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ETHANOL–BIODIESEL–DIESEL BLENDS AS A DIESEL EXTENDER OPTION ON COMPRESSION IGNITION ENGINES

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Abstract. Increasing fuel demand, decreasing natural reserves and environmental consciousness have together led to testing and implementing new fuels and blending components of compression ignition engines. Biofuels are very commonly added to fossil fuels, mostly ethanol to gasoline and FAME to diesel. Harmonizing their properties with engines is a great challenge for automotive and oil industry. Increasing demand for diesel oil in Europe raised the question about the possibility of increasing the amount of bio extenders. There were and certainly there are a number of experiments aimed at substituting or blending diesel with other fuels. One group of such fuels makes bioethanol–biodiesel–diesel oil mixtures. The paper proposes a global overview on literature and presents the obtained results. The article explores the possibility of using bioethanol–biodiesel–diesel oil mixtures in vehicles and agricultural compression ignition engines. The main aspect of researches was to find blends substitutable for compression ignition engines. Investigations were made to determine the maximum volume of a renewable part thus reaching the same or similar power output with lowering emissions. The received results were used for environmental and economical investigations. The valorisation of the results shows that bioethanol–biodiesel–diesel blends fulfil the cetane number, viscosity and lubricity requirements for standard diesel. Practical measurements and engine tests show that the utilization of a new fuel decreases emissions from the engine. The results of agricultural feedstock calculation indicate that in Hungary the biofuel part of the investigated fuels can be produced from an overflow.

Keywords: ethanol, biodiesel, diesel, blends, compression, ignition, engines.

1. Introduction

European legislation and new engine technologies require better quality fuels. At the same time, a decrease in fossil resources and new, rigid emission standards make necessary for looking after new energy sources. The most significant factor of assessing an automotive fuel is its potential to reduce emissions, increase fuel efficiency and widen the range of base resources to reduce dependency on decreasing oil stocks. As these potentials also depend on engine and vehicle technology and especially on the technology for exhaust gas after-treatment, differentiation between older technologies representing the major part of the current vehicle fleet and modern, state-of-the-art vehicles is practical. Another important point is that fuels provide similarly good drivability behaviour as modern conventional fuels do. Extreme climate conditions like cold and hot temperatures and high altitudes also play an important role. Moreover, fuels should be compatible with typical engines and materials for tank systems. Ethanol could be a very good option based on high vaporization heat, a positive effect on soot formulation, continuous quality and the fact that the production of the first generation is a well known technology. Biodiesel or FAME is a conventional diesel extender having nearly the same heating value as diesel, good viscosity and lubricity. Various experiments were carried out making different ethanol–biodiesel, bioethanol–diesel and biodiesel–diesel blends. Investigations into ethanol–biodiesel–diesel blends are not so common. The conducted tests investigated the effect of biocomponents on emission and engine properties. The performed measurements focused on the analytical testing of combustion and handling relevant parameters of the engine.

As a summary of literature overview (Ajav *et. al.* 1999; Satgé de Caro *et al.* 2001; Aakko *et al.* 2002; Hancsók 2004; Emőd *et. al.* 2005, 2006; EN ISO 3104:1994; Lengyel, Peidl 2006; Török 2009), the following tendencies seem to be important for the utilisation of ethanol as a blending component of diesel oil used in the compression ignition engine. The values are presented in Fig. 1.

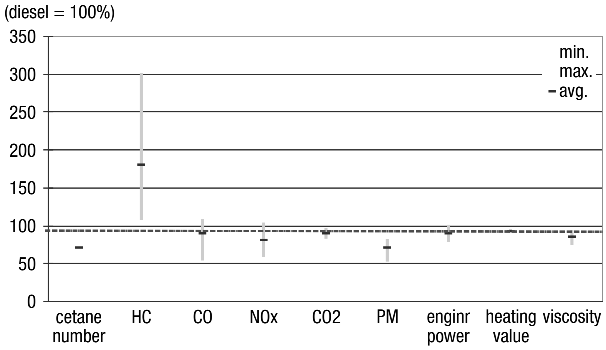

Fig. 1. A summary of the results of ethanol-diesel investigation (source: Ajav *et al.* 1999; Satgé de Caro *et al.* 2001; Aakko *et al.* 2002; Hancsók 2004; Emőd *et al.* 2005, 2006; EN ISO 3104:1994; Lengyel, Peidl 2006; Török 2009)

