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THE EFFECT OF FUEL ADDITIVE SO-2E ON DIESEL ENGINE PERFORMANCE WHEN OPERATING ON DIESEL FUEL AND SHALE OIL

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Abstract. The purpose of this research is to perform comparative analysis of the effect of fuel additive SO-2E on the economical and ecological parameters of a direct-injection Diesel engine, operating on Diesel fuel and shale oil alternately. It was proved that multifunctional fuel additive SO-2E applied in proportion 0,2 vol % is more effective for improving combustion of shale oil than Diesel fuel. At light operation range the treated shale oil savings based upon fuel energy content throughout wide speed range 1400–2000 min^{-1} reduce from 14,6–12,3MJ/kWh to 11,6–11,8 MJ/kWh or by 20,5–4,1 %. Maximum NO emission for treated Diesel fuel was reduced by 7,8–11,8 %, whereas NO_2 simultaneously increased by 3,8–7,4 %. In the case of treated shale oil both harmful pollutants were reduced by 22,9–28,6 % and by 41,6–13,4 %, respectively. The exhaust gas opacity and CO emissions at the rated performance regime for both fuels were obtained a bit higher, whereas HC emission for treated shale oil increases 1,9 times and for Diesel fuel remains on the same level.

Keywords: Diesel engine, fuel additive, shale oil, performance efficiency, emissions, smoke opacity.

1. Introduction

In spite of the reduction of crude oil resources and permanently growing prices of mineral fuels, the increasing number of heavy-duty trucks, tractors, mobile agricultural technique and personal Diesel-powered cars increases Diesel fuel consumption. Therefore, besides increased financial expenses, population year by year confronts growing ecological problems. Economical and more popular recently than gasoline ones, Diesel engines can become the main air pollution source in the nearest future. Experts predict that in 2010 the amount of carbon dioxide in the atmosphere can compile nearly 0,06 % and, as an outcome, the average temperature of the earth can be increased by 2,5 ^{o}C or, according to pessimistic prognosis, – up to 6 ^{o}C [1].

Polluted air can become one of the main causes that leads to climate changes and has a negative impact on plants, animals and people health. Air toxics contribute to the formation of interactive hurricanes, heavy rains and floods that destroy property, damage historical buildings and statues, especially in the urban areas. To prevent the degradation of nature and to avoid serious ecological problems ground transportation vehicles and agricultural self-propelled machines should be explored observing strict EU emission requirements. For this reasons it is necessary to extend the practical usage of Diesel engine fuelling renewable and alternative energy sources available.

The abundant reserves of Estonian oil shale deposit lying in the area of about 2000 km^2 compound nearly $5\cdot10^9$ t of crude ore [2]. According to the author the quality of shale oil that is produced from the Baltic resources may be rated as one of the best in the world. Therefore, the Baltic oil shale basin could be regarded as an important alternative source of hydrocarbons that are suitable for shale oil production [3]. High quality shale oil, after processing, purification and proper conditioning, could be used primary for running of low-speed fishing boats and power generation stations, especially in remote rural areas. In Lithuania, as well as in other Baltic States, shale oil is widely used for heating boilers fuelling because it is half as expensive as commercial Diesel fuel.

2. The analysis of technical properties and related problems

During the last years in some countries investigations continued to be conducted with an intention to examine the technical properties of shale oil and to adjust it for high-speed direct-injection Diesel engine fuelling [4–6]. As it was proved, direct-injection Diesel engine could be fuelled with the Estonian shale oil, because it does not incorporate solid paraffin ingredients and has a considerably low pour point at the temperature –35 °C. However, testing to date has revealed several problems related to shale oil specific properties. One of them is linked with higher density and viscosity, poor volatility and worse auto-ignition of small portions injected per cycle that leads to Diesel engine unstable performance and reduced energy conversion, especially at light operation range. Due to poor auto-ignition, misfiring cycles and incomplete combustion of fuel-lean mixtures concentration of CO in the exhausts increases up to 10 times. The other serious problem that has been experienced is considerably higher total nitrogen oxides NO_x emission that from oxygen + nitrogen (7–8 %) saturated shale oil under engine maximum torque and rated power increases by 22 and 28 %, respectively [5].

Emerging air pollution problems could be alleviated by the application of multifunctional fuel additives. The fuel additive SO-2E is produced by Estonian Viru Chemistry Group Ltd. (former Viru Ölitööstus Ltd.) located in Kohtla-Järve. For the production of this additive 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 properties. Additive SO-2E looks like a dark brown flowing liquid with a specific odour that is distinguished by large molecular weight (330–342), heavy density and high viscosity. This viscous flowing substance maintains a low acid number of 0,44 mg KON/g and a high pour point at the temperature –4°C. According to references [7–8], additive SO-2E improves the operational data of liquid fuels, assists in removing tar deposits as well as enhances anti-wear and anti-corrosion characteristics. Technical properties of Diesel fuel, shale oil and additive SO-2E are given in Table 1.

