PERFORMANCE AND EMISSION CHARACTERISTICS OF OFF-ROAD DIESEL ENGINE OPERATING ON RAPESEED OIL AND ETHANOL BLENDS

Gvidonas Labeckas, Stasys Slavinskas
Lithuanian University of Agriculture
gvidonas.labeckas@lzua.lt, stasys.slavinskass@lzua.lt

Abstract. This article presents the bench testing results of a four stroke, four cylinder, direct injection, unmodified, naturally aspirated diesel engine operating on neat rapeseed oil (RO) and its 7.5 vol% blend with ethanol (ERO7.5). The purpose of the research was to investigate the effect of ethanol inclusion in the RO and preheating temperature on biofuel viscosity, engine brake power, specific fuel consumption, brake thermal efficiency and emission composition changes, including NO, NO2, NOx, CO, CO2, HC and opacity of the exhausts.

It was determined that inclusion in the RO 7.5 vol% of ethanol blend viscosity at ambient temperature of 20°C diminishes by 28.3%. During operation under constant air-to-fuel equivalence ratio $\lambda = 1.6$ at the maximum torque mode 1800 min$^{-1}$ and rated 2200 min$^{-1}$ speed blend ERO7.5 ensures the power output lower correspondingly by 2.3% (bmep = 0.752 MPa) and 9.1% (bmep = 0.673 MPa) than that of neat RO case. The bsfc at maximum torque (259.7 g/kWh) and rated power (274.0 g/kWh, for blend ERO7.5 is higher by 4.4% and 10.7% comparing with neat RO and the brake thermal efficiency lower by 1.5% and 7.6%, respectively. The tests revealed also that during operation of the fully loaded engine at rated 2200 min$^{-1}$ speed, ethanol inclusion in the RO up to 7.5 vol% diminishes NO, NOx, HC, CO2 emissions, smoke opacity and temperature of the exhausts however it may increase simultaneously NO2, NO2/NOx and CO emissions.

Key words: diesel engine, rapeseed oil, ethanol, effective parameters, emissions, smoke opacity.

Introduction

Directive 2003/30EC of the European Parliament and Council calls for Member States to ensure a minimum proportion of biofuels and other renewable fuels for transport purposes on their markets by 31 December 2010 shall be 5.75% on the basis of energy content. To achieve this goal, along with Rape Methyl Ester (RME), neat rapeseed oil (RO) could also be used for the local tractor fuelling. Potential advantages and disadvantages of the RO as biofuels variety extender have been elucidated in investigation [1]. RO is also sulphur free (0.04-0.002%), during short term application suggests a bit higher maximum brake thermal efficiency (bte = 0.38-0.39) than that of the 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 [2]. This environmental friendly and renewable fuel is less depended on the fiscal policy and more economically attractive especially when applied along with pressing of oilcake for farming. Bearing in mind that inexpensive low energy cold-pressing (<50 °C), filtering, sedimentation and decanting facilities could be established in some rural areas, usage of neat RO suggests advantages related to minimised production and transportation prices and its competitiveness on the market could be even better comparing with RME.

However, the biggest problem associates with high viscosity of RO that at ambient temperature of 20 °C is about 13 times higher than that of traditional diesel fuel. High viscosity of neat RO may aggravate oil flow in the fuel lines worsening injection pump performance and fuel spray patterns, its lower volatility and higher both flash point (220-280 °C) and auto-ignition temperature (320 °C) may affect biofuel evaporation and combustion, engine performance efficiency and related emissions.

One of the ways to reduce oil’s viscosity is its mixing with a lighter ethanol that is also renewable and environmental friendly, safe to store and easy to handle, not toxic and sulphur free material, and when applied in proper proportions, ethanol can increase the energy conversion efficiency, improve fuel economy, solve the fuel shortage problems and reduce harmful emissions of the exhausts [3]. Ethanol differs as having 19.5 times lower molecular weight and its viscosity at temperature of 40 °C is 27 times lower than that of RO, which along with low pour point at the temperature below of -40 °C may reduce blend’s viscosity and improve its flow through delivery lines, increase fuel sprays penetration, injection and atomisation quality. However, low both calorific value (26.82 MJ/kg) and cetane number (8) of ethanol, its high auto-ignition temperature of about 420 °C and high latent heat of evaporation (910 MJ/kg) may create significant cooling effect of the fuel sprays and lead to longer...
auto-ignition delay, retarded start of combustion and relocate all the phases of process towards the expansion stroke and provoke misfiring cycles [4].

