THE EFFECT OF DIESEL FUEL BLENDING WITH RAPESEED OIL AND RME ON ENGINE PERFORMANCE AND EXHAUST EMISSIONS

Gvidonas Labeckas

Stasys Slavinskas

Transport and Power Machinery Department
Engineering Faculty, Lithuanian University of Agriculture
Student Str. 15, P.O. Box LT-53067, Kaunas Academy, Lithuania
fax/call: +370 37 752 311
e-mail: gvidonas@info.lzuu.lt
e-mail: sslavins@tech.lzuu.lt

Abstract

The purpose of this research is to determine the effect of Diesel fuel blending with rapeseed oil (RO) and RME on the brake specific fuel consumption of a direct-injection Diesel engine, fuel energy conversion efficiency and evaluate the quantitative emission composition changes and smoke opacity of the exhausts.

Test results show that the application for engine fuelling of Diesel fuel and rapeseed oil RO25 (1:4 by volume) as well as rapeseed methyl ester RME20 (1:5 by volume) blends at low-to-moderate revolutions does not affect greatly the brake specific fuel consumption (bsfc) however at the rated speed and fully opened throttle the bsfc for blends RO25 and RME20 is higher by 4.7% and 11.9%, respectively. The maximum emission of nitrogen oxides NO_x at the rated power for blend RO25 is lower by 11.7% and for blend RME20 is higher by 44.7% related to Diesel fuel.

The smoke opacity, emissions of carbon dioxide CO_2, monoxide CO and unburned hydrocarbons HC released into atmosphere from the engine run at fully opened throttle on blend RO25 are more or less similar to that of Diesel fuel whereas during operation at the rated power on blend RME20, because of higher specific fuel consumption, the smoke opacity increases to 42.6% and emission of CO_2 to 9.9%.

1. Introduction

The Commission White Paper European policy predicts that by year 2010 the carbon dioxide emissions from transport will be risen to about 1 113 million tones with the main responsibility resting on a road transport, which accounts for 84% of transport related CO_2 emissions. Having in mind urgent environmental problems Directive 2003/30EC of the European Parliament and Council has been approved that calls for Member States to insure a minimum proportion of biofuels and other renewable fuels placed for transport purposes on their markets by 31 December 2010 shall be 5.75% on the basis of energy content. Lithuania, as a new Member State, shall also monitor the effect of using in unmodified vehicles of biofuels in Diesel blends above 5% and shall take measures necessary to insure compliance with the relevant Community legislation on emission standards too.

Neat Rapeseed Methyl Ester (RME) and its blends with fossil fuels are widely used for Diesel engine fuelling because of less harmful emissions behaviour and contribution to the global CO_2 cycle as well as known advantages in many ecological aspects [1,4]. The other method allowing utilisation of the Rapeseed Oil (RO) as renewable energy source is the usage of it for the local tractors fuelling in a neat form [2,8] or in mixture with Diesel fuel [9,11]. This method could be considered as cheap and efficient because small capacity RO pressing,

filtration and decanting facilities arranged in some rural areas would be less dependent on the fiscal policy and economically attractive especially when applied along with pressing of oilcake for farming. Investigations conducted on different Diesel engines [2, 5] proved that RO could be recognised as a fossil fuel extender. Laboratory tests revealed, however, some technical problems related to RO high viscosity, carbonaceous deposits and lacquer formation on the surfaces of engine inners parts because of incomplete combustion, especially at light-to-moderate loads [8].

One of the mostly used methods allowing to solve oil's viscosity problem and improve its technical properties insuring smooth flow through a fuelling system is mixing with lighter Diesel fuel (DF) [1,3,5,9,11]. However, blending of RME and RO in various proportions with fossil fuel may result into a bit different effect on fuel energy conversion efficiency and emission characteristics. Besides of high kinematical viscosity of RO (38.0 mm^2/s at 40 ^{o}C) the latter differs as having higher density (0.916g/cm^3), cold filter plugging point (+15 ^{o}C), pour point (+20 ^{o}C), water content (75 mg/kg) and overall contamination. Differences in RO physical properties along with its higher flash point (220-230 ^{o}C), flame point (275-290) and lower cetane number (44-48) may have different influence on fuel spray parameters, its distribution in the combustion chamber, evaporation peculiarities and auto-ignition delay than in the case of mixing RME with Diesel. Mentioned peculiarities may change a bit differently the quantity of fuel premixed for rapid combustion affecting the engine performance at various loading conditions.