Estonian researchers conducted three investigation series of automobile Diesel engines by applying summer Diesel fuel with additive SO-2E in proportion 0,1 % by volume. The biggest effect on CO (15,5 %), HC (22,0 %) and NO_x (2,3 %) reduction was found in the 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 CO, HC and NO_x were reduced by 3,7; 5,2; 2,4 % and 1,1; 3,4; 0,2 %, respectively [7].

The effectiveness of this additive has been proved also in heating boilers fuelled with the local shale oil. However, the comparative analysis of the effect of fuel additive SO-2E on energy conversion rate and emission composition changes as well as on smoke opacity of the exhausts, running the engine alternately on different fuels, has not been accomplished before.

To get the answer how multifunctional fuel additive SO-2E affects the performance of direct-injection Diesel engine, its emission characteristics and exhausts opacity comprehensive bench tests are needed. The purpose of the research is to provide the comparative analysis of the influence of fuel additive SO-2E on economical and ecological para-

Table 1. Properties of Diesel fuel, shale oil and additive SO-2E

Technical properties	Diesel fuel (grade F)	Shale oil	Additive SO-2E
Appearance	–	Dark brown flowing liquid	Dark brown flowing liquid
Density at (20 °C), g/cm^3	0,839	0,925	1,030
Kinematic viscosity at 20 °C, mm^2/s	3,50	10,2	295–305
Flash Point (open cup), above °C	64	68	80–100
Pour Point, °C	–10	–35	–4
Polycyclic aromatic hydrocarbons, max %	4	42	5,3 (phenol)
Sulphur content, max %	0,0248	0,80	0,53
Ash content, max %	0,01	0,02	0,04
Water content, max %	0,0031	0,20	Traces
Net Heating value of Combustion, MJ/kg	42,5	41,12	–

meters of a high-speed direct-injection Diesel engine, when fuelling it alternately with Diesel fuel and shale oil. The objectives of this research may be stated as follows:

1. To analyse the influence of multifunctional fuel additive SO-2E on the brake specific energy consumption of Diesel engine running it alternately on Diesel fuel and shale oil over a wide range of loads and revolutions per minute.

2. To examine the influence of multifunctional fuel additive SO-2E on the emission composition changes, including nitrogen oxides NO, NO_2, NO_x, carbon monoxide CO, hydrocarbons HC and smoke opacity of the exhausts running it alternately on Diesel fuel and shale oil over a wide range of loads and speed.

3. Objects, experimental apparatus and methodology of the research

Testing was conducted on completely commissioned, four cylinder, four stroke, naturally aspirated, water cooled, 59 kW direct injection Diesel engine D-243 with splash volume $V_1 = 4{,}75\ dm^3$, bore of 110 mm, stroke of 125 mm and compression ratio of $\varepsilon = 16:1$. Diesel engine was fuelled with Diesel fuel and shale oil that was brought from Viru Õlitööstus Ltd., Kohtla-Järve, Estonia.

The fuel was delivered by the in-line model 4UTNM fuel-injection pump through five holes injection units into the chamber in a piston head. The fuel injection pump was adjusted to the initial delivery start at 25 ^{o} before the top dead centre (BTDC). The initial needle valve lifting pressure for all injectors was set up to 17,5±0,5 MPa.

The fuel consumption was determined by weighing it with an electronic scale VLK-500. Volumetric flow rate of air was measured by means of the rotor type gas counter RG-400-1-1.5 installed in the air tank for reducing pressure pulsation. 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. This aeronautical device determines the revolution frequency with the accuracy of ±0,2 %.

Load characteristics were taken with asynchronous 110 kW electrical AC stand dynamometer at steady engine performance modes and constant crankshaft revolutions n = 1400, 1600, 1800, 2000 and 2200 min^{-1}. After all load characteristics were taken for the engine performance on F category summer Diesel fuel as baseline parameters, the latter was treated by the maximum proportion of 1:500 (0,2 vol %) with the fuel additive SO-2E and similar experiments were conducted with the same range of engine loads and revolution frequencies.

Afterwards, Diesel engine performance characteristics were repeatedly taken over the appointed above test ranges running it alternately on neat shale oil and shale oil that was intentionally pre-treated by the same ratio of 1:500 (0,2 vol %) with the fuel additive SO-2E.

