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Smoke and NO_X emissions of combustion engine using biofuels

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Abstract. Production of solid particles significantly increases the dangerousness of combustion engines. The excellent sorbtion characteristics of the solid particles increases their harmful effects and makes them very dangerous component of emissions which causes health problems. Currently there are many design solutions which aim to reduce smoke of combustion engines. One of the most significant solutions suggests increasing the injection pressures up to the limit of 250 MPa and filtering the exhaust gases. The paper compares different fuels and biofuels, whether used alone or in mixtures, and their effect on smoke of supercharged CI engine. The comparison uses the 8-point NRSC (Non-Road Steady Cycle) test during which the following fuels were used: diesel, rapeseed methyl ester, rapeseed oil, Jatropha curcas oil, biobutanol, hydrotreated oil and other blended fuels. The measurement and comparison results show that using biofuels can significantly reduce smoke of combustion engine by up to tens of percent in comparison to diesel.

Key words: Combustion engine, biofuels, harmful emissions, performance.

INTRODUCTION

Environmental protection makes the polluters reduce production of harmful substances. This restriction significantly affects the automotive industry as well, i.e. cars, trucks and agricultural machinery. Agricultural machines are driven mainly by diesel combustion engines. The most harmful products of diesel combustion engines are particles, smoke and nitrogen oxides.

The literature describes several basic possibilities of how to reduce smoke of diesel combustion engines in order to meet increasingly strict limits set by the international regulations. (Armas et al., 2013; Sun et al., 2013; Amanatidis et al., 2014; Hwang et al., 2014; Athappan et al., 2015; Liu et al., 2015; Cao et al., 2016; Kang & Choi, 2016; Woo et al., 2016). Utilitzation of different biofuels is also one of the options.

– Butanol – In comparison with ethanol, butanol has a lower auto-ignition temperature, it is less evaporative and releases more energy per unit of mass. It also has a higher cetane number, higher energy content and better lubricating ability than ethanol and methanol. It is also less corrosive and better miscible with vegetable oils, diesel and FAME (Hönig et al., 2015a; Hönig et al., 2015b; Müller et al., 2015).

– Fame (Fatty acid methylester) – FAME has a lower mass calorific value, higher density and higher viscosity than diesel (Pexa & Mařík, 2014). FAME can be made from vegetable oil and animal fat (Sirviö et. al., 2014; Čedík et al., 2015). The inferior storage and oxidative stability are the main disadvantages of FAME. Another disadvantage of FAME is a high feedstock cost, especially when the vegetable oil is used as a raw material.

– Vegetable oil – Utilization of the vegetable oil as a fuel is known for many years. In comparison with diesel the vegetable oil is denser and has a higher viscosity. In order to utilize the vegetable oil in a conventional combustion engines it is necessary to lower its viscosity. This is usually done by preheating or in a chemical way. The rapeseed oil, sunflower oil, palm oil or oil from jatropha curcas are the most commonly used oils. (Altaie et al., 2015, Abu-Hamdeh et al., 2015; Fernandes et al. 2015; Kumar et al., 2015, Reham et al., 2015, Verma et al., 2016).

– HVO (Hydrotreated Vegetable Oil) – HVO is fuel obtained by hydrodeoxygenation of vegetable oil. It consists of paraffinic hydrocarbons with a linear chain, it is free from aromatics, oxygen and sulphur, it has a high cetane number, lower density than diesel oil and comparable calorific value. Thus there are no problems usually connected with bio diesel (FAME), such as increased NOX emission, deposit formation, storage stability problems, faster aging of engine oil or high cloud point (Aatola et al., 2008; Kučera & Rousek, 2008; Knothe, 2010; Hartikka et al., 2012; Naik et al., 2010;No, 2014;). HVO has lower fuel consumption, lower loss of power and higher motor efficiency than conventional bio diesel (Duckhan et al., 2014; Kim et al., 2014).

