesel, separation of biowaste and other by-products, and collection of biodiesel.

The ethanol-based biodiesel blends with conventional diesel were prepared in the ICE laboratory with mixing of the produced ethanol-based biodiesel in various percentages with Eurodiesel. The test fuels were pure Eurodiesel, denoted by “diesel,” and 10 and 25% percentage of ethanol-based biodiesel volume in the total volume of blended diesel, denoted by “EB10,” and “EB25,” respectively.

3. Experimental Results and Discussion

The measurements of exhaust emissions were carried out for increasing engine speeds from idle to full throttle. The measurements started from engine at atmospheric temperature and were recorded for increasing engine temperature until fully warm-up. For the measurement of the exhaust emissions which were produced from the test fuels, the engine speed, the lubricant oil temperature (corresponding to the engine warm-up evolution), and the emitted smoke expressed with the CLO in (m^{-1}) were recorded for lubricant oil temperature approximately around 40, 60, 80, 90, and 95°C, at engine speeds of 1000, 2000, 3000, and 3500 revolutions per minute (rpm).

The experimental results of the emissions of pure diesel blends are firstly described, then the emissions of methanol-based biodiesel blends are presented, followed by the experimental results of the emissions of the ethanol-based biodiesel blends. Finally, the emissions of methanol-based and ethanol-based biodiesel blends are compared against the emissions of pure biodiesel and discussed.

3.1. Emissions Results of Pure Biodiesel. The measurements of emissions from the diesel ICE for pure diesel at engine temperature approximately 40, 60, 80, 90, and 95°C at increasing engine speeds are presented in Figure 5. It can be seen that the emitted smoke decreases slightly with a minimum value at 2000 rpm, and increases considerably when the engine speed is higher than 3000 rpm for all the engine temperatures.

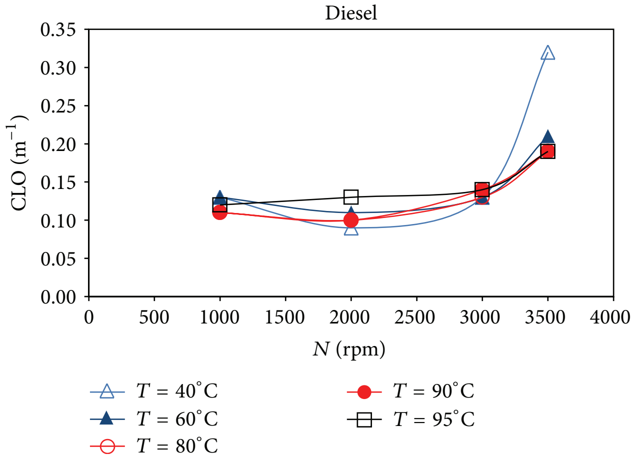

FIGURE 5: Smoke emissions measurements as function of engine speed at increasing engine temperatures for pure diesel.

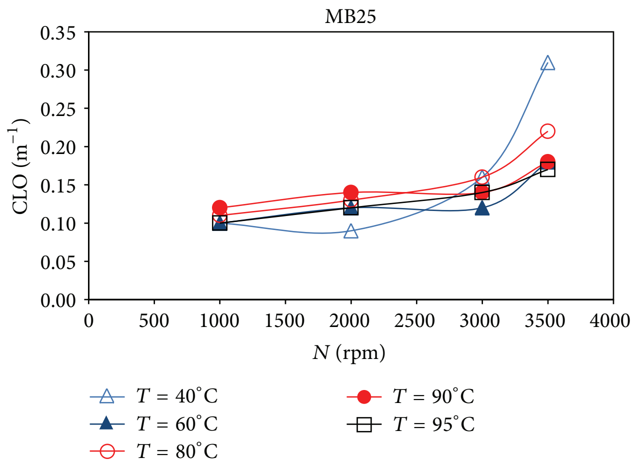

FIGURE 6: Smoke emissions measurements as function of engine speed at increasing engine temperature for MB25 test fuel.

As it is shown in Figure 5, the maximum amount of emitted smoke occurs for cold engine operation at maximum engine speed, which reveals that there is no sufficient time for the air/fuel mixture to be prepared and combustion to be completed.

3.2. Emissions Results of Methanol-Based Biodiesel Blends. The measurements with methanol-based biodiesel blend MB25 are included in Figure 6. For all engine temperatures, the emitted smoke amount slightly increases in a linear trend with the increasing engine speed until 3000 rpm. Thereafter, it can also be seen that at the peak speed, the rate of increase of the smoke amount increases and that the maximum quantity of smoke is emitted for cold engine operation. The trends that are observed are similar to the trends of pure diesel fuel, thus the engine operation according to the emissions does not deteriorate.