The engine emission characteristics were measured at 6–7 variable load-points as the latter gradually has been changed from the point that was close to zero up to its maximal value of 28–29 Nm. This means that the effective power of the engine at rated speed n = 2200 min^{-1} had been increased from the minimum up to 110 % of its rated value.

The amounts of carbon monoxide CO (ppm), dioxides CO_2 (vol %), nitrogen monoxide NO (ppm) and dioxides NO_2 (ppm) in the exhausts were measured with the gas analyser Testo 33. The total emission of nitrogen oxides NO_x was calculated as a sum of both harmful pollutants NO and NO_2.

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

The smoke opacity D (%) of the exhausts was measured with the Bosch device RTT 100/RTT 110 in 1–100% scale with ±0,1 % accuracy.

In the article and figures located below Diesel fuel and neat shale oil are marked as abbreviations “DF” and “Sh. oil”, whereas Diesel fuel and shale oil treated with fuel additive SO-2E are noted by capital letters as “DF+SO-2E” and “Sh.oil+SO-2E”, respectively.

4. The research results

The net heating value of shale oil is on average by 3,3 % lower than that of Diesel fuel. In order to eliminate discrepancies in the heating value and to gain a more convenient position for the comparison of the results it has been decided to take into account brake specific energy consumption (bsec) in MJ/kWh of both tested fuels. As it follows from the analysis of graphs in Fig 1, the specific shale oil consumption based upon its energy content for rotation speeds of 1400–2200 min^{-1} is by about 10,0–14,5 % higher than that of conventional Diesel fuel.

Higher shale oil energy consumption in MJ per unit of mechanical energy in kWh developed was obtained probably because of a relatively higher amount of carbons in the shale oil composition. The proportion in mass between carbons and hydrogen in the Baltic shale oil reaches 7,5–8,1 in comparison with that of Diesel fuel, which remains equal to 6,9. According to [9], carbon atoms have a tendency to burn at a lower speed than hydrocarbons and, consequently, ensure a lower energy conversion rate. Other possible reasons of lower shale oil energy conversion efficiency can be linked with altering of fuel sprays penetration across a combustion chamber and poor atomisation quality due to its higher density and viscosity relative to conversional Diesel.

The analysis of graphs in Fig 1 points out that the application of additive SO-2E in Diesel fuel does not lead to noticeable bsec improvement. When running the engine on the treated fuel at revolutions of 1400 min^{-1} the minimum bsec was reduced by 0,3 % only. Obtained fuel savings can be regarded as negligible and remain within the measurement accuracy available. Whereas during fully loaded engine run at the rated speed of 2200 min^{-1} and the maximum torque (n = 1800 min^{-1}) the bsec due to the application of fuel additive increased by 1,2 % and over 2,0 %, respectively.

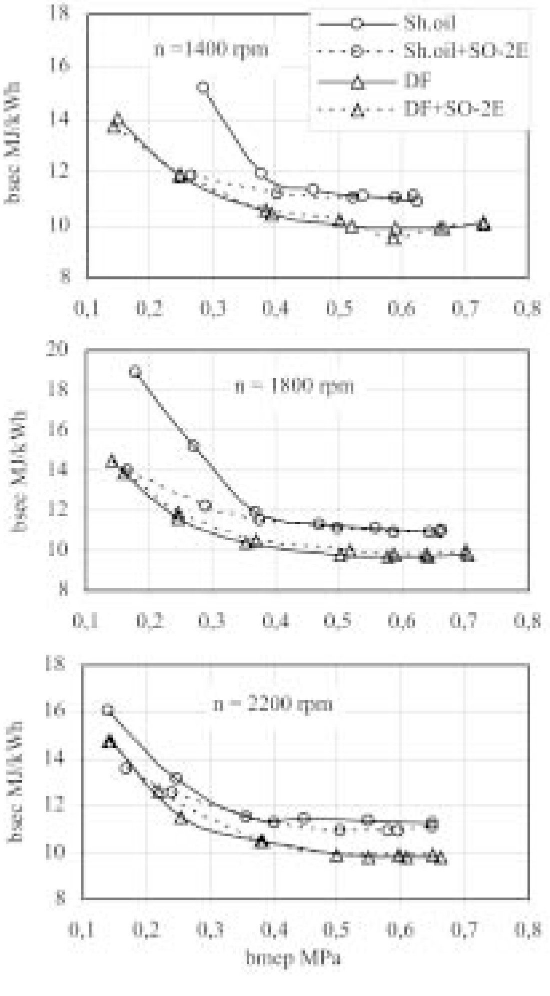

Fig 1. The brake specific energy consumption (bsec) as a function of engine load (bmep) at various revolution frequencies

In contrast to Diesel fuel, the application of multifunctional fuel additive SO-2E in shale oil insures significant improvement of bsec, especially during engine performance at light-to-moderate loads. Observing graphs of Fig 1, it becomes clear that for speed range of 1400–2000 min^{-1} and brake mean effective pressure (bmep) of 0,3 MPa the application of fuel additive bsec reduces from 14,6–12,3 MJ/kWh to 11,6–11,8 MJ/kWh or by 20,5–4,1 %.