The aim of this paper is to verify the possibility of reducing the emission production of nitrogen oxides and solid particles (PM – Particulate Matter) by using different kinds of biofuels. The verification is done by means of the 8-point NRSC (Non-Road Steady Cycle) test applied on a turbocharged engine Zetor Forterra 8641. The purpose of the verification is to find fuels or appropriate fuel additives which reduce the production of nitrogen oxides and solid particles, do not affect other harmful emissions and do not significantly reduce the performance parameters.

MATERIALS AND METHODS

The measurement was done using the tractor engine Zetor 1204 supercharged by means of turbocharger and placed in the tractor Zetor Forterra 8641 (Fig. 1). It is in-line 4 cylinder engine, its displacement volume is 4.156 l and rated power 60 kW (it is 53.4 kW on PTO (Power Take Off) according to the measurement made by Deutsche Landwirtschafts-Gesellschaft), the maximum torque is 351 Nm, the nominal specific fuel consumption is 253 g kWh^{-1} and the rated speed is 2,200 min^{-1}. The fuel is delivered to the engine by means of mechanical in-line injection pump, injecting is done by one injection with pressure 22 MPa. The injection pressure is given by manufacturer and before measurement it was checked on the manual measuring device. The start of the injection is kept constant at 12° before top dead center. The operating time of the mentioned engine does not exceed 100 operating hours.

Figure 1. Tractor Zetor Forterra 8641 and dynamometer AW NEB 400.

The engine was loaded by the dynamometer AW NEB 400 (Fig. 1) connected to PTO, torque was recorded by the torque sensor MANNER Mfi 2,500 Nm_2,000 U min^{-1} with accuracy 0.25%. The torque values recorded by the sensor placed on PTO are converted to the engine torque by means of appropriate gear ratio (3.543). The losses in the gearbox have no effect on the comparative measuring of the influence of fuel on the external speed characteristics of the engine and therefore they are not taken into consideration. Data were saved on the hard disk of the measuring computer HP mini 5103, with the use of A/D converter LabJack U6 with frequency of 2 Hz, in the form of text file. For measurement of gaseous emissions components the emission analyser BrainBee AGS 200 was used. For measurement of the PM concentration, the opacimeter Atal AT 600 was used. The values of opacity were converted into mass concentration using the converting table given by manufacturer. The precision and measurement range of both devices is shown in the Table 1.The programmes MS Excel and Mathcad were used for data evaluation.

Table 1. Parameters of the emission analysers

	Resolution	Measurement range	Precision
NO_X	1 ppm	0–5,000 ppm	10 ppm vol. or 5% read value
PM	1 mg m^{-3}	0–900 mg m^{-3}	20 mg m^{-3}

Mixed fuels were made from the following basic fuels presented in Table 2: diesel which meets the standard EN 14 214 rapeseed methyl ester (RME), rapeseed oil, Jatropha curcas oil, n-butanol (BUT) and hydrotreated vegetable oil (HVO). The table presents parameters for these basic fuels such as: density, viscosity, cetane number and calorific value (the values of cetane number and calorific value were taken from literature). The selected mixed fuels do not harm the fuel system of the combustion engine. These fuels have appropriate viscosity and density determined by standard EN 590 and EN 14 214.

Table 2. Basic parameters of the fuels (Aatola et al., 2008; Tziourtzioumis & Stamatelos, 2012; Murali Krishna, et al., 2014; Qi et al., 2014; Atmanli et al., 2015; Kibuge, et al., 2015)

Fuel	Density at 15°C (kg m^{-3})	Calorific value (MJ kg^{-1})	Viscosity at 40 °C (mm^2 s^{-1})	Cetane number
HVO	780	44	2.5–3.5	80–99
RME	880	37.5	4.5	51
n-butanol	810	33.1	2.63	17
Rapeseed oil	918	36.995	23.91	44–48
Jatropha Curcas oil	914	39.63	46.82	45
diesel – EN 590	825	43.3	2.5	50

