PERFORMANCE AND EMISSION CHARACTERISTICS OF DIESEL ENGINE FUELLED WITH ETHANOL-DIESEL-BIODIESEL BLEND

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Abstract. The article presents comparative bench testing results of a four stroke, four cylinder, direct injection, unmodified, naturally aspirated diesel engine operating on baseline (DF) arctic class 2 diesel fuel (80 vol %), rapeseed methyl ester (5 vol %) and anhydrous (200 proof) ethanol (15 vol %) blend (B5E15). The purpose of the research is to investigate the effect of simultaneous ethanol and RME addition into diesel fuel on brake mean effective pressure (*bmep*) of the engine, its brake specific fuel consumption (*bsfc*), the brake thermal efficiency (η_e) and emission composition changes, including NO, NO_2, NO_x, CO, CO_2, HC and smoke opacity of the exhausts. The *bsfc* of a fully loaded engine operating on ethanol-diesel-biodiesel blend B5E15 under *bmep* = 0.75, 0.76 and 0.68 MPa is higher by 10.30 %, 10.71 % and 9.65 % because of both net heating value of biofuel lower by 6.18 % comparing with diesel fuel and brake thermal efficiency lower by 5.56 %, 2.86 % and 2.86 % relative to that of neat diesel fuel at corresponding 1400, 1800 and 2200 min^{-1} speeds. The maximum NO_x emissions emanating from blend B5E15 are lower by 13.4 %, 18.0 % and 12.5 % and smoke opacity is diminished by 13.2 %, 1.5 % and 2.7 % throughout a whole speed range relative to their values measured from neat diesel fuel. As a reasonable payoff for NO_x related advantages, CO amounts from oxygenated blend BE15 are lower by 6.0 % for low 1400 min^{-1} speed and they are bigger by 20.1 % and 28.2 % for a higher 1800 and 2200 min^{-1} speeds and emissions of HC are higher by 35.1 %, 25.5 % and 34.9 % relative to that measured from neat diesel fuel at corresponding 1400, 1800 and 2200 min^{-1} speeds. In the case of operating on blend B5E15 residual oxygen O_2 content in the exhaust manifold is lower by 5.0 %, 7.4 % and 4.3 % and carbon dioxide CO_2 emissions are higher by 2.8 %, 3.4 % and 2.4 % relative to that obtained from diesel fuel at speeds of 1400, 1800 and 2200 min^{-1}.

Key words: diesel engine, diesel fuel, anhydrous ethanol, rapeseed oil methyl ester, performance efficiency, emissions, smoke opacity.

Introduction

The biggest problem of the 21st century is linked with increasing prices of mineral fuels, eventual depletion of fossil reserves and growing society concern about global warming. In spite of high prices of the diesel fuel its demand for transportation and agricultural purposes increases year by year and overcomes production possibilities. Increased fuel consumption leads to climate changes because of air pollution by harmful NO, NO_x, CO, CO_2 and HC emissions that all together lead to frequent hurricanes, heavy rains and deadly floods. To extend the variety of environment friendly energy sources, a special interest among researchers has been focused towards reducing dependence on fossil fuels replacing them as much as possible by viable and renewable biofuels, which could curb the carbon dioxide CO_2 emission in a global cycle. The environmental advantages that could be utilised by using cleaner and renewable biofuels would be essentially important for reducing air pollution caused by activities in transportation and agricultural sectors in order that the amount of the exhaust gases of off-road vehicles powered by the diesel engines should comply with the ISO 8178 emission standards.

In order to reduce the demand of fossil fuels and alleviate emerging environmental problems some percentage of the diesel fuel could be substituted with ethanol that has successfully been used for many years in blends with petrol to improve performance of spark ignition engines. On aside lands grown 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. Several methods can be used to employ a certain amount of ethanol for diesel engine fuelling, which are known as alcohol fumigation [1], application of dual injection systems [2], using of the alcohol-diesel fuel micro-emulsions [3] and preparation of the alcohol-diesel fuel blends [1; 4; 5].

