THE INFLUENCE OF FUEL ADDITIVE ON DIRECT-INJECTION DIESEL ENGINE FUEL CONSUMPTION AND EXHAUST EMISSIONS

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Abstract

One of the methods that allows reduce the specific fuel consumption of Diesel engines and avoid possible damage of the environment by harmful exhaust gases is application of the fuel additives. The purpose of this research is to determine the influence of the fuel additive SO-2E on the fuel consumption of a direct-injection Diesel engine and to evaluate the quantitative emission composition changes and smoke opacity of the exhausts.

Investigations were conducted on the four cylinder, four stroke, naturally aspirated, water cooled, 59 kW Diesel engine D-243. Test results show that the application of fuel additive SO-2E in proportion 1:500 (by volume) does not have significant influence on the brake specific fuel consumption. The total emission of nitrogen oxides NO_x at the rated performance regime due to the usage of the fuel additive reduces by 11.6 %, primary because of lower NO concentration.

The carbon monoxide CO emission from fully loaded engine at the rated speed due to application of the fuel additive SO-2E increases up to 20 %, although at other performance regimes the additive influence is minor. The smoke opacity from treated fuel at light-to-moderate loads slightly decreases, however at the engine rated speed it becomes by 5 - 10 % higher.

Keywords: Diesel engine, fuel additive, fuel consumption, nitrogen oxides, carbon monoxide, hydrocarbons, smoke opacity.

1. Introduction

Crude oil resources of the Earth are being depleted year by year, therefore prices of the mineral fuels, including Diesel, permanently increase. In spite of high prices, the growing number of heavy-duty trucks, tractors, mobile agricultural technique and Diesel-engined personal cars increases the fuel consumption and atmospheric air pollution. More economical, than petroleum ones, Diesel engines may become in the nearest future the main air pollution source. Experts predict, that in year 2010 the amount of carbon dioxide in the atmosphere will compile nearly 0.06 % and, as an outcome, average temperature of the Earth can be increased by 2.5 °C or, according to pessimistic variant, by 6 °C [2].

Besides the carbon dioxides CO_2 Diesel engines exhaust environmentally harmful nitrogen oxides NO_x, carbon monoxide CO, unburned hydrocarbons HC, soot and other particle matters (PM). Polluted air leads to climate changes, has a negative impact on plants, animals and people health. Acid rains damage historical buildings and statues, especially in the urban areas. Air pollution problems become very important because of the application by EU strict emission requirements. Some ecological questions, especially those related with Diesel exhausts, could be alleviated by application of multifunctional fuel additives. Liquid fuel additives are used in many haulage and shipping companies around the world.

The fuel additive SO-2E is produced in Estonia by Viru Chemistry Group Ltd. (former Viru Ölitööstus Ltd.) in Kohtla-Järve. For production of this additive the shale oil fraction 320-360 °C is used. This fraction contains 5.3 % of phenols that are based on high polar alkyl resorcinols with long-side chains (C_7 - C_{12}) and neutral oxygen compounds with dispersing and antioxidant abilities. The additive SO-2E looks like a dark brown flowing liquid with a specific odour that distinguishes by having a large molecular weight (330-342), heavy density and high viscosity. This poor soluble in Diesel fuel material contains 0.53 % of sulphur, maintains a low acid number of 0.44 mg KON/g and high pour point at temperature of –4 ^{o}C. Alkali components of the phenol reduce fuels acidity and assist in removing tar deposits. Additive SO-2E improves the operational data of liquid fuels, enhances anti-wear and anti-corrosion activity [4,6]. Technical properties of Diesel fuel and additive SO-2E are given in Table 1.