Based on the fuels analysis (the viscosity and density of selected fuels are presented in Table 3) the following mixed fuels were chosen:

- 100% diesel according to the regulation EN 590 (Diesel - EN 590) – the tested diesel oil contained 5.5% RME, diesel without RME additive was used for other fuel mixtures,
- 100% rapeseed oil methyl ester (100% RME),
- 100% hydrotreated vegetable oil (100% HVO),
- 19.7% rapeseed oil methyl ester / 80.3% diesel oil (19.7% RME / 80.3% Diesel),
- 33.9% rapeseed oil methyl ester / 67.1% diesel oil (33.9% RME / 67.1% Diesel),
- 48% rapeseed oil methyl ester / 52% diesel oil (48% RME / 52% Diesel),
- 5.5% Jatropha curcas oil / 94.5% diesel oil (5.5% Jatropha curcas / 94.5% Diesel),
- 19.7% Jatropha curcas oil / 80.3% diesel oil (19.7% Jatropha curcas / 80.3% Diesel),
- 5.5% rapeseed oil / 94.5% diesel oil (5.5% rapeseed oil / 94.5% Diesel),
- 19.7% rapeseed oil / 80.3% diesel oil (19.7% rapeseed oil / 80.3% Diesel),
- 10% n-butanol / 90% rapeseed oil methyl ester (10% BUT / 90% RME),
- 30% n-butanol / 70% rapeseed oil methyl ester (30% BUT / 70% RME),
- 50% n-butanol / 50% rapeseed oil methyl ester (50% BUT / 50% RME),
- 60% n-butanol / 40% rapeseed oil (60% BUT / 40% rapeseed oil),
- 30% HVO / 70% rapeseed oil methyl ester (30% HVO / 70% RME),
- 50% HVO / 50% rapeseed oil methyl ester (50% HVO / 50% RME).

Table 3. Viscosity and density of selected mixed fuels

Mixed fuels	Density at 15 °C (kg m^{-3})	Viscosity at 40 °C (mm^2 s^{-1})
10% BUT / 90% RME	869.9	3.301
50% BUT / 50% RME	844.5	2.214
30% HVO / 70% RME	851.2	3.965
50% HVO / 50% RME	831.5	3.533
60% BUT / 40% rapeseed oil	858.5	5.381

The external speed characteristics of the engine were measured for all tested fuels. Then the measuring points of the eight-point NRSC test were determined according to ISO 8178-4 (type C1) (Fig. 2.). The points of the test are defined by rotation speed (idle, at max. torque and rated) and load in percentage (0, 10, 50, 75 and 100%). The test was used for measuring the specific emissions production. According to the standard ISO 8178-4, the time spend at each speed/load point was 3 minutes and the last 60 s was used for the calculation. Specific emissions production for the whole NRSC test was calculated according to the equation (1). In every predetermined measurement point the measured parameters were stabilized.

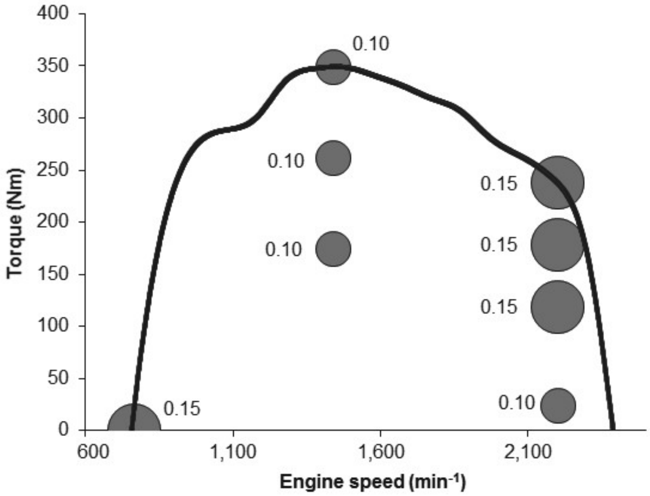

Figure 2. Measurements points for the NRSC test for HVO with weight factors.

