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THE EFFECT OF ETHANOL, PETROL AND RAPESEED OIL BLENDS ON DIRECT INJECTION DIESEL ENGINE PERFORMANCE AND EXHAUST EMISSIONS

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Abstract. The article deals with the testing results of a four stroke four cylinder, DI diesel engine operating on pure rapeseed oil (RO) and its 2.5vol%, 5vol% and 7.5vol% blends with ethanol (ERO) and petrol (PRO). 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 a diesel engine and its emission composition, including NO, NO_2, NO_x, CO, CO_2, HC and the smoke opacity of exhausts. The addition of 2.5, 5 and 7.5vol% of ethanol and the same percentage of petrol into RO, at a temperature of 20 ºC, diminish the viscosity of the blends by 9.2%, 21.3%, 28.3% and 14.1%, 24.8%, 31.7% respectively. Heating biofuels up to a temperature of 60 ºC, diminishes the kinematic viscosity of RO, blends ERO2.5–7.5 and PRO2.5–7.5 4.2, 3.9–3.8 and 3.9–3.7 times accordingly. At a speed of 1400–1800 min^{-1}, bmep higher by 1.3% if compared with that of RO (0.772–0.770 MPa) ensures blend PRO2.5, whereas at a rated speed of 2200 min^{-1} , bmep higher by 5.6–2.7% can be obtained when fuelling the loaded engine, $\lambda = 1.6$, with both PRO2.5–5 blends. The bsfc of the engine operating on blend PRO2.5 at maximum torque and rated power is respectively 3.0% and 5.5% lower. The highest brake thermal efficiency at maximum torque (0.400) and rated power (0.415) compared to that of RO (0.394) also suggests blend PRO2.5. The largest increase in NO_x emissions making 1907 ppm (24.8%) and 1811 ppm (19.6%) compared to that of RO was measured from a more calorific blend PRO7.5 (9.99% oxygen) at low (1400 min^{-1}) and rated (2200 min^{-1}) speeds. The emission of carbon monoxide from blends ERO2.5–5 throughout the whole speed range runs lower from 6.1% to 32.9% and the smoke opacity of the fully loaded engine changes from 5.1% which is a higher to 46.4% which is a lower level if compared to the corresponding data obtained using pure RO. The CO_2 emissions of carbon monoxide and the temperature of the exhausts generated by the engine running at a speed of 2200 min^{-1} diminish from 7.8 vol% to 6.3vol% and from 500 ºC to 465 ºC due to the addition of 7.5vol% of ethanol to RO.

Keywords: diesel engine, ethanol, petrol, rapeseed oil, performance efficiency, emissions, smoke opacity.

1. Introduction

Biofuels represent the best sustainable, secure and renewable alternative to mineral fuels. They include environmental concerns, foreign exchange savings and social-economical issues related to the rural sector and could also be regarded as a supplementary measure taken into account to solve the problems of mineral fuel shortage. The Directive 2003/30EC of the European Parliament and the Council (2003) promotes the use of biofuels targeting to substitute 5.75% of conventional transport fuels on the basis of energy content with biofuels and other renewable fuels by 31 December 2010.

The main objectives include replacing diesel fuel for transport purposes in European Countries realizing policy connected with meeting climate change commitments, reducing ambient air pollution and pursuing an environmentally friendly life style. To promote the intended initiatives, researchers worldwide provide bench tests attempting to enhance the use of biofuels for diesel engine fuelling, improve their performance efficiency and diminish fuel consumption and emission of exhausts.

Research works performed during the last decades with an aim to extend biofuel production and enlarge the variety of renewable fuels indicate that rapeseed oil (RO) could also be used for tractor fuelling (Bialkowski *et al.* 2004; McDonnell *et al.* 2000; Labeckas and Slavinskas 2006a; Nwafor *et al.* 2000). Potential advantages and disadvantages as well as the main properties related to the use of RO and its various blends with ethanol, petrol and

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diesel fuel for tractor engine fuelling have been elucidated in the previous investigations (Labeckas and Slavinskas 2005, 2006a, 2009a and 2009b; Nwafor *et al.* 2000).

Rapeseed oil is almost sulphur free (0.04–0.002%) the use of which for engine fuelling ensures slightly better maximum brake thermal efficiency (*bte* = 0.38–0.39) relative to that of diesel fuel (0.37–0.38), by 40.5% to 52.9% lower CO, 27.1% to 34.6% lower smoke opacity and close to zero (2–3 ppm) HC emissions (Labeckas and Slavinskas 2005). According to a considerable number of biodiesel test results summarised by Lyotko *et al.* (Льотко *и др.* 2000), brake specific energy consumption (*bsec*), the increment of cylinder gas pressure, combustion durability, engine noise, NO_x concentration and smoke density produced from vegetable oils, especially that of pure RO, are slightly better under heavy loading conditions rather than those of diesel fuel.

This environmentally friendly and renewable fuel is less depended on fiscal policy and more economically attractive especially when used as a sub-product extracted producing oilcakes for animal farming. Inexpensive low energy cold-pressing (<50 °C), filtering, sedimentation and decanting facilities could be arranged in rural areas. The use of crude RO for fuelling agricultural tractors can improve cost efficiency because of lower production and transportation prices and increase its competitiveness on the market in respect of rapeseed methyl ester (RME).

The biggest problem is linked with high RO viscosity up to 13 times higher comparing with that of commercial diesel fuel. High viscosity may create problems related to the cold-flow of pure RO worsening its delivery through the fuelling system, the performance of the injection pump and the quality of fuel spray patterns. The low volatility of RO aggravated by both a high flash point (220–280 °C) and auto-ignition temperature reaching up to 320 °C (Савельев 2006) may affect fuel evaporation, mixing with in-cylinder air and combustion, the performance of the engine and related emissions.

The analysis of the brake thermal efficiency of the diesel engine operating on rapeseed oil (RO) and its blends with ethanol (ERO), petrol (PRO) and both improving agents (EPRO) equally applied in 50:50 vol% proportions (Labeckas and Slavinskas 2009a) as well as the results of other tests conducted on diesel fuel oxygenated with ethanol up to 10vol% and more (Hansen and Zhang 2003; Hansen *et al.* 2006; Can *et al.* 2004; Lin and Huang 2003) show, that ethanol can be used for alleviating the problems of mineral fuel shortage, improving fuel combustion under heavy loads and reducing its harmful emissions.

The tests performed on the International 7.3 L engine running on a blend containing 10% of ethanol, the additive of 1% of GE Betz and 89% of low sulphur diesel fuel testified that engine performance was not affected apart from the expected 4% decrease in power output (Hansen and Zhang 2003). The authors determined that the addition of ethanol to diesel fuel diminishes PM emissions while the amount of other harmful exhausts depends largely on the engine type and varies with speed and loads (Hansen *et al.* 2001).

Ethanol addition to RO diminishes its viscosity ensuring an efficient and environmentally friendly performance of the diesel engine. As a positive property of ethanol, one can mention that ethanol is also renewable, not toxic and sulphur-free and its composition distinguishes as having lower carbon to hydrogen ratio (C/H = 4) and three-fold higher bound oxygen content (34.8%) comparing with RO having 6.5 and 10.8% respectively which, in the case of mixing with less oxygenated RO, allows to increase the local air-to-fuel equivalence ratio within fuel-rich spray patterns and achieve better combustion of big fuel portions injected ensuring a better performance of the engine; therefore, all of them embracing CO, HC emissions and smoke opacity could be diminished under heavy loads and low speeds.

It was determined (Yoshimoto and Onodera 2002) that smoke emission from the ether oxygenates blended in RO decreased linearly with an increase in the content of fuel bound oxygen. A significantly lower molecular weight of ethanol, in the order of 46 as compared to 885 for RO and the absence of sulphur contribute to the production of less soot PM and smoke under similar performance conditions. The authors noted that alcohols and alcohol-ethers allowed obtaining completely dissolved RO mixtures with the inclusion rate up to 29% and 33%, however, ethanol mixes with RO properly only up to 9%. Because of the incompatibility of RO and ethanol water absorbed at larger amounts, phase separation may occur in the blend.