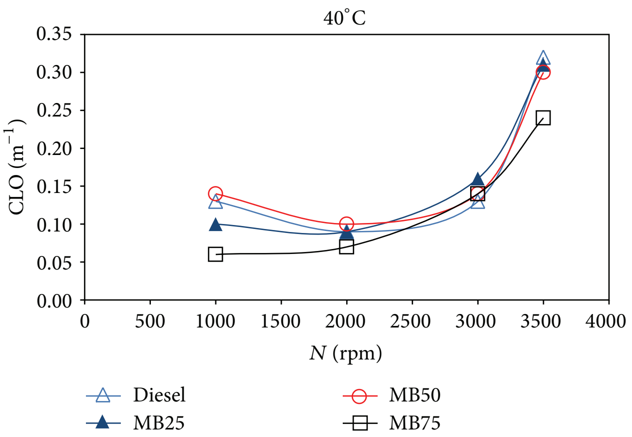

FIGURE 7: Smoke emissions measurements at cold engine temperature as function of engine speed for increasing blending percentage of methanol-based biodiesel in diesel.

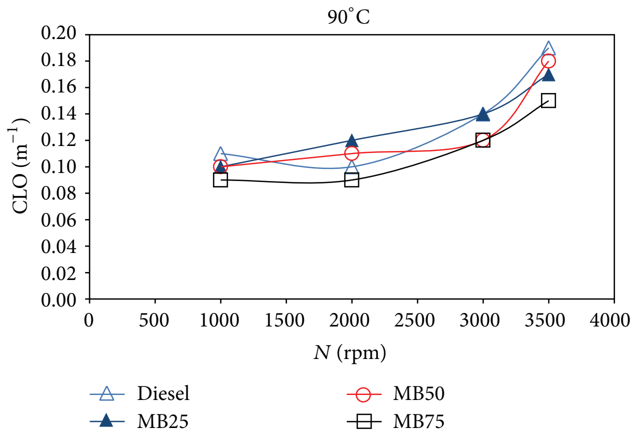

FIGURE 8: Smoke emissions measurements at hot engine temperature as function of engine speed for increasing blending percentage of methanol-based biodiesel in diesel.

The measurements of smoke with methanol-based biodiesel blends for the test fuels MB25, MB50, and MB75 are compared against the emitted smoke from pure diesel fuel in Figure 7. Figure 7 shows the effect of engine speed for cold engine operation for the different test fuels. It can be observed that smoke decreases slightly from 1000 to 2000 rpm for all the test fuels except for MB75, and then the emitted smoke slightly increases until 3000 rpm. For engine speeds greater than 3000 rpm, the emitted smoke increases substantially. The differences between emitted amount of smoke for diesel fuel, MB25, and MB50 are small, while the lower amount of emitted smoke takes place for the MB75, which shows that increasing the blending percentage of methanol-based biodiesel reduces the amount of smoke for all engine speeds. Therefore, for cold engine operation, the utilization of increased percentage of biodiesel is considered beneficial for the engine operation.

The measurements of smoke with methanol-based biodiesel blends for the test fuels diesel, MB25, MB50, and MB75 for hot engine operation for increasing engine speeds are compared in Figure 8. Figure 8 shows that smoke slightly increases from 1000 to 3000 rpm for all the test fuels. For engine speeds higher than 3000 rpm, the emitted smoke rate of increase is higher than the rate for speeds lower than 3000 rpm. The differences between emitted amount of smoke for all test fuels are negligible for the range of speeds from 1000 rpm to 3000 rpm, and for higher engine speeds, the emitted smoke decreases by around 20%, when the blending percentage increases from 0 to 75%.

Thus, the trend observed in Figure 8 is similar regarding the levels of emitted amount of smoke at high engine speeds, and increasing the blending percentage of methanol-based biodiesel it can improve the engine performance. It is obvious that, for hot engine operation, using increased percentage of biodiesel in the blend improves air/fuel mixing and combustion quality especially at high engine speeds.

Overall, from Figures 5, 6, 7, and 8, it can be observed that the emitted smoke trends are rather similar for pure diesel, MB25, MB50, and MB75. However, the highest amount of smoke is emitted when the engine is cold and running at maximum speed with pure diesel fuel, and the lowest amount of smoke is exhausted when the engine is hot and operating at low engine speed when the fuel blend has the maximum blending percentage of methanol-based biodiesel.

