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Original Research

The Influence of Injection Advance Angle on Fuel Spray Parameters and Nitrogen Oxide Emissions for a Self-Ignition Engine Fed with Diesel Oil and FAME

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Abstract

This paper presents results of investigations and the assessment of the effects of basic significant parameters of the injection process in an AD3.152UR engine fed with diesel oil and fatty acid methyl esters (FAME) on the concentration of nitrogen oxides and carbon dioxide in the exhaust gas. The basic parameters of the injection process were: the fuel dose per engine operation cycle, spray tip penetration and spray angle, and also the Sauter mean diameter. Tests were carried out on a dynamometer stand equipped with an exhaust gas analyzer, a system for the measurement of fast-varying quantities, and control and measuring instrumentation for the measurement of the engine operating parameters.

Keywords: diesel engine, injection advance angle, emissions, FAME

Introduction

At present, one of the main development trends in internal combustion engines is set by seeking the lowest possible fuel consumption and the minimization of the atmospheric emissions of toxic compounds, while assuring the highest possible efficiency. In recent years, the development of IC engines has been greatly affected by environmental protection, which has become the main driving factor behind the growth of the automotive industry over the last decade [1]. Our paper presents the results of investigations aimed at examining the effects of fuel type and of the basic parameters of fuel injection to the cylinder on the effectiveness of engine operation and the concentration of nitrogen oxides and carbon dioxide in the exhaust gas emitted to the environment [2-5]. The process of injection and the quality of the spraying of the fuel injected to the cylinder influence the process of formation of the air-fuel mixture and its combustion [6-8]. It is essential that the injected fuel dose, the injection advance angle and duration, injection speed, and the size of the injected fuel dose should be adjusted to the instantaneous speed-load conditions of engine operation. The quality of fuel spraying is greatly influenced by the type and construction of the sprayer and the physicochemical properties of the fuel [9-12]. As regards the physicochemical properties of the fuel, the greatest effect on the quality and fineness of fuel spraying is exhibited by viscosity and surface tension. The injection and combustion are the most complex, cyclically repeating, fast-varying processes occurring within the cylinder of an internal combustion engine. The assessment of the operation of an engine supplied with fuels of varying physicochemical properties requires the use of accurate measurements of quantities characterizing the phenomena occurring

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Table 1. Basic technical specification of the investigated engine.

AD3.152 UR self-ignition engine		
Parameter	Unit	Value
Cylinder arrangement	-	inline
Number of cylinder	-	3
Injection type	-	direct
Compression ratio	-	16.5
Displacement volume	dm^3	2.502
Max power	kW	33.6 kW at 2,000 rpm
Max torque	N·m	168.7 N·m at 1,300 rpm
Injection strategies		Single injection

not only in the injection system, but also in the cylinder of the engine.

Testing Apparatus and the Scope of Investigation

The object of investigation was an AD3.152 UR self-ignition engine with direct fuel injection to the combustion chamber situated in the piston crown. The characteristic parameters and technical specification of the AD3.152 UR engine under investigation are shown in Table 1.

The engine feed system consists of a DPA-type distributor injection pump with a mechanical rotational speed governor and fuel injectors featuring four-orifice sprayers. Fig. 1 presents a schematic diagram of the DSL150.A38 four-orifice sprayers.

Experimental tests were carried out on a dynamometer stand consisting of the examined AD3.152 UR engine, an eddy-current brake, a control and measuring cubicle, and a data acquisition system. The testing stand was equipped with a system for measuring fast-varying quantities, i.e. variations of pressure in the cylinder, the sprayer needle lift and fuel pressure in the injection line. A schematic diagram of the testing stand is shown in Fig. 2.