Poor distribution across the combustion chamber of small portions of viscous shale oil injected, its low volatility and insufficient flammability at low gas temperatures in the cylinder leads to misfiring cycles and unstable performance at light operation range. Under such circumstances fuel additive SO-2E can help to auto-ignite and burn fuel-lean (λ = 6,50–3,80) mixtures completely, improving the overall engine performance efficiency and reducing bsec at these particular regimes. As soon as the engine load reaches a certain (bmep ≥ 0,4 MPa) level, the gas temperature in the cylinder increases to such a degree, that shale oil evaporation and combustion processes start to progress efficiently enough. Therefore, fuel additive SO-2E loses gradually its stimulating effect on bsec reduction that was proved throughout low-to-moderate operation range.

At the maximum rotation speed of 2200 min^{-1} bsec savings due to the usage of treated shale oil were obtained at reduced loads mainly. Fig 1 shows that at the bmep of 0,2 MPa the bsec of shale oil diminishes from 14,3 to 13,0 MJ/kWh or by 9,1 %, whereas during run at the rated power fuel energy savings compile 2,4 % only. It is clearly seen in the graphs that bsec smoothly decreases with the load tending to converge to the one obtained during Diesel operation on pure shale oil.

The analysis of a nitrogen oxides formation process can be made on the basis of the world-known chain reactions mechanism that was developed by Zeldovich. According to [10], the active role belongs to free atoms of nitrogen and oxygen built up at high gas temperatures (above 2000 K). The oxides of nitrogen emerge usually due to very fast changes of gas pressure and temperature in the cylinder. The final concentration of NO in the exhausts depends also upon gas cooling rate during expansion stroke.

Dependencies of nitrogen oxides NO and NO_2 emission on the engine load (bmep) when running it at different rotation speed on Diesel fuel and shale oil, both with and without fuel additive SO-2E, are given in the graphs of Fig 2. It was determined that the emission of nitrogen oxides for shale oil at light-to-moderate loads is much lower in comparison with that measured from conventional Diesel fuel [11, 12]. But at heavy loads, with higher peak pressures and temperatures, and larger regions of close-to-stoichio-

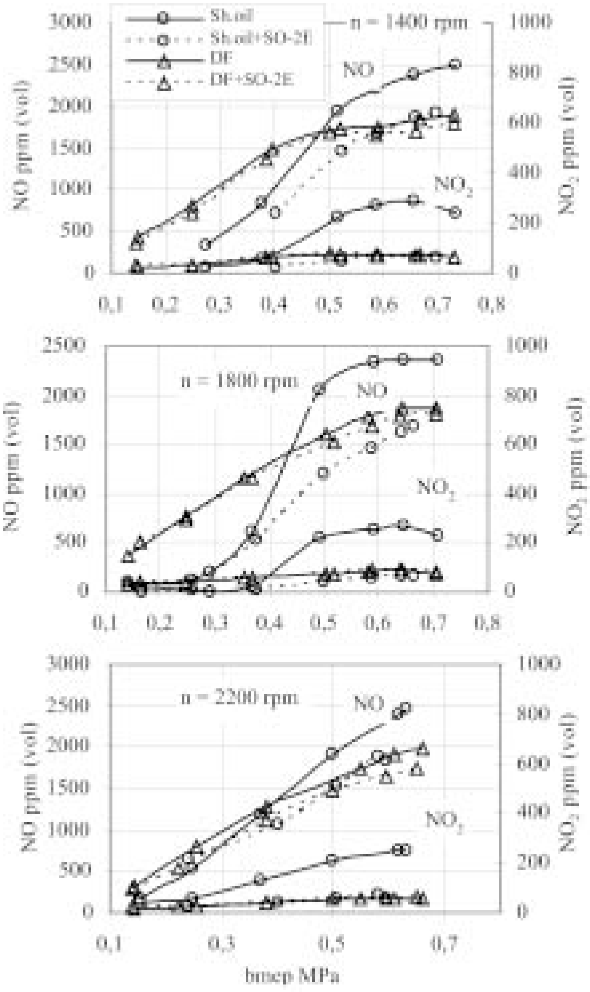

Fig 2. Dependencies of nitric monoxide NO and nitrogen dioxide NO_2 emissions on the engine load (bmep) at various revolution frequencies

metric burned gas, NO levels for shale oil have a tendency to increase rapidly. Though the overall air-fuel equivalence ratio increases proportionally as the amount of fuel injected is decreased, much of the fuel still burns close to stoichiometric. Thus in the case of conventional Diesel fuel NO emissions should be roughly proportional to the mass of the fuel injected because provided burned gas pressures and temperatures do not change greatly [9].

