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

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The purpose of this research is to perform comparative analysis of the effect of fuel additive SO-2E on performance parameters of direct-injection Diesel engine, when operating on Diesel fuel and shale oil alternately. Multifunctional fuel additive SO-2E proved itself more efficient when applied in shale oil than at application in Diesel fuel. At the light-load operation the consumption of treated (0.2 vol%) shale oil based upon fuel energy content throughout speed range 1400-2000 min^{-1} diminishes from 14.6–12.3 MJ/kWh to 11.6–11.8 MJ/kWh or by 20.5–4.1%. The maximum NO and NO_2 emissions for treated shale oil are lower by 22.9–28.6% and by 41.6–13.4%, respectively. Opacity of the exhaust gas and CO emissions for both fuels treated are a bit higher.

Introduction

Experts predict that in the year 2010 the amount of carbon dioxide in the atmosphere may compile nearly 0.06% and, as an outcome, the average temperature of the Earth can be increased by 2.5 °C to 6 °C [1]. To prevent nature degradation and avoid ecological problems, ground transportation vehicles and self-propelled agricultural machines must be explored in accordance with strict EU emission requirements. For this reasons it is necessary to use for Diesel engine fuelling renewable and alternative fuels, especially treated with multifunctional additives to reduce harmful emissions.

The abundance of Estonian oil shale deposit lying in an area of about 2000 km^2 compiles nearly $5 \cdot 10^9$ t of crude ore [2]. According to the author of

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the paper, the quality of this shale oil 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 for shale oil production [3]. In Lithuania, as well as in other Baltic States, high-quality shale oil after processing, purification and proper conditioning could be used for powering of fishing boats and electrical generators, especially in remote rural areas.

The analysis of technical properties and related problems

During the last years investigations continued with an intention to examine technical properties of shale oil and to adjust it for fuelling high-speed direct-injection Diesel engine [4, 5]. The direct-injection Diesel engine could be fuelled with Estonian shale oil because it does not contain solid paraffin ingredients and its pour point at the temperature –35 °C is considerably low. However, testing to date has revealed several problems related to specific properties of shale oil. One of them concerns higher density and viscosity, poor volatility and worse auto-ignition that lead to unstable performance of Diesel engine at light-load operation. The other problem that has been experienced is considerably higher (by 22 to 28%) total emission of nitrogen oxides NO_x caused by high content of oxygen + nitrogen (7-8%) in shale oil [4].

Emerging performance and air pollution problems could be alleviated by application of multifunctional fuel additives [5, 6]. Fuel additive SO-2E is produced by Estonian Viru Chemistry Group Ltd. (former Viru Õlitööstus Ltd.) at Kohtla-Järve. For production of this additive, shale oil fraction of 320–360 °C is used, which contains 5.3% phenols and neutral oxygen compounds of dispersing and antioxidant properties. Additive SO-2E looks like a dark brown fluid liquid of a specific odour. The additive is characterized by large molecular weight (330–342), heavy density and high viscosity. Additive SO-2E improves operational data of liquid fuels, assists in removing tar deposits as well as enhances anti-wear and anti-corrosion characteristics. In more detail the technical properties of shale oil and additive SO-2E are given in [4–6].

The effectiveness of additive SO-2E has been proved in the BMW D engine [6] as well as in heating boilers fuelled with Estonian shale oil. However, comparative analysis of the effect of fuel additive SO-2E on energy conversion rate and emission composition changes as well as on smoke opacity, when running the engine alternately on different fuels, has not been accomplished before.

The purpose of the research is to provide comparative analysis of the influence of fuel additive SO-2E on performance parameters 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. Analysis of the influence of fuel additive SO-2E on the brake specific energy consumption of a Diesel engine when running it alternately on Diesel fuel and shale oil over a wide range of loads and revolutions per minute.

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

Objects, experimental apparatus and methodology of the research

Testing was conducted on a four-cylinder, four-stroke, naturally aspirated, water-cooled, 59-kW direct-injection Diesel engine D-243 with splash volume 4.75 dm^3, bore of 110 mm, stroke of 125 mm and compression ratio of ε = 16:1. The Diesel engine was fuelled with Diesel fuel (grade F) and shale oil brought from Viru Õlitōōstus Ltd., Kohtla-Järve, Estonia.

Load characteristics were determined with an electrical AC dynamometer at revolutions n = 1400, 1600, 1800, 2000 and 2200 rpm when operating alternately on pure shale oil and the shale oil treated with fuel additive SO-2E at the same ratio of 1:500 (0.2 vol%) as Diesel fuel.

