Journal of Polish CIMAC
Gdansk University of Technology
The Faculty of Ocean Engineering and Ship Technology

PERFORMANCE AND EMISSION CHARACTERISTICS OF THE DIESEL ENGINE OPERATING ON THREE-COMPONENT FUEL

Gvidonas Labeckas, Stasys Slavinskas

Lithuanian University of Agriculture, Students street, 11, LT-53361 Kaunas-Academy, E-mail: gvidonas.labeckas@.lzuu.lt; stasys.slavinskas@.lzuu.lt;

Abstract

The article deals with bench testing results of a DI (60 kW) diesel engine D-243 operating on reference (DF) arctic class 2 diesel fuel (80vol%), anhydrous (200 proof) ethanol (15vol%) and rapeseed methyl ester (5vol%) blend B15E5. The purpose of the research is to investigate the effect of simultaneous ethanol and RME addition in the diesel fuel on brake specific fuel consumption (bsfc), the brake thermal efficiency (η_e) and noxious emissions, including NO, NO_2, NO_x, CO, CO_2, HC and smoke opacity of the exhausts. The bsfc of the diesel engine operating on three-component fuel B15E5 under maximum load of bmep = 0.75, 0.76 and 0.68 MPa is higher by 10.3%, 10.7% and 9.6% because of both net heating value lower by 6.18% and brake thermal efficiency lower by 3.4%, 3.7% and 2.8% relative to that of reference diesel at 1400, 1800 and 2200 min^{-1} speeds. The maximum NO_x emission produced from oxygenated blend B15E5 was reduced by 13.4%, 18.0% and 12.5% and smoke opacity diminished by 13.2%, 1.5% and 2.7% under considered loading conditions relative to that of a neat diesel fuel. The CO amounts produced from three-component fuel B15E5 were lowered by 6.0% for low 1400 min^{-1} speed only and they increased by 20.1% and 28.2% for higher 1800 and 2200 min^{-1} speeds and the HC emissions were also higher by 35.1%, 25.5% and 34.9% throughout a whole speed rage comparing with respective values measured from neat diesel fuel.

Key words: *diesel engine, diesel fuel, anhydrous ethanol, rapeseed oil methyl ester, brake specific fuel mass consumption, NO_x, CO, HC emissions, smoke opacity*

1. Introduction

Both high prices of mineral fuels and society's concern about global warming encourage researchers to intensify investigations on alternative and renewable energy sources, which could diminish the CO_2 emission in a global cycle. As potential mineral fuel extender bioethanol is indigenous and locally available, environment friendly and renewable, sustainable and reliable, safe to store and easy to handle, non-polluting and sulphur-free material, and is one of the cleaner-burning alternatives to mineral fuels. In order to solve technical problems, there several methods can be adapted to employ a certain amount of ethanol for diesel engine fuelling, which are known as alcohol fumigation [1], application of a dual injection systems [2], preparation of the alcohol-diesel fuel micro-emulsions [3] and using of the alcohol-diesel fuel blends [1,4-6].

Investigations conducted on a single cylinder DI, variable compression ratio diesel engine [1] confirmed that biofuel blends prepared by mixing of anhydrous (200 proof) ethanol and diesel fuel would also be acceptable for the diesel engine fuelling when applied in proper up to 15% proportions. Advantages and disadvantages of ethanol additives used for rapeseed oil treatment and diesel engine fuelling have been elucidated in reports [7,8]. The molecular weight of ethanol is lower 3.91 times, its density at temperature of 20 ^{o}C is lower by 4.9% and kinematic viscosity at temperature of 40 ^{o}C is also lower 1.47 times relative to that of the diesel fuel, which together with a low CFPP at the temperature below of –38 ^oC may elevate biofuel flow in the fuelling system and improve starting of the engine under winter conditions.

The miscibility of anhydrous ethanol with the diesel fuel is excellent and it makes clear one phase mixture however during a long-term application of ethanol-diesel mixtures the lubrication problems of the injection pump's plunger-barrel unit may emerge at higher than 15vol% blending ratios. To improve lubrication properties of the blend and increase the content of biofuel in the mixture RME from 5vol% to 10vol% as co-solvent can be recommended for ethanol-diesel blends [9,10]. The addition of RME as a stabilizer of ethanol-diesel mixture, suggests an extra advantage because this method allows avoid phase separation between the pure diesel fuel and the ethanol fraction during long term storage.