The test results [1] show that biofuel blends prepared by mixing of anhydrous ethanol and diesel fuel would also be acceptable for the diesel engine fuelling when applied in proper up to 15 vol % proportions because researchers do not determine big differences in performance of the engine and reported reduction of controlled emissions. The authors noted that the optimum percentage for ethanol fumigation is 20 %, which produced an increase of 7.5 % in brake thermal efficiency, 55 % in CO and

36 % in HC emissions and reduces by 51 % soot mass concentration. The optimum (15 %) percentage of ethanol-diesel fuel blend produced an increase of 3.6 % in brake thermal efficiency, 43.3 % in CO emissions, 34 % in HC and suggested reduction of 32 % in soot mass concentration.

Potential advantages of ethanol and petrol additives used for RO treatment and diesel engine fuelling have been elucidated in investigations [6; 7]. The addition of ethanol into diesel fuel has actually two contradictory effects on biofuel blend properties. Ethanol is known as having 3.91 times lower molecular weight, by 4.9 % lower density at temperature of 20 ºC and its kinematic viscosity at temperature of 40 ºC is also 1.47 times lower relative to that of the diesel fuel, which along with low CFPP at the temperature below of -38 ºC may reduce biofuel viscosity, elevate its flow in the fuelling system and improve the injection quality facilitating starting of the engine under severe winter conditions. However, low cetane number (8) of ethanol and its high autoignition temperature of 420 ºC along with high volatility and up to 3.5 times bigger latent heat for evaporation (910 $kJ \cdot kg^{-1}$) relative to that of the diesel fuel and absorbed water content may aggravate autoignition of biofuel portions injected.

The miscibility of anhydrous (99.81 purity) ethanol with diesel fuel is excellent and it makes clear one phase mixture however during a long-term application of biofuel the lubrication problem of the injection pump plunger-barrel unit may emerge at higher (15 vol %) blending ratios. To improve lubricity of the blend and increase the content of biofuel in the mixture RME from 5 vol % to 10 vol % as co-solvent can be recommended for ethanol-diesel blends [8; 9]. The addition of biodiesel as a stabilizer of ethanol-diesel mixture, suggests extra advantages because this method allows avoiding phase separation between the pure diesel fuel and the ethanol fraction during long term storage.

The purpose of the research is to investigate the effect of simultaneous anhydrous (200 proof) ethanol and rapeseed oil methyl ester (RME) addition into arctic class 2 diesel fuel on biofuel blend properties and conduct comparative bench tests to examine the brake specific fuel consumption (*bsfc*), the brake thermal efficiency (η_e) and emission composition changes, 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 operating of the fully loaded engine alternately on neat diesel fuel and biofuel blend B5E15 containing 80 vol % diesel fuel, 15 vol % ethanol and 5 vol % RME over a wide range 1400, 1800 and 2200 min^{-1} of speeds.

Objects, apparatus and methodology of the research

The tests have been conducted on four stroke, four cylinder, 60 kW DI diesel engine D-243 (60 kW) with a splash volume V_l=4.75 dm^3, bore 110 mm, stroke 125 mm, compression ratio ε = 16:1 and toroidal type combustion chambers in the piston head. The fuel was delivered by an in line fuel injection pump thorough five holes injection nozzles with the initial fuel delivery starting at 25º before the top dead centre (TDC). The needle valve lifting pressure for all injectors was set to 17.5±0.5 MPa.

The load characteristics were taken at 1400, 1800 and 2200 min^{-1} speeds when operating alternately on neat DF (arctic class 2) and ethanol-diesel-biodiesel blend B515E prepared by pouring anhydrous ethanol (15 vol %), diesel fuel (80 vol %) and RME (5 vol %) into the container and mixing them to keep the blend in homogeneous conditions. The torque of the engine was increased from close to zero point up to its maximum values that correspond to standard *bmep* = 0.75, 0.76 and 0.68 MPa, respectively.

Edition of a small (5 vol %) amount of RME into ethanol (15 vol %) and diesel (80 vol %) blend improves both the phase stability and lubricity of the biofuel that has sense at a higher blending ratios. Blend B5E15 distinguishes itself as having the fuel bond oxygen mass content 6.1 %, stoichometric air-to-fuel equivalence ratio 13.55 $kg \cdot kg^{-1}$ and net heating value 39.92 $MJ \cdot kg^{-1}$.