The application of fuel additive NO emission of fully loaded engine run at speed range of 1400–2200 min^{-1} reduces by 7,8–11,8 %, whereas the emission of other harmful component NO_2 increases simultaneously by 3,8–7,4 %. As an issue, the total concentration of NO_x in the exhausts from treated Diesel fuel becomes possible to reduce by about 6,1–11,6 % [11]. Variations in engine speed have only a little effect on the shape of NO and NO_2 curves changing with the load as well as on the influence of fuel additive on these pollutants.

Starting from a considerably low level the concentrations of NO and NO_2 for shale oil increase with the load, and hence the quantity of fuel injected, with considerably higher increment rate than that for conventional Diesel. More intensive rise of harmful nitrogen monoxides at intermediate loads occurs, presumably, because tested shale oil incorporates about 7–8 % of oxygen + nitrogen. In contrast to NO produced from atmospheric nitrogen, the amounts of fuel nitrogen converted to NO are more sensitive to the air-fuel equivalence ratio (λ reduces from 4,60 to 1,35), and hence to the quantity of shale oil injected per cycle, than to gas pressure and temperature in the cylinder. When running the engine at full throttle on fuel-rich mixture, the amounts of shale oil incorporated oxygen and nitrogen in the cylinder increase to take an active role in the nitrogen monoxide generation. This NO from shale oil composition NO produced contributes to the amounts of NO formed normally at high gas temperatures from the atmospheric nitrogen to increase the total NO_x amount and air pollution. The last but not the least role belongs also to shale oil aromatics that compile over 42 % and are known as contributing to emissions of particle matters (PM) and NO_x too [13].

Emissions of NO and NO_2 for pure shale oil reach at the top level up to 2500 ppm and 288 ppm, respectively. Under such circumstances the effect of fuel additive on nitrogen oxides obtains more stimulus. The fuel additive did effectively reduce the maximum NO concentration at rotation speeds of 1400; 1800 and 2200 min^{-1} by 572 ppm (22,9 %); 732 ppm (28,6 %) and 587 ppm (23,8 %). In contrast to Diesel fuel, the maximum emission of NO_2 at typical revolutions also diminishes simultaneously by 33,7 %, 41,6 % and 13,4 %. As it obvious from Fig 2, the maximum NO and NO_2 emissions for treated shale oil decrease down to such a degree that is observed usually from conventional Diesel. Moreover, at the intermediate loads the NO and NO_2 emissions descend even below the baseline level.

Fig 3 shows that during engine performance on Diesel fuel additive SO-2E does not have significant influence on the carbon monoxide emission. At the minimum speed and light-to-moderate loads CO emission for treated Diesel fuel increases by 8,7–11,5 %, whereas during run under the maximum load it reduces by 7,1–12,5 %. At higher revolutions of 1800 min^{-1} the effect of fuel additive becomes minor, whereas at the rated speed the CO emission for treated Diesel fuel increases on average by 20 %.

In contrast to NO_x, CO emission for pure shale oil at light operation modes is incredibly high and reaches at reduced speeds up to 5000 ppm. The main reason of drastically increased carbon monoxide emis-