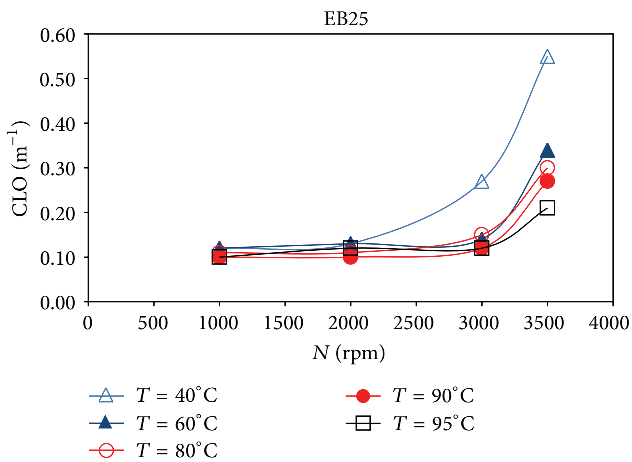

FIGURE 9: Smoke emissions measurements as function of engine speed at increasing engine temperature for EB25 test fuel.

3.3. Emissions Results of Ethanol-Based Biodiesel Blends. The measurements with ethanol-based biodiesel blend EB25 are included in Figure 9. For all engine temperatures, the emitted smoke amount is almost the same for engine speeds up to 3000 rpm and for engine temperatures higher than 60°C. For 3000 rpm, the smoke amount increases dramatically, and the maximum quantity of smoke is emitted for cold engine operation. This reveals that the engine operation worsens when the engine is cold and operating with ethanol-based biodiesel blends even at low percentages. This can be explained by the different physical properties of the ethanol-based biodiesel which result in poor air/fuel mixing, evaporation, and incomplete combustion. Test measurements were performed with test fuels at higher blending percentage

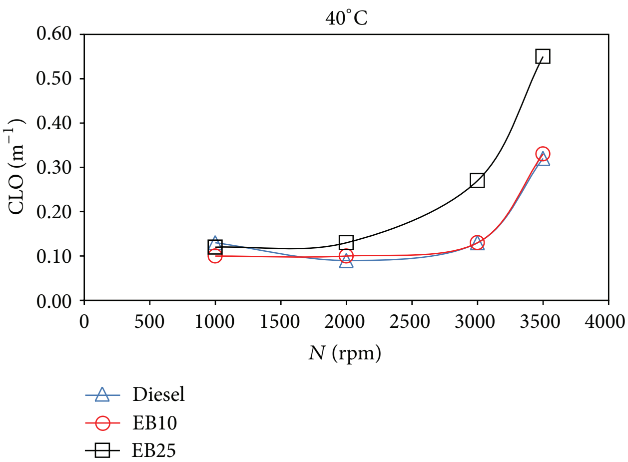

Figure 10: Smoke emissions measurements at cold engine temperature as function of engine speed for increasing blending percentage of ethanol-based biodiesel in diesel.

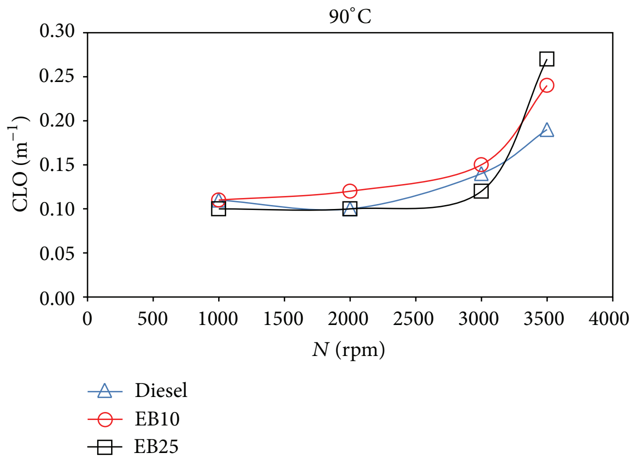

Figure 11: Smoke emissions measurements at hot engine temperature as function of engine speed for increasing blending percentage of ethanol-based biodiesel in diesel.

than 25% of ethanol-based biodiesel blends, which resulted in unstable engine operation, when vibrations and heavy noise occurred.

The measurements of smoke with ethanol-based biodiesel blends for the test fuels EB10 and EB25 are compared against the emitted smoke from pure diesel fuel in Figure 10. Figure 10 shows the effect of engine speed for cold engine operation for three test fuels at increasing blending percentage of ethanol-based biodiesel. It can be observed that the amount of smoke is almost constant for 1000 to 2000 rpm for all the test fuels. However, for higher engine speeds, the emitted smoke increases dramatically for the EB25. The differences between emitted amount of smoke for diesel and EB10 test fuels are negligible, which suggests that ethanol-based biodiesel can be used without inhibiting engine's performance. However, it is prohibited to use ethanol-based biodiesel at increasing blending percentages in the blends since the engine operation dramatically deteriorates.