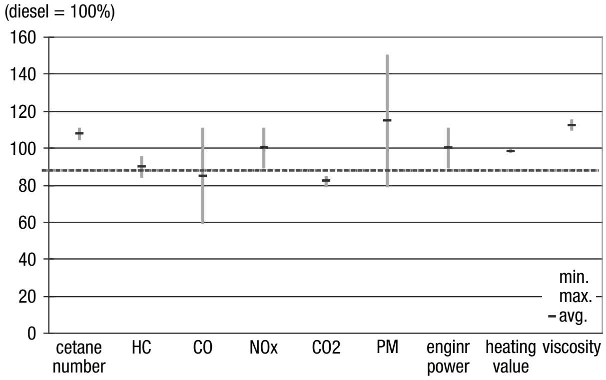

Fig. 2. A summary of the results of biodiesel-diesel investigation (source: Pächter, Hohl 1991; Emőd, Finichiu 1995; Farkas 2004; Jánosi, Földi 2004; Barabás *et al.* 2005; Hofmann *et al.* 2006; Yamane, Kawasaki 2007; Raslavičius, Bazaras 2009)

Ethanol blending with diesel decreases the cetane number. Approximately 10 v/v% of ethanol in the fuel involves approximately a 30% decrease in the cetane number. An increase in HC emission is unquestionable in literature; however, sources founded very different rates. Some investigators established an increase in some percentage, whereas others measured doubled CH emission or even more. Other emission parameters show tendencies towards reduction and only CO emission was increased in some sources. NO_x reduction could reach 50%. The effect of ethanols on particulate emission is very positive: 10% of ethanol decreases this type of emission in between 30÷50%. Ethanol decreases the heating value of the blend lower than its blending rate. The viscosity of the blends was lowered by ethanol: 10 v/v% of ethanol caused a decrease in 10÷25%.

2. Biodiesel–Diesel Blends

Based on literature (Pächter, Hohl 1991; Emőd, Finichiu 1995; Farkas 2004; Jánosi, Földi 2004; Barabás *et al.* 2005; Hofmann *et al.* 2006; Yamane, Kawasaki 2007; Raslavičius, Bazaras 2009), the following tendencies could be summarised as the main utilisation characteristics of biodiesel–diesel blends. An increasing blending rate of biodiesel increases the cetane number of the blend, which has a positive effect on HC and CO_2 emission. Other emissions are judged differently by resources. CO seems to be decreasing and NO_x was nearly the same as for diesel. Most of literature diagnosed that particulate emission was increased if the proportion of biodiesel would be increased in the blend. The power of the engine and the energy content of the blends was 1÷2% lower than that with normal diesel. The utilisation of biodiesel increases blend viscosity. The detailed results are displayed in Fig. 2.

3. Ethanol–Biodiesel–Diesel Blends

In some investigations (Aydin, İlkılıç 2010), ethanol was used as an additive to research the possible use of higher percentages of biodiesel in an unmodified diesel engine. Commercial diesel oil is produced from 20% of biodiesel mixed with 80% of diesel fuel. A blend of 80% biodiesel mixed with 20% of ethanol was investigated in a single cylinder, 4 stroke direct injection diesel engine. The effect of tested fuels on engine torque, power, brake specific fuel consumption, brake thermal efficiency, exhaust gas temperature, CO, CO_2, NO_x and SO_2 emissions was investigated. The experimental results showed that the performance of the compression ignition engine was improved using biodiesel-ethanol, particularly in comparison with 20% of biodiesel. Besides, exhaust emissions from bioethanol–diesel were fairly reduced.

Euro 5 diesel, pure biodiesel and biodiesel blended with 5%, 10% and 15% of ethanol or methanol were tested on a 4-cylinder naturally-aspirated direct-injection diesel engine reported in (Zhu *et al.* 2010). Experiments were conducted under five engine loads at a steady speed of 1800 rpm. Based on the obtained results and compared with Euro 5 diesel, the blended fuels could lead to a reduction in both NO_x and PM of the diesel engine, along with biodiesel–methanol blends being more effective than biodiesel–ethanol blends. The effectiveness of NO_x and particulate reductions is more effective with an increase of alcohol in the blends. With a high percentage of alcohol in the blends, HC and CO emissions could increase and brake thermal efficiency might be slightly reduced. Moreover, using 5% of blends could also reduce HC and CO emissions.