The torque of the diesel engine was measured with 110 kW electrical AC stand dynamometer and the revolution frequency of the crankshaft was determined by using the universal ferrite-dynamic stand tachometer TSFU-1 and its counter ITE-1 that guarantees the accuracy of ±0.2 %. The fuel mass consumption was measured by weighting it on the electronic scale SK-1000 with a definition rate of ±0.05 g 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 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 Testo 350 XL flue gas analyser. The total emission of nitrogen oxides NO_x was determined as a sum of both harmful NO and NO_2 components. The 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 %.

Results and discussions

The addition of 15 vol % of ethanol and 5 vol % of RME into diesel fuel does not change greatly the density of biofuel blend B5E15 and its kinematic viscosity relative to the corresponding values of a neat diesel fuel because the lower density (790.0 $kg \cdot m^{-3}$) and viscosity (1.40 $mm^2 \cdot s^{-1}$) of ethanol is compensated by 1.12 times higher density (884.7 $kg \cdot m^{-3}$) at temperature of 20 ºC and by 3.42 times higher viscosity (4.79 $mm^2 \cdot s^{-1}$) at temperature of 40 ºC of RME portion premixed.

Table 1

Testing conditions of diesel engine operating on arctic class 2 diesel fuel and ethanol-diesel-biodiesel blend B5E15

Rotation speed, min^{-1}	Brake mean effective pressure, MPa	Air-to-fuel equivalence ratio λ	
	DF / B5E15	DF	B5E15
1400	0.75	1.45	1.42
1800	0.76	1.42	1.37
2200	0.68	1.49	1.47

As it is shown in Table 1, a comparative analysis of the engine performance and emission parameters when operating alternately on diesel fuel and ethanol-diesel-biodiesel blend B5E15 was conducted under the same brake mean effective pressures 0.75, 0.76 and 0.68 MPa corresponding to the standard torque changing behaviour versus crankshaft rotation 1400, 1800 and 2200 min^{-1} speeds.

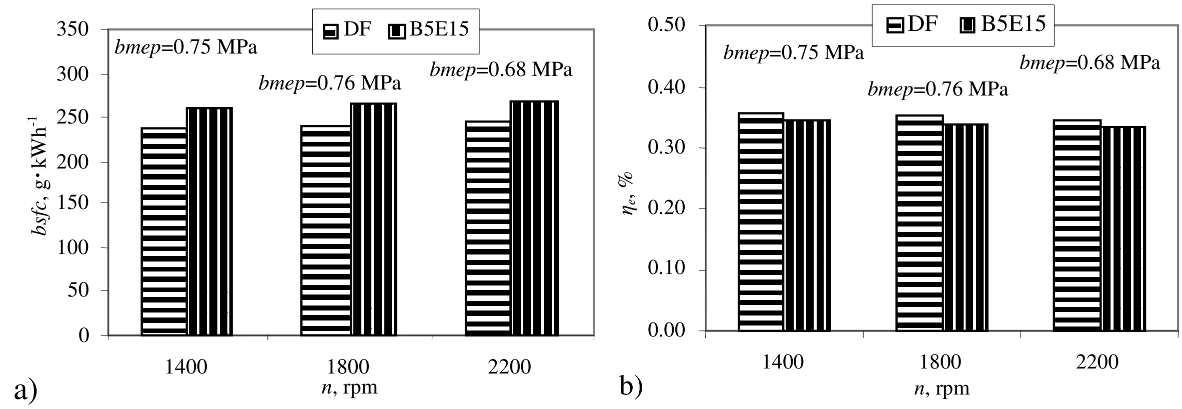

Fig. 1. **Brake specific fuel consumptions (*bsfc*) (a) and brake thermal efficiency (η_e) (b) for neat diesel fuel and biodiesel blend B5E15 as a function of engine speed (*n*)**

The test results show (Fig. 1, a) that the brake specific fuel consumptions (*bsfc*) for respective *bmep* values developed by the engine (Table 1) are by 10.30 %, 10.71 % and 9.65 % higher in the case of operating on ethanol-diesel-biodiesel blend B5E15 comparing with that of neat diesel fuel at corresponding 1400, 1800 and 2200 min^{-1} speeds.