The purpose of the research is to investigate the effect of ethanol inclusion in the RO and preheating temperature on blend’s viscosity and conduct comprehensive bench tests to study the brake mean effective pressure, brake specific fuel consumption, brake thermal efficiency, smoke opacity of the exhausts and emission composition changes, such as nitrogen oxides NO, NO₂, NOₓ, carbon monoxide CO and dioxide CO₂, and total unburned hydrocarbons HC when fuelling the engine alternately with neat rapeseed oil and its 7.5vol% blend with ethanol over a wide range of loads and speeds.

**Objects, apparatus and methodology of the research**

Tests have been conducted on popular in Baltic’s 59 kW DI diesel engine Belarus D-243. In order to increase flow rate of viscous RO the fuelling system was modified by mean of installing of two joined in parallel a honeycomb shaped design fine porous fuel filters. The fuel was delivered by an in line fuel injection pump thorough five holes injection nozzles with the initial fuel delivery starting at 25° before top dead centre. The needle valve lifting pressure for all injectors was set to 17.5±0.5 MPa.

Load characteristics of the engine were taken at the revolution frequencies 1400, 1600, 1800, 2000 and 2200 min⁻¹ when running it alternately on neat RO and its 7.5vol% blend with ethanol. The engine load characteristics were taken with a gradual increase from the point that was close to zero up to its maximum value of 290-310 Nm. This means that the effective power of the engine at rated 2200 min⁻¹ speed had been changed from the minimum up to 110% of its rated value.

Torque of the engine was measured with 110 kW electrical AC stand dynamometer and the revolution frequency of the crankshaft was determined with the universal ferrite-dynamic stand tachometer TSFU-1.

The fuel mass consumption was measured by weighting it on the electronic scale SK-1000 and the volumetric air consumption was determined by means of the rotor type gas counter RG-400-1-1.5 installed at the air tank for reducing pressure pulsations.

The amounts of carbon monoxide CO (ppm), dioxide CO₂ (vol%), nitric oxide NO (ppm), nitrogen dioxide NO₂ (ppm) and the residual content of oxygen O₂ (vol%) in the exhausts were measured with the Testo 33 gas analyser. The total emission of nitrogen oxides NOₓ was determined as a sum of both NO and NO₂ components.

The amounts of unburned hydrocarbons HC (ppm vol) and the residual oxygen O₂ (vol%), which were determined afterwards, as well as the carbon monoxide CO (vol%) and dioxide CO₂ (vol%) emissions, in the exhaust gases were additionally checked with the TECHNOTEST Infrared Multigas TANK gas analyser model 488 OIML.

The smoke opacity D (%) of the exhausts was measured with the Bosch device RTT 100/RTT 110, the readings of which are provided as Hartridge units in scale I - 100% with ±0.1% accuracy.

**Results and discussions**

It was determined that inclusion in the RO 7.5vol% of ethanol the oil’s viscosity at ambient temperature of 20 °C diminishes by 28.3% and makes much easy oil flow through the fuelling system. In order to improve further the filtration properties of RO and its 7.5vol% blend with ethanol the biofuel preheating in the heat exchanger can be used as supplementary measure. Test results indicate that heating from ambient conditions of 20 °C up to the temperature of 60 °C the viscosity of neat RO and blends ERO7.5 diminishes 4.2 and 3.8 times, respectively.

Dependencies of the brake specific energy consumption (bsfc) in MJ/kWh as a function of speed obtained during engine operation on neat RO and blend ERO7.5 for three typical loading groups characterised by air-to-fuel equivalence ratios \( \lambda = 6.0, 3.0 \) and 1.6 have been superimposed as shown in Fig. 1. Analysing test results one should bear in mind that blend ERO7.5 contains 12.6% of the fuel conserved oxygen against that 10.8% based in neat RO. Taking into account that the stoichiometric air-to-fuel equivalence ratio for ethanol is much lower (9.07) than that for neat RO (12.63%), this is translated into slightly lower 12.36 the stoichiometric air-to-fuel equivalence ratio of tested blend ERO7.5.
As it follows from the analysis of data, at low 1400 min⁻¹ speed the bsec of blend ERO7.5 is by 15.9% higher for light, \( \lambda = 6.0 \), and approximately the same for medium and heavy loads. Differences in the bsec between both biofuels tested have tendency to diminish with revolutions and the bsec curves for easy loaded engine coincide actually when revolutions increase up to 2000 min⁻¹ speed and beyond. During engine operation at medium load, \( \lambda = 3.0 \), the bsec curve of blend ERO7.5 oscillates along speed axis in close vicinity to that of neat RO, whereas during its run under heavy loading conditions bsec for both biofuels remains nearly the same, except upper 2000 and 2200 min⁻¹ speeds where the bsec of blend ERO7.5 increases against that of neat RO from 2.2 to 8.3%, respectively.

