EFFECT OF FUEL ADDITIVES ON DIESEL ENGINE PERFORMANCE AND EXHAUST EMISSIONS

ИССЛЕДОВАНИЕ ВЛИЯНИЯ ТОПЛИВНОЙ ПРИСАДКИ НА РАБОТУ ДВИГАТЕЛЯ И ЭМИССИЮ ОТХОДНЫХ ГАЗОВ

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Abstract: *The performance and combustion emissions of diesel engine can be modified using various chemical fuel additives. Fuel additives consist of a variety of chemical compounds. It contains chemical elements such as: hydrocarbons, C11-C14, C10-C13, n-alkanes, isoalkanes, cyclics aromatics, cycloalkane, 2-ethylhexyl nitrates. Analysis has been conducted on diesel fuel and diesel fuel and additives blends. Fuel additives No.1, No.2 and No.3 consisting of these chemical elements have been analysed. The obtained results show, that the amounts of carbon monoxide emissions at low engine loads (IMEP = 0.32 MPa) increases up to 35% compared to pure diesel fuel. While using additives, the hydrocarbons emissions at low engine loads almost doubles compared to pure diesel fuel. The break specific fuel consumption with the engine powered by pure diesel fuel was lowest in all modes. The highest increase on in cylinder pressure 11% was only determined with the fuel additive No.3 at the maximum load of 1.12 MPa at the speed of 1800 rpm.*

KEYWORDS: FUEL ADDITIVES, EXHAUST EMISSIONS, INDICATED MEAN EFFECTIVE PRESSURE, HYDROCARBONS, N-ALKANES, CYCLOALKANE, 2-ETHYLHEXYL NITRATE, NAPHTHALENE

1. Introduction

Vehicles with internal combustion engines typically use petroleum-based fuel. In internal combustion engines, these fuels release thermal energy which is converted into work. During combustion, petroleum products release carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), nitrogen oxides (NOx), particulate matter (PM). These chemical compounds contribute to environmental pollution and increase the greenhouse effect. High environmental contamination changes the living conditions of people, affects the health of biological organisms.

Combustion emissions of internal combustion engines can be reduced by various measures. However, combustion emission neutralisers, catalytic converters and particulate filters have their own limits and today their technical capabilities have reached their limit. To reduce emissions of combustion products, it is possible to use alternative fuels, optimize combustion processes, use fuel additives and other sources of energy such as electricity or hydrogen.

At the petrol stations or automotive parts' stores, the supply of various additives is quite high. According to manufacturers, fuel additives optimize the combustion process, reduce the number of harmful particles in combustion emissions, cleanse the engine from pollutants, and provide additional functions improving one or another property of the fuel.

The fuel additives, which are intended to optimize the combustion process typically has following chemical elements: hydrocarbons, C11-C14, C10-C13, n-alkanes, isoalkanes, cyclics aromatics, cycloalkane, 2-ethylhexyl nitrates. The amount of these elements varies in each additive depends on its manufacturer, while their actual composition is not disclosed. Only the approximate composition is provided in the safety data sheets.

The alkanes used in fuel additives are organic compounds composed of carbon and hydrogen atoms. The use of alkane compounds in fuel impacts on autoignition delay period. This autoignition delay time depends on the gas pressure in the cylinder and the air surplus ratio. The autoignition delay time is to be understood as the period during which the temperature of the air-fuel mixture rises from the initial to 400 K [1]. Shorter autoignition delay time of fuel leads earlier beginning of the to the combustion process in the cylinder. This increases the heat release rate and pressure in the cylinder. These factors reduce the level of smoke, carbon monoxide, and hydrocarbons in the combustion emissions. A negative effect – increased nitrogen oxide emissions.