The bigger biofuel mass content consumed for the same amount of energy produced by the engine can be attributed primarily to lower, on average by 6.18 %, net heating value (39.52$MJ \cdot kg^{-1}$) of blend B5E15 comparing with that of the diesel fuel (42.55 $MJ \cdot kg^{-1}$). However, the difference in the heating values of the tested fuels is probably not the main reason that leads to higher ethanol-diesel-biodiesel blend consumption in grams per unit energy developed. To compensate both lower net heating value of ethanol-diesel-biodiesel blend and its a little bit worse energy conversion efficiency and restore the effective power of the engine bigger fuel delivery per plunger active stroke must be adjusted.

As it can be seen in the columns of Fig. 1, b in the case of substitution diesel fuel with blend B5E15 the brake thermal efficiency is lower by 5.56 %, 2.86 % and 2.86 % relative to its values given from the diesel fuel at respective speeds. The lower thermal efficiency can be attributed to the changes occurring in the combustion process [1]. The extremely low cetane number (8) of ethanol, its low calorific value (26.82 MJ·kg^{-1}) and significant cooling effect of the fuel sprays caused by high latent heat for evaporation (910 kJ·kg^{-1}) may lead to retarded start of combustion, relocate maximum cylinder gas pressure and temperature points towards the expansion stroke and increase incomplete diffusion burning of fuel reach portions [11]. 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 15 vol % ethanol additions [8].

As it follows from the data given in Table 1, the biodiesel operates on oxygenated (6.1 % oxygen) and less (by 6.18 %) calorific blend B5E15 under air-to-fuel equivalence ratios lower, on average, by 2.07 %, 3.52 % and 1.34 % at 1400, 1800 and 2200 min^{-1} speeds. This may be the main reason as to why the brake thermal efficiency is relatively lower for biodiesel than that of a normal diesel and the brake specific fuel consumption is considerably higher in the case of operating on blend B5E15. Worsening in the performance efficiency of biodiesel is evidently demonstrated by corresponding NO_x (Fig. 2, a), CO (Fig. 2, b) and HC (Fig. 3, a) emissions behaviour under the considered loading conditions.

The amounts of NO and NO_x emissions depend on the 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 [10; 11]. 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]. Besides the mentioned factors, a key role in the NO_x production is played by the oxygen mass (weight) content in the biofuel, its chemical composition, i.e., presence of double bonds between oxygen and hydrocarbons and the performance efficiency related cylinder maximum gas temperature [7; 10; 12].

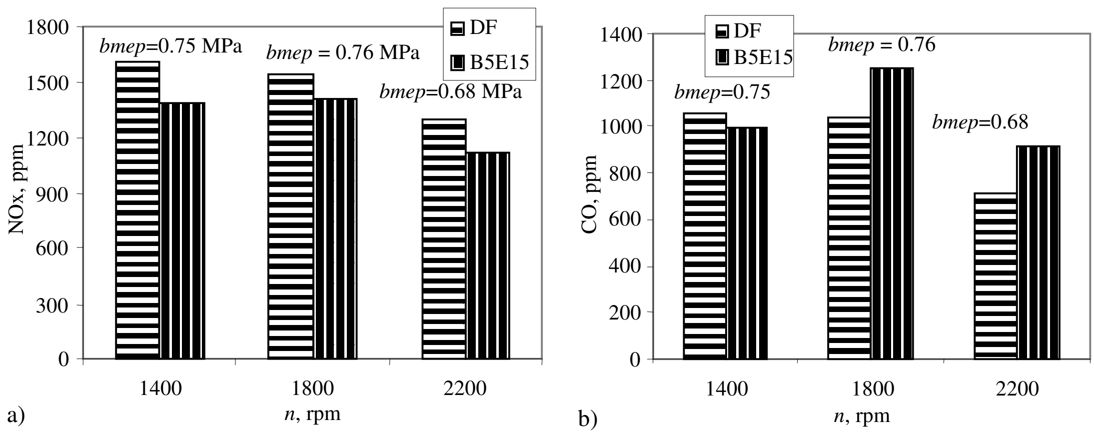

Fig. 2. **Total nitrogen oxides NO_x (a) and carbon monoxides CO (b) emissions generated by diesel fuel and biodiesel blend B5E15 as a function of engine speed (*n*)**