Table 1. Properties of the additive SO-2E

Technical properties	SO-2E
Appearance	Dark brown flowing liquid
Density at 20 ^{o}C, g/cm^3	1.030
Kinematic viscosity at 20 ^{o}C, mm^2/s	295-305
Flash Point, above ^{o}C	80-100
Pour Point, ^{o}C	-4
Phenol, max %	5.3
Sulphur content, max %	0.53
Ash content, max %	0.04
Water content, max %	Traces

Estonian researchers conducted recently a three investigation series of automobile Diesel engines by applying to summer Diesel fuel the additive SO-2E in proportion 0.1 % by volume. The biggest influence on the CO (15.5 %), HC (22.0 %) and NO_x (2.3 %) reduction was determined in case of BMW D engine. Although the influence of additive SO-2E on emission composition changes from Nissan 2.5D and Scania 12TD engines was considerably small. Harmful emissions of the CO, HC and NO_x were reduced by 3.7; 5.2; 2.4 % and 1.1; 3.4; 0.2 %, only [4].

The effectiveness of this additive has been proved in small heating boilers and low-powered fishing bouts. Bench tests with multifunctional fuel additive SO-2E, those were conducted previously at our university, also disclosed some peculiarities of emission composition changes for different load groups. Laboratory tests with Diesel engine D-243 proved that this fuel additive applied in proportion 1: 500 (0.2 vol%) has contrary effect on harmful nitrogen oxide components NO and NO_2 [3]. In order to get the answer how this fuel additive affects the brake specific fuel consumption of a high-speed direct-injection Diesel engine, its emission composition changes and exhaust gas opacity comprehensive bench tests are necessary.

2. Purpose of the Research

The purpose of the research is to determine the influence of the fuel additive SO-2E 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 influence of multifunctional fuel additive SO-2E 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 influence of multifunctional fuel additive SO-2E on the emission composition changes, including the nitrogen oxides NO, NO_2, NO_x, carbon monoxide

CO, hydrocarbons HC and the smoke opacity of the exhausts when running it over a wide range of loads and speed.

3. Research Objects, Apparatus and Methods

Laboratory experiments 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^o before top dead centre (BTDC). The initial needle valve lifting pressure for all injectors was set up to 17.5±0.5 MPa.

Load characteristics were taken at steady engine performance modes and constant crankshaft revolution frequencies n = 1400, 1600, 1800, 2000 and 2200 min^{-1}. After all load characteristics were taken for engine performance on summer Diesel fuel grade F, it was treated with the fuel additive SO-2E in maximum proportion 1:500 (0.2 vol%), and similar experiments were conducted over the same range of engine loads and revolution frequencies.

Torque of the engine was measured with a three phase asynchronous 110 kW electrical AC 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 maximal value of 28-29 Nm.

The revolution frequency of the crankshaft was measured with the universal ferrite-dynamic stand tachometer TSFU-1 and its counter ITE-1 connected to the meter sensor DTE-2. The fuel consumption was determined by weighting it on the electronic scale SK-1000. Volumetric air flow rate was measured by means of the rotor type gas counter RG-400-1-1.5 installed at the air tank for reducing pressure pulsation.

Emission of the exhausts was measured at 6 – 7 variable load points as the latter gradually has been changed from the minimal 20 % up to 110 % of its rated value. The amounts of carbon monoxide CO (ppm), dioxides CO_2 (%), nitrogen monoxide NO (ppm) and dioxides 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 NO and NO_2 components.

Afterwards the carbon monoxide CO (vol%), dioxides CO_2 (vol%) and hydrocarbons HC (ppm vol) emissions as well as the amount of free oxygen O_2 (vol%) in the exhausts were additionally checked with the automobile gas analyser TECHNOTEST Infrared Multigas TANK mode 488 OIML.

Smoke opacity D (%) of the exhausts was measured with Bosch device RTT100/RTT110.

4. The Research Results

As it follows from the graphs of Fig. 1, the application of the fuel additive SO-2E does not affect noticeably the brake specific fuel consumption. When running the engine on the Diesel fuel, that was intentionally treated with additive, at revolution frequency n =1400 min^{-1} the minimum of brake specific fuel consumption (bsfc) is lower by 0.3 %. These obtained fuel savings can be regarded as considerably small and remain within the measurement accuracy available. When running the engine on treated fuel at the rated power (n = 2200 min^{-1}) and the maximum torque (n = 1800 min^{-1}) the bsfc was obtained correspondingly by 1.2 % and 3.3 % higher.