Researchers have long known about the 2-ethylhexyl nitrate additive of diesel fuels, which improves the entire combustion process. The primary effect of the 2-ethylhexyl nitrate additive is to accelerate the preignition radical-pool formation, thus shortening the autoignition period. This effect is most significant at the lowest gas temperature-density conditions and least significant at the highest temperature-density conditions [2]. The observations support the arguments that 2-ethylhexyl nitrate decomposes very early in the spray development and enhances the earliest phases of the radical pool formation leading up to ignition and combustion. The later stages of the radical pool formation are controlled by the parent fuel chemistry, and are not similar like to a fuel which has the same natural cetane number [2].

The most commonly used for this purpose is the 2-ethylhexyl nitrate, which can improve the combustion characteristics, shorten ignition delay and decrease the burning point. The primary effect of the additive is to initiate early formation of a radical pool by providing an efficient mechanism for hydroxyl production [3].

When assessed in terms of performance, diesel fuel has the maximum value of average brake torque and brake power compared with other fuels. Addition of 10% ethanol, 2% 2-ethylhexyl nitrate in to diesel fuel, increased the cetane number by 5.45% in comparison with mixture of 10% ethanol and 90% diesel. Whereas 2-ethylhexyl nitrate has caused a slight decrease in kinematic viscosity, lower heating value and a slight increase in density [4].

Mixing of various chemical additives or their compounds in diesel fuels might change fuel properties and combustion chemical reactions. It changes the speed of chemical reactions, combustion temperatures and at the same time combustion emissions. The increase in chemical additives in fuels is limited by factors having both positive and negative impact. Fuel additives affect the cetane number, viscosity, and pour point of diesel fuel. Some chemical elements are volatile and if kept for a long time, they simply evaporate from the fuel.

2. Preconditions and means for resolving the problem

The stand test was performed at the Engine Testing Laboratory in the Institute of Power and Transport Machines, Faculty of Agricultural Engineering, of Aleksandras Stulginskis University, Turbocharged, four-stroke, four-cylinder, common rail (CR), direct-injection (DI), diesel engine (FIAT 1.9 JTD 8V) with a swept volume of 1.9 dm^3 and compression ratio of 18:1 was used for the experiment. The schematic view of the test stand, equipment, and apparatus used for the experiments shows Fig. 1.

Air consumption was measured with AVL Sensyflow P14243 ± 0.25% measuring system. The engine torque was measured by using a three-phase asynchronous 110 kW AC stand dynamometer KS-56-4 with a definition rate of ±1 Nm. The engine revolution was measured by using the AVL crank angle encoder 365C mounted at the front end of the crankshaft that guaranteed an accuracy of less than ±0.2% of measured value. A high-speed multichannel indicating system, consisting of the AVL angle encoder 365C and high-performance pressure transducer GU24D coupled to the AVL microIFEM piezoelectric amplifier and signal acquisition platform IndiModul 622, connected to PC was used. PC was equipped with the AVL IndiCom Mobile software which was used for the recording, acquisition, and processing of fast crank-angle gas pressure signals in the first cylinder. A piezoelectric uncooled transducer GU24D with the measurement range of 0 – 280 bars were used to measure gas pressure for every load-speed setting point with an accuracy of ±0.1 bar within the temperature range of 25 °C to 200 °C. The crank angle was recorded by using the AVL encoder 365C with an accuracy of ±0.1° CAD.

Thus, the heat release characteristics were calculated by using a single cycle diagram of the in-cylinder pressure versus crank angle as the input data average over the 100 subsequent combustion cycles, instantaneous cylinder volume and their first order derivatives with respect to crank angle. The data post-processing software AVL Concerto advanced edition was used to improve productivity and accuracy of the test results.

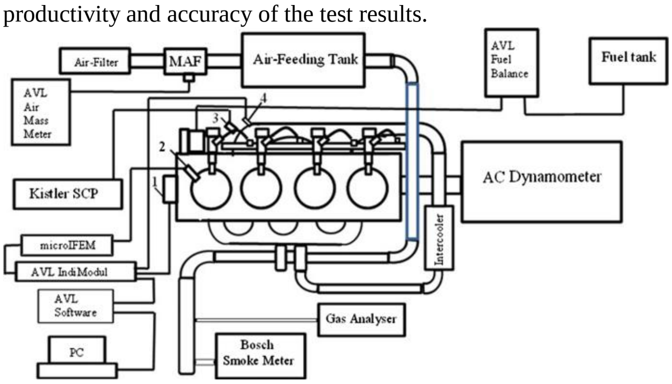

Fig. 1. *Schematic arrangement of the engine test stand (1) AVL crank-angle encoder; (2) piezoelectric in-cylinder pressure transducer; (3) fuel high-pressure line transducer at the injector; (4) air boost pressure sensor in the intake manifold.*