The amounts of carbon monoxide CO (ppm), nitrogen monoxide NO (ppm) and dioxides NO_2 (ppm) in the exhausts were measured with gas analyser Testo 33. Emissions of HC were determined with gas analyser TECHNOTEST Infrared Multigas TANK mode 488 OIML. Smoke opacity (%) of the exhausts was measured with Bosch device RTT 100/RTT 110.

In the article and figures, Diesel fuel and pure shale oil are marked with abbreviations “DF” and “Sh.oil”, whereas Diesel fuel and shale oil treated with fuel additive SO-2E are denoted by abbreviations “DF+SO-2E” and “Sh.oil+SO-2E”, respectively.

Research results

Net heating value of shale oil is on average by 3.3% lower than that of Diesel fuel. In order to eliminate the difference in the heating value and provide accurate analysis of the results it has been decided to calculate the brake specific energy consumption (bsec) in MJ/kWh (Fig. 1). As it follows from the graphs, bsec of shale oil is by about 10.0-14.5% higher than that of Diesel fuel.

Higher consumption of shale oil for producing the same amount of energy is needed, because shale oil contains relatively more carbon. The mass proportion of carbon to hydrogen in Baltic shale oil reaches 7.5–8.1 while that of Diesel fuel is 6.9. According to [7], carbon atoms have a tendency to burn at a lower speed than hydrocarbons do and, consequently, ensure lower efficiency of energy conversion.

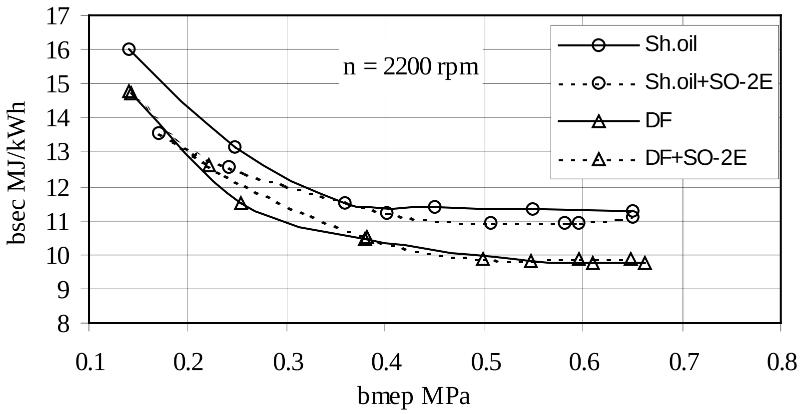

Fig. 1. The brake specific energy consumption (bsec) as a function of engine load (bmep)

The analysis of Fig. 1 shows that application of additive SO-2E in Diesel fuel does not lead to noticeable improvement in bsec. In contrast to Diesel fuel, the usage of additive SO-2E in shale oil ensures a significant reduction in bsec, especially at light and moderate loads. At low speed and light brake mean effective pressure (bmep) 0.3 MPa, the usage of additive SO-2E results in reduced value of bsec from 14.6–12.3 MJ/kWh to 11.6–11.8 MJ/kWh, or by 20.5– 4.1%.

Poor distribution of small portions of viscous shale oil injected across the combustion chamber and low volatility of oil along with insufficient flammability at low temperatures of gas leads to misfiring cycles and unstable performance of the engine at light-load operation. In such circumstances, fuel additive SO-2E favors autoignition and complete burning of fuel mixtures improving the efficiency of engine performance, reducing the bsec rate and harmful emissions.

At the rated speed 2200 rpm, the bsec savings due to the usage of treated shale oil were obtained at reduced loads mainly. Figure 1 shows that at bmep 0.2 MPa, the bsec of treated shale oil diminishes from 14.3 to 13.0 MJ/kWh, or by 9.1%, whereas at a fully opened throttle the savings in fuel energy compile 2.4% only.

In contrast to Diesel fuel [8], the emission of nitrogen monoxide from shale oil at light and moderate loads is much lower (Fig. 2), but at heavy loads, NO levels for shale oil have tendency to increase more rapidly. Though the overall equivalence ratio of air to fuel increases with the reduced portion of injected fuel, much of the fuel still burns close to stoichiometric ratio. Thus in the case of Diesel fuel NO emissions should be roughly proportional to the mass of injected fuel, because pressure and temperature of burned gas do not change greatly [7].