Test results indicate that during operation under constant air-to-fuel equivalence ratio \( \lambda = 1.6 \) at the maximum torque mode 1800 min⁻¹ and rated 2200 min⁻¹ speed the fully loaded engine fuelled with blend ERO7.5 develops by the same, 1.738-1.742 MJ/kg, energy content of fuel-rich mixture the brake mean effective pressure (bmep) by 2.3% and 9.1% lower than that of neat RO case. The lower energy conversion efficiency obtained from the easy loaded engine run on blend ERO7.5 can be linked with appearing misfiring cycles and unstable performance whereas worsening of performance efficiency of the fully loaded engine at maximum torque and rated speed can be attributed to significant cooling effect of the ethanol that lowers temperature within fuel spray cores and leads to longer auto-ignition delay, retarded start of combustion and relocates all the phases of process towards the expansion stroke [4].

The emissions of NO\(_x\) along with performance conditions of the engine and its regulations [4], depend actually on both the composition and chemical structure of the fatty acids [5] and the fuel injection timing advance determined in the case of the rotor type Stanadyne fuel injection pump on its physical properties largely [6]. Analysis of graphs in Fig. 2 shows, that the maximum NO\(_x\) emissions emanating from blend ERO7.5 within the lower speed range 1400-1800 min⁻¹ are up to 12.8-3.9% higher than that of neat RO. The higher NO\(_x\) emissions have been obtained because of up to 8.0% higher NO and from 4.5 to 4.9 times higher NO\(_2\) emissions that can be related reasonably to more intensified burning of the combustible mixture premixed. Because RO differs as having higher start of vapourisation (299 °C) related to the diesel fuel (177.8 °C) and about same vapourisation end (345-346 °C) [5], mixing RO with lighter ethanol may advance the start of vapourisation that, on the one part, accelerates preparation of combustible mixture but, on the other part, the lower cetane number of ethanol and presence of fuel based oxygen can increase the NO\(_x\) emissions due to longer auto-ignition delay and higher amount of fuel premixed for rapid combustion.
In contrast to low revolutions, at the upper 2000-2200 min⁻¹ ranges, emissions of NO from blend ERO7.5 diminish because of lowering both energy conversion efficiency and, consequently, maximum cylinder gas temperature of the fully loaded engine. During operation under heavy loads and high speeds the combustion process of oxygenated blends ERO7.5 deteriorates diminishing performance efficiency of the engine and temperature related NOx emissions too. Higher NO₂ emissions emanating from blend ERO7.5 indicate that combustion process of blend ERO7.5 is complicated enough and proceeds, likely, with the presence of cooler regions, which are widespread across the combustion chamber and may quench the conversion back to NO [7]. During engine operation at light loading conditions, \( \lambda = 6.0 \), it results into NO₂/NOx ratios generated by blend ERO7.5 being from 1.32 to 6.3 times higher than that from neat RO and noted differences increase rapidly with the rotation speed.

According to the latest test results of the International T 444E HT turbocharged and intercooled 7.3 L CI engine fuelled with 5% and 10% ethanol-diesel fuel blends, there decrease in NOx emissions also was measured by close to 3% and authors came to the conclusion that ethanol could act as an effective NOx emissions reducing additive [8]. The other biodiesel tests conducted on the International V-8 diesel fuelled with 100% soy methyl ester, 2% biodiesel, 10% ethanol-diesel fuel, and 5% ethanol in biodiesel also showed that there no correlation exists between fuel conserved oxygen and the total NOx emissions [9]. Thus in the case of RO blended with oxygenated ethanol, the NOx emissions behaviour differs actually from traditional biodiesel test results reported in Ref. [2, 5, 10].

Emission of CO vary with the engine load, speed and quantity of ethanol premixed into RO. Starting at light load, \( \lambda = 6.0 \), and low 1400 min⁻¹ speed from comparably high 332 ppm (RO) and 473 ppm (ERO7.5) levels, CO emissions diminish slightly for medium loads and increase again up to 596 ppm (RO) and 770 ppm (ERO7.5) for heavy loading conditions at rated speed (Fig. 3.).