Diesel engine performance parameters when operating on neat RME and pure RO have been examined previously in investigations [7,8]. According laboratory tests, adding of up to 25vol% of rapeseed oil into Diesel fuel increases blend viscosity at a room temperature from 3.59 to about 8.41 mm^2/s that can be regarded as more or less acceptable for the normal operation. Concerning RME, its viscosity is more similar to that of Diesel fuel and compiles at a temperature of 40 ^{o}C about 4.70 mm^2/s. In France, Italy, Spain, Sweden, Czech Republic and other European Countries up to 5 – 30vol% RME and Diesel fuel blends are popular. Therefore, from the scientific point of view it would be reasonable to conduct the comparative analysis of the effect of mixing RME and RO with commercial Diesel fuel on the engine performance at various loading conditions.

2. Purpose of the Research

The purpose of the research is to conduct the comparative analysis of the effect of two different biofuels as Diesel fuel (80vol%) and rapeseed methyl ester (20vol%) as well as Diesel fuel (75vol%) and rapeseed oil (25vol%) blends on the economical and ecological parameters of a high-speed direct-injection Diesel engine when operating at a wide range of loads and speeds. The objectives of this research may be stated as follows:

1. Determine the effect of RME20 and RO25 blends on the brake specific fuel consumption of a Diesel engine when running it over a wide range of loads and revolutions per minute.

2. Evaluate the effect of RME20 and RO25 blends on the emission composition changes, including the nitrogen oxides NO, NO_2, NO_x, carbon monoxide CO, hydrocarbons HC and smoke opacity of the exhausts when running it over a wide range of loads and speed.

3. Research Objects, Apparatus and Methods

Tests were conducted on the four cylinder, four stroke, naturally aspirated, water cooled, 59 kW direct injection Diesel engine D-243 with splash volume V_l = 4.75 dm^3, bore of 110 mm, stroke of 125 mm and compression ratio of ε = 16:1. The fuel was delivered by the in

line fuel injection pump through five holes injection units into a toroidal type compression-ignition combustion chamber in a piston head. The fuel injection pump was adjusted to the initial fuel delivery start at 25° before top dead centre (BTDC).

RME and pure RO were brought from a new production plant "Rapsoila", Lithuania, which started in May 2004 with the capacity of 10 thousand tons. The net heating values of both biofuels were declared as being equal to 37.23 MJ/kg for RME and 36.87 MJ/kg for RO. Fuel blend RME20 was prepared by a splash mixing technique, which consist of pouring the RME into a Diesel container in the proportion of 80% DF and 20% RME by volume. Other blend RO25 was prepared by the same technique, i.e. by splash mixing in the fuel container of 75% DF and 25% RO by volume. The net calorific value of Diesel fuel was as standard 42.55 MJ/kg. By applying this technology two different biofuels have been obtained with quite similar calorific values of 41.49 MJ/kg for RME20 and 41.13 MJ/kg for RO25 blends, which where calculated from the percentage inclusion rate of each fuel component.

To obtain the baseline parameters, the engine was operated on a Diesel fuel grade C first. Load characteristics were taken at fixed load modes and constant crankshaft revolutions of n = 1400, 1600, 1800, 2000 and 2200 min^{-1}. After all load characteristics were taken for the engine performance on Diesel fuel, the Diesel fuel was replaced by blend RME20 and similar experiments were conducted over the same range of engine loads and revolution frequencies. Afterwards, the blend RME20 was replaced by blend RO25 and the engine performance characteristics were again taken over the same test ranges.

Torque of the engine was measured with a three phase asynchronous 110 kW electrical AC stand dynamometer with a definition rate of ±1 Nm. 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 the rated speed n = 2200 min^{-1} had been changed from the minimum up to 110% of its rated value.