The measurements of smoke with ethanol-based biodiesel blends for the test fuels diesel, EB10 and, EB25 for hot engine operation at increasing engine speeds are presented in Figure 11. Figure 11 shows that smoke slightly increases in the speed range of 1000 to 3000 rpm for all the test fuels. For engine speeds higher than 3000 rpm, the emitted smoke amount increases dramatically for EB10 and EB25, while for diesel fuel the smoke increases by around 20%. The differences between the emitted amount of smoke for all test fuels are negligible for the range of speeds from 1000 rpm to 3000 rpm, and for higher engine speeds, the emitted smoke increases when blending percentage is increasing.

The trend observed in Figure 11 regarding the increase of smoke with increasing engine speed for hot engine operation is similar to the trend shown in Figure 10, regarding the levels of emitted amount of smoke. However, at high engine speeds, increasing the blending percentage of ethanol-based biodiesel increases dramatically the amount of emitted smoke, and this is more evident during hot engine operation. Thus, for both cold and hot engine operation, increasing the blending percentage of ethanol-based biodiesel in the blend affects the air/fuel mixing and the combustion quality especially at high engine speeds.

Overall, from Figures 9, 10, and 11, it is found that EB25 and fuels with higher blending percentages should not be used for blending diesel fuel.

3.4. Emissions Comparisons of Methanol-Based and Ethanol-Based Biodiesel Blends. The comparisons of the measurements of emitted smoke from the diesel ICE for pure diesel, MB25, and EB25 test fuels at engine temperature approximately 40, 60, 80, 90, and 95°C at low, medium, and high engine speeds are presented below.

In Figure 12, the low engine speed results are included, and it can be seen that the amount of smoke fluctuates and the levels are low for all test fuels. However, the lowest amount of smoke is produced with methanol-based biodiesel and the maximum amount of smoke is emitted with ethanol-based biodiesel blend. It can be seen that using methanol-based biodiesel reduces the amount of smoke compared to diesel and EB25 at low engine temperatures, whereas using ethanol-based biodiesel blend increases the amount of smoke compared to diesel and methanol-based biodiesel blend at hot engine conditions.

In Figure 13, the emitted amount of smoke is compared for pure diesel, MB25, and EB25 test fuels at medium engine speed. The differences are small, but it is evident that EB25 results in higher amount of smoke for cold engine operation. However, at hot engine conditions the level of emitted smoke is almost the same for all test fuels.

Increasing the engine speed to high levels results in similar trends for the emitted smoke with diesel and MB25 as shown in both Figures 14 and 15. The first trend is that, for diesel and MB25 test fuels, the emitted smoke slightly decreases when the engine temperature is increasing. The second trend is that the emitted amount of smoke for EB25 decreases when the engine temperature is increasing, which reveals that the air/fuel mixing, evaporation, and

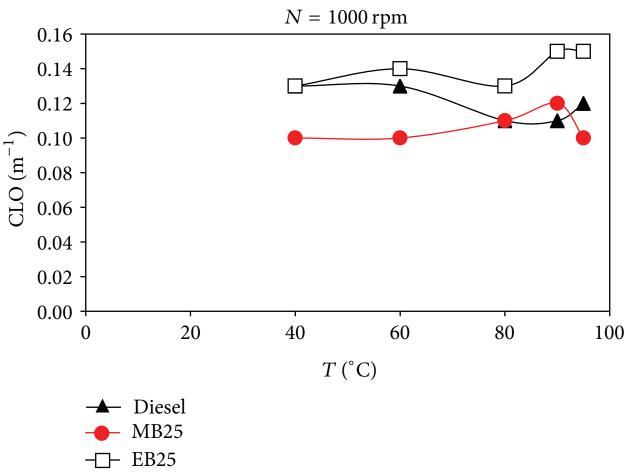

FIGURE 12: Smoke emissions measurements at low engine speed (1000 rpm) as function of engine temperature for pure diesel, MB25, and EB25 test fuels.