The purpose of the research was to study the effect of anhydrous (200 proof) ethanol and rapeseed oil methyl ester (RME) addition to arctic class 2 diesel fuel on biofuel properties and conduct comparative bench tests to examine changes in the brake specific fuel consumption (bsfc), the brake thermal efficiency (η_e) and the emission composition, including nitrogen oxides NO, NO_2, NO_x, carbon monoxide CO and dioxide CO_2, total unburned hydrocarbons HC, residual oxygen O_2 content and smoke opacity of the exhausts when running the engine alternately on a neat diesel fuel and three-component blend B15E5 containing 80vol% diesel fuel, 15vol% ethanol and 5vol% RME over a wide range of loads and speeds.

2. Objects, apparatus and methodology of the research

Tests have been conducted on four stroke, four cylinder, DI (60 kW) diesel engine D-243 with a splash volume V_l = 4.75 dm^3, bore 110 mm, stroke 125 mm and compression ratio ε = 16:1. The fuel was delivered by an in line fuel injection pump thorough five holes injector nozzles with the fuel delivery starting at 25^o before TDC.

The three-component blend was prepared by pouring diesel fuel (80vol%), anhydrous (99.81 purity) ethanol (15vol%) and RME (5vol%) into container and mixing them to keep the blend prepared in homogeneous conditions. Three-component biofuel B15E5 distinguishes itself as having the fuel bond oxygen mass content 6.1%, stoichometric air-to-fuel equivalence ratio 13.55 kg/kg and net heating value 39.92 MJ/kg.

Load characteristics were taken at speeds of 1400, 1800 and 2200 min^{-1} when operating alternately on neat diesel fuel (arctic class 2) and ethanol-diesel-biodiesel blend B15E5. The torque of the engine was increased from close to zero point up to its maximum values those correspond standard bmep = 0.75, 0.76 and 0.68 MPa changing behaviour at respective speeds.

The torque of the engine was measured with 110 kW AC stand dynamometer with a definition rate of ±0.5 Nm and the rotation speed was determined with the universal stand tachometer TSFU-1 that guarantees the accuracy of ±0.2%. The fuel mass consumption was measured by weighting it on the scale SK-1000 with accurateness of ±0.05 g and the volumetric air consumption was determined with the rotor type gas counter RG-400-1-1.5. The time spent for consumption of 2 m^3 of air and 100 g of fuel has been measured with the second-meter with a definition rate of ±0.01 s.

The amounts of carbon monoxide CO (ppm), dioxide CO_2 (vol%), nitric oxide NO (ppm) and nitrogen dioxide NO_2 (ppm), unburned hydrocarbons HC (ppm vol%) and the residual oxygen O_2 (vol%) content in the exhaust manifold were measured with a flue gas analyser Testo 350 XL. Smoke density D (%) of the exhausts was measured with a Bosch RTT 100/RTT 110 opacity-meter, the readings of which are provided as Hartridge units in scale I - 100% with the accuracy of ±0.1%.

3. Results and discussions

The addition of 15vol% of ethanol and 5vol% of RME into diesel fuel does not change greatly density and kinematic viscosity of biofuel blend relative to respective values of a neat diesel fuel because the lower density (790.0 kg/m^3) at temperature of 20 ^{o}C and critically reduced viscosity (1.40 mm^2/s) at temperature of 40 ^{o}C of ethanol were compensated with 1.12 times higher density (884.7 kg/m^3) and 3.42 times bigger viscosity (4.79 mm^2/s) of RME portion premixed. Because of simultaneous addition of improving additives having different chemical and physical properties the injection and atomisation characteristics of three-component fuel B15E5 should not vary much from those of a neat diesel fuel.

Tab.1. Testing conditions of the diesel engine operating on arctic class 2 diesel fuel and ethanol-diesel-biodiesel blend B15E5

Rotation speed, min^{-1}	Brake mean effective pressures, MPa for both cases DF and B15E5			Air-to-fuel equivalence ratio λ					
	heavy	medium	light	DF			B15E5		
1400	0,75	0.47	0.14	1,45	2.39	5.30	1,42	2.31	5.06
1800	0,76	0.44	0.15	1,42	2.47	5.21	1,37	2.38	5.73
2200	0,68	0.41	0.07	1,49	2.31	6.14	1,47	2.32	5.93