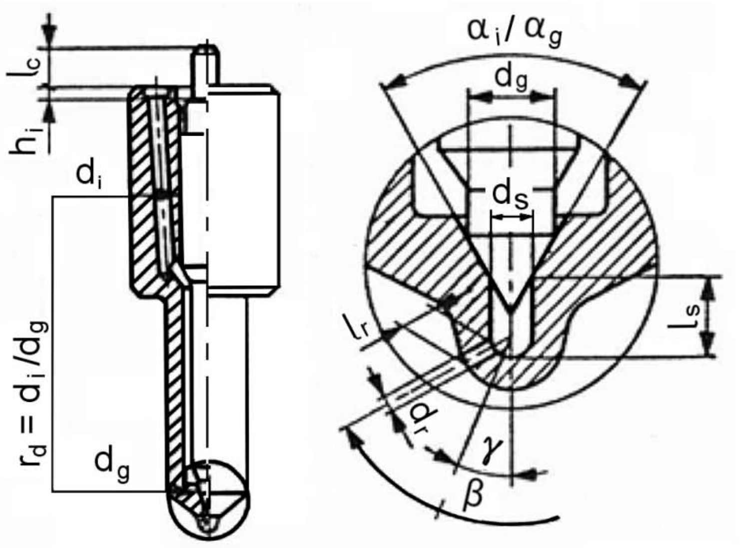
During testing, the engine was fed with two fuels: diesel oil and fatty acid methyl esters (FAME), whose physicochemical properties are given in Table 2.

During the experimental tests, the engine operated under full loading and was fed with two fuels: diesel oil and fatty acid methyl esters (FAME). The measurements of the basic engine operation parameters were taken for three different injection advance angles: 13°, 17°, and 21° CA.

Fuel Spray Parameters

The fuel spray is characterized by the following parameters: spray tip penetration (S), spray angle (Θ), and the Sauter mean diameter (SMD) [7, 16]. The distribution of droplets in the spray, and thus the local fuel concentrations, are very uneven. The droplets forming at the initial state of injection meet an immovable gas medium, rapidly lose their speed, and their displacement is only caused by the movement of the gas. Droplets, which follow those that were the first to move, experience less resistance and gain higher initial velocities at the exit from the sprayer orifices. These droplets catch up with the delayed ones and, as a consequence, they merge. In the cross-section of the spray, the quantity and velocity of droplet motion increase as the droplets approach the stream axis [17]. A schematic diagram of the fuel spray is shown in Fig. 3.

The knowledge of the physicochemical properties of the fuel and the technical specification of the examined engine, including the geometrical dimensions of the DSL 150.A38 sprayer and the experimentally determined diagrams of indicated pressures in the cylinder and the injection line, as well as the measurements of the sprayer needle lift, made it possible to calculate the yield of the fuel flowing out from the sprayer, and thus the dose injected to the cylinder during one cycle of engine operation. On the basis



$h_i = 0.25^{+0.05}$ mm
$d_i = 6^{+0.020}_{-0.005}$ mm
$d_g = 3$ mm
$r_d = d_i/d_g = 6$ mm/3 mm
$d_s = 1.2^{+0.06}$ mm
$l_s = 1.16 \pm 0.1$ mm
$d_r = 0.28^{+0.01}$ mm
$l_r = 0.8_{-0.1}$ mm
$i_r = 4$
$\gamma = 25^{\circ}$
$\beta = 150^{\circ}$

Fig. 1. Basic specification and parameters of the sprayer used in the investigated AD3.152 UR engine [13].

of the variations in cylinder pressure, pressure in the injection line and the sprayer needle lift, and on the knowledge of the basic parameters of engine operation, it is possible to determine fuel spray parameters, such as the spray tip penetration, the spray angle and the Sauter mean diameter [17, 18]. For this purpose, it is necessary to calculate the following criterial numbers: the Weber number (We), the Reynolds number (Re), and the Ohnesorge number (Z) [19, 20]. The dose of fuel injected during a single cycle of engine operation was calculated from the formula [21]:

$$m = \int_{\Theta_{SOI}}^{\Theta_{EOI}} \frac{\dot{m}_f}{6 \cdot N} d\Theta \qquad (1)$$

Many correlations based on experimental data and turbulent gas jet theory have been proposed for fuel spray penetration [22]. The spray tip penetration was calculated from the formula [23-26]:

$$t<t_{break} \qquad S_{BREAK\ UP} = 0.39 \cdot (2 \cdot \Delta p)^{0.5} \cdot (\rho_{fuel})^{-0.5} \cdot t \qquad (2)$$

$$t>t_{break} \qquad S = 2.95 \cdot \Delta p^{0.25} \cdot \rho_g^{-0.25} \cdot (d_r \cdot t)^{0.5} \qquad (3)$$

...where: $t_{break} = 28.65 \cdot \rho_{fuel} \cdot d_r \cdot (\rho_g \cdot \Delta p)^{-0.5}$