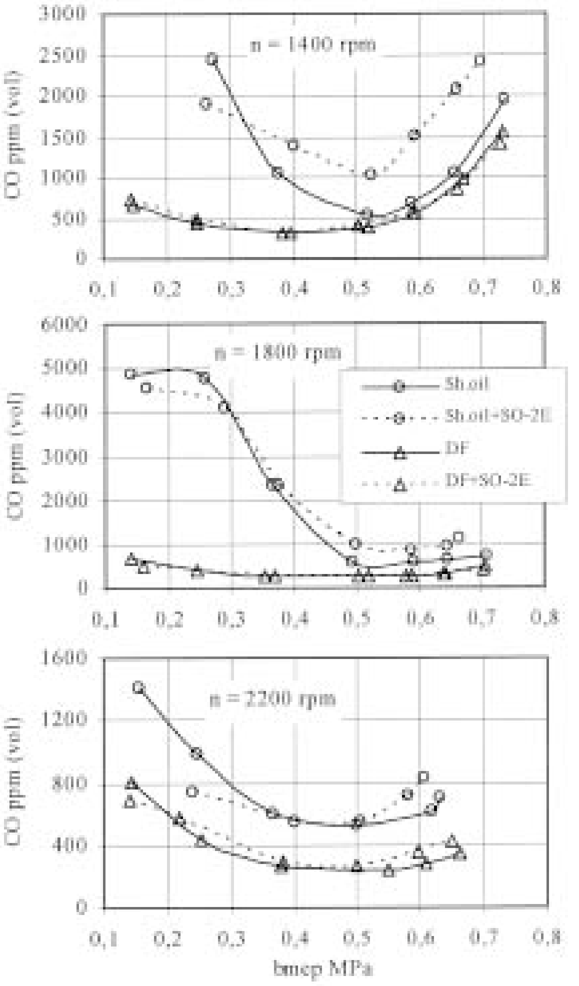

Fig 3. Carbon monoxide CO emissions in the exhausts as a function of engine load (bmep) at various revolution frequencies

sion may be related to worse combustibility of fuel-lean mixtures, because of its poor volatility at low gas temperatures in the cylinder, a bit higher flash point and emerging misfiring cycles. On the other hand, it is difficult to atomise and distribute evenly small portions of viscous shale oil across the combustion chamber volume. Therefore even in overall fuel-lean mixtures in some particular areas, especially in the core regions of each fuel spray, where the local air-fuel equivalence ratios are low enough, the lack of atmospheric oxygen needed for complete combustion may occur. As soon as the engine load, gas pressure and temperature increase to a certain degree, the combustion efficiency becomes higher and CO emission for shale oil goes down.

At the intermediate throttle position the carbon monoxide emission for shale oil descends to the minimum values, although starting from a certain load level CO concentration tends to increase again. Higher CO emission may occur due to incomplete combustion of fuel-rich mixtures resulting from the local oxygen deficiency. As it is obvious from Fig 3 the application of fuel additive CO emission reduces at light operation modes only. At every particular revolution frequency exists a certain point of engine load when CO emission, generated by treated shale oil, exceeds the primary level and becomes higher relative to that of pure fuel.

At the minimum speed of 1400 min^{-1} and light loads CO emission for treated shale oil diminishes by 22,1 % and more. Similar CO reduction tendencies remain in value for fuel-lean mixtures throughout all revolution range tested. Although at the maximum bmep = 0,7 MPa and critically reduced air-fuel equivalence ratio of λ =1,65 CO emission, when running on treated shale oil, increases by up to 61,7 %.

At higher rotation speeds of 1600–2200 min^{-1} and heavier loads CO emission for pure shale oil obtains a more acceptable character. As the engine speed, load and fuel injection pressure increase, CO emission decreases noticeably due to higher gas pressure and temperature in the cylinder At rated speed carbon monoxide concentrations locate somewhere between 500–1000 ppm, however at a full load CO emission for treated shale oil becomes by 16,3 % higher. The higher CO concentration emerging at heavy loads remains in good agreement with drastically reduced NO_x concentration and verifies about different origin of these two species [9, 10]. Since changes that reduce NO_x may cause a decrease in cylinder peak temperature that results in an increase of CO and corresponding increase in the smoke opacity that follows below.

Fuel carbon builds up in the extremely rich fuel vapour core as an issue of the lack of local oxygen needed for complete combustion of soot particles. The other important source of soot is pyrolysis of the fuel molecules that may occur at high temperatures in the fuel-rich areas before mixing to leaner equivalence ratios. However, when a combustion process goes properly almost all (over 90 %) of the soot particles those built up during a diffusive combustion process are oxidised prior to exhaust [9].

During a normal Diesel operation the smoke increases gradually with the load and variations of rotation speed do not have any significant effect on the behaviour of smoke curves. The highest gas opacity was measured at the loads that were close to the maximum only. Observing Fig 4, it is clear that the effect of fuel additive on the smoke opacity at various performance conditions is different. As it was noted analysing CO emission peculiarities at light-to-moderate loads the fuel additive demonstrates smoke reduction tendencies, but as the engine load gradually increases, gas smoke emerging from treated Diesel