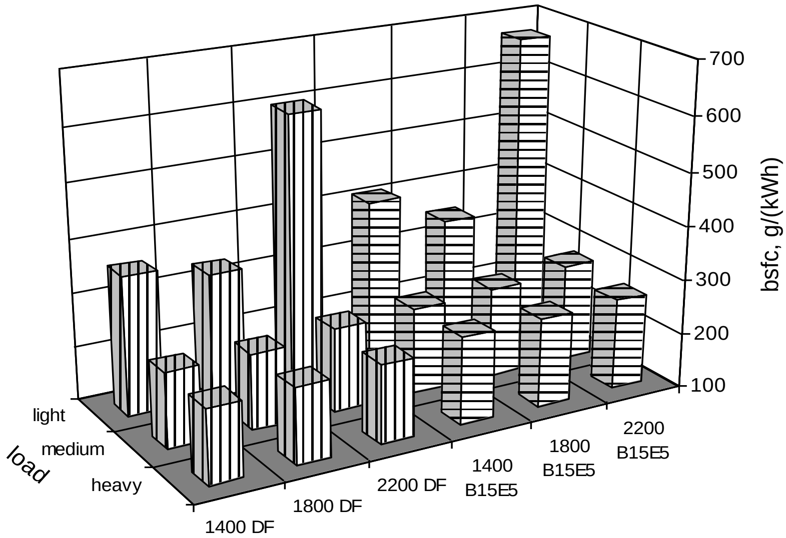

Fig. 1. The brake specific fuel consumption (bsfc) for neat diesel fuel and three-component fuel B15E5 as a function of engine load and speed

As is shown in Table 1, comparative analysis of the engine performance parameters and its emission changes when operating alternately on neat diesel fuel and ethanol-diesel-biodiesel blend B15E5 was conducted for light, medium and heavy loading conditions, i.e. for both cases under the same brake mean effective pressures developed at respective 1400, 1800 and 2200 min^{-1} speeds. The biggest values of bmep = 0.75, 0.76 and 0.68 MPa correspond to standard torque changing behaviour of the engine versus crankshaft's rotation speed of 1400, 1800 and 2200 min^{-1}. Such approach suggests a little bit lower air-to-fuel equivalence ratios for biodiesel that should be taken into account when considering engine performance and its emission composition changes.

As it follows from the analysis of columns in Fig. 1, the biggest 14.9% and 12.0% increase in the brake specific fuel consumption (bsfc) relative to that of a mineral diesel (356.7 g/kWh and 598.0 g/kWh) takes place when running of the easy loaded engine on blend B15E5 at critical speeds of 1400 and 2200 min^{-1}. In the case of using in-line fuel injection pump the combustible mixture prepared at extremely light load is more heterogeneous that together with a lower cetane number of ethanol-diesel-biodiesel blend may aggravate the autoignition leading to incomplete combustion of small fuel portions injected at low and high speeds. Nevertheless, performance efficiency of the easy loaded (0.15 MPa) biodiesel improves at speed of 1800 min^{-1} corresponding maximum torque mode where the bsfc diminishes to 348.5 g/kWh and difference in specific fuel consumptions between considered cases reduces to 5.3%.

After load of the engine increases to medium and heavy values the bsfc of three-component fuel remains higher by 8.4%, 10.8, 10.5% and 10.3%, 10.7%, 9.6% comparing with that of a neat diesel fuel at speeds of 1400, 1800 and 2200 min^{-1}. The bigger biofuel mass consumption spent for the same amount of energy produced can be attributed primarily to lower, on average by 6.18%, net heating value (39.52MJ/kg) of three-component fuel B15E5 comparing with that of the diesel fuel (42.55 MJ/kg). However difference in the heating value of the tested fuels is probably not the main reason that leads to the higher three-component fuel consumption in grams per unit of energy developed.

After substitution of the diesel fuel (0.24) with blend B15E5 the biggest 7.3% decrease in brake thermal efficiency was suffered when operating at light 0.14 MPa load and low 1400 min^{-1} speed. Whereat the performance mode of biodiesel was changed to medium and heavy loads the η_e increased to 0.32-0.34 sustaining at lower by 1.6%, 3.8%, 3.6% and 3.4%, 3.7%, 2.8% levels relative to values determined for reference diesel at 1400, 1800 and 2200 min^{-1} speeds. The lower thermal efficiency of biodiesel can be attributed to changes occurring in the combustion process [1]. Extremely low cetane number (8) of ethanol, its low calorific value (26.82 MJ/kg) along with a high volatility and significant cooling effect of the fuel sprays caused by 3.5 times bigger latent heat for evaporation (910 kJ/kg) relative to that of the diesel fuel and tendency to absorb ambient water may aggravate the autoignition of biofuel portions injected resulting into retarded start of combustion, relocating the maximum cylinder gas pressure and temperature points towards the expansion stroke and increasing incomplete diffusion burning of fuel reach portions [12]. A twice as much higher autoignition temperature (420 ^oC) of ethanol relative to that of diesel fuel (230 ^oC) aggravates autoignition and provokes misfiring cycles at easy loads and sharp knocking under heavy loads for bigger than 15vol% ethanol additions [9].