The fuel mass consumption was determined by weighting it on the electronic scale SK-1000. 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 pulsation.

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

The amounts of unburned hydrocarbons HC (ppm vol) were determined with the gas analyser TECHNOTEST Infrared Multigas TANK model 488 OIML.

Smoke opacity D (%) of the exhausts was measured with Bosch device RTT100/RTT110 in scale 1 − 100% with ± 0.1% accuracy.

4. The Research Results

Graphs of the brake specific fuel consumption (bsfc) as a function of load obtained during engine operation on Diesel fuel, blends RME20 and RO25 at speeds of 1400, 1800 and 2200 min^{-1} have been superimposed as shown in Fig. 1. As it obvious from the analysis, application of blends RME20 and RO25 does not affect significantly the bsfc rate in mass. At the minimum speed of 1400 min^{-1} and maximum load of bmep = 0.77 MPa the bsfc is lower by 1.6% for blend RME20 and higher by 2.3% for RO25 related to Diesel fuel (238 g/kWh).

At a higher rotation speed of 1800 min^{-1} that corresponds to the maximum torque area, blend RME20 suggests for the fully loaded engine the bsfc rate nearly the same (233 g/kWh) as that of Diesel fuel (230 g/kWh) whereas blend's RO25 consumption remains at 3.1% higher level. However, as soon as the engine speed increases up to the rated 220 min^{-1} value its performance on both biofuels deteriorates more noticeably. When running the engine at a
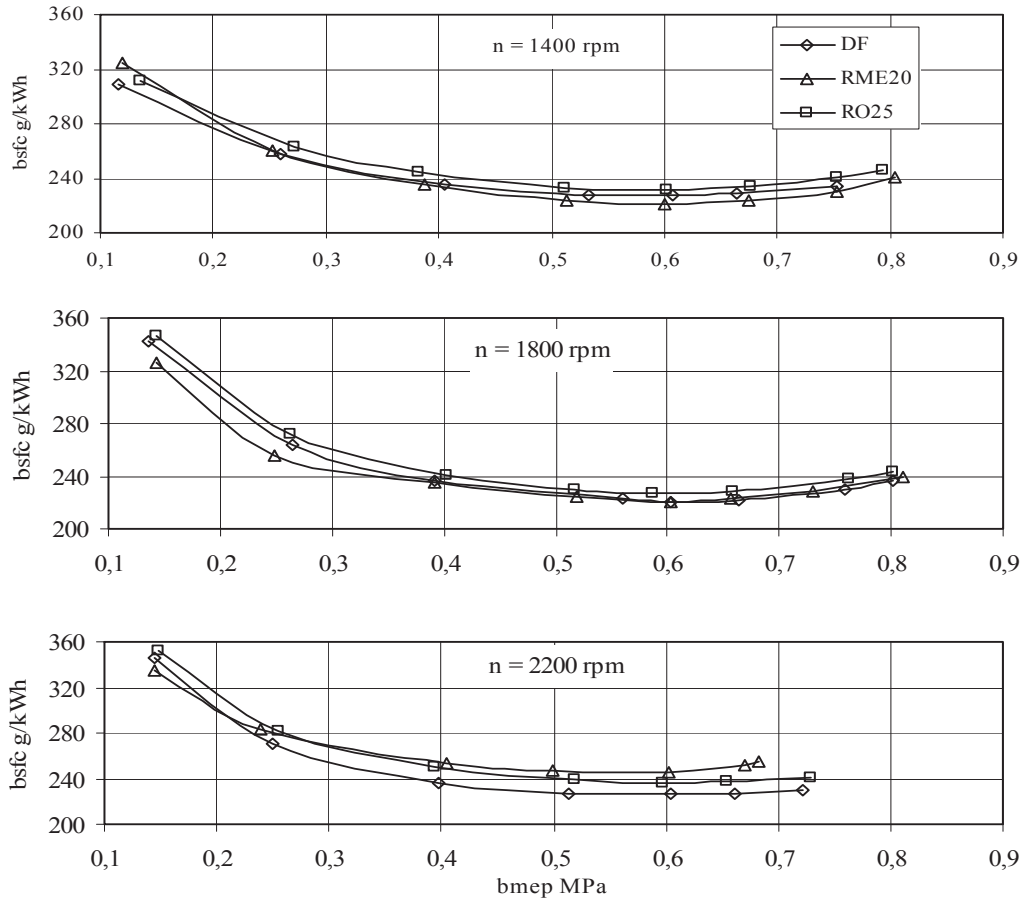
Fig. 1. The brake specific fuel consumption (bsfc) as a function of engine load (bmep)