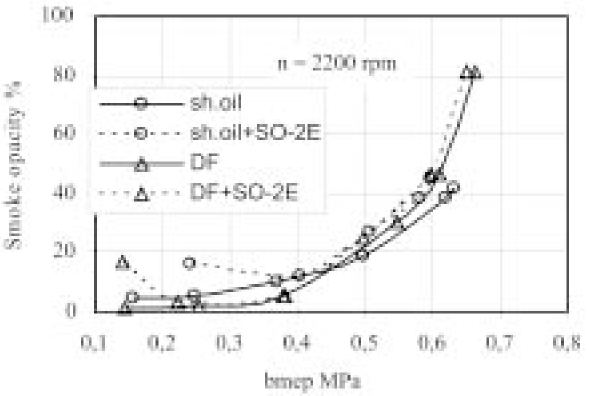

Fig 4. Smoke opacity of Diesel exhausts as a function of load (bmep) at various revolution frequencies

fuel may become a bit higher. Only at the rotation speed of 1800 min^{-1} the gas opacity almost throughout all load alternation zone remains on average by 14,5 % lower, whereas at the rated performance regime it is by about 5–10 % higher.

It should be noticed that smoke opacity during engine run on shale oil at various loads obtains a different origin. At light loads and reduced speed due to poor combustion of fuel-lean mixtures at critically low gas temperatures a lot of small unburned fuel droplets appear in the form of bright white aerosols exhausted into atmosphere. Whereas during engine run under the maximum load at high gas pressures and temperatures in the cylinder the smoke of burned fuel-rich mixtures obtains dark-grey colour similar to that observed normally from conventional Diesel. It is important to emphasise that smoke opacity for shale oil throughout all speed variation range at wide-open throttle area remains by 30–35 % lower than that of Diesel fuel [5].

Lower smoke opacity was obtained regardless of the relatively higher carbon content in shale oil composition and 10 times as much more polycyclic aromatic hydrocarbon included. It is known that carbon burns at lower speed than hydrogen tending to produce more smoke at equivalent air-fuel equivalence ratios relatively. Furthermore, at low temperatures aromatic hydrocarbon can produce soot via a relatively fast direct route that involves the condensation of the aromatic rings into a graphitelike structure [9]. Nevertheless, in spite of many reasons to predict higher smoke opacity the latter remains much lower than that generated by conventional Diesel fuel, presumably, due to more complete combustion of oxygen saturated fuel-rich mixtures.

The influence of fuel additive SO-2E on gas smoke appearing from shale oil run engine under various performance conditions is also different. Because fuel additive improves the fuel-lean mixture reaction with surrounding oxygen, gas temperature slightly increases and, consequently, more unburned fuel vapours as airborne aerosols appear in the exhausts. As it follows from the analysis of Fig 4, bright-white opacity for treated shale oil at light-to-moderate loads and critically reduced speed boosts up for about two times. As the engine load, gas pressure and temperature in the cylinder increase, the exhausts obtain naturally dark-grey colour and differences in gas smoke for shale oil with and without additive diminish. Nevertheless, at minimum revolutions of 1400 min^{-1} gas smoke from a fully loaded engine run on treated shale oil remains by 6,2 % higher.

At higher rotation speed of 1800 min^{-1} and light-to-moderate loads much more unburned oil vapours appear in the atmosphere, therefore, the considered discrepancies in smoke opacity diminish. Nevertheless, at moderate-to-heavy loads gas smoke for treated shale oil remains on average by 25–30 % higher. At the rated speed of 2200 min^{-1} and fully opened throttle gas opacity from treated shale oil also boosts up by 35 %. Again, here one should have in mind that opacity is greater usually for dark smoke rather than for white aerosols exhausted at light loads. Higher gas opacity accompanied by increased CO and HC emissions can be regarded as unobjectionable penalty that must be paid for drastically reduced NO_x concentration in the exhausts. Increased cetane number of treated fuel also can be one of the reasons as to why excessive CO, HC and smoke accompanied by reduced emission of NO and NO_2 were obtained [14, 15].

Hydrocarbon constituents vary from methane to the heaviest hydrocarbons, which remain in the vapour phase in the heated sampling line only (at about 190 °C). The main source of unconsumed hydrocarbons is related to incomplete mixing of locally over-rich mixture or quenching of the oxidation process within low temperature areas [9]. For these reasons during idling and light run significantly higher hydrocarbon emissions may have place than at full load operation. On the other hand, when operating under heavy loads HC emissions can also slightly increase due to the lack of the local oxygen necessary for hydrocarbon combustion.

Observing Fig 5, it is obvious that HC emissions for both fuels tested remain comparably low. Nevertheless, when running the engine on different sorts of fuel some of HC behaviour peculiarities can be considered. At light loads and speed range of 1600–2000 min^{-1} HC emissions for pure shale oil were approximately threefold higher than those for Diesel fuel. The maximum amount of HC at the speed of 1800 min^{-1} reaches up to 66 ppm, whereas HC concentration for Diesel fuel remains between 18–20 ppm. Suspiciously low HC emission for shale oil at light loads and critically reduced speed of 1400 min^{-1} was measured probably because of condensation of the heaviest hydrocarbons due to low gas temperature in the sampling line [16].