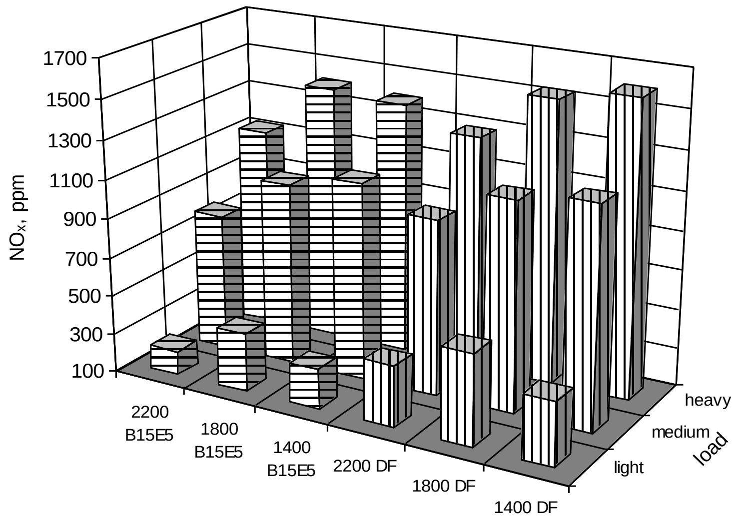

Fig. 2. Total nitrogen oxides NO_x emissions produced from diesel fuel and three-component fuel B15E5 as a function of engine load and speed

As it follows from data given in Table 1, to develop the same torque and effective power as that of reference diesel a fully loaded engine run on less (by 6.18%) calorific three-component fuel B15E5 is imposed to operate with a bigger fuel mass portion delivered per cycle, i.e. under air-to-fuel equivalence ratios on average lower by 2.1%, 3.5% and 1.3% at respective speeds. Engine performance under marginal oxygen deficiency can be one of a main reason why the brake thermal efficiency of biodiesel was lower and the bsfc of oxygenated (6.1% oxygen) fuel was accordingly higher than that of reference diesel. Incomplete combustion of biofuel blend tested results into corresponding changes in NO_x (Fig. 2), CO (Fig. 3) and HC (Fig. 4) emissions behaviour.

The amounts of NO_x emissions depend on performance conditions of the engine, the feedstock oil used for engine fuelling and iodine number, the composition and chemical structure of the fatty acids as well as on variations in actual fuel injection timing advance and autoignition delay caused by changes in physical properties, such as the effect of bulk modulus, viscosity and density of the biofuel [11,12]. A key role in the NO_x production plays also oxygen mass (weight) content accumulated in the biofuel, its composition and chemical structure, including presence of double bonds, as well as performance efficiency related maximum cylinder gas temperature [8,11,13]. Test results with a Case model 188D four cylinder, DI diesel engine confirm that up to 60% of replacement of diesel fuel by ethanol can be achieved however engine misfiring appears because of extreme autoignition delay and severe knocking occurs under some testing conditions [2].