Emissions of nitric oxide NO (ppm), nitrogen dioxide NO_2 (ppm), carbon monoxide CO (ppm), carbon dioxide CO_2 (vol. %), and total unburned hydrocarbons HC (ppm) were measured with Test 350 XL flue gas analyser. The total nitrogen oxides NOx was calculated as a sum of both the NO and the NO_2 components with an accuracy of ±5 ppm. The smoke density (%) was measured with a "Bosch" RTT 110 opacity-meter, readings of which are provided as Hartridge units (% opacity) in a scale range of 0-100% with an accuracy of ±0.1%.

The properties of the tested fuel are presented in Table 1. A fossil diesel fuel (DF) and additives in diesel fuel No.1 (which contains hydrocarbons, C11-C14, n-alkanes, isoalkanes, cycloalkane, 2-ethylhexyl nitrates), No.2 (alkyl nitrate, kerosine (petroleum), hydrodesulfurised naphthalene, odourless kerosene, solvent naphtha, heavy aromatic), and No.3 (Di-tert-butyl peroxide, hydrocarbons, C10-C13, n-alkanes, isoalkanes, cyclics aromatics) were used in this study. The structure of the fuel additives is presented in Table 2.

Table 1*: The diesel fuel properties*

Fuel Property	Diesel	Standart
Kinematic viscosity at 40 °C, mm^2/s	2.65	LST EN ISO 3104
Density at 15 °C, kg/m^3	841.3	LST EN ISO 3675
Flash Point, °C	56	LST EN ISO 2719
Cetane number	51.3	LST EN ISO 5165
Lubricity (HFRR), µm	401	LST EN ISO 12156-1
RME, %	6.69	LST EN 14078

3. Solution of the examined problem

The purpose of the research was to investigate the effect of fuel additives (No.1, No.2 and No.3) on engine performance and exhaust emission characteristics.

During the experiment, the key controlled parameters were the torque and the revolutions of the engine's crankshaft. The load characteristics of the engine were taken at 1800 rpm and 2200 rpm. The engine has been loaded with a dynamometer stand KS-56-4 at constant torque modes by 49.05, 88.29, 117.72, 147.15, 176.58 and 206.01 Nm. Were calculated to the mean effective pressure (IMEP): 0.32, 0.50, 0.62, 0.78, 0.94 and 1.13 MPa. In this case, of engine loads and crankshaft speeds the fuel consumption and exhaust emissions were measured. The coolant liquid and lubricating oil temperatures were within the range 80 – 85 °C.

Table 2: *The structure of fuel additives [5, 6, 7]*

Name	Volumetric Volume %
No.1	
Hydrocarbons, C11-C14, n-alkane, isoalkanes, cycloalkanes	50 – 100
2 – ethylhexyl nitrates	5 – 10
No.2	
Alkyl nitrate	5 – 10
Kerosine (petroleum) hydrodesulfurised	1 – 5
Naphthalene	< 1
Odourless kerosene	60 – 100
Solvent naphtha, heavy aromomatic	1 – 5
No.3	
Hydrocarbons, C10-C13, n-alkanes, isoalkanes, cyclics, aromatics	75 – 90
Di-tert-butyl peroxide	5 – 10
Solvent naphtha, heavy aromatic	1 – 2.5
Naphthalene	0.1 – 1

The mineral diesel fuel and additives blends was prepared according to the provided instructions. The proportion of the mixed blends used in the test presented in table 3.