$$m_{NRSC} = \frac{\sum_{i=1}^{8}\left(M_{Pi} \cdot WF_i\right)}{\sum_{i=1}^{8}\left(P_{PTO,i} \cdot WF_i\right)} \tag{1}$$

where: m_{NRSC} – specific emission production for whole NRSC test (g kWh^{-1}); $M_{P,i}$ – hourly emision production (g h^{-1}); WF_i – weight factor (–); $P_{PTO,i}$ – power on the PTO (kW).

RESULTS AND DISCUSSION

The resulting values showing smoke of all measured fuels are presented in Fig. 3. The mixed fuels are sorted according to the amount of smoke, from the smallest to the largest. 0.365 g kWh^{-1} was the largest smoke value reached by Diesel – EN 590. By contrast, the lowest amount of smoke 0.026 g kWh^{-1} was reached by the fuel 50% BUT / 50% RME. Changing the fuel helped to significantly reduce smoke by up to 90%. The NRSC test determined the limit of 0.4 g kWh^{-1} for this tractor engine. It can be stated that this limit was met in all cases and it is depicted in figure 3 as a line marked as Limit – PM. As a progressive value for higher category of the engines of non-road vehicles, the standard is determined more strictly to 0.025 g kWh^{-1}. Therefore it would seem that from the point of view of smoke the engine can be shifted to a higher category of emission standards only by means of using a different fuel. However, the value

0.025 g kWh^{-1} is reached during the transient NRTC cycle (Non Road Transient Cycle) which is much more demanding and the engines produce more pollutants.

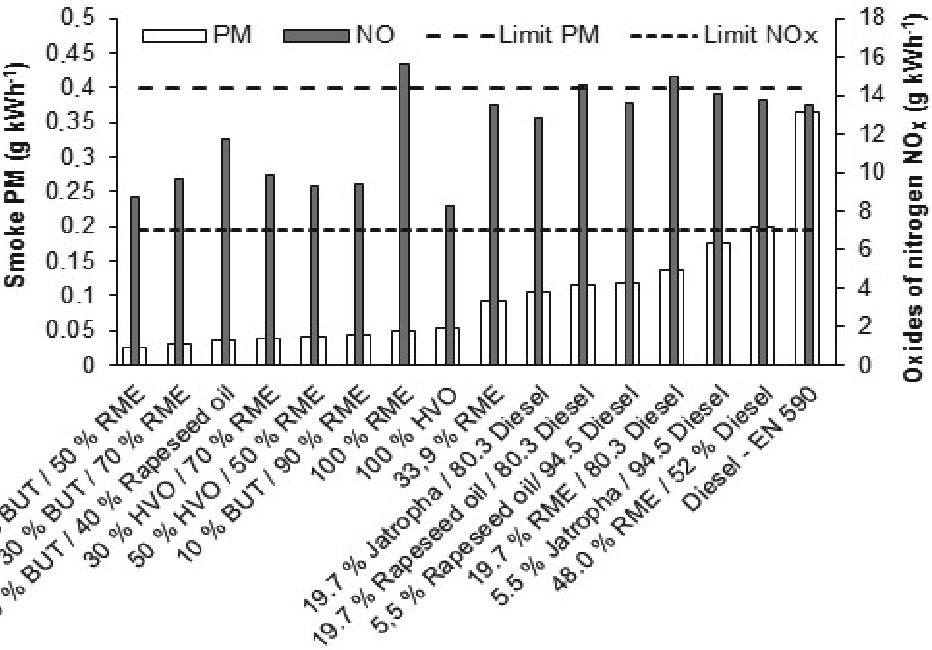

Figure 3. Production of NOx and smoke during NRSC test using different fuels.