On the one hand, ethanol has 19.5 times lower molecular weight and its viscosity at a temperature of 40 °C is 27 times lower than that of RO which along with a low pour point (–40 °C), may reduce oil viscosity, improve its cold-flow properties and injection, fuel spray penetration and atomisation. On the other hand, six-fold lower cetane number (8) of ethanol rather than that of RO (44–48) and its high auto-ignition temperature reaching up to 420 °C together with high volatility and tendency to absorb water may aggravate auto-ignition and stimulate misfiring cycles.

The conducted investigations on the four-stroke single-cylinder open chamber diesel engine Yanmar NFD-12 (Shudo *et al.* 2005) show that palm oil methyl ester and ethanol at the blending ratio of 10vol%, diminishes the cloud point by nearly 4 degrees and decreases a solidifying temperature of the fuel, increases the volatility and oxygen content of the blend, improves its cold-flow properties and atomisation of fuel sprays, lowers the boiling point and has a positive effect on mixture formation. The carried out and other investigations prove that the use of ethanol for RO blending is economically useful and technically acceptable.

The amounts of NO_x emissions produced from blends ERO can be dependent on the feedstock of oil used for diesel fuelling and iodine number (Peterson *et al.* 2000) and on changes in actual fuel injection and auto-ignition timings caused by differing physical properties (Tat and Gerpen 2003, 2004). The effect of biofuel blends on performance efficiency and emission changes depends also on engine design, its fuelling system, load and speed, and therefore NO, NO_2, NO_x, CO and HC emissions can also differ (Labeckas and Slavinskas 2005, 2006b).

Combustion and NO_x emissions very much depend on the composition and chemical structure of fatty acids (Graboski and McCormick 1998) and fuel physical properties (Tat and Gerpen 2004). It was determined that during tests on 6V92TA MUI engine operating on both rapeseed (canola) and soy esters blends with CARB and low sulphur diesel fuels, NO_x emission increases proportionally to the weight percent of oxygen in the fuel composition. However, in the case of biodiesel, it is not clear whether increments in NO_x emissions occur under all operating conditions or in certain regions of the engine performance map only (Graboski and McCormick 1998).

Differently, a high viscosity of RO could also be diminished by blending it with mineral petrol. The miscibility of petrol with RO (PRO) is excellent as being 4.3% lighter than ethanol it reduces the viscosity of RO even more efficiently. In addition, blends PRO are stable and no phase stratification takes place during storage that lets regard them as ones extending the variety of potential biofuels. For oil blending, low octane petrol (grade A-76/80) with a cetane number ranging from 20 to 25 and an auto-ignition temperature slightly lower (300 °C) than that of RO would be the most suitable.

The addition of petrol extends evaporation temperature range from 35 to 195–210°C comparing with that of a single boiling point (78°C) of ethanol that is very important. The earlier start of evaporation may intensify the preparation of a combustible mixture and facilitate the auto-ignition of low volatile rapeseed oil because this temperature is much lower than that of the initial distillation point of RO.

It is worth noticing that the market prices of petrol are much lower as those of sugar-beets distilled dry ethanol, and therefore the use of petrol for RO blending would be a good technical solution. Small amounts of petrol may facilitate oil flow through the fuelling system and increase fuel spray penetration and atomisation elevating engine performance on crude RO.

Lubricating properties of RO are excellent comparing with those of diesel fuel that allows blending oil with ethanol and petrol without a risk to damage the fuelling system. The density of ethanol and petrol is 13.9% and 17.6% relatively lower than that of RO (0.916 g/cm^3) and their net heating values also differ from 26.82 MJ/kg to 42.88 MJ/kg. A lower density and viscosity of both additives may affect the injected biofuel quantity, energy content accumulated within various ERO and PRO blends, biofuel mass consumption as well as the performance of the engine and its emissions.

RO distinguishes itself as having a higher start of vaporization (299 °C) related to diesel fuel (177.8 °C) and nearly the same vaporization end (345–346 °C) (Graboski and McCormick 1998), and therefore mixing RO with lighter agents may advance the start of evaporation, i.e. first, improves the quality of a combustible mixture and second, a lower cetane number of both improvers can increase NO_x emissions through longer auto-ignition delay and a higher amount of fuel premixed for rapid combustion. It is also expected that widely differing chemical and physical properties of ethanol and petrol against neat RO will affect the penetration of fuel sprays, oxygen content available for complete combustion within fuel spray patterns and close to stoichiometric conditions zones and consequently, will influence engine performance efficiency and the type of soot and NO formation along with other related emissions.

Comparing with the case of ethanol, reliable reference sources reflecting comprehensive test results of the diesel engine operating on various petrol and rapeseed oil blends are completely limited in the available literature. The deficiency of reference sources and intention to obtain a new knowledge of the performance efficiency of the diesel engine operating on petrol and rapeseed oil blends and its emission changes encouraged us to perform bench tests at various loads and speeds.

The purpose of this research was to determine the effect of adding different origin improvers such as ethanol and petrol into rapeseed oil on blend viscosity and performance efficiency of a four stroke four cylinder, direct injection diesel engine along with percentage changes in emission composition when operating on varying percentages of ERO2.5–7.5 and PRO2.5–7.5 blends. The objectives of this study may be stated as follows:

1. to conduct bench tests on the diesel engine and provide a comparative analysis of the effect of ethanol and petrol addition to rapeseed oil on brake mean effective pressure, brake specific fuel consumption and brake thermal efficiency when operating on pure RO and its blends under constant air-to-fuel equivalence ratio, $\lambda = 1.6$, and various rotating speeds;
2. to study changes in the percentage of emission composition such as nitrogen oxides NO, NO_2, NO_x, carbon monoxide CO and dioxide CO_2, the total unburned hydrocarbons HC, the smoke opacity and temperature of exhausts when operating alternately on rapeseed oil and its blends with ethanol and petrol over a wide range of loads and revolutions per minute.

2. Experimental Apparatus and Methodology of Research

Tests on a four stroke four cylinder, direct injection diesel engine D-243 have been performed. The experimental set up consists of a diesel engine, an engine test bed, fuel and air consumption metering equipments, an analyser of exhaust gases and smoke meter. The schematic diagram of the experimental set up is shown in Fig. 1.

The torque of the engine was measured using a three phase asynchronous 110 kW electrical AC dynamometer with a definition rate of ±1 Nm. The rotation speed of the crankshaft was measured applying a stand tachometer that guarantees the accuracy of ±0.2%. Fuel mass consumption was measured weighting it on the electronic scale SK-1000 with a definition rate of ±0.05 g and volumetric air flow was determined by the means of the

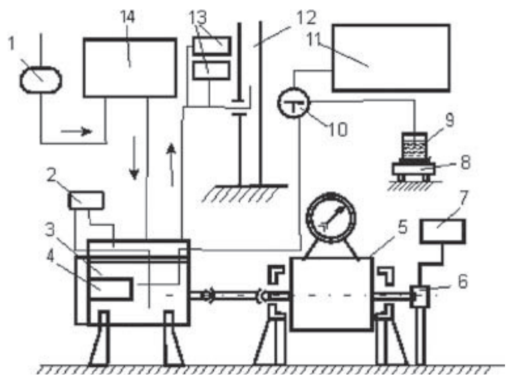

Fig. 1. A schematic view of the engine test bed: 1 – air consumption meter; 2 – oil and cooling temperature meters; 3 – engine; 4 – fuel injection pump; 5 – stand dynamometer; 6 and 7 – speed counter and tachometer; 8 – electronic scale; 9 – fuel metering vessel; 10 – fuel-tap; 11 – fuel tank; 12 – exhaust manifold; 13 – emissions and smoke opacity meters

rotor type gas counter installed at the air tank for reducing pressure pulsations. A time of 100 g of fuel and 2 m^3 of air consumption were measured with a second-meter with a definition rate of ±0.01 s. Exhaust gas temperature was measured employing a thermocouple connected to a galvanometer.

Cooling water and lubricating oil temperatures of the engine were kept within the range of 85–90 °C and monitored using thermo-electrical diesel package MKD-50M.

Biofuel was delivered with an in line fuel injection pump through five hole injection nozzle with needle valve lifting pressure of 17.5±0.5 MPa and initial fuel delivery start at 25° before TDC. In order to increase the flow rate of viscous RO, two fine porous fuel filters connected in parallel were used in the fuelling system. Fuel passing through the check valve was directed back to the transfer pump and fuel droplets penetrating through the injector needle valve unit were forwarded to the fuel metering vessel.