The diagram showing the stages of diesel–biodiesel–ethanol blends was studied (Kwanchareon *et. al.* 2007) at different purities and temperatures of ethanol. It was found that fuel properties were close to the standard limit of diesel fuel; however, the flash point of blends containing ethanol was quite different from that of conventional diesel. A high cetane value of biodiesel could compensate for a decrease in the cetane number of the blends caused by the presence of ethanol. The heating value of blends containing less than 10% of ethanol was not significantly different from that of diesel. As for emissions from blends, it was found that CO and HC reduced significantly under high engine load, whereas NO_x increased, when compared to those of diesel. Taking these facts into account, a blend of 80% of diesel, 15% of biodiesel and 5% of ethanol was the most suitable ratio for diesohol production because of acceptable fuel properties (except flash point) and reduction in emissions.

Researchers presented (Barabás *et. al.* 2010) the obtained experimental results concerning the performances and pollution of the diesel engine fuelled with diesel–biodiesel–ethanol blends comparatively with tested diesel fuel. To evaluate pollution, the emissions of CO, CO_2, NO_x, HC and smoke have been measured. An increase in brake specific fuel consumption, especially at lower engine loads, with a maximum of 32.4% reducing engine brake thermal efficiency with a maximum of 21.7% has been observed. CO emissions decrease, especially at high loads with a maximum of 59% on the basis of increased CO_2 emissions. NO_x emissions slightly increase, especially at partial and high loads, meanwhile HC and smoke emissions decrease in all load cycles of the engine.

The article (Labeckas, Slavinskas 2010) deals with results testing a 4 stroke 4 cylinder direct injection diesel engine operating on pure rapeseed oil and its 2.5v/v%, 5v/v% and 7.5v/v% blends with ethanol and petrol. The purpose of this study is to examine the effect of ethanol and petrol addition to RO on blend viscosity, percentage changes in brake mean effective pressure (bmep), brake specific fuel consumption (bsfc), the brake thermal efficiency (η_e) of the diesel engine and its emission composition, including NO, NO_2, NO_x, CO, CO_2, HC and smoke opacity of exhausts. Ethanol has a decreasing effect on blend viscosity. Biocomponents have a negative effect on fuel consumption and BMEP. The increased high NO_x emission of pure vegetable oil cannot be compensated with ethanol based on these measurements.

The diesel biodiesel–diesel oil–bioethanol mixture displays real potential uses as an alternative fuel according to (Barabás, Todoruț 2009). The idea comes from the fact that a series of properties of the two biofuels complete each other. Therefore, in this study, biodiesel and bioethanol were blended with a commercial diesel fuel at 5%, 10%, 15%, 20% and 25% and 30% on a volume basis to characterize the most relevant fuel properties of the blends such as density, viscosity, surface tension, lubricity, flash point and cold filter plugging point. The densities of diesel oil-biodiesel-bioethanol blends are in the range of 841÷852 kg/m^3, which is very close to the diesel fuel requirement related to EN 590. In the case of the investigated blends, kinematic viscosity is in the range of 2.176÷2.756 mm^2/s. The flash points of the blends containing 5% of ethanol are in the range of 16÷18°C, and those containing 10% of ethanol are less than 16°C.

The detailed analysis (Raslavičius, Bazaras 2009) of D–RME–E (diesel-rapeseed methyl ester-ethanol) characteristics was carefully performed fuelling an 18 kW capacity tractor unit equipped with the 4 stroke D21A1 diesel engine (combustion chamber consists of a dished piston). The conducted on-field test demonstrated a positive effect on the dynamic and ecological characteristics of the tractor unit while fuelling the engine with a biodiesel blend of 70% of D+30% RME (hereinafter – B30) admixed with the dehydrated ethanol additive (5 v/v%). This compound did not affect a decrease in the power of the diesel engine, and in the range of experiment error, showed a tendency of ~2% fuel economy compared to pure B30. A dramatic decrease in PM (40%), HC (25%) and CO (6%) emissions comparing to fossil diesel was observed when operating the tractor unit at maximum traction power which is a characteristic operating mode of the heavy duty transport means of agricultural purpose. NO_x emission of the proposed D–RME–E blend showed a tendency to decrease to 4% compared to B30.

4. Test Description

To reach the defined goals, the author carried out tests on an engine test bench using a 4 cylinder direct injection compressed ignition Audi engine and a single cylinder tested engine having different ratio blended fuels. Besides the cetane number, viscosity and lubricity measurements were done. These results were used for the purpose of environmental and economical investigations. The following tests and calculations during the complex investigation included cetane number determination, viscosity measurement, lubricity measurement, the engine test bench and emission measurement. Moreover, the below listed types of fuels were utilized during investigation:

- pure fuels:
  - diesel oil;
  - rapeseed–methyl–esther (biodiesel, RME);
  - bioethanol;
- bioethanol–biodiesel–diesel blends (Table 1).