Table 3*: Proportion of mixed blends [5, 6, 7]*

	Diesel fuel	Additive
No.1 Blend	80 liters	250 ml.
No.2 Blend	60 liters	200 ml.
No.3 Blend	70 liters	325 ml.

All collected data was processed and saved by AVL IndiCom software. The single-cycle and summarized over 100 consecutive cycles the in-cylinder pressure versus crank angle were recorded for every 0.10 crank angle degree (CAD).

The exhaust emission was estimated as an average value measured over the 25 - 30 seconds of the engine combustion process. In this time interval, the data was fixed every second and average of obtained results was calculated.

At the constant engine load and crankshaft rotation speed, the consumption time of the supplied fuel amount was measured three time, with each measurement performed in 30 seconds. From these results, fuel mass consumption and brake specific fuel consumption was calculated.

4. Results and discussion

When the engine is running at relatively low load (0.32 – 0.5 MPa) and rotation speed of 1800 rpm the emission of carbon monoxide values was the highest by 170 – 204 ppm in case of using diesel fuel. Using diesel fuel and additives No.1, No.2 and No.3 blends, the emissions of carbon monoxide emissions values, produced by the engine was 108 – 182 ppm. After the engine load increased to 0.55 MPa and 0.9 MPa, the situation has changed. The lowest CO emission of 100 ppm was obtained by working on a normal diesel fuel. For the diesel fuel and additives blends were higher by 35% respectively. At higher load (0.9 – 1.12 MPa), the CO emission values increased to 202 - 356 ppm.

When the engine was working throughout the load range the emission of unburned hydrocarbons was the lower in case of using normal diesel fuel (Fig.2). The HC emission has changed from 537 to 682 ppm. When the engine operates on diesel fuel and additives No2 blend, HC emission values have been rising from 773 to 875 ppm. The higher HC values have been produced from 841 to 1115 ppm, when the engine was operating on the diesel fuel – additives No.1 and No.3 blends.

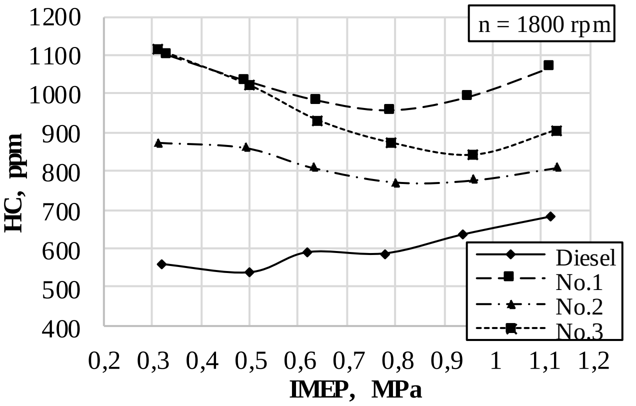

Fig. 2 *Emissions of unburned hydrocarbons HC as a function of engine load (IMEP) at 1800 rpm*

The highest NOx concentrations have been observed at the increasing load of the engine in case of using diesel fuel and diesel fuel - additives blends (Fig.3). The factor that may have influence on the increase of nitric oxide emission is the rising average gas temperature in cylinder. At low load (IMEP = 0,35MPa) and 1800 rpm, the higher gas temperature in cylinder was 1660 K. After reaching the maximum engine load (IMEP = 1.2 MPa) the gas temperature in cylinder increasing by 2495 K.

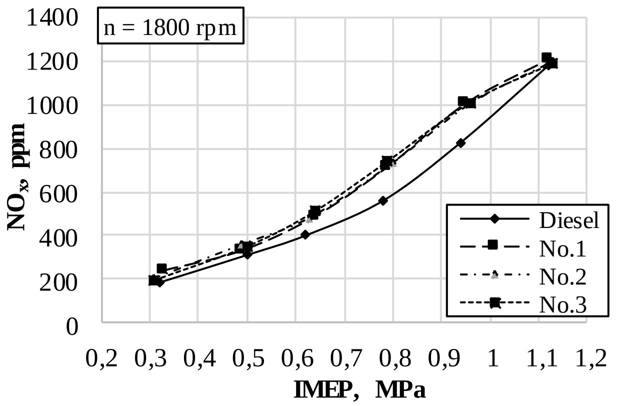

Fig. 3 *The nitrogen oxides emission produced from DF and different fuel additives as a function of engine load (IMEP) at 1800 rpm*