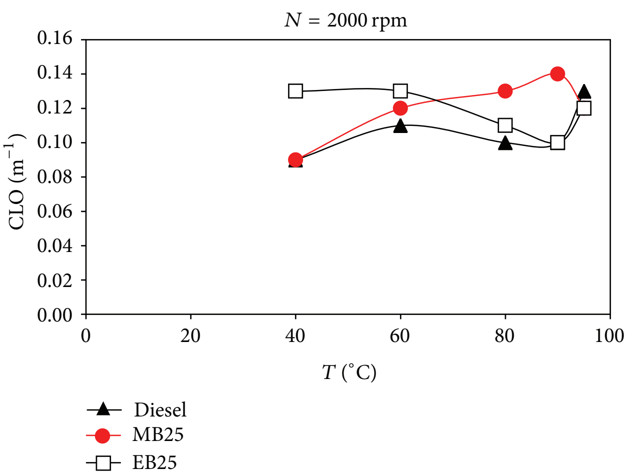

FIGURE 13: Smoke emissions measurements at medium engine speed (2000 rpm) as function of engine temperature for pure diesel, MB25, and EB25 test fuels.

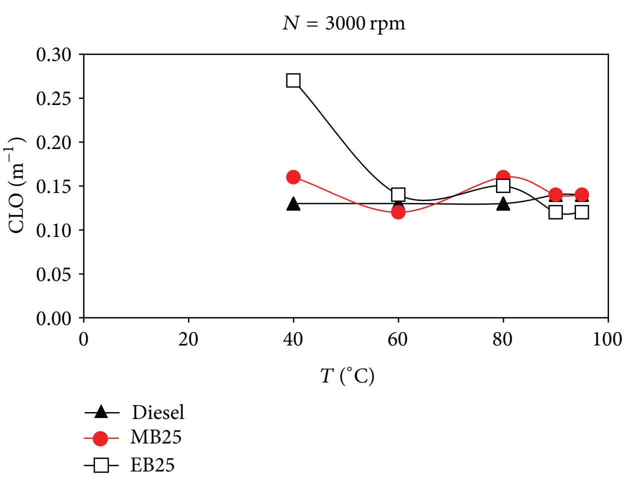

FIGURE 14: Smoke emissions measurements at high engine speed (3000 rpm) as function of engine temperature for pure diesel, MB25, and EB25 test fuels.

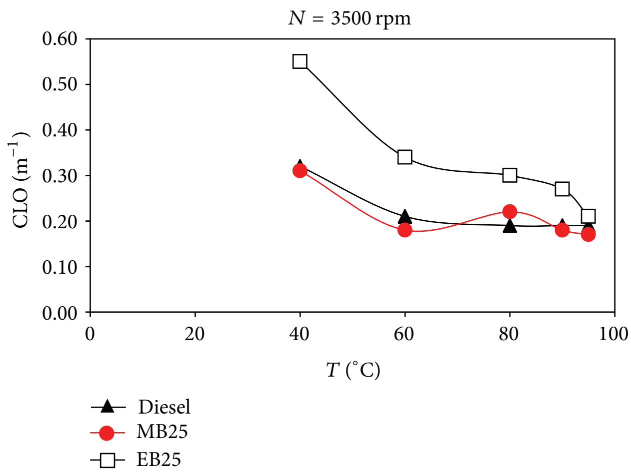

FIGURE 15: Smoke emissions measurements at high engine speed (3500 rpm) as function of engine temperature for pure diesel, MB25, and EB25 test fuels.

combustion quality are improved. This can be explained by the improved physical properties of the ethanol-based biofuel blend when heating takes place in the cylinder of the diesel ICE.

4. Conclusions and Recommendations

For increasing blending percentage of methanol-based biodiesel blends, the highest amount of smoke is emitted when the engine is cold and running at maximum speed with pure diesel fuel, and the lowest amount of smoke is emitted when the engine is hot and operating at low engine speed when the fuel blend has the maximum blending percentage of methanol-based biodiesel. The adaptation of methanol-based blends is recommended because they reduce smoke.

At higher engine speeds the emitted smoke increases when blending percentage is increasing for ethanol-based biodiesel blends. However, ethanol-based biodiesel blends at low blending percentage can be used, but should be further investigated. However, blends with higher blending percentages should not be used for blending diesel fuel. It is recommended to examine preheating of ethanol-based biodiesel blends at increasing blending percentages.

For both methanol-based biodiesel blends and ethanol-based biodiesel blends, further investigations on NO_x emissions quality, as well as the effects of blended diesel on engine thermal efficiency and brake power, should be performed. Furthermore, other types of diesel engines should be used, including naturally aspirated engines, for investigations of effects of biodiesel blends on engine performance and emissions.

The physical properties of biodiesel fuels, including methanol-based biodiesel and ethanol-based biodiesel, and resulting blends should be examined experimentally and computationally in order to relate and quantify the effects of their physical properties on the diesel engine emissions and engine overall performance.

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