However, the application of the fuel additive SO-2E leads to the noticeable changes of harmful exhaust emissions. Preconditioned Diesel fuel produces in combustion process considerably less nitrogen oxides. As it follows from the analysis of Fig. 2, at light loads and, consequently, low temperatures of burned gases, the total NO_x emission remains small and the effect of the fuel additive on nitrogen oxide components is negligible. As far as the engine load gradually increases to the brake mean effective pressure (bmep) of 0.2 – 0.3 MPa, the total emission of NO_x from treated fuel becomes reduced by 75 – 125 ppm (4.0 - 6.5 %). At higher loads and faster rotation speeds the burned gas temperature in the cylinder becomes higher and the formation process of nitrogen oxides obtains more stimulus.

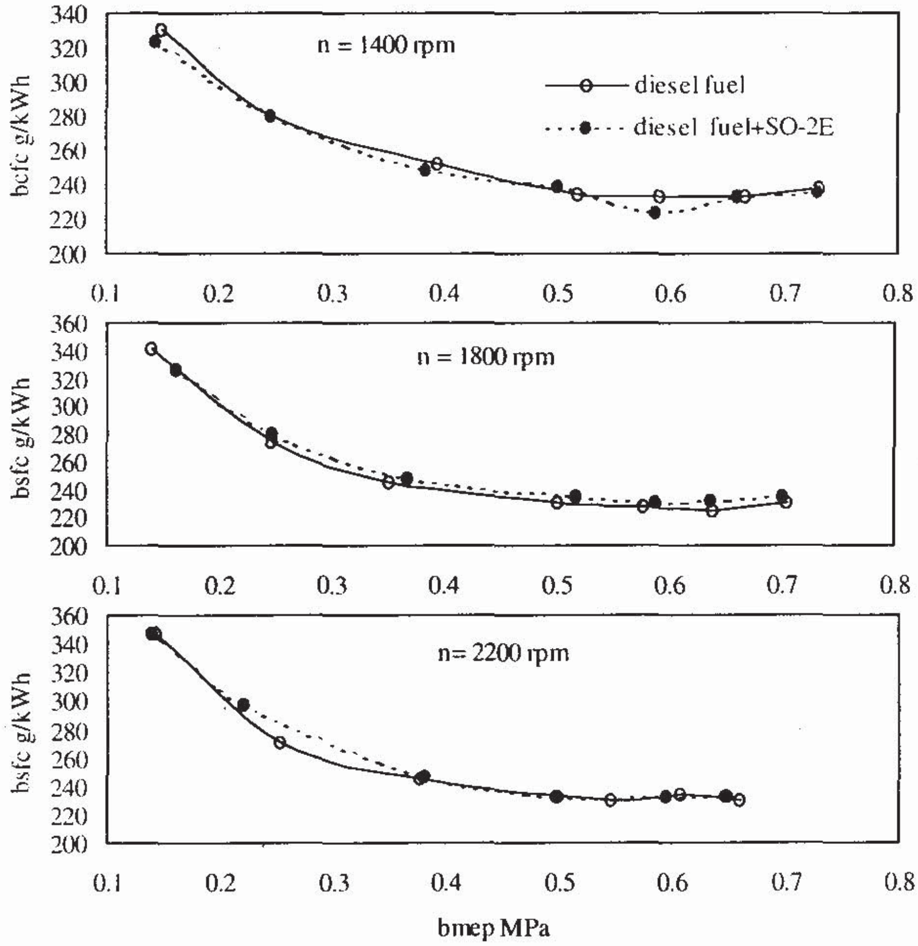

Fig. 1. Dependencies the brake specific fuel consumption (bsfc) on the engine load (bmep) at different revolution frequency (n)

According to the world-known chain reactions mechanism developed by Zeldovich [5], the nitrogen oxides built up beyond the flame from free atoms of nitrogen and oxygen at high gas temperatures (above 2000 K). The amount of nitric oxide increases due to very fast changes of gas pressure and temperature in the cylinder. The final concentration of NO depends also on gas cooling rate in the expansion stroke. Therefore, at higher rotation speed application of the fuel additive becomes more efficient. During fully loaded engine run at rated 2200 min^{-1} speed, the NO_x emission due to the usage of additive SO-2E reduces by 241 ppm or by 11.6 %. Whereas, when running it at reduced revolutions of 1800 and 1400 min^{-1}, the emission of NO_x from treated fuel diminishes by 6.2 % and 4.5 %, respectively.