In order to get the baseline data, the engine was fuelled first with rapeseed oil and load characteristics were taken at constant speeds of n = 1400, 1600, 1800, 2000 and 2200 min^{-1} and torque increased from the point close to zero up to the maximum value of 290–310 Nm with increments from 4 to 5 Nm depending on the load.

After load characteristics were taken from the engine operating on rapeseed oil, three RO and ethanol (E) blends were prepared by mixing ethanol and rapeseed oil in the following proportions by volume: 97.5% RO and 2.5% ethanol (ERO2.5), 95% RO and 5% ethanol (ERO5) and 92.5% RO and 7.5% ethanol (ERO7.5). Mixing RO and ethanol in the given proportions allowed obtaining various biofuel blends with the calorific values of 36.62, 36.37 and 36.12 MJ/kg. After blends ERO2.5–7.5 had been prepared, similar experiments were performed over the same range of loads and speeds. To ensure that the fuelling system was flushed of the previous blend, the engine was operated at least for 15 min after test procedures were finished.

Afterwards, three rapeseed oil and petrol (P) blends were prepared applying the same splash mixing technique and pouring petrol into a RO container in the following proportions by volume: 97.5% RO and 2.5% petrol (PRO2.5), 95% RO and 5% petrol (PRO5) and 92.5% RO and 7.5% petrol (PRO7.5). The tests were performed again over the same range of loads and speeds. Due to the addition of more calorific petrol in RO, the net heating values of blends PRO2.5–7.5 were increased to 37.02, 37.17 and 37.32 MJ/kg respectively. In order to remove blends ERO from the fuelling system, fine porous fuel filters were changed and the engine was operated at least for 15 min.

When operating on the ethanol-diesel blends of 10vol% and higher, the additives of 1% of GE Betz (Hansen and Zhang 2003) or 1% of isopropanol (C_3H_7OH) (Schumacher *et al.* 2001) are recommended to ensure homogeneity and cold flow, to increase cetane number and to improve lubricity, volatility and auto-ignition properties. In this research, ERO2.5–7.5 and PRO2.5–7.5 blends were prepared without using fuel additives.

Along with the performance efficiency of biodiesel, its emission characteristics as well as the smoke opacity and temperature of exhausts were measured under the same loads and speeds.

The emission of carbon monoxide CO (ppm), dioxide CO_2 (vol%), nitric oxide NO (ppm) and nitrogen dioxide NO_2 (ppm) was measured employing Testo 33 gas analyser. The total emission of nitrogen oxides NO_x was determined as a sum of both NO and NO_2 components.

Afterwards, the concentration of the content of hydrocarbons HC (ppm vol%) and residual oxygen O_2 (vol%) in exhausts was determined apart from that carbon monoxide CO (vol%) and dioxide CO_2 (vol%) emissions were measured using Infrared gas analyser TECHNOTEST model 488 OIML.

Smoke density D (%) of exhausts was measured applying Bosch RTT 100/RTT 110 opacity-meter the readings of which are provided as Hartridge units scale in I – 100% with the accuracy of ±0.1%.

The analysis of brake mean effective pressure (*bmep*), brake specific fuel consumption (*bsfc*), brake thermal efficiency (*bte*) and percentage emission changes in the engine running on various ERO2.5–7.5 and PRO2.5–7.5 blends with respect to baseline parameters was performed at low 1400 min^{-1}, moderate 1800 min^{-1} and rated 2200 min^{-1} speeds. Other data on performance and emissions were also obtained at speeds of 1600 and 2000 min^{-1} and taken into account for better analysis. To guarantee more or less adequate combustion conditions for different concentration and origin blends, the analysis of engine performance and percentage emission changes in various speeds was made at constant for all combustion chamber volume air-to-fuel equivalence ratio λ determined under heavy, λ = 1.6, loading conditions.

3. Test Results and Analysis

It was determined that adding 2.5vol%, 5vol% and 7.5vol% of ethanol and the same percentages of petrol in RO diminishes oil viscosity by 9.2%, 21.3%, 28.3%

and 14.1%, 24.8%, 31.7% respectively increasing biofuel flow through fine porous fuel filters.

Heating from an ambient temperature of 20 up to 60 °C diminishes the viscosity of RO and ERO2.5–7.5 and PRO2.5–7.5 blends 4.2, 3.9–3.8 and 3.9–3.7 times. However, the effect of heating biofuels diminishes with the amount of ethanol and petrol added into RO. The lower rapeseed oil temperature is the stronger effect of adding both improvers on biofuel viscosity can be obtained and vice versa.

The combinative rapeseed oil viscosity reducing method is attractive because the treatment of oil with lighter agents facilitates starting the engine under cold weather conditions, whereas preheating in the heat exchanger allows maintaining blend viscosity acceptable for operating under moderate and heavy loads. It was determined that due to the addition of 7.5vol% of ethanol and 7.5vol% of petrol into RO with its initial viscosity of 84 mm^2/s at a temperature of 20 °C and heating blends ERO7.5 and PRO7.5 up to a temperature of 60 °C, biofuel viscosity diminishes to 16.0 and 15.6 mm^2/s, respectively.

Experiments on a Common Rail injection system demonstrated that heating decreased rapeseed oil kinematical viscosity and improved the atomisation of the fuel portions injected (Bialkowski *et al.* 2004). A large number of test results summarised by Lyotko *et al.* (Льотко *и др*. 2000) shows that the atomisation quality (mean Sauter diameter) and velocity of injected biofuel does not have a significant effect on the duration of auto-ignition delay in contrast to a substantial influence of increasing up to 1000 K temperature of the air charged, engine load and its rotating speed and the feedstock of biofuel used for diesel fuelling, i.e. its cetane number and fuel conserved oxygen content all together tend to diminish auto-ignition delay and through relevant changes in heat released from the prepared combustible mixture affect the efficiency of engine performance and its harmful emissions.

The dependencies of brake mean effective pressure (bmep) as a function of the percentage of ethanol and petrol added into RO for heavy loading conditions specified by constant air-to-fuel equivalence ratio, λ = 1.6, and five rotation speeds of 1400–2200 min^{-1} have been superimposed as shown by the columns in Fig. 2.

It was determined that when operating under heavy, λ = 1.6, load and at a low speed of 1400 min^{-1}, certain benefits could be extracted from using blend PRO2.5 because the engine fuelled with this blend develops bmep higher by 1.3%, whereas as shown in the farthermost columns in Fig. 2, fuelling the engine with blend ERO2.5 suggests bmep nearly the same 0.768 MPa as that of rapeseed oil (0.772 MPa). Running the engine on higher percentage blends results into the development the same 0.758–0.760 MPa (ERO5–PRO5) or bmep lower by 1.8% (ERO7.5) and 6.7% (PRO7.5) relative to that of pure RO.

After transition to higher speeds of 1600–1800 min^{-1}, bmep related benefits that could be utilized in the case of operating on blends ERO2.5 and PRO2.5 also remain

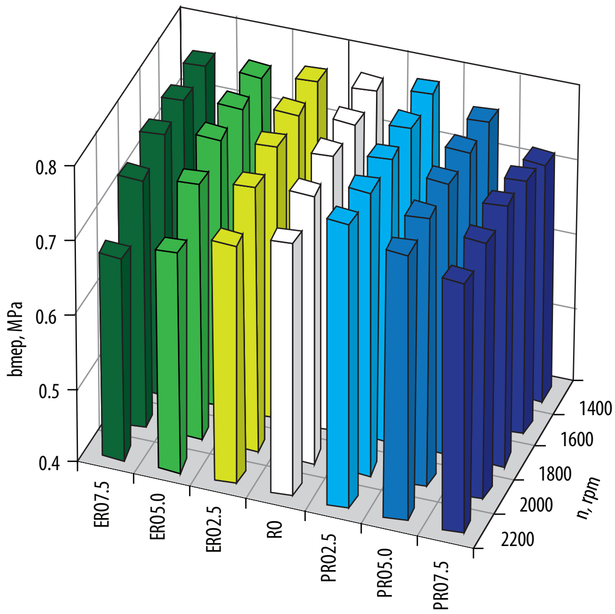

Fig. 2. Dependencies of brake mean effective pressure (bmep) on the percentage of ethanol (ERO) and petrol (PRO) added into RO for five speed ranges and constant air-to-fuel equivalence ratio, λ = 1.6

in value, 0.767–766 MPa and 0.780 MPa, whereas when using higher percentage blends ERO7.5 and PRO7.5, bmep = 0.770 MPa obtained from pure RO diminishes to bmep = 0.755–0.752 MPa and 0.740-0.750 MPa or by 2.0–2.3% and 3.9–2.6% respectively. Possible reasons leading to lower bmep when operating on more calorific blend PRO7.5 are not completely clear, however, effective power loses could be linked with a low cetane number of petrol, its advanced start of evaporation and potential danger of vapours emerging in the fuelling system.