However, the performance parameters decreased simultaneously with the smoke parameters which is a negative impact of most biofuels. Performance parameters of the best fuels decreased by more than 10%. Fig. 4 presents the limit values of torque and engine power and the performance parameters of other fuels.

From the point of view of smoke and performance parameters the best fuels are the following: 30% HVO / 70% RME, 50% HVO / 50% RME, 10% BUT / 90% RME, 100% RME and 100% HVO. From the point of view of other emission parameters for diesel engines, the nitrogen oxides are particularly monitored. Measured values of production of nitrogen oxides during the NRSC test are presented in the figure 3, as well as the limit value. It is evident that the standard value 7 g kWh^{-1} NOx is not reached by any fuel. However, the production of NOx was significantly reduced by using the fuel 100% HVO or 10% BUT / 90% RME. When compared to Diesel – EN 590 the production was reduced by 30–40% to the value close to the limit determined by the NRSC test.

Using the BUT fuel increased production of carbon monoxide, but none of the fuel samples exceeded the value determined by the NRSC test. To conclude, fuels containing n-butanol and HVO could be used more in the future.

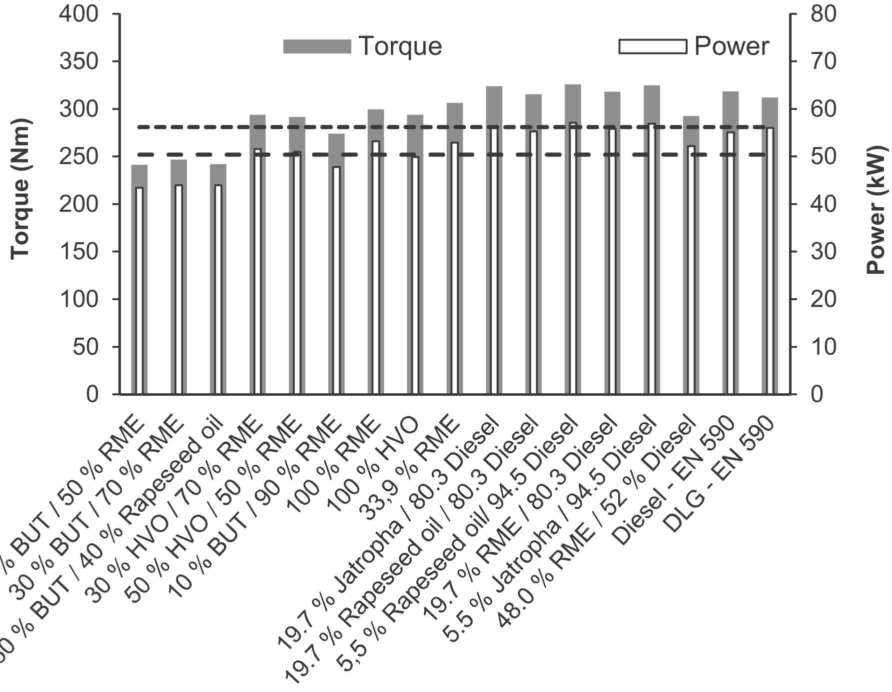

Figure 4. Performance parameters of the engine using different fuels.

CONCLUSIONS

The measuring results proved that change of fuel significantly affects the production of combustion engine pollutants. Smoke was reduced in all used mixed fuels during the standard NRSC test. It was reduced by up to 90% in comparison to the standard fuel Diesel – EN 590.

The HVO fuel and fuels containing n-butanol proved to be the most suitable because the smoke was reduced as well as and the production of nitrogen oxides which was reduced by up to 40%. The fuels containing 30 and 50% of n-butanol managed to reduce smoke the most. However, along the reduction of smoke, the performance parameters were reduced as well, by more than 10%. The resulting values of production of nitrogen oxides and smoke are presented in the figure 3 and decrease of performance parameters is presented in the figure 4.

The performed tests proved that the most suitable fuels for common CI combustion engines are fuels based on HVO or fuels containing n-butanol.

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