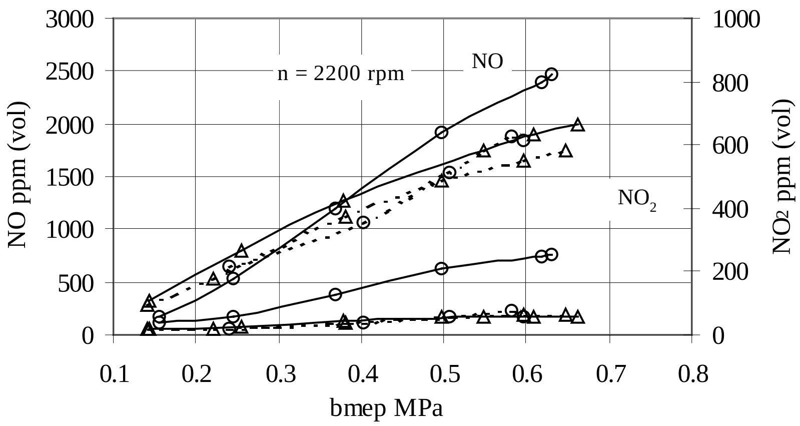

Fig. 2. Dependencies of the nitric monoxide NO and nitrogen dioxide NO_2 emissions on the engine load (bmep)

Due to application of fuel additive SO-2E, NO emission of the fully loaded Diesel engine is reduced by 7.8–11.8%, whereas the emission of other harmful component NO_2 increases simultaneously by 3.8–7.4%. As an outcome, the total concentration of NO_x in the exhausts from the treated Diesel fuel diminishes by 6.1–11.6% [8]. Variations in engine speed have only a little effect on the changes in NO and NO_2 levels with the load as well as on the influence of fuel additive on NO_x emissions.

Starting from a considerably low level, NO and NO_2 emissions from shale oil increase with the load, and hence the quantity of fuel injected, with considerably higher increment rate than that of conventional Diesel. An intensive rise in the amount of nitrogen monoxides at intermediate loads occurs, presumably, because shale oil contains about 7–8% oxygen + nitrogen. In contrast to the NO produced from airborne nitrogen, the amounts of fuel nitrogen converted to NO are more sensitive to the air to fuel equivalence ratio (λ reduces from 4.60 to 1.35), and hence to the quantity of shale oil injected, than to gas pressure and temperature changes in the cylinder.

During engine operation under full load, the amounts of shale oil oxygen and nitrogen increase with the portion of fuel injected to take active role in the nitrogen monoxide production. This extra NO arising from burned shale oil contributes to the amounts of NO formed from the airborne nitrogen at high temperatures of gas to increase the common emission of NO_x. Last but not least, shale oil aromatics that compiles over 42% play a certain role in NO_x formation and contribute to emissions of particle matters (PM), too [9].

Emissions of NO and NO_2 from pure shale oil reach, at the top level, up to 2500 ppm and 288 ppm, respectively. In such circumstances, application of fuel additive SO-2E is very efficient. At speeds 1400, 1800 and 2200 rpm, additive reduces the maximum concentration of NO by 572 ppm (22.9%); 732 ppm (28.6%) and 587 ppm (23.8%), respectively. In contrast to Diesel fuel, the maximum emission of NO_2 at considered revolutions diminishes simultaneously by 33.7%, 41.6% and 13.4%. As it obvious from Fig. 2, the maximum emissions of NO and NO_2 from treated shale oil decrease to such a degree that is observed usually in the case of conventional Diesel. Moreover, at intermediate loads NO and NO_2 emissions from the treated shale oil descend far below the baseline levels obtained during operation with ordinary Diesel.

At the minimum speed and light to moderate loads, CO emission from the treated Diesel fuel increases by 8.7–11.5%, whereas during engine operation under the maximum load it diminishes by 7.1–12.5%. The positive effect of fuel additive SO-2E on the emission of carbon monoxide diminishes with the speed. As an outcome, during operation at the rated regime, CO emission from the treated Diesel fuel increases on average by 20%.

In contrast to NO_x, CO emission from shale oil at light operation modes is very high and reaches at reduced speeds up to 5000 ppm. The main reason of drastically increased CO emission may be related to worse combustibility of fuel lean mixtures because of its poor volatility at low temperatures of cylinder gas, a bit higher flash point and misfiring cycles. Therefore CO emissions from treated shale oil were reduced mainly at light loads. Moreover, at every particular speed there exists a critical point of engine load at which CO emission from treated shale oil overcomes the baseline level suggesting a bit higher CO concentrations under heavy loads.