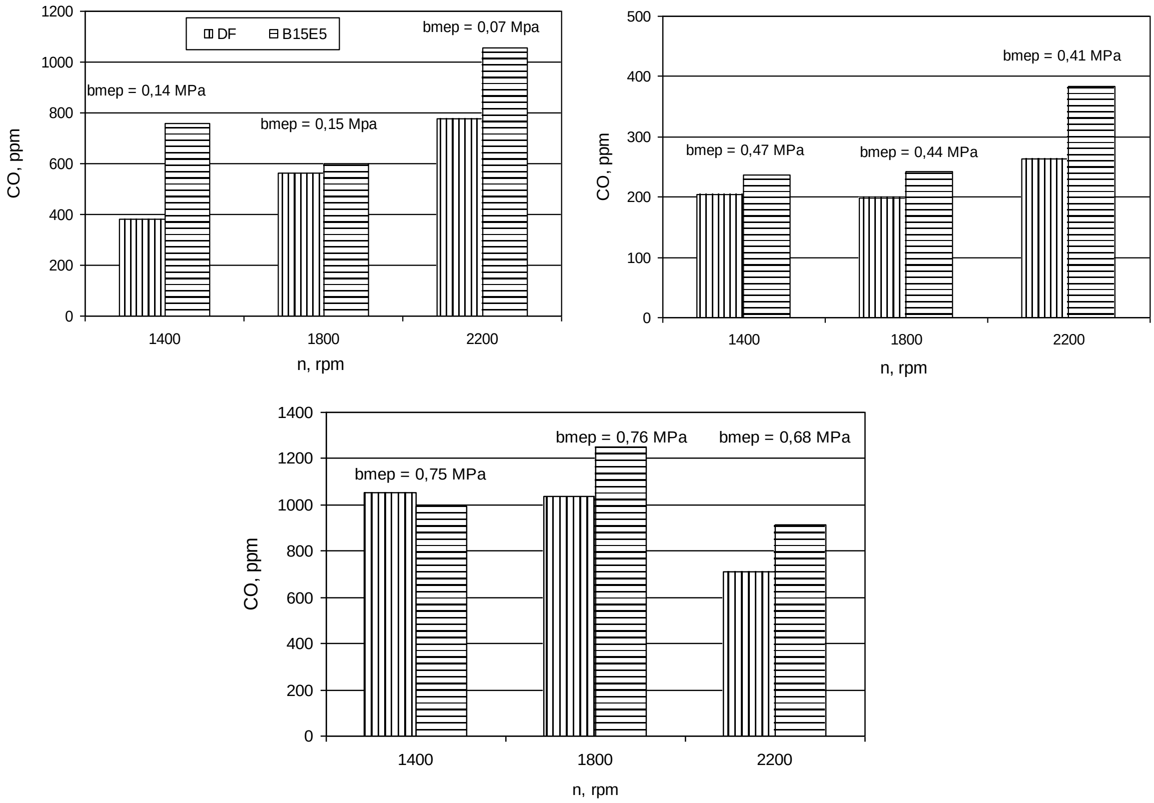

Fig. 3. Emissions of carbon monoxide CO produced from diesel fuel and three-component fuel B15E5 as a function of engine load and speed

Analysis of columns in Fig. 2 indicates, that maximum NO_x emissions produced by the engine operating on three-component fuel B15E5 are lower by 13.4% (1394 ppm), 18.0% (1416 ppm) and 12.5% (1129 ppm) throughout the whole speed range comparing with those values generated from diesel fuel. The intermediate NO_x emission values determined for biodiesel operating under light and medium loads, as it is shown by headmost columns, are also lower by 39.6%, 14.4%, 27.1% and 32.5%, 18.7%, 21.2% at respective 1400, 1800 and 2200 min^{-1} speed.

In spite of a higher fuel bond oxygen mass content (6.1%), worse performance efficiency of biodiesel and lower maximum cylinder gas temperature does not create conditions necessary for production of NO_x [13]. Experiments conducted with a turbocharged and intercooled 7.3 l diesel engine T 444E HT confirmed that maximum cylinder gas pressures and temperatures decreased slightly with increasing the proportion of ethanol, therefore benefits in reduced NO_x emissions were also observed, ethanol-diesel blend E10 decreased NO_x emissions by close to 3% [4].

The carbon monoxide CO emissions depend on load, hence quantity of fuel delivered per cycle and air-to-fuel equivalence ratio, engine speed, i.e. cylinder air swirl turbulence intensity, and biofuel conserved oxygen mass content. When operating on three-component fuel B15E5 at light and under medium loads CO emissions emanating from biodiesel are bigger by 99.7% (759 ppm), 6.4% (598 ppm), 35.3% (1054 ppm) and 15.7% (236 ppm), 22.2% (242 ppm), 45.5% (384 ppm) relative to those determined for reference fuel at 1400, 1800 and 2200 min^{-1} speeds (Fig. 3).

In the case of running a fully loaded engine, the CO emissions produced from blend B15E5 are lower by 6.0% (992 ppm) only at a low 1400 min^{-1} speed and they increase against those measured from reference diesel by 20.1% (1248 ppm) and 28.2% (913 ppm) for higher speeds. Diminished CO emissions at low revolutions can be attributed to a lower C/H ratio of blend B15E5 (6.45) comparing with that of the diesel fuel (6.90) whereas significant CO increase at higher speeds of 1800 and 2200 min^{-1} may take place due to worse ethanol operating properties and such result matches well with a lower NO_x emission (Fig. 2) emerging from biodiesel.