The mean droplet diameter is used for the analysis of numerous very important quantities and processes, such as: spray tip penetration and the heat and mass exchange. The size of the mean droplet diameter is influenced by many factors that can be divided into controlled quantities, such as the sprayer design and the physicochemical properties of the fuel, and uncontrolled quantities, such as liquid turbulence and vibrations [27]. For the determination of the reduced droplet sizes, a large number of empirical formulas have been developed, which take into consideration the effect of the aforementioned factors. The spray angle, depending on the duration as counted from the beginning of the injection, in its basic section was calculated from the formula [28, 31, 32]:

$$tg\left(\frac{\Theta}{2}\right) = 0.00751 \cdot We^{0.32} \cdot M^{-0.07} \cdot E^{-0.12} \cdot \rho_g^{0.5} \cdot \rho_{fuel}^{-0.5} \qquad (4)$$

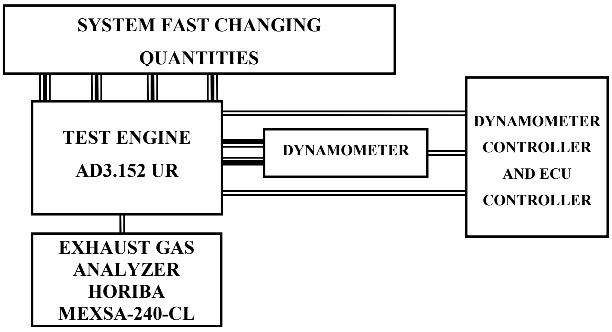


Fig. 2. A block diagram of the testing stand.

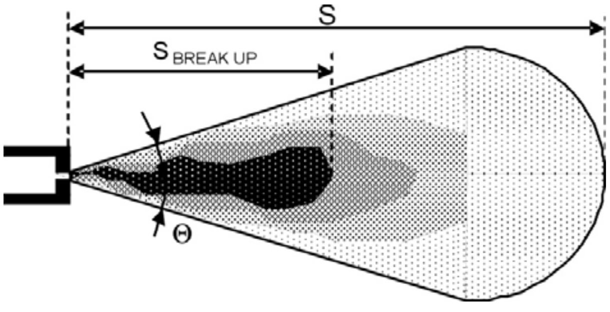


Fig. 3. A schematic diagram of the fuel spray.

Table 2. Basic physicochemical properties of the mineral and plant fuels [14, 15].

Parameter	Diesel fuel Ekodiesel Ultra D	Plant fuel FAME
Cetane number	51.4	51
Calorific value, [MJ/kg]	43.2	36.7
Density at 15ºC, [g/cm³]	0.8354	0.883
Kinematic viscosity, [mm²/s] (~40ºC)	2.64	4.55
Surface tension, σ_{fuel}, [N/m] (20ºC)	$3.64 \cdot 10^{-2}$	$3.58 \cdot 10^{-2}$
Ignition temperature, [ºC]	63	above 130
Cold filter plugging temperature, [ºC]	-23	-14
Average elementary fuel composition:		
C	0.872	0.768
H	0.127	0.121
O	0.001	0.111
Content of sulphur, S, [mg/kg]	9	8.1
Water content, [mg/kg]	43.8	113
Solid impurity content, [mg/kg]	5	18

The analysis of formula (4) shows that the angle magnitude is influenced both by the gaseous medium density and by fuel density.

The SMD was calculated from the formula below [29-32]:

$$SMD = 1.445 \cdot d_r \cdot Z^{0.1466} \cdot We^{-0.266} \cdot \rho_g^{-0.266} \cdot \rho_{fuel}^{0.26} \qquad (5)$$

Results and Discussion

Fig. 4 presents the effective power and the fuel dose for the engine operating under full loading, being fed with diesel oil and FAME, with an injection advance angle of 13º, 17º, and 21º CA, respectively. The figure shows that with the examined injection advance angles, the achieved effective power was higher in the case where the engine was fed with diesel oil. This implies that the calorific value of diesel oil is higher than that of the FAME fuel by approx. 6.5 MJ/kg. The engine developed the greatest power at the factory setting of the injection advance angle, which was 17º CA, while the lowest engine power was obtained at an injection advance angle of 21º CA. This might result from the combustion process starting too early. That causes too large negative work performed in the cylinder. With the increase in the rotational speed of the engine crankshaft, the fuel dose per single operation cycle decreased. The increase in the engine crankshaft rotational speed, with the unchanged setting (adjustment) of the injection system, results in a shortening of the injection process duration and, as a consequence, a smaller amount of injected fuel. Lower doses of fuel injected to the cylinder were obtained for the engine being fed with diesel oil and operating at the injection advance angles established in the tests.