The amount of smoke increases gradually with the load, and variations in rotation speed do not have any significant effect on smoke behaviour. The highest opacity of gas was measured at loads close to the maximum only. Observing Fig. 3, it is pretty clear that the effect of fuel additive on smoke opacity at various loading conditions differs to some extent. At high speed and easy loads the fuel additive may increase opacity of the smoke from both treated fuels more noticeably, whereas at heavy loads the effect of fuel additive is negligible. At reduced revolution 1800 rpm corresponding to the maximum torque, the visible smoke from the treated Diesel fuel is on average by 14.5% lower whereas at the rated regime it is by 5–10% higher.

It should be noted that smoke opacity during engine operation on shale oil may have a different origin. At light loads and speeds, because of poor combustion of fuel lean mixtures, a lot of small unburned fuel droplets appear in the form of bright white aerosols emitted into the atmosphere. During engine run under the maximum load the smoke of burned fuel-rich mixtures obtains a dark-grey colour similar to that of ordinary Diesel fuel. It is very important that opacity of the smoke from fully loaded engine run on shale oil throughout all speed variation range remains by 30–35% lower than in the case of Diesel fuel [4].

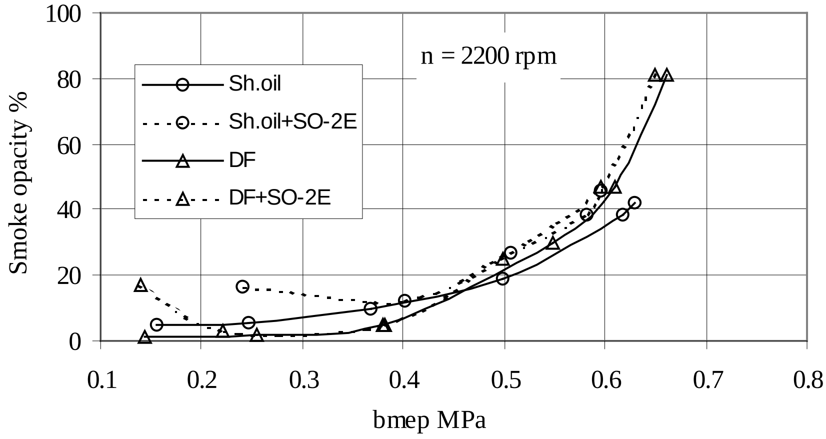

Fig. 3. Smoke opacity of Diesel exhausts as a function of load (bmep)

The influence of fuel additive SO-2E on smoke opacity during operation on shale oil at various performance conditions is different. Because fuel additive improves the reaction of fuel lean mixture 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. 3, the bright-white smoke from the treated shale oil at easy and moderate loads boosts up for about two times. As the engine load, gas pressure and temperature increase, difference in opacity of the smoke from treated and pure shale oil diminish again, however, at the rated speed and fully opened throttle the amount of gas smoke from the treated shale oil increases by 35%.

One should have in mind that opacity of dark smoke is usually greater than that of white aerosols suspended in the atmosphere at light loads. Higher opacity of gas from both treated fuels accompanied by increased emissions of CO and HC can be regarded as an unavoidable penalty linked with drastically reduced concentration of NO_x in the exhausts. Increased cetane number of both treated fuels may also be one of the reasons of why excessive CO, HC and smoke accompanied by reduced emission of NO and NO_2 were obtained [10].

The maximum amounts of HC from shale oil reach 66 ppm, those from Diesel fuel range from 18 to 20 ppm. The effect of additive SO-2E on HC emissions from both fuels is ambiguous and depends on the engine speed and loading conditions.

Conclusions

1. Application of fuel additive SO-2E in proportion 0.2 vol% proves to be a more efficient measure for shale oil than for Diesel fuel. The effect of treated shale oil is greater at light loads – fuel savings based upon fuel energy content at speeds 1400-2000 rpm are reduced from 14.6–12.3 MJ/kWh to 11.6–11.8 MJ/kWh, or by 20.5–4.1%.
2. The positive effect of fuel additive SO-2E on NO_x emissions from shale oil is also greater. The maximum NO and NO_2 emissions from the treated shale oil are reduced by 22.9–28.6% and 41.6–13.4%, respectively, decreasing to such a degree which is usually measured for conventional Diesel.
3. Opacity of gas from the treated shale oil at light loads and low speeds increases about two times as the result of unburned fuel vapours suspended in the atmosphere, whereas that of gas from the treated Diesel fuel diminishes by 14.5%. At rated power of the engine the amount of dark-grey smoke increases for both treated fuels by 35% and 5–10%, respectively.
4. The effect of fuel additive SO-2E on CO and HC emissions from both fuels seems to be ambiguous and largely depends on engine speed and load. At the rated performance regime CO emission increases by 16.3% for treated shale oil and by 20% for treated Diesel fuel.

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