As reflected in the columns in Fig. 2, reduction in power output developed by the loaded engine operating on less calorific blends ERO5 and ERO7.5 has already begun to occur at a speed of 2000 min^{-1}. After the speed increases up to 2200 min^{-1}, the maximum bmep = 0.740 MPa obtained from pure RO diminishes to bmep = 0.673 MPa or by 9.1% due to 7.5vol% ethanol addition into RO. A decrease in an effective power of the engine follows with corresponding changes in gas temperature that increases from 500 °C (RO) to 525 (ERO2.5) and afterwards diminishes to 512 °C (ERO5) and down to 465 °C (ERO7.5) due to the addition of ethanol.

The efficient combustion of blends ERO5–7.5 under heavy load and at a high speed of 2200 min^{-1} can be affected by a low cetane number of ethanol, its high latent heat for evaporation (910 kJ/kg) and auto-ignition temperature (420 °C). Since time intended for apropos burning of fuel rich mixtures is limited at high speed, longer auto-ignition delay and a lower calorific value of blends ERO5–7.5 may aggravate heat release diminishing the performance efficiency of the loaded engine.

In contrast to ethanol, petrol demonstrates advantages linked with its threefold higher cetane number, lower auto-ignition temperature (300 °C) and a calorific value better by 62.5% that in the case of using blends PRO2.5–5 translates into bmep higher by 5.6–2.7% relative to baseline parameters. However, adding 7.5vol% of petrol and more into RO does not lead to a better performance of the engine neither under easy nor heavy loads at a high speed of 2200 min^{-1}.

The dependencies of brake specific fuel consumption (*bsfc*) as a function of the percentage of ethanol (ERO) and petrol (PRO) premixed in RO determined for the engine operating under heavy load, specified by air-to-fuel equivalence ratio λ = 1.6 and five speeds have been superimposed as shown in Fig. 3.

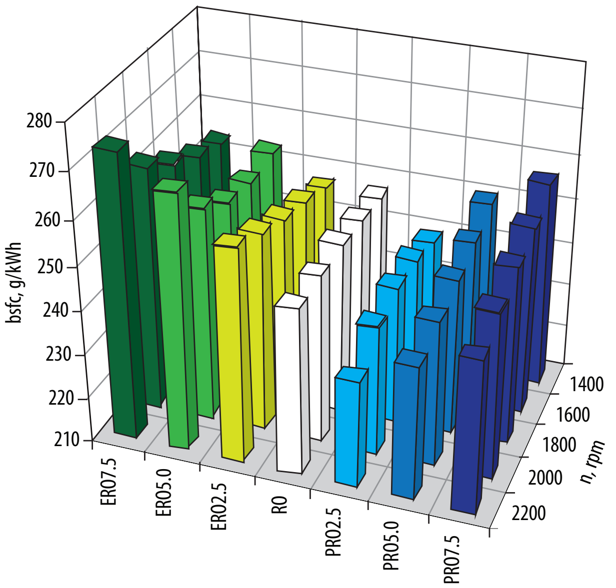

Fig. 3. Dependencies of brake specific fuel consumption (*bsfc*) on the percentage of ethanol (ERO) and petrol (PRO) added in RO and the rotational speed of a heavy loaded, λ = 1.6, engine

When analysing test results, one should bear in mind that oxygen content accumulated in blends ERO increases from 10.8% (RO) to 11.4%, 12.0% and 12.6% due to 2.5, 5 and 7.5vol% ethanol (34.8%) addition to RO, whereas when the same amounts of petrol are added, biofuel conserved oxygen diminishes to 10.53%, 10.26% and 9.99% respectively. Taking into account that the stoichiometric air-to-fuel ratio for ethanol is relatively lower (9.07) to pure RO (12.63), this translates into slightly lower 12.54, 12.45 and 12.36 values of stoichiometric air-to-fuel ratios in the case of fuelling the engine with blends ERO, whereas when using petrol for RO treatment, these ratios increase to 12.68, 12.73 and 12.77 for the same percentage of blends PRO.

Because of different biofuel oxygen contents, the air and ERO blend mixtures may reach stoichiometric conditions 1.1–3.2% faster comparing with the corresponding air and PRO blend mixtures increasing the part of fuel occupied regions ready for rapid combustion. In order to ensure the same air-to-fuel equivalence ratios for ERO2.5–7.5 blend mixtures, fuel mass portions should be slightly increased, whereas those for adequate blends PRO2.5–7.5 diminished, correspondingly. However, due to a lower density of petrol (0.755 g/cm^3) against that of ethanol (0.789 g/cm^3), for having the same air-to-fuel equivalence ratio, volumetric fuel delivery in both cases remains almost the same.

As follows from the analyzed data (Fig. 3), the bsfc of blend ERO2.5 is about similar, 247.2 g/kWh, to that of pure RO (247.0 g/kWh) at a low speed of 1400 min^{-1}. After transition to ERO5 and ERO7.5 blends, bsfc increases by 2.4% and 2.7% respectively. A higher bsfc of ERO5 and more oxygenated blends can be attributed, primarily, to a lower by 27.3% net heating value of ethanol relative to that of RO, 36.87 MJ/kg; nevertheless, it is probably not the main reason that leads to having higher biofuel consumption in mass per unit energy developed because the maximum values of brake thermal efficiency in the case of fuelling the loaded engine with considered blends (Fig. 4) are lower by 0.3% (ERO5) and 0.8% (ERO7.5).

In the case of running the engine on blend PRO2.5, brake specific fuel consumption is lower by 3.2% at a low speed of 1400 min^{-1}, whereas using higher PRO5 and PRO7.5 blends, in spite of a better calorific value, results into bsfc increase in 1.2% and 3.9% with its increment rate that is higher in case the percentage of petrol blended in the RO is also larger.

Higher bsfc values of more than 2.5vol% for both ERO and PRO blends were obtained probably because of significantly lower cetane numbers of ethanol and petrol that may increase the auto-ignition delay of biofuel portions injected under heavy loads (Льотко *и др.* 2000). The poor auto-ignition of the tested blends and aggravated combustion of heavy RO molecules do not result into better fuel economy, especially at a low speed of 1400 min^{-1} and diminished fuel injection pressures. Such estimation is especially true for the case of fuelling the engine with blends PRO5–7.5 because their net heating values increase with the percentage of petrol added in RO.

Another reason that should also be taken into account when considering a higher brake specific consumption of blends ERO5–7.5 is great latent heat, 910–915 kJ/kg, for evaporating ethanol comparing with that, 297–300 kJ/kg, of low octane petrol. According to research results obtained by Lyotko *et al.* (Льотко *и др.* 2000), higher latent heat for evaporation aggravated by a low calorific value of ethanol may create a significant cooling effect of fuel spray patterns leading to longer auto-ignition delay and a retarded start of combustion relocating diffusion combustion towards late phases of expansion stroke promoting misfiring cycles and incomplete burning. These features probably are mainly responsible as to why under considered loading conditions, bsfc increases more noticeably with revolutions in oxygenated ERO5 and higher blends.