Table 1. Bioethanol-biodiesel-diesel blends (source: own research)

	bioethanol [v/v%]	biodiesel [v/v%]	diesel [v/v%]
blend1	10	10	80
blend2	5	5	90
blend3	2.5	7.5	90
blend4	7.5	2.5	90
blend5	5	7.5	87.5
blend6	2.5	5	92.5
blend7	2.5	2.5	95
blend8	2	4	94
blend9	4	8	88

5. Laboratory Test Results Using Ethanol–Biodiesel–Diesel Blends

5.1. Viscosity

The author performed viscosity measurements according to EN ISO 3104:1994. This standard specifies a procedure for determining the kinematic viscosity of liquid petroleum products both transparent and solid by measuring time for the volume of liquid to flow under gravity through a calibrated glass capillary viscometer.

Dynamic viscosity can be obtained multiplying measured kinematic viscosity by the density of the liquid. The measuring principle of the standard is that time is measured for a fixed volume of liquid to flow under gravity through the capillary of the calibrated viscometer under a reproducible driving head and at a certain and closely controlled temperature. Kinematic viscosity is a product of the measured flow time and the calibration constant of the viscometer.

The repeatability of the test using test fuels is 0.005 mm^2/s^2 and reproducibility is 0.003 mm^2/s^2 in the test range.

The effect of ethanol and biodiesel on the viscosity of the blend is shown in Fig. 3. Measurements were done by the author on mixing bioethanol and biodiesel with diesel oil (a part of biofuel blended with diesel made 5÷20 v/V%) which allows holding blend viscosity according to standard EN ISO 3104:1994. The author detected the below presented formula in the field of 30÷60 °C as follows:

$$\eta_{kev} = \left(2 \cdot n_e \cdot \eta_e + 3 \cdot n_{bd} \cdot \eta_{bd} + n_g \cdot \eta_g + 0.71\right) \cdot 0.91, \quad (1)$$

where: η_{kev} – the viscosity of the blend; n_i – the ratio of components (*e* – ethanol, *bd* – biodiesel, *g* – diesel); η_i – the viscosity of components (*e* – ethanol, *bd* – biodiesel, *g* –diesel).

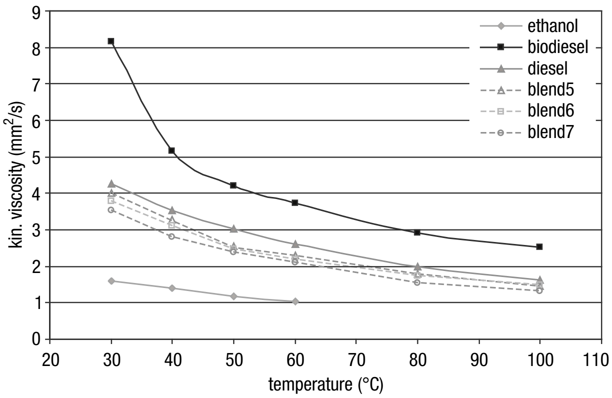

Fig. 3. The effect of ethanol and biodiesel on the viscosity of the blend (source: own measurement)

From the point of view of utility, the presented result means that a joint blend of ethanol and biodiesel has a low decreasing effect on blend viscosity in the tested blending rates. The blends can be used as diesel engine fuels due to their viscosity parameters.

5.2. Cetane Number

The author also carried out tests according to standard EN ISO 5165:1998 which sets up rating the fuel of the compression ignition engine in terms of an arbitrary scale of cetane numbers using a standard single cylinder, 4 stroke engine with variable compression ratio and indirect fuel injection. The cetane number provides a measure of the ignition characteristics of fuel in compression ignition engines. It is determined testing a precombustion chamber-type compression ignition engine at a constant speed. The standard is applicable for the entire scale range from zero cetane number (CN) to 100 CN; however, typical testing is performed in the range from 30 to 65 CN. For unconventional fuels, such as synthetics or vegetable oils, different CN can be used.