When the engine was running at relatively low load (IMEP = 0,32 MPa) and speed of 2500 rpm, the emission of carbon monoxide produced from diesel fuel - additives blends were the highest values from 291 – 403 ppm. At rising the maximum engine load, the CO emission values decreased to 89 – 123 ppm.

The lowest HC emission values from 844 to 747 ppm has been received on the pure diesel fuel. The higher HC value from 1081 – 1054 ppm has been produced, when the engine operated on diesel fuel and additives No.1 blend.

The total emission of nitrogen oxides normally scales up when load of engine increases. Such the NO_x emission behaviour completely corresponds with the estimations of fundamental theory of the internal combustion engines. The behaviour of the emission of NOx with load and their changing tendencies remained more or less the same when the engine was running on the low engine speed. When the engine is running on low load (IMEP = 0.32 MPa), the NOx emissions ranged values from 366 to 426 ppm. In case of medium engine load (IMEP = 0.5 MPa), the NO_x emission level decreased values to 179 - 249 ppm. When the diesel fuel and diesel fuel - additives blends are used and the engine load was increased, the NO_x emissions values continue rising to 862 - 934 ppm.

The highest brake specific fuel consumption was obtained at the low engine load (0.32 MPa) at 1800 and 2500 rpm speeds (Fig.4). In case the engine load increases, the brake specific fuel consumption is gradually decreasing. Using the diesel fuel and additive blends, the brake specific fuel consumption increased. When the engine is running on 2500 rpm at full load, the brake specific fuel consumption is equal to diesel fuel. At high engine load (IMEP = 1.0 MPa), the brake specific fuel consumption was 228 g/kWh. At full engine load (IMEP = 1.2 MPa), the brake specific fuel consumption was 223 g/kWh. When the engine was running at the low load (IMEP = 0.32 MPa), using diesel fuel and additive blends, the brake specific fuel consumption was higher by 5% and 7% in comparison to the engine running on pure diesel fuel.

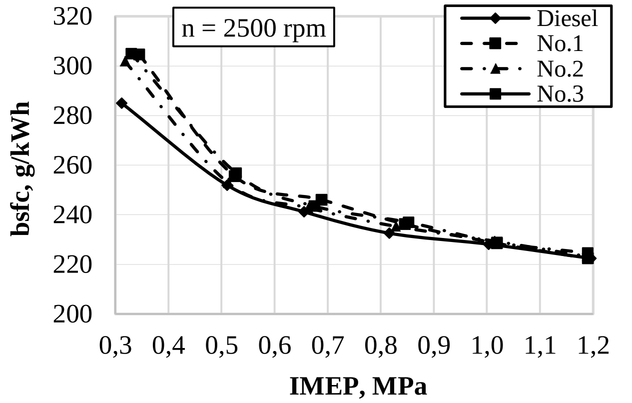

Fig. 4 *The brake fuel consumption (bsfc) as a function of engine load (IMEP) at 2500 rpm*

After testing, it can be argued that the diesel fuel and additives blends were not affected on the average gas pressure in the cylinder at low and medium load at rotation speed of 1800 rpm. The higher changes in the average gas pressure in cylinder occurred when increasing load to IMEP = 1.12 MPa at crankshaft speed of 1800 rpm (Fig.5).