The analysis of data in Fig. 2 shows, that emission of NO_x depends primary on the engine load (bmep) and structural changes of combustible mixture prepared (λ gradually declines from 5.75 to about 1.65), i.e. on the maximum gas temperature in the cylinder than on the crankshaft revolution frequency and gas turbulence intensity. The fuel additive suppresses primary the most harmful for the environment and people health emission of nitrogen monoxide NO. At engine rated power the NO emission reduces from 1987 to 1752 ppm

(11.8 %), whereas the emission of other harmful component NO_2 simultaneously becomes by 5 - 33 ppm higher.

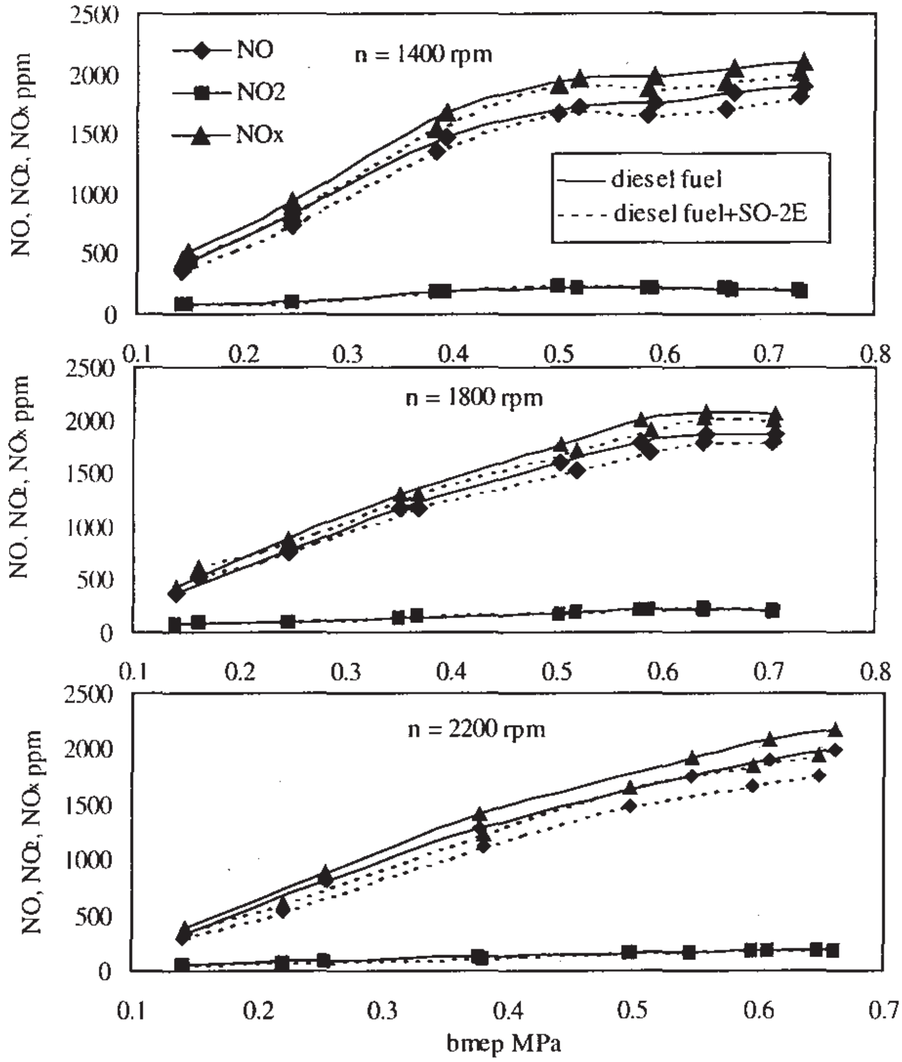

Fig. 2. Dependencies of nitrogen oxides on the engine load (bmep) at different revolution frequency (n)

Although the NO_2 emission of 184 - 211 ppm compiles only about tenth part of the NO concentration and it does not play a key role on the total NO_x background determined.