Fig. 5 represents the variation in pressure in the injection line and in the sprayer needle lift for n=2000 rpm, at the full loading of the engine fed with diesel oil and FAME and at the injection advance angle of 13º, 17º, and 21º CA, respectively. The maximum pressures in the injection line were smaller for the engine being fed with FAME. These differences were up to 2 MPa for the engine operating under full loading. The beginning of the sprayer needle lift, and thus the injection of fuel to the cylinder, occurred earlier for larger injection advance angles. For feeding with diesel oil, the sprayer needle lift occurred later by approx. 1º CA compared with FAME. This is due to the difference in the physicochemical properties of the examined fuels, i.e. density and kinematic viscosity, which determine the velocity of propagation of pressure waves. The examination of these diagrams shows that, depending on the fuel type and the injection advance angle, there occur differences in the time and character of the full lift of the sprayer needle,

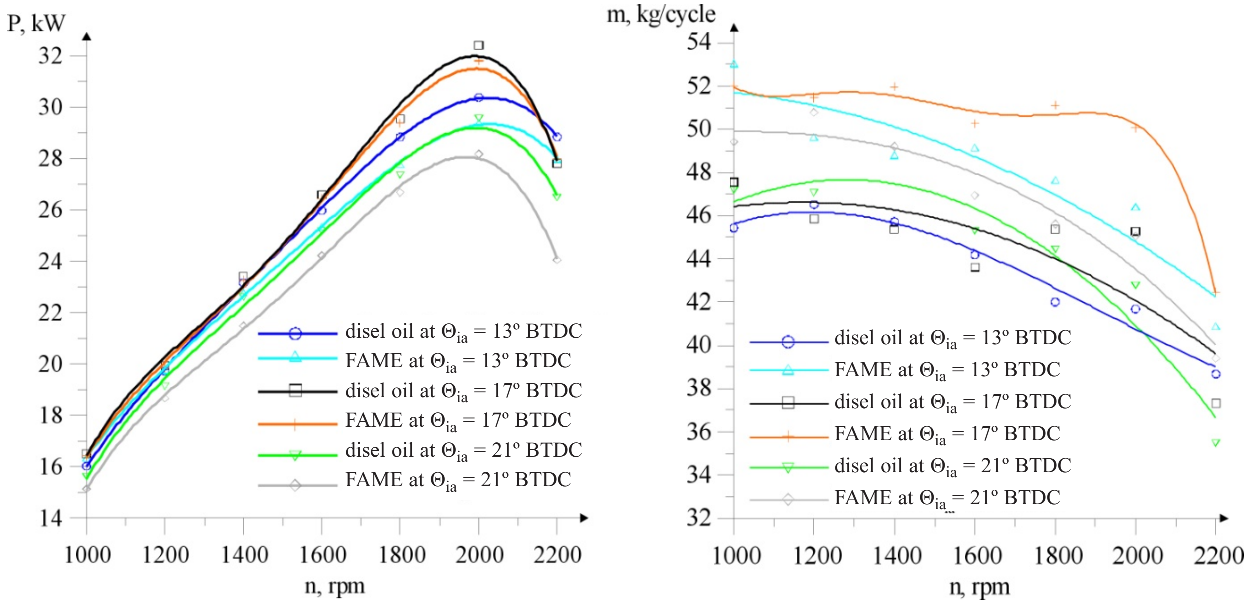


Fig. 4. Effective power and the fuel dose for the engine supplied with diesel oil and FAME at the injection advance angles of concern.