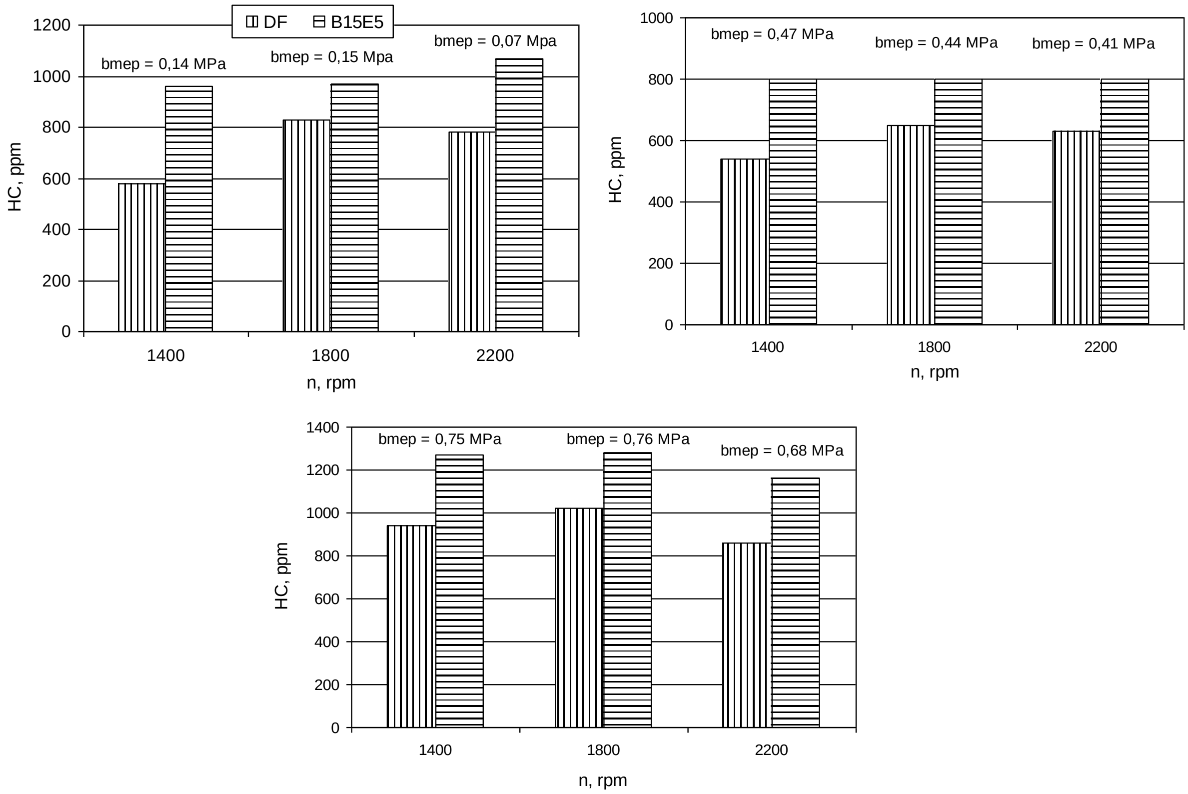

Fig. 4. Emissions of total unburned hydrocarbons HC produced from diesel fuel and three-component fuel B15E5 as a function of engine load and speed

Emissions of HC generated from fuel B15E5 are higher throughout a whole load and speed range (Fig. 4). The biggest 65.5% (960 ppm) HC emission increase occurs at light load and low speed because of diminished fuel injection pressure, cylinder air swirl turbulence intensity, gas pressure and temperature. As speed of the easy loaded biodiesel increases to 1800 and 2200 min^{-1} HC emissions scale up to 970 and 1070 ppm, however their increments regarding baseline values diminish to 16.9% and 37.2%. When running at medium load the HC emission generated from blend B15E5 sustains actually at the same 800 ppm level for a whole speed range, i.e. is by 48.1%, 23.1%, 27.0% higher respective to its baseline values, and increases again to 1270 ppm (35.1%), 1280 ppm (25.5%), 1160 ppm (34.9%) for heavy loads. The test results of a single cylinder Cummins 4 type engine indicate that with increasing ethanol percentage in the blended diesel fuel reduction in NO_x varied from zero to 4-5%. Both decreases and increases in CO emissions occurred, while THC increased substantially, but both were still well below the regulated emissions limit [5].