Using petrol for RO blending purposes has proved itself as being even a more efficient measure than ethanol because it produces a more stable mixture with rapeseed oil and accelerates the start of evaporating blends PRO. However, the cetane number of petrol is also too low for a normal operation of the engine and this may increase the amount of fuel premixed for rapid combustion during the first heat release phase. Smart burning at start does not always converts into efficient diffusion combustion and adequate heat release during the expansion stroke. The problems of incomplete burning may arise more likely when an engine operates on fuel-rich mixtures, and therefore, in spite of a higher (by 16.3%) net heating value of petrol, bsfc under heavy loads, $\lambda = 1.6$, increases when more than 2.5vol% of petrol is premixed in RO.

At higher speeds of 1600–1800 min^{-1}, the increased fuel injection pressure and intensified air turbulence intensity create better conditions for adequate atomisation and distribution across a toroidal combustion chamber volume of heavy RO droplets stimulating the evaporation of the mixture and diminishing auto-ignition delay due to higher cylinder gas pressure and temperature ensuring better combustion. In spite of better preconditions, the bsfc of the engine, $\lambda = 1.6$, operating on oxygenated blends increases by 0.6–1.3% (ERO2.5), 1.6–1.8% (ERO5) and 3.2–4.4% (ERO7.5) comparing with that of pure RO, 248.0–248.7 g/kWh, for corresponding speeds. In contrast to blends ERO, when operating under the same testing conditions on more calorific petroleum treated oil, bsfc is lower by 2.8–3.0% (PRO2.5) and 0.2–1.4% (PRO5). However, as soon as the percentage of petrol added into RO increases to 7.5vol%, brake specific fuel consumption becomes higher by 2.0–0.7%.

After rotation speed increases up to 2000 and 2200 min^{-1}, the period of time intended for preheating the injected biofuel portions, evaporation, mixing with in-cylinder air, auto-ignition and complete combustion is limited. Under such circumstances, the role of the inherent properties of both improving agents resulting into bigger bsfc changes in heavy loading conditions becomes more evident.

As it is clear from the analysis of Fig. 3, bsfc increases almost proportionally with the percentage of ethanol added in rapeseed oil scaling up against that of RO, 248.0 and 247.5 g/kWh, by 2.8–4.2% (ERO2.5), 4.0–8.0% (ERO5) and 6.9–10.7% (ERO7.5) respectively at high speeds of 2000–2200 min^{-1}. In spite of better atomization of heavy oil droplets and an extra amount of ethanol oxygen available for the complete combustion of fuel-rich portions, a lower cetane number and net heating value of ethanol remain the main cause as to why a loaded engine running on oxygenated RO blends does not operate efficiently at speeds of 2000–2200 min^{-1}. The appearing combustion problems of fuel-rich air and blend ERO7.5 mixture, $\lambda = 1.6$, are posed by exhaust temperature that has lowered from 500 °C down to 465 °C at a high speed of 2200 min^{-1}.

The tests conducted using a single cylinder, DI Diesel engine operating at a constant speed of 1900 min^{-1} and fuelled with RO blended in various proportions with eight kinds of alcohols and alcohol-ethers showed similar brake specific energy consumption (bsec) at heavy loads and higher by 2–5% bsec at low loads (Yoshimoto and Onodera 2002). However, the conducted research demonstrated that combustion stability with 9vol% of ethanol blended with RO deteriorated along with decreasing engine loads, and therefore the data was not obtained over the whole operating range.

Our test results showed that the performance of a fully loaded diesel engine fuelled with higher than ERO7.5 blends was unstable at a rated speed of 2200 min^{-1}. One of the reasons leading to an unstable performance of the engine can be related to a poor miscibility of ethanol with RO (Yoshimoto and Onodera 2002). According to biodiesel test results summarised Lyotko *et al.* (Льотко *и др*. 2000), the main disadvantage of ethanol as a potential diesel fuel extender can be linked with its low cetane number, high energy consumption of evaporation at limited heat transfer from the in-cylinder air, inner engine parts and a high temperature of auto-ignition that burdens affect combustion and engine performance. The authors determined that temperature within spray patterns diminishes by up to 150–200 °C and auto-ignition delay becomes longer due to a significant cooling effect created by various diesel fuels and alcohol blends. When actual fuel injection timing advance remains nearly the same, a part of biofuel premixed for rapid combustion and its diffusion increases and burning can extend over the late-cycle of expansion stroke.

Comparing with blends ERO, the addition to petrol utilises advantages related to a three-fold higher cetane number and excellent miscibility with RO that along with its wider evaporation range, lower auto-ignition temperature and better net heating value results into the bsfc of the engine running on blend PRO2.5 lower by 3.4% and 5.5% at speeds of 2000 and 2200 min^{-1}. Lower specific fuel consumption matches well with a higher temperature of 530 °C in exhausts. In the case of operating on blends PRO5 and PRO7.5 under considered performance modes, bsfc is also lower by 2.0–3.0% and 0.2–1.4% relative to neat RO.

To evaluate the energy conversion of blends ERO and PRO, the following factors including biofuel mass consumption, the net heating value of RO and both improving agents as well as their blending ratios and biofuel oxygen contents were taken into account. The analysis of brake thermal efficiency (*bte*) was performed on the basis of data gathered all together for adequate burning conditions specified by constant air-to-fuel equivalence ratio $\lambda = 1.6$ typical for heavy loads. Under such preconditions, energy content accumulated by the air and biofuel mixtures for tested conditions remains nearly the same, 1.738–1.741 MJ/kg, and suggests a more accurate analysis of the data obtained.

As indicated in Fig. 4, when operating under heavy load, $\lambda = 1.6$, and under a low speed of 1400 min^{-1}, maximum (0.408) brake thermal efficiency develops blend PRO2.5. After transition to more petroleum treated blends PRO5 and PRO7.5, brake thermal efficiency diminishes by 2.0% and 5.3% relative to that of RO (0.396), whereas fuelling the engine with blends ERO2.5–7.5 does not greatly change the energy conversion efficiency (0.398–0.393) of the loaded engine running at a low speed of 1400 min^{-1}.

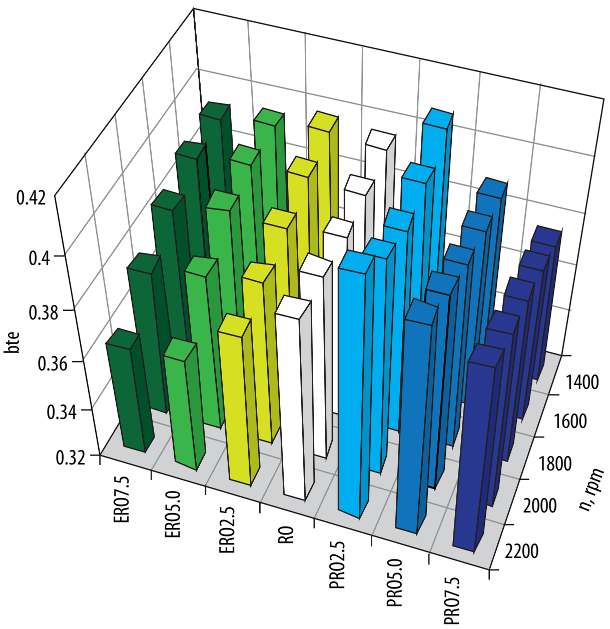

Fig. 4. Dependencies of brake thermal efficiency (*bte*) on the percentage of ethanol (ERO) and petrol (PRO) added in RO and the rotational speed of a heavy loaded, λ = 1.6, engine

At higher speeds of 1600 and 1800 min^{-1}, both PRO2.5-5 blends ensure slightly better performance and make 0.402–0.393 the brake thermal efficiency of the engine comparing with that of RO 0.393–0.392. Acceptable performance efficiency, 0.394-0.391, also suggests ERO2.5–5 blends, however, as speed increases up to 2200 min^{-1}, brake thermal efficiency 0.394 developed by the engine run on pure RO diminishes to 0.381, 0.366 and 0.364 respectively due to the addition of 2.5, 5 and 7.5vol% of ethanol.

The conducted analysis presented in Fig. 4 clearly shows that in spite that a considerable amount of fuel oxygen, 11.4% to 12.6%, accumulated in blends ERO2.5 and ERO7.5 should effectively promote combustion within fuel-rich spray patterns, it does not improve the performance efficiency of the engine operating at a speed of 2200 min^{-1}. Such outcome occurs due to the fact that time necessary for the combustion of heavy oil portions is limited at high speeds and fuel bound oxygen may come into effect with a little help and rather to be late to ensure an efficient performance of the engine (Rakopoulos *et al.* 2006).