fully opened throttle (bmep = 0.68 MPa) the bsfc is higher by 4.7% for blend RO25 and by 11.9% for RME20 comparing with Diesel fuel consumption of 228 g/kWh.

The higher biofuels consumption can be related primary to the lower on average by 2.5% and 3.3% of net heating value of blends RME20 and RO25. However, the comparably small differences in the heat content of the tested biofuels is probably not the main reason leading to the higher biofuels consumption in grams per unit energy developed. As one can see on the bsfc graphs, at all loads the bsfc for both blends RME20 and RO25 increases with revolutions more rapidly than that of ordinary Diesel. Economical parameters of Biodiesel have been affected, probably, by changes in the fuel timing advance, its evaporation behaviour, auto-ignition delay and actual start of combustion occurring because of the effect of biofuels specific properties such as a feedstock, calorific value, volatility, iodine and cetane numbers, density and viscosity, pressure waves propagation speed and isentropic bulk modulus [14].

The brake thermal efficiency increases with the load reaching at the minimum 1400 min^{-1} speed the top efficiency values of 0.373, 0.377 and 0.392 for Diesel fuel, blends RO25 and RME20. In terms of the engine performance efficiency advantages due to biofuel usage have been obtained at low revolutions and high loads mainly. At speed of 1800 min^{-1} corresponding to the maximum torque area, the maximum value of the brake thermal efficiency for blend RO25 (0.385) is nearly the same as that for ordinary Diesel (0.383) whereas for blend RME20 remains at a slightly higher (0.393) level. However, as far as the engine speed increases up to 2200 min^{-1}, the energy conversion efficiency of Biodiesel starts to reduce rapidly enough, especially when operating on blend RME20. At the rated speed and fully opened throttle (bmep = 0.68 MPa) the maximum thermal efficiency values are equal to 0.375, 0.371 and 0.354 for Diesel fuel, blends RO25 and RME20, respectively. Given results

indicate about importance of further investigations in order to improve performance efficiency of conventional engine run on unmodified blends RO20 and RME25 at all loads and speeds.