Because of incomplete burning at light load and low speed, the smoke opacity appearing from three-component fuel B15E5 is vaporous and compiles only 1.5%, however it increases to 5.1% and 5.5% becoming by 70.0% and 14.6% bigger, for higher 1800 and 2200 min^{-1} speeds (Fig. 5). Vaporous smoke emerging from the easy loaded biodiesel matches well with a bigger specific fuel mass consumption (Fig. 1), higher CO (Fig. 3) and HC (Fig. 4) emissions and reasonably lower emission of NO_x (Fig. 2). In the case of running partially loaded biodiesel smoke opacity does not change greatly with speed sustaining actually at the same 20.1-20.5% level, however it is by 32.0% (1400 min^{-1}) to 99.0% (1800 min^{-1}) bigger than that produced from neat diesel fuel.

When operating of the fully loaded engine on fuel B15E5 smoke opacity was reduced by 13.2%, 1.5% and 2.7% comparing with its baseline 61.3%, 66.0% and 69.6% values generated from reference diesel at 1400, 1800 and 2200 min^{-1} speeds. Experiments conducted in a steel combustion chamber with 5vol%, 10 vol% and 20vol% ethanol-diesel blends showed that blending diesel fuel with additives having considerably higher H/C ratios improves the combustion process, reducing pollutants and soot mass concentration in the exhausts [3]. However, when using biofuel B15E5 the fuel bond oxygen may come into effect with a little help and, rather, to late to improve performance efficiency of the engine reducing CO, HC and other related emissions [14].

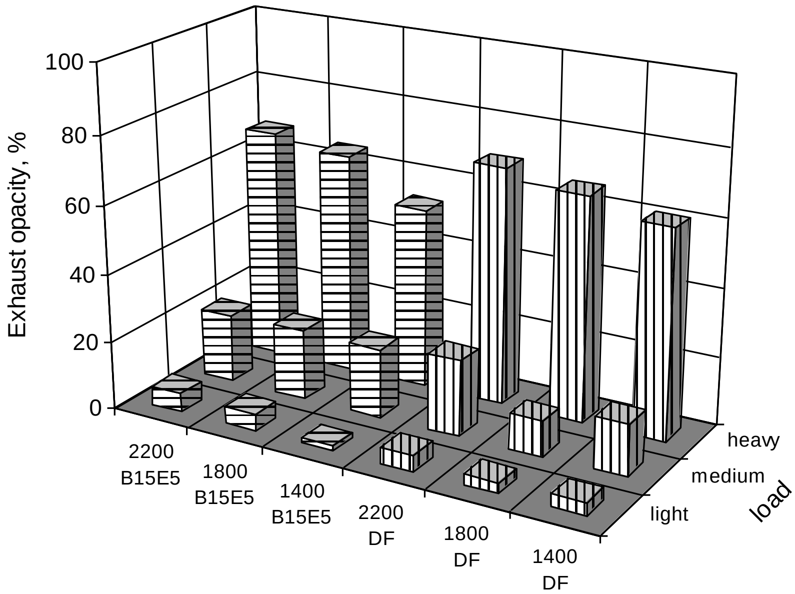

Fig.5. Smoke opacity of the exhausts produced from neat diesel fuel and three-component fuel B15E5 as a function of engine load and speed

In the case of running a fully loaded engine on biofuel B15E5 residual oxygen O_2 content in the exhausts was lower, on average, by 5.0% (7.17vol%), 7.4% (6.10vol%) and 4.3% (7.16vol%) and carbon dioxide CO_2 emission was higher by 2.8% (10.21vol%), 3.4% (10.99vol%) and 2.4% (10.22vol%) relative to that measured from neat diesel fuel at 1400, 1800 and 2200 min^{-1} speeds.

Conclusions

1. Test results indicate that when operating of a fully loaded engine on three-component fuel B15E5 the brake specific fuel mass consumption is bigger by 10.3%, 10.7% and 9.6% comparing with that 237.2, 239.5 and 244.7 g/kWh of a neat diesel fuel. Substitution of the diesel fuel with oxygenated (6.1% oxygen) fuel B15E5 results into the brake thermal efficiency of the fully loaded engine lower by 3.4%, 3.7%, 2.8% relative to values determined for a neat diesel fuel at respective 1400, 1800 and 2200 min^{-1} speed.