Effect of additive SO-2E on HC emissions for both fuels is ambiguous and depends on engine speed and load. At the lowest speed HC emission generated by fully loaded engine for Diesel fuel and shale oil reduces by 26,3 % and 30,2 %, respectively. At higher revolutions of 1800 min^{-1} and fully opened throttle no clear effect due to the usage of fuel additive was found at all, whereas at light load operation HC emission for Diesel fuel and shale oil was lower 1,5 and 3,3 times, respectively. Finally, HC concentration at the rated performance regime for treated shale oil increases by about 1,9 times and for Diesel fuel remains on the same level.

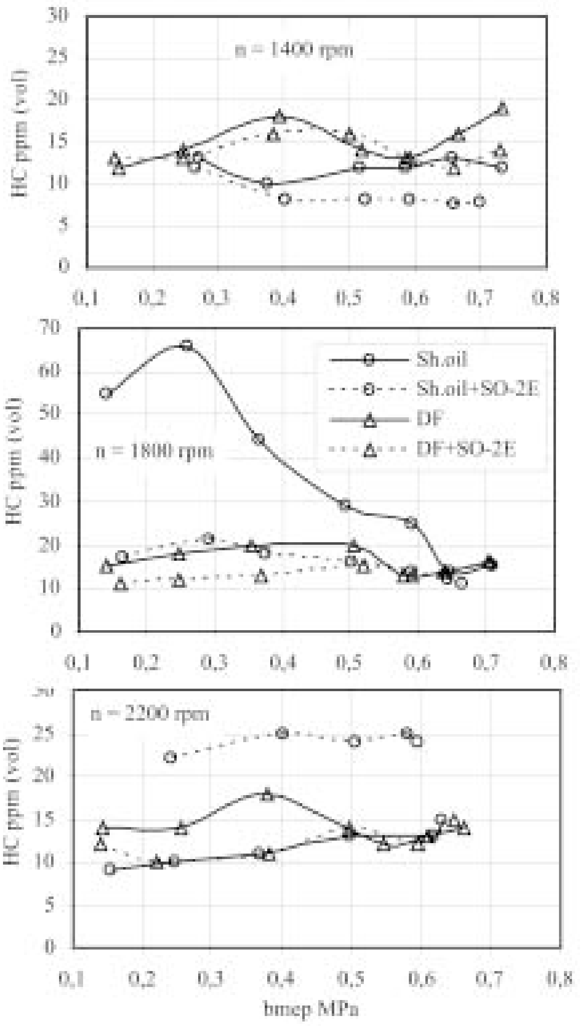

Fig 5. Hydrocarbons HC emissions in Diesel exhausts as a function of engine load (bmep) at various revolution frequencies

5. Conclusions

1. The application of fuel additive SO-2E in proportion 0,2 vol % proves to be more effective for improving combustion efficiency of shale oil than commercial Diesel fuel. The rated value of bsec due to the usage of additive for shale oil decreases by 2,4 %, whereas for commercial Diesel fuel increases by 1,2 %. Although, at light operation range the effect of the application of treated shale oil is more evident, - fuel savings based upon fuel energy content throughout wide speed range 1400–2000 min^{-1} reduce from 14,6–12,3 MJ/kWh to 11,6–11,8 MJ/kWh or by 20,5–4,1 %.

2. The effect of fuel additive SO-2E on diminishing of maximum NO_x emission generated by shale oil is also much higher. Maximum emissions of NO and NO_2 from treated shale oil reduce by 22,9–28,6 % and 41,6–13,4 %, respectively, descending to such a degree which is usually measured for conventional Diesel fuel. In the case of treated Diesel fuel the maximum emission of NO diminishes by 7,8–11,8 %, whereas the concentration of NO_2 increases simultaneously by 3,8–7,4 %.

3. The gas opacity due to the application of fuel additive at light loads and critically reduced speed boosts up for about two times as the result of unburned shale oil vapours suspended in the exhausts, whereas smoke of treated Diesel fuel diminishes by 14,5 %. At the engine rated power dark-grey smoke increases by 5–10 % for treated Diesel fuel and by 35 % for shale oil.

4. The effect of fuel additive SO-2E on CO and HC emissions for both tested fuels seems to be ambiguous and depends largely on the engine speed and load applied. At the rated speed and full load, CO emission for treated shale oil increases by 16,3 % and for Diesel fuel by 20 %, whereas HC concentration boosts up 1,9 times and remains on the same level, respectively.

6. Aknowlegements

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