As it follows from the analysis of graphs in Fig. 2, the total NO_x emission increases gradually with the load, reaching at revolutions of 1400, 1800, 2200 min^{-1}, the maximum
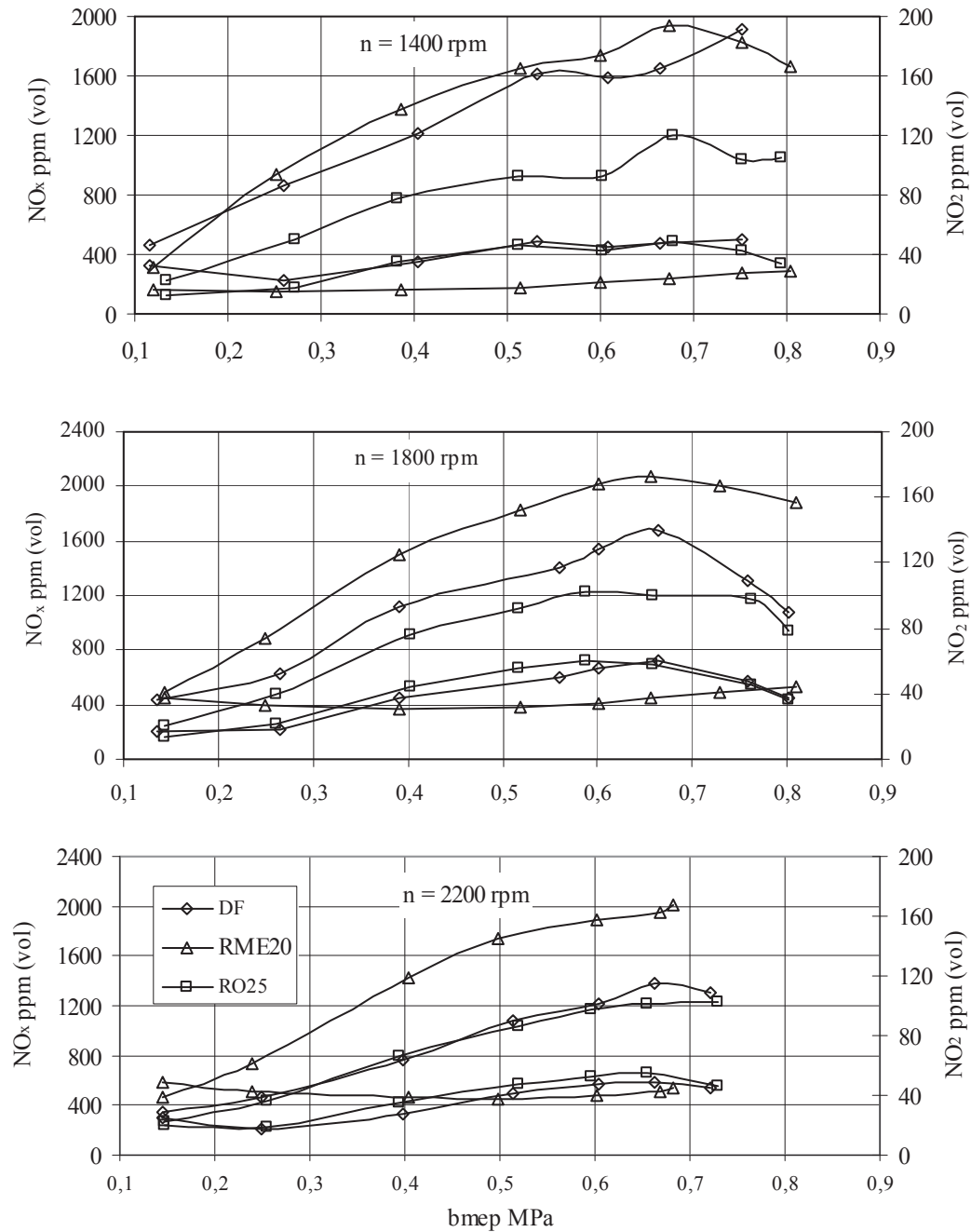

Fig. 2. The total nitrogen oxides NO_x and dioxide NO_2 emissions as a function of load (bmep) at various speeds (n)

values of 1937, 2071 and 2006 ppm for blend RME20 and 1911, 1674, 1386 ppm for Diesel fuel. Considerably high NO_x emission levels generated from blend RME20 can be related primary to its composition that differs as having higher oxygen content (2.5%) related to ordinary Diesel (0.4%) [4]. The other possible reason of correspondingly higher by 1.4%, 23.7% and 44.7% emissions of NO_x measured for blend RME20 can be related presumably to the earlier actual start of combustion that may occur because of its higher cetane number (54)

and changes in actual timing advance [14]. According to the world-known chain reactions mechanism developed by Zeldovich, the nitrogen oxides built up beyond the flame from free atoms of nitrogen and oxygen at gas temperatures above 2000 K. At earlier start of auto-ignition the maximum temperature of burned gases increases and consequently the higher levels of NO_x emission can be expected [6,10].

In spite of higher fuel based oxygen content (3.0%), the NO_x emissions from blend RO25 proceed with the load at a pretty lower level than that produced by blend RME20. In this case the maximum NO_x emissions compile 1196, 1227 and 1224 ppm, respectively. The lower NO_x emissions can be explained, presumably, by blend's RO25 higher density and viscosity that along with a poor volatility and high boiling point reduce quantity of fuel remixed for rapid combustion. Because of a lower peak temperature of burned gases, the maximum NO_x emissions from blend RO25 have been reduced by 37.4%, 26.7% and 11.7%, respectively.