2. Maximum emissions of NO_x produced from three-component fuel B15E5 were diminished by 13.4%, 18.0% and 12.5% throughout a whole speed 1400, 1800 and 2200 min^{-1} range relative to 1609 ppm, 1539 ppm and 1291 ppm generated from neat diesel fuel that can be attributed reasonably to worse performance efficiency of biodiesel.
3. The carbon monoxide, CO, emissions from biodiesel are bigger by 99.7% for light 0.14 MPa load and 1400 min^{-1} speed relative to reference 380 ppm value, however difference in the CO amounts exhausted descents by 6.0% (992 ppm) below reference level for the maximum load of 0.75 MPa and low speed of 1400 min^{-1} increasing again by 20.1% (1248 ppm) and 28.2% (913 ppm) for higher 1800 and 2200 min^{-1} speeds.
4. The biggest 65.5% (960 ppm) increase in emission of the HC regarding reference diesel fuel occurs at a light 0.14 MPa load and reduced 1400 min^{-1} speed. When operating under full load, the three-component fuel B15E5 suggests HC emission bigger by 35.1% (1270 ppm), 25.5% (1280 ppm) and 34.9% (1160 ppm) at corresponding 1400, 1800 and 2200 min^{-1} speed.
5. Smoke opacity emerging from a fully loaded engine operating on oxygenated fuel B15E5 is lower by 13.2%, 1.5% and 2.7% relative to respective 61.3%, 66.0% and 69.6% values measured from neat diesel fuel at speeds of 1400, 1800 and 2200 min^{-1}. Residual oxygen O_2 content in the exhausts is lower by 5.0%, 7.4%, 4.3% and carbon dioxide CO_2 emissions are bigger by 2.8%, 3.4%, 2.4% when operating under full throttle on three-component fuel B15E5 relative to that measured from neat diesel fuel at respective speeds.

References

[1] Abu-Qudais, M., Haddad, O., Qudaisat, M. The effect of alcohol fumigation on diesel engine performance and emissions. Energy Conversion and Management, 2000, Vol. 41, p. 389-399.

[2] Shropshire, G.J., Goering, C.E. Ethanol injection into a Diesel-engine. Transactions of the ASAE, Vol. 25(3) 1982, p. 570-575.

[3] Asfar, K.R., Hamed, H. Combustion of fuel blends. Energy Conversion and Management, 1998, Vol. 39, Issue 10, p. 1081-1093.

[4] Hansen, A.C., Gratton, M.R., Yuan, W. Diesel engine performance and NO_x emissions from oxygenated biofuels and blends with diesel fuel. Transactions of the ASAE, 2006, Vol. 49 (3), p. 589-595.

[5] Hansen A.C., Zhang Q, Lyne P.-W.L. Ethanol-diesel fuel blends – a review. Bioresource Technology, 2005, Vol. 96, p. 277-285.

[6] Jha, S.K., Fernando, S., Columbus, E., Willcutt, H. A comparative study of exhaust emissions using diesel-biodiesel-ethanol blends in new and used compression ignition engines. Paper Number: 066138. An ASABE Meeting Presentation, Portland, Oregon, USA, 9-12 July 2006. p. 12.

[7] Labeckas, G., Slavinskas, S. Comparative performance of direct injection Diesel engine operating on ethanol, petrol and rapeseed oil blends. Energy Conversion and Management, Vol. 50 (2009), Issue 3, p. 792-801.

[8] Labeckas, G., Slavinskas, S. Study of exhaust emissions of direct injection Diesel engine operating on ethanol, petrol and rapeseed oil blends. Energy Conversion and Management, Vol. 50 (2009), Issue 3, p. 802-812.

[9] Xing-cai, L., Jian-guang, Y., Wu-gao, Z., Zhen, H. Effect of cetane number improver on heart release rate and emissions of high speed diesel engine fuelled with ethanol-diesel blend fuel. Fuel, Vol. 83, 2004, p. 2013-2020.

[10] Chen, H., Shuai, S-J., Wang, J-X. Study on combustion characteristics and PM emission of diesel engine using ester-ethanol-diesel blended fuels. Proceedings of the Combustion institute, Vol. 31, 2007, p. 2981-2989.

[11] 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, Elsevier Science Ltd.
[12] Lotko, W., Lukanin, V.N., Khatchiyan, A.S. Usage of Alternative Fuels in Internal Combustion Engines. –Moscow: MADI, 2000. –311 p. (in Russian).
[13] Heywood, J.B. Internal Combustion Engine Fundamentals. –Co - Singapore for manufacture and export (International edition) 1988. 930 p.
[14] Rakopoulos C.D., Antonopoulos K.A., Rakopoulos D.C., Hountalas D.T., Giakoumis E.G. Comparative performance and emissions study of a direct injection Diesel engine using blends of Diesel fuel with vegetable oils or bio-diesels of various origins. Energy Conversion and Management. 2006, Vol. 47, p. 3272-3287.

Województwo Zachodniopomorskie

The paper was published by financial supporting of West Pomeranian Province