Analysis of the columns in Fig. 2, a shows, that the maximum NO_x emissions emanating from blend B5E15 are lower by 13.4 % (1394 ppm), 18.0 % (1416 ppm) and 12.5 % (1129 ppm) throughout the whole speed range relative to that of diesel fuel. In spite of a higher biofuel bond oxygen mass content (6.1 %), little worse performance efficiency of biodiesel (Fig. 1, b) and reduced cylinder gas temperature suggest significantly diminished NO_x emissions from blend B5E15 [12]. The experiments conducted with a turbocharged and intercooled diesel engine 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, E10 decreased NO_x emissions by close to 3 % [4].

Carbon monoxide CO emissions depend on the engine load, i.e., the quantity of fuel delivered per cycle and air-to-fuel equivalence ratio, engine speed and biofuel bond oxygen mass content. In the case of running a fully loaded engine according to determined by standard torque changing behaviour, CO emissions produced from blend BE15 are lower by 6.0 % (992 ppm) at a low speed of 1400 min^{-1} and they increase by 20.1 % and 28.2 % for higher 1800 and 2200 min^{-1} speeds relative to that measured from neat diesel fuel (Fig. 2, b). Diminished CO emissions at low 1400 min^{-1} revolutions can be attributed to lower C/H ratio of the blend B5E15 (6.45) comparing with that of the diesel fuel (6.90) whereas significant CO increase for higher 1800 and 2200 min^{-1} speeds may occur because of worse ethanol operating properties and such result matches well with lower NO_x emissions.

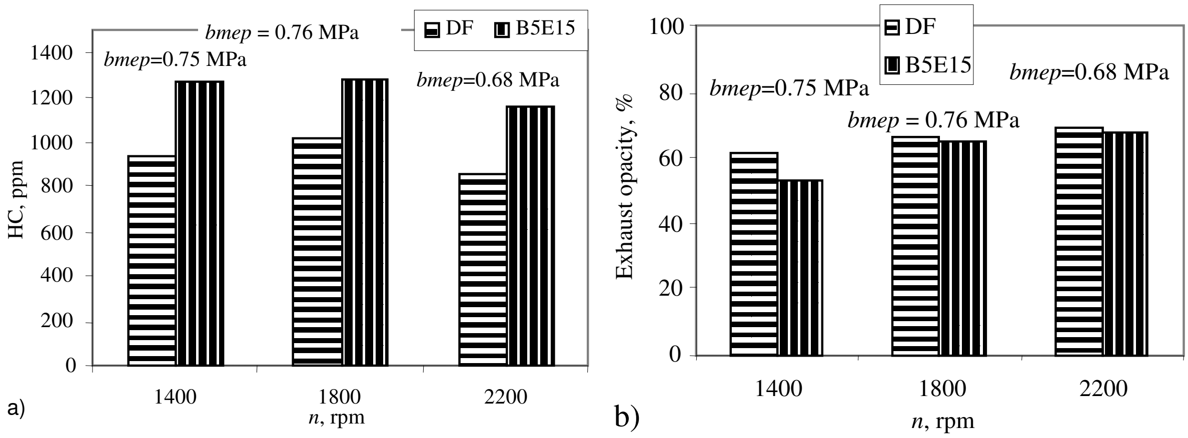

Fig. 3. **Emissions of total unburned hydrocarbons HC (a) and smoke opacity of exhausts (b) from diesel fuel and biodiesel blend B5E15 as a function of engine speed (*n*)**

As it can be seen in Fig. 3, a, when operating on blend B5E15 emissions of hydrocarbons HC increase by 35.1 % (1270 ppm), 25.5 % (1280 ppm) and 34.9 % (1160 ppm) relative to that from diesel fuel at speeds of 1400, 1800 and 2200 min^{-1}. The test results of a single cylinder Cummins 4 type engine confirm that with increasing ethanol percentage in the blended diesel fuel, both decreases and increases in CO emission occurred, while the level of total hydrocarbons THC in the exhausts was higher substantially [2]. The higher HC emissions from blend B5E15 have been obtained because the addition of lighter and low octane ethanol led to longer autoignition delay, retarded diffusion combustion and worse performance efficiency of the diesel engine (Fig. 1, b) that diminishes the cylinder gas temperature related NO_x emission and, as a penalty, increases CO, HC and other emissions, which nature of origin and production circumstances are completely different.