Emissions of the nitrogen dioxides NO_2 have tendency to increase slightly with the load reaching the maximum 29 – 45 ppm values for blend RME20 and 50 – 60 ppm for RO25. As one can see on the graphs, the NO_2 emission for blend RO25 changes with the load in a very similar way as that of ordinary Diesel does. According to investigations [6], the higher NO_2 emissions emerging from blend RO25 can be related to the lower gas temperature that could quench the conversion back to NO. However, the NO_2 emission compiles about twentieth part of NO concentration therefore it does not play a key role on the total NO_x background determined.
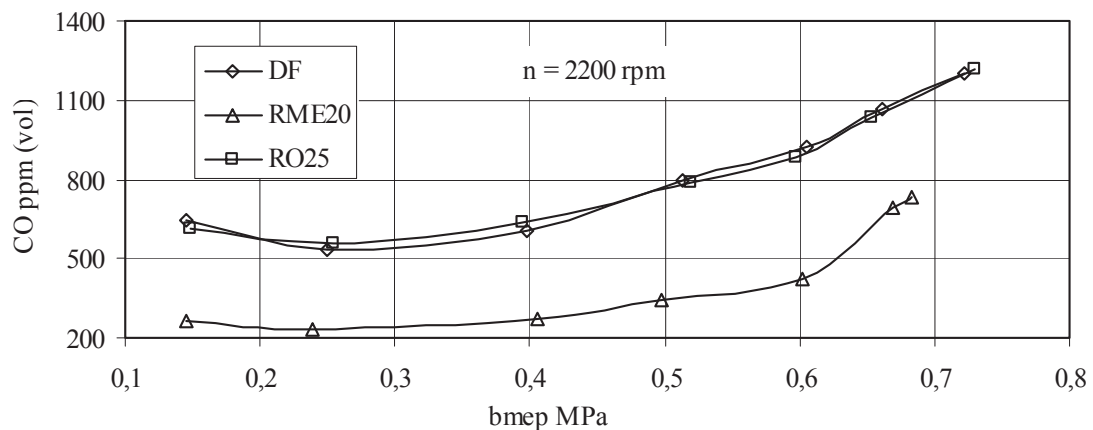

Fig. 3. Carbon monoxide emissions as a function of load (bmep)

The carbon monoxide CO emissions at the rated 2200 min^{-1} speed are shown on the graphs in Fig. 3. Emissions of CO increase smoothly with the load and portion of fuel injected reaching at the rated bmep = 0.68 MPa load the maximum 735 ppm value for blend RME20 and about similar amounts of 1107 and 1100 ppm for both Diesel fuel and blend RO25. The maximum CO emissions generated from blend RME20 remain at speeds of 1400, 1800 and 2200 min^{-1} lower by 29.2%, 32.1% and 33.6 % related to ordinary Diesel. The lower CO concentrations in the exhausts correlate reasonably well with much higher NO_x emissions considered above indicating about different origin of these two species [6].

Exhaust opacity depends on the fuel cetane number, soot particles formation and its eventual burning rate set up by diffusion processes at a final combustion stages varying with the chemical structure and amount of fuel injected. As it follows from the graphs in Fig. 4, the exhaust smoke at light-to-moderate loads proceeds at considerably low level ranging from 3 to 10 %. However, as soon as the engine load increases beyond 0.5 – 0.6 MPa the values of exhaust smoke scale up more rapidly. At the rated 2200 min^{-1} speed and bmep of 0.68 MPa, the smoke opacity for blend RO25, Diesel fuel and RME20 reaches 21.7%, 25.8% and 42.6%,