Having lower fuel oxygen content (10.53%), the best thermal efficiency, 0.405–0.415, of the loaded engine insures blend PRO2.5 at high speeds of 2000 and 2200 min^{-1}. Nevertheless, as the amount of petrol premixed into RO increases up to 5 vol% and 7.5vol%, brake thermal efficiency diminishes to 0.398–0.404 and 0.390–0.395 respectively.

The emission of nitric monoxide NO and nitrogen dioxide NO_2 (ppm) increases with the load and their values depend on engine speed and the type of biofuel used (Labeckas and Slavinskas 2006b). In contrast to research where diesel fuel as a basic component was used for producing biofuels, the percentage of RO oxygen is higher (10.8%) and due to its blending with ethanol (34.8%) and petrol, oxygen mass contents have varied from 9.99 (PRO7.5) to 12.60% (ERO7.5).

To have a better impression about the effect of ethanol and petrol addition on the the total emission of nitrogen oxides, percentage changes in maximum NO_x emissions, as a sum of NO and NO_2, for three speeds and six biofuel blends (ERO2.5–7.5) and (PRO2.5–7.5) relative to pure RO with the corresponding NO_x emissions denoted at each set of columns have been superimposed as shown in Fig. 5. The testing results indicate that NO_x emissions emanating from blends ERO are lower than those from adequate percentage blends PRO and have a tendency to increase with the mass percent of biofuel bound oxygen; however, producing NO_x is complicated enough and needs detailed analysis.

As one can see in Fig. 5, changes in the percentage of NO_x emissions with the amount of biofuel oxygen depend on engine speed. At the speeds of 1400 min^{-1} and 1800 min^{-1}, the highest NO_x emissions reach 1723 ppm and 1617 ppm which is by 12.8% and 3.9% higher comparing with that of RO, generates more oxygen saturated (12.6%) blend ERO7.5, whereas blend ERO2.5 (11.4% oxygen) produces NO_x emissions lower by 16.2% and 13.3%. As speed increases up to 2200 min^{-1}, minimum NO_x emissions, 1369 ppm or lower by 9.6%, suggests blend ERO5 (12.0% of oxygen) and the highest NO_x emissions, 1514 ppm, generates RO having a minimum 10.8% of fuel oxygen.

As clearly shown in Fig. 5, the emission of NO_x from blend ERO2.5 has a tendency to increase with speed whereas those emanating from the engine running on blends ERO5 and ERO7.5 relatively diminish. When analysing the test results, one should remember that RO composition distinguishes from that of diesel fuel as having 10.8vol% of oxygen and oil mixing with ethanol diminish the net heating value of the blend that at higher ethanol additions may affect the emission of NO_x due to lower cylinder gas pressure and flame temperature.

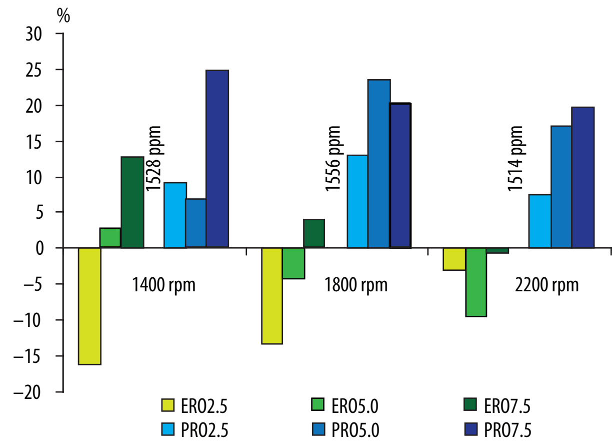

Fig. 5. Percentage changes in maximum nitrogen oxides (NO_x) emissions depending on the amount of ethanol (ERO2.5–7.5) and petrol (PRO2.5–7.5) added in rapeseed oil (RO) for three speed ranges

Taking into account the above mentioned circumstances, it seems to be clear why the behaviour of NO_x emissions from blends ERO2.5–7.5 actually differs from that obtained from a four cylinder turbocharged indirect-injection diesel engine fuelled with 10vol% and 15 vol% ethanol-diesel blends where the addition of ethanol reduces CO, soot and SO_2 emissions and causes an increase in NO_x emissions and power reduction by 12.5% and 20% at high speeds of 2500–3000 min^{-1}. Lower CO emissions and soot were measured because of higher oxygen content in ethanol-diesel fuel blends and more complete burning, whereas increased ignition delay followed by higher cylinder pressure and combustion temperature resulted in slightly higher NO_x emissions (Can *et al.* 2004).

In the case of using blends ERO5–7.5, due to cooling effect caused by fuel sprays, the combustion efficiency and production of harmful emissions depend on auto-ignition conditions (Льотко *и др.* 2000). Because higher amounts of ethanol may aggravate the auto-ignition of fuel-rich mixtures, the loaded engine running on plenty oxygenated blends ERO does not operate steadily at a high speed of 2200 min^{-1}. This could be an answer to why maximum NO_x emissions emanating from blends ERO5–7.5 relatively diminish along with speed. In the case of fuelling the engine with oxygenated blends ERO at high speeds, cylinder gas temperature plays a key role in producing $NO_{x,}$, and therefore higher amounts of ethanol in RO blends suppress maximum NO_x emissions.

Such point of view support changes in NO_x emissions determined in the case of fuelling the engine with various blends of PRO2.5–7.5. Despite the fact that adding petrol diminishes the content of biofuel oxygen, the improved net heating value, better atomisation of fuel sprays and the final combustion occurring earlier in the expansion stroke may cause higher cylinder peak temperature and create more favourable conditions for NO_x production (Schumacher *et al.* 2001). It is worth noticing that blend PRO7.5 having minimum fuel bound oxygen (9.99%) due to a higher net heating value (37.32 MJ/kg) produces maximum NO_x emissions, 1907 ppm (24.8%), at a speed of 1400 min^{-1} and tends to increase NO_x to 1811 ppm (19.6%) at high revolutions reaching 2200 min^{-1}. At a speed of 1800 min^{-1}, maximum NO_x emissions, 1924 ppm or higher by 23.7%, produce blend PRO5 (10.26% oxygen). The highest NO_x emissions emanating from blend PRO5 are from 3.9% to 29.4% higher than those produced from adequate blend ERO5 at speeds of 1400 and 1800 min^{-1}.

The analysis of the acquired data shows that NO_x emissions increase up to a certain degree with the amount of ethanol or petrol added in RO, however, changes in their behaviour with engine speed for blends having different concentration and origin are different. According to research by Heywood (1988), the processes of pollutant formation are strongly dependent on fuel distribution and the way distribution changes during a certain period of time due to mixing.

From such point of view, it is clear why minor differences in changes in the emission of NO_x for the same percentage of ERO and PRO blends were registered when operating at a speed of 1400 min^{-1} and the larger ones at higher speeds. Thus, in the case of oxygenated RO, changes in the behaviour of NO_x emissions with the percentage of ethanol in blend composition actually belong on engine performance efficiency and differ from the test results of diesel fuel and ethanol blends obtained by many other researchers where a direct dependency of NO_x emissions on the weight percent of fuel bound oxygen was reported (Peterson *et al.* 2000; Tat and Gerpen 2004; Graboski and McCormick 1998; Schumacher *et al.* 2001; Rakopoulos *et al.* 2006).

According to the test results of International engine T 444E HT operating on 5% and 10% ethanol-diesel fuel blends, diminishing NO_x emissions was also measured by 3% and the authors came to the conclusion that ethanol could act as an effective additive reducing NO_x emissions (Hansen *et al.* 2006). Other conducted tests on biodiesel using V–8 diesel fuelled with 100% soy methyl ester, 2% biodiesel, 10% ethanol-diesel fuel and 5% ethanol also showed that no correlation existed between fuel bound oxygen and total NO_x emissions (Yuan *et al.* 2005).

In order to gain more knowledge about the peculiarities of biofuel combustion, particular interest was focused on percentage changes in NO and NO_2 emissions at a constant overall air-to-fuel equivalence ratio of $\lambda = 1.6$ for three speed ranges and six biofuel blends (ERO2.5–7.5) and (PRO2.5–7.5) relative to RO with the corresponding data denoted at each set of columns as illustrated in Fig. 6.