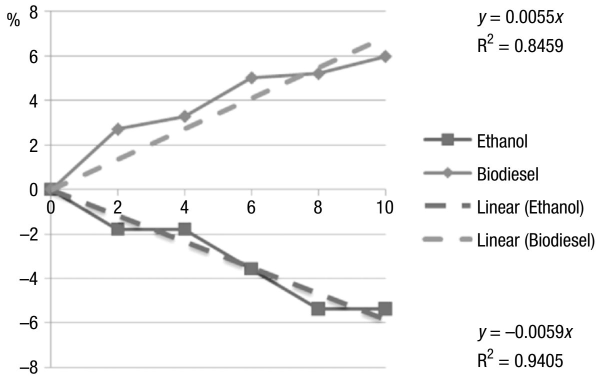

Fig. 4. The effect of blending ethanol, biodiesel and diesel oil on the cetane number (source: own measurement)

The cetane number of the fuel was measured, which resulted in a decrease in the cetane number and an increase in bioethanol and CN when mixing with biodiesel (Fig. 4). A multi linear model was applied for modelling the compensation factor of adding biodiesel and bioethanol to diesel oil. The cetane number of the blend can help with satisfying requirements for diesel. The multi linear model resulted in the below displayed formula for the dependency of cetane numbers on the content of ethanol and biodiesel. The obtained formulas show the dependency of components:

$$CN_{ebdg} = CN_d - 0.59 n_e + 0.55 n_{bd}, \quad (2)$$

where: CN_{ebdg} – the calculated cetane number of the blend; CN_d – the cetane number of diesel oil; n_e – ethanol ratio in the blend [v/v%]; n_{bd} – biodiesel ratio in the blend [v/v%].

Ethanol caused a decrease in 0.6 CN that can be well-compensated by an increase of 0.55 CN caused by biodiesel. If the goal of blending is to hold the original cetane number, then, the two components should be mixed approximately 1:1 into diesel. The result of multi linear modelling is presented in Fig. 5.

5.3. High-Frequency Reciprocating Rig (HFRR) Results

The author carried out the test according to standard ISO 12156-1:2006 using the high-frequency reciprocating rig (HFRR) (see Fig. 6). A sample of the fluid under the test is placed in a test reservoir maintained at a specified temperature of testing. A fixed steel ball is held in a vertically mounted chuck and forced against a horizontally mounted stationary steel plate with an applied load. The test ball is oscillated at a fixed frequency and stroke length while the interface with the plate is fully immersed in the fluid. The metallurgies of the ball and plate, temperature, load, frequency and stroke length are specified. The ambient conditions of temperature and humidity during the test are used for correcting the size of the wear scar generated on the test ball to a standard set of ambient conditions. The corrected wear scar diameter is a measure for fluid lubricity.

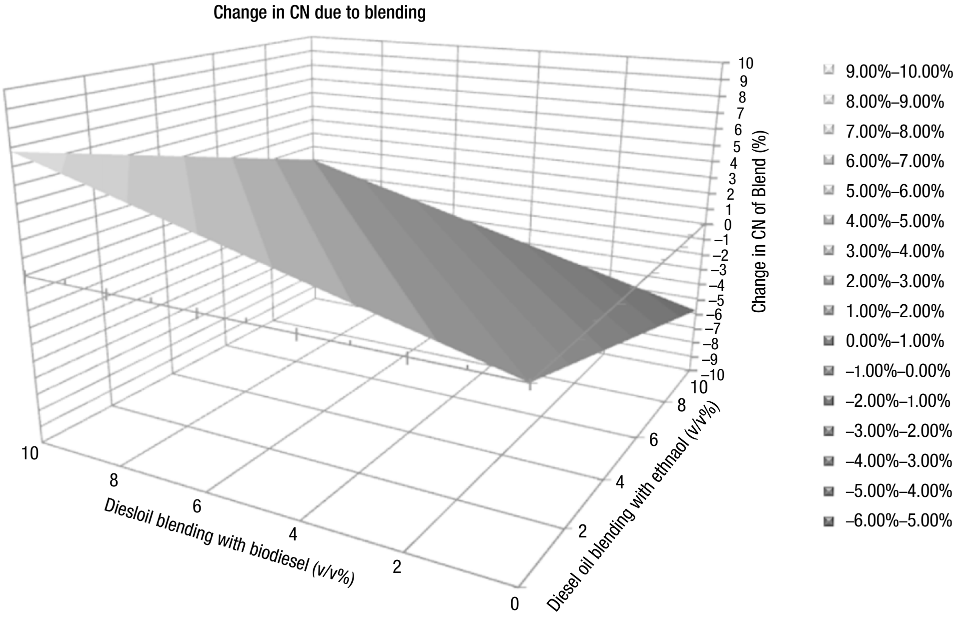

Fig. 5. The graphical results of the multi-linear model (source: own measurement)