respectively. The higher smoke opacity produced by blend RME20 can be obtained, probably, because of combustion peculiarities that especially may have place at high speeds and heavy loads. At lower revolutions and easier loads there no significant differences in the smoke opacity between blends RO25, RME20 and Diesel fuel were observed at all.
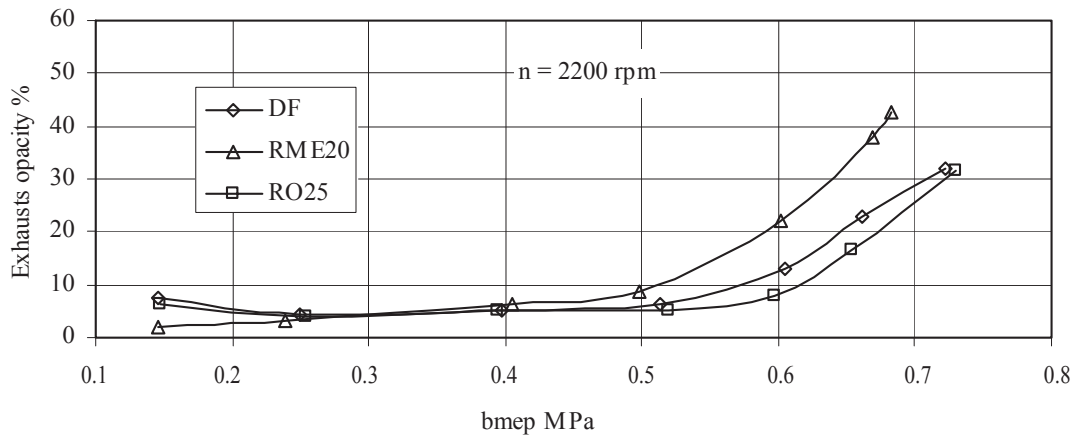

Fig. 4. Smoke opacity of the exhausts as a function of load (bmep)

Emissions of unburned hydrocarbons HC increase slightly with the load and portion of fuel injected, but HC levels are comparably low and their top values do not exceed 8 to 25 ppm. At the minimum 1400 min^{-1} speed, HC emission for both biofuels is similar enough whereas at higher 1800-2200 min^{-1} revolution it ranges for blend RME20 at approximately 5 ppm lower level comparing with Diesel fuel. Lower CO and HC emissions remain in a good agreement with the higher NO_x concentration generated from blend RME20. Blend RO25 indicates about the same HC emission changes with a load as ordinary Diesel except more rapid increase at heavy loads only. Temperatures of gases exhausted from the fully loaded engine operating at the rated speed and constant air-to-fuel equivalence ratio of $\lambda = 1.6$ were as high as 477, 495 and 540°C for blend RO25, Diesel fuel and blend RME20, respectively.

Emissions of carbon dioxide CO_2 increase with the load about proportionally to the fuel consumption in mass reaching at the rated 2200 min^{-1} speed and load bmep = 0.68 MPa the same 6,5vol% values for Diesel fuel and blend RO25 and being slightly higher (9.9vol%) for blend RME20.

5. Conclusions

1. Application for Diesel engine fuelling of fuel blends RME20 and RO25 at low-to-moderate revolutions does not affect greatly the brake specific fuel consumption in units of mass however at the rated 2200 min^{-1} speed and a fully opened throttle the bsfc rate is higher by 4.7% for blend RO25 and by 11.9% for RME20 than that of ordinary Diesel (228 g/kWh).
2. The brake thermal efficiency at the minimum 1400 min^{-1} revolution reaches the top efficiency values of 0.373, 0.377 and 0.392 for Diesel fuel, blends RO25 and RME20. As soon as the engine speed increases to the rated value, the fuel energy conversion efficiency reduces slightly reaching the maximum values of 0.375, 0.371 and 0.354, respectively.
3. The maximum NO_x emissions generated from a heavy loaded engine run on blend RME20 at speeds 1400, 1800 and 2200 min^{-1} are higher by 1.4%, 23.7% and 44.7% whereas when fuelling it with blend RO25 the top NO_x emission levels appeared as being by 37.4%, 26.7% and 11.7% lower related to Diesel fuel.
4. The maximum CO emissions emerging from the engine run at a fully opened throttle on blend RME20 are correspondingly by 29.2%, 32.1% and 33.6 % lower whereas when

operating on blend RO25 emissions of CO range with a load at very similar levels as those of ordinary Diesel reaching at the engine rated power 1100 ppm.