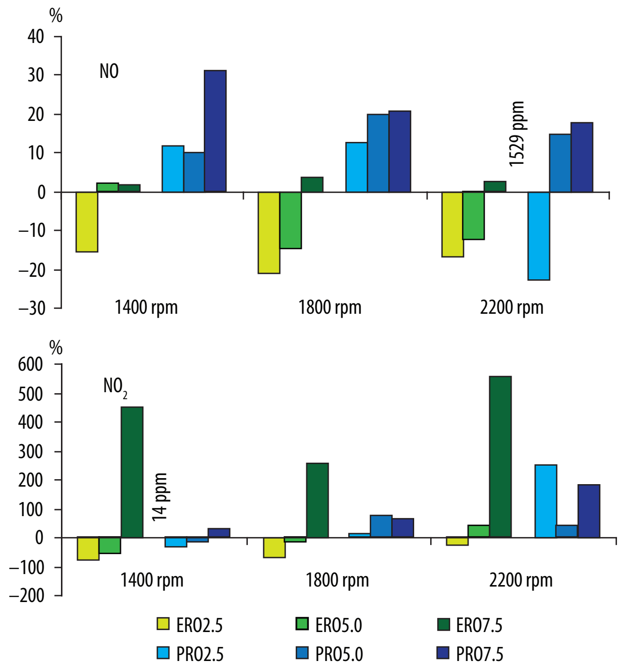

Fig. 6. Percentage changes in nitric oxide NO and nitrogen dioxide NO_2 emissions depending on the amount of ethanol (ERO2.5–7.5) and petrol (PRO2.5–7.5) added in rapeseed oil (RO) for three speed ranges at a constant air-to-fuel equivalence ratio, $\lambda = 1.6$

As follows from data analysis, when running the fully loaded engine on blends ERO, emissions of nitric oxide NO are lower, especially those produced from blend ERO2.5, 1218 ppm (15.5%), 1113 ppm (21.0%) and 1273 ppm (16.7%) at speeds of 1400, 1800 and 2200 min^{-1}. An important point is that diminished NO emissions from blend ERO2.5 are accompanied by lower levels of nitrogen dioxide NO_2, 3 ppm (78.6%), 6 ppm (68.4%) and 9 ppm (30.8%) respectively. More or less similar NO and NO_2 emissions also suggest blend ERO5, however, using more oxygenated blend ERO7.5 leads to a rapid increase in NO_2 emissions and those scale up 5.5, 3.6 and 6.5 times respectively.

Nitrogen dioxide emissions produced from RO remain at a low level of 13 to 19 ppm, and therefore a big NO_2 increase in the case of fuelling the engine with blend ERO7.5 can be connected with a significant cooling effect caused by the evaporation of ethanol with low cetane properties which may extend auto-ignition delay, stimulate misfiring cycles and lead to the poor burning of big fuel portions injected under heavy loads (Yoshimoto and Onodera 2002). Considering the behaviour of NO_2 emissions shows that the combustion of blend ERO7.5 is complicated and can be affected by the emergence of cooler regions that are widespread across the combustion chamber and may quench flame retarding conversion back to NO (Heywood 1988).

Flame temperature related nitric oxide NO emissions produced from more calorific blends PRO are higher and have a tendency to increase up to a certain degree with the load, speed and percentage of petrol added in RO that matches well with better performance efficiency of the engine (Fig. 4). When operating on blends PRO2.5 and PRO5, the emission of NO relatively increase with speed reaching maximum values at certain intermediate revolutions, whereas in the case of using blend PRO7.5, those have a tendency to diminish, 1890 ppm (31.1%), 1701 ppm (20.7%) and 1798 ppm (17.6%) at speeds of 1400, 1800 and 2200 min^{-1}.

The emission of nitric dioxide NO_2 produced from the tested blends is nearly tenfold lower than NO, however, increase with load from close to zero (2–3 ppm) level to maximum 85 ppm (ERO7.5) and 46 ppm (PRO2.5) at rated power remaining at up to 6.5 and 3.5 times higher levels relative to that of RO (13 ppm).

Nitrogen dioxide NO_2 emissions measured from blends PRO also show increasing tendencies for speed and in the case of using blend PRO2.5, change from 35.7% lower (1400 min^{-1}) to 3.5 times higher (2200 min^{-1}) level relative to that measured from pure RO. It is worth noticing, that NO_2 emissions from blend PRO7.5 remain lower within the whole speed range than those produced from an adequate percentage of oxygenated blend ERO7.5. The analysis of Fig. 5 and Fig. 6 shows certain NO_x and NO related disadvantages that could be actually appreciated as unavoidable trade-off due to achieving a more efficient performance of the engine operating on more calorific blends PRO because the evaporation of petrol starts earlier and its latent heat is lower comparing with that of ethanol.

The dependencies of carbon monoxide CO emissions and smoke from exhausts as a function of the percentage of ethanol (ERO2.5-7.5) and petrol (PRO2.5-7.5) added in rapeseed oil for three speeds and a constant air-to-fuel equivalence ratio, $\lambda = 1.6$, have been superimposed as shown in Fig. 7. The first issue clearly visible in the columns is that in the case of running the fully loaded engine on ERO2.5-5 blends, CO emissions throughout the whole speed range of 1400-2200 min^{-1} are from 6.1% to 32.9% lower comparing with those generated by pure RO. An exception belongs only to mostly oxygenated blend ERO7.5 producing CO emissions from 16.4% to 29.2% higher at speeds of 1800 and 2200 min^{-1} which remains in a good agreement with the behaviour of NO_2 emissions (Fig. 6) under considered performance modes.

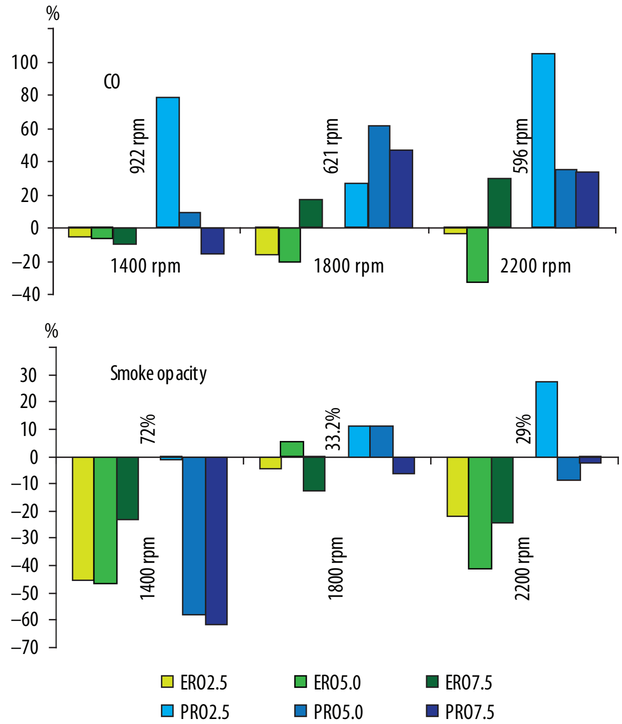

Fig. 7. Percentage changes in carbon monoxide CO emissions and smoke opacity from exhausts depending on the amount of ethanol (ERO2.5–7.5) and petrol (PRO2.5–7.5) added in rapeseed oil (RO) for three speed ranges at a constant air-to-fuel equivalence ratio, $\lambda = 1.6$

Higher CO emissions have been measured due to the low octane properties of ethanol and incomplete burning of blend ERO7.5. Time intended for clean combustion is limited at high speeds that along with longer auto-ignition delay and a later start of combustion converts into higher CO emissions. However, higher fuel oxygen content in the case of using blend ERO7.5 tends to diminish CO by 9.65% at a low speed of 1400 min^{-1}.

The opacity of exhausts from the fully loaded engine operating on blend ERO5 is also lower by 46.4% and 41.4% at speeds of 1400 min^{-1} and 2200 min^{-1}. The test results show that the final combustion of oxygenated blends ERO at late phases of the expansion stroke may lead to the lower emission of NO, CO, HC and smoke but does not contribute to having better brake mean effective pressure, higher thermal efficiency and biofuel savings at a high speed of 2200 min^{-1}.