The experiments in a steel combustion chamber with 5 vol %, 10 vol % and 20 vol % 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]. In the case of running a fully loaded engine on ethanol-diesel-biodiesel blend B5E15 the smoke opacity of the exhausts is reduced by 13.2 %, 1.5 % and 2.7 % at speeds of 1400, 1800 and 2200 min^{-1} comparing with its baseline 61.3 %, 66.0 % and 69.6 % values measured from neat diesel fuel (Fig. 3 *b*). Having in mind that comparison of all emissions generated from blend B5E15 is performed under diminished air-to-fuel equivalence ratios (Table 1), such result is acceptable and matches well with lower NO_x amounts (Fig. 2 a) and bigger both HC (Fig. 3 a) and CO emissions (Fig. 2 b) at higher speeds.

In the case of running a fully loaded engine on blend B5E15 the residual oxygen O_2 content in the exhausts manifold is lower, on average, by 5.0 % (7.17 vol %), 7.4 % (6.10 vol %) and 4.3 % (7.16 vol %) and carbon dioxide CO_2 emissions are higher by 2.8 % (10.21 vol %), 3.4 % (10.99 vol %) and 2.4 % (10.22 vol %) comparing with that measured from neat diesel fuel at respective 1400, 1800 and 2200 min^{-1} speeds. A little bit higher carbon dioxide emission released into atmosphere by combustion of oxygenated biofuel blend can be compensated by growing plants for ethanol and RME production, therefore it makes not significant net contribution to global warming.

Conclusions

1. The test results indicate that when operating of a fully loaded engine on blend B5E15 the brake specific fuel mass consumption is higher by 10.30 %, 10.71 % and 9.65 % comparing with that of neat diesel fuel at corresponding speeds of 1400, 1800 and 2200 min^{-1}.
2. In the case of substitution diesel fuel by oxygenated blend B5E15 the brake thermal efficiency of a fully loaded engine is lower by 5.56 %, 2.86 % and 2.86 % comparing with its baseline parameters obtained from diesel fuel at respective 1400, 1800 and 2200 min^{-1} speeds.
3. The maximum NO_x emissions produced from blend B5E15 are diminished by 13.4 %, 18.0 % and 12.5 % comparing with that of diesel fuel at speeds of 1400, 1800 and 2200 min^{-1}. Lower cylinder gas temperature related NO_x emissions generated from oxygenated blend B5E15 can be attributed reasonably to worse performance efficiency of biodiesel.
4. Carbon monoxide, CO, emissions are lower by 6.0 % at a low 1400 min^{-1} speed and by 20.1 % and 28.2 % bigger at a higher 1800 and 2200 min^{-1} speeds relative to that measured from diesel fuel.
5. Emissions of unburned hydrocarbons HC generated from blend B5E15 increase by 35.1 %, 25.5 % and 34.9 % comparing with that from diesel fuel at speeds of 1400, 1800 and 2200 min^{-1}.
6. Exhausts opacity from a fully loaded engine operating on blend B5E15 is lower by 13.2 %, 1.5 % and 2.7 % relative to its values measured from diesel fuel at speeds of 1400, 1800 and 2200 min^{-1}.
7. When operating on blend B5E15 the residual oxygen O_2 content in the exhausts is lower by 5.0 %, 7.4 % and 4.3 % and carbon dioxide CO_2 emissions are higher by 2.8 %, 3.4 % and 2.4 % comparing with that measured from neat diesel fuel at respective speeds of 1400, 1800 and 2200 min^{-1}.

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