The carbon monoxide CO builds up mainly in the local fuel-supersaturated zones where the access to oxygen necessary to burn completely the over-rich mixture is strongly limited. At idle or light loads it is rather difficult to distribute evenly across all combustion chamber volume a very small fuel portions injected per cycle. Therefore, even at high on the average air-to-fuel equivalence ratio of $\lambda = 5.75 - 4.50$ along the fuel spouts propagation pathways the lack of oxygen needed for complete combustion may occur. On the other hand, at the increased fuel delivery up to the load approaching the critical smoke limit zone, the emission of CO due to the deficiency of oxygen becomes unavoidable. That is the answer as to why the carbon monoxide emission throughout tested speed variation range approaches to the minimum values approximately at the moderate loads.

The graphs of Fig. 3 show, that the fuel additive SO-2E does not have any clear influence on carbon monoxide emission. At light-to-moderate loads and rotation speed of 1400 min^{-1} fuel additive the CO emission increases by 8.7 - 11.5 %, whereas during the engine run under the maximum load it reduces by 7.1 - 12.5 % respectively. At the rotation speed of 1800 min^{-1} the influence of fuel additive on the CO emission becomes minor. Whereas at the engine rated speed of 2200 min^{-1} due to the usage of treated fuel the CO emission increases on the average