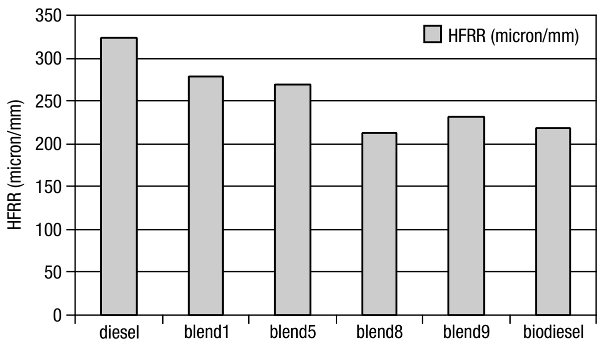

Fig. 6. HFRR results of blends (source: own measurement)

Table 2. Tested engine parameters (source: own results)

Engine manufacturer	AUDI
Volume	1896 cm^3
Cylinder nr	4
Nominal power	66 kW (90LE) 4000 1/min
Nominal torque	202 Nm 1900 1/min
Fuel system	Direct injection system
Compression ratio	19.5:1

The difference between the results of two tests obtained using the same operator and apparatus under constant operating conditions on identical test material would in the long run and normal and correct operation of the test method exceed the value given below in the case of twenty with r = 63 μm.

The difference between two single and independent results obtained using different operators working in different laboratories on identical test material would in the long run and normal and correct operation of the test method exceed the value given below in the case of twenty with r = 102 μm.

It was established that on the basis of HFRR measurements the blend of three components allows to hold blend lubricity in the range of ASTM D6079-11 standard the maximum of which makes 460 μm.

6. Engine Test Results

For testing a full load, the author employed AUDI 1.9 TDI engine running on 1.9 litres supercharged indirect injection diesel engine having 4 strokes and 4 cylinders in line (Table 2).

The engine is mounted on an AVL 160 dynamometer equipped with a data acquisition system based on the AVL system. With reference to the obtained results (Fig. 7), it was established that a decrease in the blends of power output in the TDI engine was higher than that calculated considering their lower heating value.

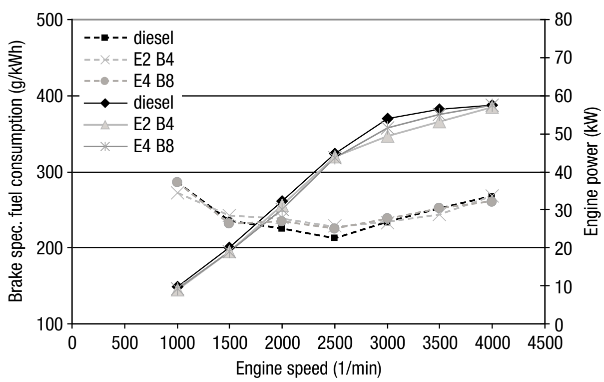

Fig. 7. The measurement results of the full load using the 1.9 TDI engine (source: own measurement)

For example, 2 v/v% of bioethanol and 4 v/v% of biodiesel (E2 B4) cause a decrease in the blend of the measured power output between 2% and 6%, although a lower heating value reaches only 1.6%. The difference is based on the running engine parameters that were optimized considering diesel fuel. Ethanol and biodiesel have different burning delay and thus causes precombustion. It is based on a shorter burning delay of ethanol and causes longer combustion with longer diffuse burning that decreases pressure and power.

7. Conclusions

The article examined the effects of mixing bioethanol and biodiesel with diesel oil and looked at the measurements of viscosity, cetane number and lubricity. Engine tests were done to determine the effects of blending on emissions. New fuel blends were analyzed applying different methods. Biofuel blends could help with decreasing energy oil dependency and lowering engine emissions. Fulfilling standards for diesel is an important aspect when determining the composition of fuel blends.

The valorisation of the obtained results shows that bioethanol–biodiesel–diesel blends fulfil the cetane number, viscosity and lubricity requirements for standard diesel. The engine tests have showed that the utilization of the new fuel decreases emissions from the engine.

Similarly to other kinds of biofuel, the process of introducing the three component blend could take place on a step-by-step basis. To improve emulsion formation, using twice more biodiesel in the blend than bioethanol is recommended. At the first stage, a blend of 1 v/v% of bioethanol, 2 v/v% of biodiesel and 97 v/v% of diesel is suggested, whereas later the bio part can be increased up to 4 v/v% of bioethanol and 8 v/v% of biodiesel according to the agricultural overflow.

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