As expected, CO emissions generated by petroleum treated blend PRO2.5 are higher, especially at speeds of 1400 min^{-1} (77.7%) and 2200 min^{-1} (104.7%). However, it is worth noticing, that in the case of blending plenty oxygenated RO with oxygen-free petrol, CO emissions and smoke opacity do not always increase at higher 5vol% and 7.5vol% blending ratios. Against expectations, the higher percentage of petrol is added in RO, the lower CO and smoke are obtained from the loaded engine. This finding, with small variations, remains in value throughout the whole tested speed range of 1400–2200 min^{-1}. Lower CO emissions and smoke probably may occur because of inherently big oxygen content (10.8%) in RO composition which due to the lower viscosity of blends PRO7.5, better atomisation of heavy RO droplets and a higher net heating value of petrol stimulates combustion.

The addition of 7.5vol% of petrol to RO diminishes both CO emissions by 15.5% and smoke opacity by 61.4% from the loaded engine operating at a low speed of 1400 min^{-1}. In spite of the aggravated combustion of big biofuel portions injected, smoke opacity produced by the engine operating on blend PRO7.5 sustains by 6.3% and 2.4% lower levels for higher speeds of 1800 and 2200 min^{-1}. Better smoke transparency actually means reducing both soot particles and the amounts of variable size volatile or soluble organic compounds (PM) suspended in exhausts (Graboski and McCormick 1998).

The emission of unburned hydrocarbons HC from blends ERO2.5–7.5 and PRO2.5–7.5 is very small, makes 2–16 ppm and increases gradually with the load and portion of the fuel injected. In the case of fuelling the engine with pure RO, the emission of HC reaches maximum only at 6 ppm. Low HC emissions may indicate a good technical state of the engine; however, a certain escape of unburned HC is unavoidable due to the condensation of the heaviest hydrocarbons within the filter-precipitator upstream of the detector (Gratton and Hansen 2003).

The addition of ethanol and/or petrol in RO tends to increase HC emissions for all performance modes since the presence of lighter fractions stimulates fuel access into an in-between cylinder and piston head and compression ring gaps where flame quenching effect takes place (Heywood 1988). The test results show that HC emissions do not change very much in speed and the percentage of ethanol and petrol suspending for blends ERO at slightly lower levels than those emanating from adequate percentage blends PRO under the same loads. Lower HC emissions emanating from blends ERO2.5–7.5 have been measured probably because of higher oxygen content (34.8%).

The emission of carbon dioxide CO_2 increases along with load and biofuel consumption in mass. In spite of higher fuel mass consumption obtained when fuelling the engine with blend ERO7.5, CO_2 the emissions and temperature of exhausts are lower at a constant air-to-fuel equivalence ratio, $\lambda = 1.6$, and due to the addition of 7.5vol% of ethanol, diminish from 7.8 to 6.3vol% and from 500 to 465 °C at a speed of 2200 min^{-1}. Lower CO_2 emissions were measured because of better C/H ratio (4.0) in ethanol composition against that of petrol (5.9). Comparing with ERO7.5 case, CO_2 emissions and exhaust gas temperature from the engine operating under adequate testing conditions on blend PRO7.5 increase up to 7.6vol% and 512 °C.

4. Conclusions

1. The brake mean effective pressure of the engine running under heavy loads, $\lambda = 1.6$, depends actually on the speed and biofuel used. At a low speed of 1400 min^{-1}, the engine fuelled with blends PRO2.5 develops bmep higher by 1.3%, whereas blend ERO2.5 suggests bmep the same as that of RO (0.772 MPa). At a speed of 1800 min^{-1}, bmep related benefits for both ERO2.5 and PRO2.5 blends remain in value, whereas after transition to a speed of 2200 min^{-1}, maximum bmep = 0.740 MPa obtained from pure RO increases by 5.6–2.7%% when fuelling the engine with blends PRO2.5–5 and diminishes to bmep = 0.673 MPa or by 9.1% due to the addition of 7.5vol% of ethanol.
2. The brake specific fuel consumption of the engine operating on blend PRO2.5 is lower by 3.2% and in the case of using blend ERO2.5, is about similar to that of RO (247.0 g/kWh) at a speed of 1400 min^{-1}. At a speed of 1800 min^{-1}, bsfc for blends ERO2.5–7.5 increases by 1.3–4.4%, whereas that for blends PRO2.5–5 diminishes by 3.0–1.4%. At a rated speed of 2200 min^{-1}, better fuel economy (5.5%) also suggests blend PRO2.5, whereas the bsfc of blends ERO2.5–7.5 increases against that of RO (247.5 g/kWh) by 4.2–10.7%, respectively.
3. The dependencies of brake thermal efficiency on the percentage of ethanol and petrol added in RO vary with engine load and speed. When operating under heavy load, $\lambda = 1.6$, and at a low speed of 1400 min^{-1}, better brake thermal efficiency (0.408) develops blend PRO2.5. At a speed of 1800 min^{-1}, a little higher thermal efficiency (0.400–0.393) relative to that of RO (0.392) ensures both PRO2.5-5 blends, whereas at a rated speed of 2200 min^{-1}, the best performance efficiency (0.415) suggests blend PRO2.5 comparing with that (0.394) of pure RO.
4. The biggest NO_x emissions, 1907 ppm (24.8%) and 1811 ppm (19.6%), relative to those of RO produce more calorific blend PRO7.5 (9.99% oxygen) at speeds of 1400 min^{-1} and 2200 min^{-1}; however, at a speed of 1800 min^{-1}, the highest amounts of NO_x, 1924 ppm or by 23.7% higher, emanate from blend PRO5 (10.26% oxygen). Adding from 2.5vol% to 7.5vol% of ethanol to RO also tends to increase NO_x emissions due to extra fuel bound oxygen available at speeds of 1400–1800 min^{-1}, however, after transition to a higher speed of 2200 min^{-1}, cylinder gas temperature may play a key role in producing NO_x, and therefore the addition up to a certain percentage of less caloric ethanol can suppress NO_x emissions.

5. The emission of nitrogen dioxide NO_2 increase with load from nearly 2–3 ppm to maximum 85 ppm (ERO7.5) and 46 ppm (PRO2.5) at a speed of 2200 min^{-1} suspending at up to 6.5 and 3.5 times higher levels relative to those emanating from RO (13 ppm). The emission of nitric oxide NO is lower from blend ERO2.5, 1218 ppm (15.5%), 1113 ppm (21.0%) and 1273 ppm (16.7%) at the tested speeds of 1400, 1800 and 2200 min^{-1} accompanied by lower nitrogen dioxide NO_2 levels, 3 ppm (78.6%), 6 ppm (68.4%) and 9 ppm (30.8%) relative to those of RO.
6. The emission of carbon monoxide CO emanating from blends ERO2.5-5 throughout the whole speed range is from 6.1% to 32.9% lower and smoke opacity for the loaded engine, $\lambda = 1.6$, operating on blend ERO5 changes by 5.1% from a higher (1800 min^{-1}) to 46.4% lower (1400 min^{-1}) level comparing with the data obtained for pure RO. In contrast to ethanol case, CO emissions from blends PRO2.5–5 are relatively higher tending to diminish for higher 7.5vol% blending ratio and smoke opacity from the fully loaded engine fuelled with blend PRO7.5 is also lower by 61.4% at a speed of 1400 min^{-1}.
7. The emission of hydrocarbons HC is very small, 2–16 ppm, and does not undergo significant changes neither in engine load, a portion of the fuel injected, speed nor the percentage of ethanol and petrol added in RO. However, HC emissions from blends ERO sustain throughout the whole speed range at slightly lower levels than those measured from adequate percentage blends PRO under the same loads.
8. The emission of carbon dioxide CO_2 increases with load and fuel mass consumption. Despite of bigger amounts of blend ERO7.5 used for effective power developed under $\lambda = 1.6$, the CO_2 emissions and temperature of exhausts are lower and diminish from 7.8vol% to 6.3vol% and from 500 °C to 465 °C due to the addition of 7.5vol% of ethanol at a speed of 2200 min^{-1}.

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