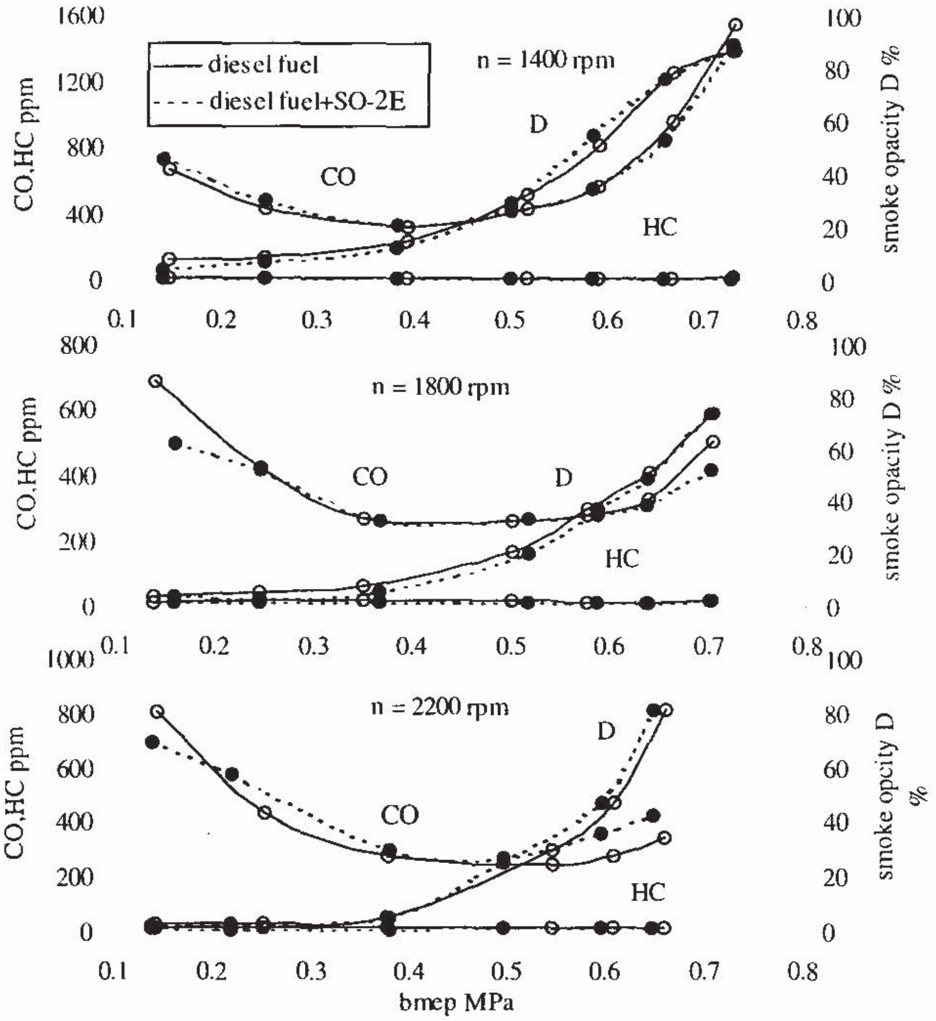

Fig. 3. Emissions of the carbon monoxide, hydrocarbons and smoke opacity of the exhausts as a function of engine load (bmep) at different revolution frequency (n)

by 20 %. Such ambiguous influence of the fuel additive SO-2E on the NO_x and CO emissions confirms different origin conditions of these two species [1].

Smoke formation occurs in the oxygen deficiency areas where thermal pyrolisis of the hydrocarbons takes place in accordance with a complicated multi-stage mechanism of fractioning and decomposing of the fuel molecules. As a result, the exhaust smoke of Diesel engines varies with the chemical structure of the fuel and the amount of aromatic hydrocarbons in the fuel composition. It depends also on the fuel cetane number, diffusion processes that follow in combustion chamber, soot particles formation rate and its combustion speed [5,7].

Influence of the fuel additive SO-2E on the exhaust smoke at engine various performance conditions also is different. Smoke of the exhausts when engine runs at light-to-moderate loads (bmep $\leq$ 0.45 MPa) does not exceed 10-20 %. As one can monitor in the graphs of Fig.3, at the light loads and reduced speed of 1400 min^{-1} application of the fuel additive stimulates the smoke reduction tendencies. As far as the engine load further increases the smoke opacity from treated fuel becomes a little higher. At the rotation speed of 1800min^{-1} the exhaust gas smoke throughout all load alternation zone remains on the average by 14.5 % lower, whereas during fully loaded engine run at the rated speed of 2200 min^{-1} it becomes by 5 – 10 % higher. The higher smoke opacity at the rated speed remains in good agreement with the higher CO and lower NO_x emissions obtained during engine run on treated fuel.

The minor tendencies towards reduction of the HC emission due to application of the multifunctional fuel additive SO-2E were determined only. The amounts of hydrocarbons in general remain negligible and alternate with the engine load and speed somewhere between 10 and 20 ppm.

5. Conclusions

1) Application of the fuel additive SO-2E in a high-speed direct-injection Diesel engine do not has significant influence on the brake specific fuel consumption.
2) The total nitrogen oxides NO_x emission from fully loaded engine when running it on the treated Diesel fuel at the rated speed of 2200 min^{-1} reduces by 11.6 %. The reduction of NO_x is obtained primary due to the lower by 11.8 % nitrogen monoxide NO concentration in the exhausts, because the emission of NO_2 from treated fuel becomes a bit (7.4 %) higher.
3) The carbon monoxide CO emission from fully loaded engine at the rated speed due to application of the fuel additive SO-2E increases up to 20 %, however at the minimum rotation speed of 1400 min^{-1} the CO concentration was found by 7.1 - 12.5 % lower.
4) Smoke opacity of the exhausts from treated fuel at the rotation speed of 1800 min^{-1} throughout tested load alternation zone remains on the average by 14.5 % lower, whereas when running fully loaded engine at the rated speed it becomes by 5 – 10 % higher.
5) The emission of hydrocarbons HC varied with engine load and speed somewhere between 10-20 ppm and only negligible tendencies towards its reduction due to application of the fuel additive were observed.

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