5. A higher specific fuel consumption in mass and higher smoke opacity accompanied by overall higher temperature of the exhausts, NO_x and CO_2 emissions, especially measured at the rated 2200 min^{-1} speed, indicate that further investigation concerning the adjustment of fuel injection timing advance for blend RME20 is warranted. In spite of quite promising results given during engine operation on blend RO25, the practical usage of rapeseed oil in blends with Diesel fuel should relay on long-term endurance and reliability tests.

References

[1] Altin R., Çetinkaya S., Yücesu H.S., The potential of using vegetable oil fuels as fuel forDiesel engines. Energy Conversion and Management. 2001, Vol. 42, p. 529-538.

[2] Bialkowski M.T., Pekdemir T., Towers D.P., Reuben R., Brautsch M., Elsbett G., Effect of Fuel Temperature and Ambient Pressure on a Common Rail Rapeseed Oil Spray. Journal of KONES Internal Combustion Engines, Vol. 11(1-2) 2004, p. 53-65.

[3] Dorado M.P., Arnal J.M., Gomez J., Gil A., Lopez F.J., The Effect of a Waste Vegetable Oil Blend with Diesel Fuel on Engine Performance. Transactions of the ASAE, Vol. 45(3) 2002, p. 519-523.

[4] Graboski M.S., McCormick R.L., Combustion of Fat and Vegetable Oil Derived Fuels in Diesel Engines. Progress in Energy and Combustion. Scientific.Vol. 24 1998, p. 125-164.

[5] He Y., Bao Y.D., Study on rapeseed oil as alternative fuel for a single-cylinder diesel engine. Renewable Energy. 2003, Vol. 28, p. 1447-1453.

[6] Heywood J.B., Internal Combustion Engine Fundamentals. – Co - Singapore for manufacture and export, 1988. – 930 p. (International edition).

[7] Labeckas G., Slavinskas S., The research of biofuels usage in Diesel engine, Proceedings of International conference TRANSBALTICA – 99. -Vilnius Gediminas Technical University and Lithuanian Academy of Science. -Vilnius "Technika" 1999, p. 409-415.

[8] Labeckas G., Slavinskas S., Ignatavicius T., The Research of Direct Injection Diesel Engine Performance Parameters when Operating on Pure Rapeseed Oil. Research papers of Lithuanian University of Agriculture VAGOS, Vol. 57(10) 2003, p. 117-123.

[9] McDonnell K.P., Ward S.M., McNulty P.B., Howard-Hildige R., Results of Engine and Vehicle Testing of Semirefined Rapeseed Oil. Transactions of the ASAE, Vol. 43(6) 2000, p. 1309-1316.

[10] Monyem A., Gerpen J.H.V., Canakci M., The Effect of Timing and Oxidation on Emissions from Biodiesel Fuelled Engines. Transactions of the ASAE, Vol. 44(1) 2001, p. 35-42.

[11] Nwafor O.M.I., Rice G., Performance of Rapeseed Oil Blends in a Diesel Engine. Applied Energy, Vol. 54(4) 1996, p. 345-354.

[12] Peterson C. L, Taberski J. S, Thompson J. C, Chase C. L., The Effect of Biodiesel Feedstock on Regulated Emissions in Chassis Dynamometer Tests of a Pickup Truck. Transactions of the ASAE, Vol. 43(6) 2000, p. 1371-1381.

[13] Schumacher L. G, Clark N. N, Lyons D. W, Marshall W., Diesel Engine Exhaust Emissions Evaluation of Biodiesel Blends Using a Cummins L10E Engine. Transactions of the ASAE, Vol. 44(6) 2001, p. 1461-1464.

[14] Tat M. E., Gerpen J. H.-V., Fuel Property Effects on Injection Timing, Ignition Timing and Oxides of Nitrogen Emissions from Biodiesel-Fuelled Engines. Paper Number: 046081. An ASAE Annual International Meeting Presentation, Ottawa, Canada, 1 - 4 August 2004. p. 18.