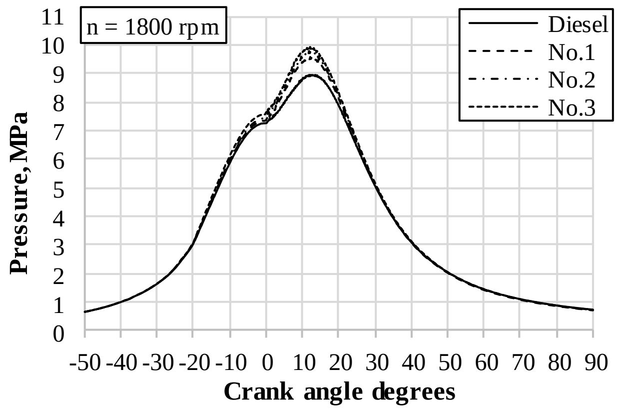

Fig. 5 *The influence of fuel additives on cylinder pressure at IMEP = 1.12 MPa and 1800 rpm*

The cylinder pressure is most pronounced using diesel fuel and additives blends when the engine is running at full load (1.12MPa) and speed of 1800 rpm (Fig. 2). At that point the maximum change in gas pressure inside the cylinder is observed. When the engine is running on normal diesel fuel, the maximum cylinder gas pressure is 8.89 MPa and with fuel additives blends it is 9.5, 9.8 and 9.87 MPa, respectively. Thus, a maximum 11% increase in pressure was obtained using additive No.3.

With the engine speed was 2500 rpm, fuel additives did not have any effect on the change of the average gas pressure in the cylinder. At both maximum and minimum loads, the gas pressure in the cylinder was changing with the same curve as when using pure diesel fuel.

There is no reason to expect big changes in brake specific fuel consumption or gas pressure. During the preparation of fuel blends, additives were mixed according to recommendations provided in the instructions. During the preparation of mixtures, 62.5ml of additive No.1, 66.67ml of additive No.2, and 92.8ml of additive No.3 were injected into 20 litres of diesel fuel respectively. The additives in the 20-litre fuel mixture only accounted for 0.31, 0.33, and 0.46 % of volume. The factor, which had the greatest impact on the gas pressure in the cylinder and the brake specific fuel consumption, was the increasing load. When the load increases, the average gas pressure in the cylinder increases too, while the brake specific fuel consumption decreases evenly at higher power outputs. Stable engine operation was ensured by the computer of the CR fuel supply and control system.

The heat release rate was stable with engine running on both pure diesel fuel and of diesel fuel and additives blends. Since the test are carried out with a common rail fuel system, the curve reflects the heat release in the pre-injection and main injection stages. The maximum heat release rate during the pre-injection stage is 12.46 J/deg, when the piston has not yet reached to top dead centre (TDC) at 17.5 degrees of the rotation angle of the crankshaft. While the maximum heat release rate is 65.85 J/deg at 12 degrees past the TDC. These values were obtained with the crankshaft rotating speed of 1800 rpm at IMEP = 1.12 MPa.

The pre-injection fuel injection portion increases the average gas temperature to ~ 1400 K. This temperature was obtained both with the engine running on pure diesel fuel and diesel fuel with additives blends. After the main fuel injection stage, the average gas temperature in the cylinder has increased to the maximum of 2500 K degrees. During the tests, at lower loads or at higher 2500 rpm crankshaft revs, the average gas temperature was lower. Due to the lower load, the average gas temperature was lower both at 1800 and 2500 rpm, respectively. The higher average gas temperature at the same load was obtained at lower 1800 rpm crankshaft revs. This could have been caused by lower engine speed and a longer time span of the gas being in the cylinder.

5. Conclusion

1. When the diesel fuel and additive No.1 blend was used in the engine running at the speed of 2500 rpm and low load, the emission of carbon monoxide increased by 35 % compared to normal diesel fuel.

2. The highest values emission from 537 to 1115 ppm of the unburned hydrocarbons, were measured when the engine running on diesel fuel and additives No.1 and No.2 blends at the low load and 2500 rpm speed, compared to diesel fuel case.

3. In case of running the engine on normal diesel fuel at low loads, the brake specific fuel consumption was lower by 5 % and 7 %, respectively.

4. When the engine was operated on diesel fuel and additive No.3 blend at the full load and speed of 1800 rpm, the gas pressure in cylinder increased by 11% compared to normal diesel fuel.

6. References

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