In the case of running the fully loaded engine, \( \lambda = 1.6 \), on blend ERO7.5, CO emissions are more or less similar to that of neat RO however they remain lower by 9.3% at low 1400 min⁻¹ revolutions and increase by 29.2% at rated 2200 min⁻¹ speed. The lower CO emissions measured from blend ERO7.5 at low revolutions can be attributed to the oxygenated nature (34.8%) of ethanol whereas rapid increase of the CO emissions during transition to rated speed correlates pretty well with lower both energy conversion efficiency (Fig. 1) and NO emissions (Fig. 2) accompanied by higher levels of NO₂.
The smoke opacity increases with load and fuel portion injected from about zero level reaching maximum 55.5% (ERO7.5) and 72.0% (RO) at low revolutions. As rotation speed increases, the visible smoke from the fully loaded engine diminishes gradually due to higher fuel injection pressure, better atomization of viscous RO droplets and more intensified mixing by cylinder air swirl. Because of oxygenated nature of blend ERO7.5, the smoke opacity from the engine run at fully opened throttle is throughout the whole speed range tested up to 22.9-24.1% lower and during operation under rated power do not exceeds 22.0% that correlates reasonably well with other related emissions.

Emissions of unburned hydrocarbons HC from blend ERO7.5 are also lower by 5.8-14 ppm and residual oxygen content in the exhaust manifold is higher 14.2vol% comparing with that from neat RO 10.6vol%, the CO2 emissions and temperature of the exhausts from the fully loaded engine, \( \lambda = 1.6 \), diminish with the ethanol inclusion in the RO from 7.0 to 6.3vol% and 490 to 460 °C, respectively, because of lower both C/H ratio and calorific value of ethanol.

Test results indicate that the fuel conserved oxygen of blend ERO7.5 effectively diminishes NO, NOx emissions and visible smoke emerging from the fully loaded engine but it comes into effect to little and, probably, to late to insure efficient engine performance at the rated power mode and obtain lower NO2 and CO emissions therefore new evidence concerning combustion peculiarities of rapeseed oil and ethanol blends (up to 10vol%) must await further investigations.

**Fig. 3. Dependencies of CO emissions and smoke opacity of the exhausts on engine speed (n) during operation under heavy loading conditions, \( \lambda = 1.6 \)**

Test results indicate that during diesel engine D-243 operation under constant air-to-fuel ratio, \( \lambda = 1.6 \), at the maximum torque 1800 min\(^{-1}\) mode and rated 2200 min\(^{-1}\) speed, blend ERO7.5 ensures the power output correspondingly lower by 2.3% and 9.1% than that of neat RO case. The brake specific energy consumption (bsec) in MJ/kWh of blend ERO7.5 at low 1400 min\(^{-1}\) speed is higher by 15.9% for light and approximately the same for medium and heavy loads whereas during engine operation at 2000 and 2200 min\(^{-1}\) speeds with the fully opened throttle, the bsec increases against that of neat RO case from 2.2 to 8.3%, respectively.

**Conclusions**

1. Test results indicate that during diesel engine D-243 operation under constant air-to-fuel ratio, \( \lambda = 1.6 \), at the maximum torque 1800 min\(^{-1}\) mode and rated 2200 min\(^{-1}\) speed, blend ERO7.5 ensures the power output correspondingly lower by 2.3% and 9.1% than that of neat RO case. The brake specific energy consumption (bsec) in MJ/kWh of blend ERO7.5 at low 1400 min\(^{-1}\) speed is higher by 15.9% for light and approximately the same for medium and heavy loads whereas during engine operation at 2000 and 2200 min\(^{-1}\) speeds with the fully opened throttle, the bsec increases against that of neat RO case from 2.2 to 8.3%, respectively.

2. The maximum NO, NO2 and NOx emissions emanating from blend ERO7.5 within the lower 1400-1800 min\(^{-1}\) speed ranges are correspondingly up to 8.0%, from 4.5 to 4.9 times and by 12.8 to 3.9% higher. At the upper 2000-2200 min\(^{-1}\) speeds, emissions of NO generated by blend ERO7.5 start to diminish because of lowering both energy conversion efficiency and related maximum cylinder gas temperature. Higher NO2 emissions appearing from blend ERO7.5 also indicate that combustion process of blend ERO7.5 proceeds, likely, with the presence of cooler regions, which may quench the conversion back to NO.
3. Emissions of CO from the fully loaded engine run on blend ERO7.5 are in general more or less similar to that of neat RO case however they remain lower by 9.3% at low 1400 min⁻¹ revolutions and are higher by 29.2% at rated 2200 min⁻¹ speed. The smoke opacity from blend ERO7.5 at the fully opened throttle throughout the whole speed range is up to 22.9-24.1% lower and during operation under rated power do not exceeds 22.0%. Emissions of HC from oxygenated blend ERO7.5 are also lower by 5.8-14 ppm along with lower both the CO₂ from 7.0 to 6.3vol% and temperature of the exhausts from 490 to 460 °C.

4. The local diesel engine fuelling with renewable and environmental friendly rapeseed oil and ethanol blend ERO7.5 should be dependent, however, on long-term endurance test results and evaluation of all benefits and detriments determined during practical exploitation.

References