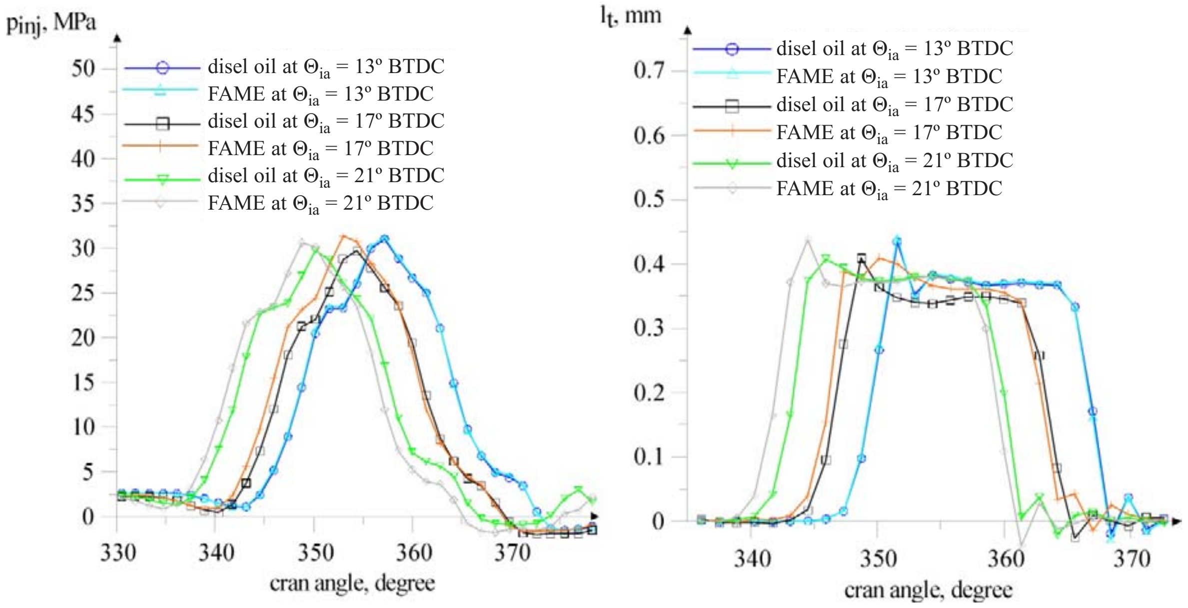


Fig. 5. Variations in injection line pressure and sprayer needle lifts for the engine operating under full loading and at n=2000 rpm, being fed with diesel oil and FAME, and at the injection advance angles established in the tests.

in the maximum pressure values, the total injection duration angles, and in the behavior of the needle settling in the sprayer seat. These differences might be caused by the occurrence of the phenomenon of self-sealing of the injection system elements, the increase in the resistance to flow of fuels with greater viscosity, and the efficiency of the filling of the suction section of the injection pump.

Fig. 6 represents the Sauter mean diameters, SMDs, and the spray angle for the engine operating under full load, being fed with diesel oil and FAME, and at the injection advance angle of 13º, 17º, and 21º CA. Smaller SMDs were obtained for feeding the engine with disel oil compared with FAME. The largest SMDs were obtained at an injection advance angle of 17º CA. The spray angle was greater in the case where the engine was fed with diesel oil. The least spray angle was obtained at an injection advance angle of 17º CA.

Fig. 7 represents the diagram of the spray tip penetration, as determined for the injection advance angles of concern and with the engine operating under full load and at n=2000 rpm, being fed with two fuels. The spray tip penetration increases for the engine feeding with FAME. The least spray tip penetration occurred for an injection advance angle of 13º CA, as compared with the injection advance angle values of 17º and 21º CA.

Fig. 8 shows the diagram of the concentrations of nitrogen oxides and carbon dioxide in the exhaust gas from the engine operating under full loading, being fed with diesel oil and FAME, and at three injection advance angles, namely 13º, 17º, and 21º CA. Nitrogen oxides form as a result of the reaction of nitrogen with the air oxygen at a high temperature occurring during the combustion process. The quantity of the formed nitrogen oxides is determined by the conditions of engine operation, the composition of the combusted air-fuel mixture and the fuel type. Fig. 8 shows that at the injection advance angles of 17º and 21º CA, the concentration of nitrogen oxides is higher, by 8% at the minimum, than when the engine is fed with FAME. At the injection advance angle of 13º CA, the nitrogen oxide concentration was comparable to the engine fed with both diesel oil and FAME. The greatest influence on the concentration of carbon dioxide is exhibited by quantity of fuel burnt during the combustion process. The carbon dioxide concentration at the injection advance angles of 13º and 21º CA and for the engine feeding with FAME is lower compared with the engine fed with diesel oil. For the factory-set injection

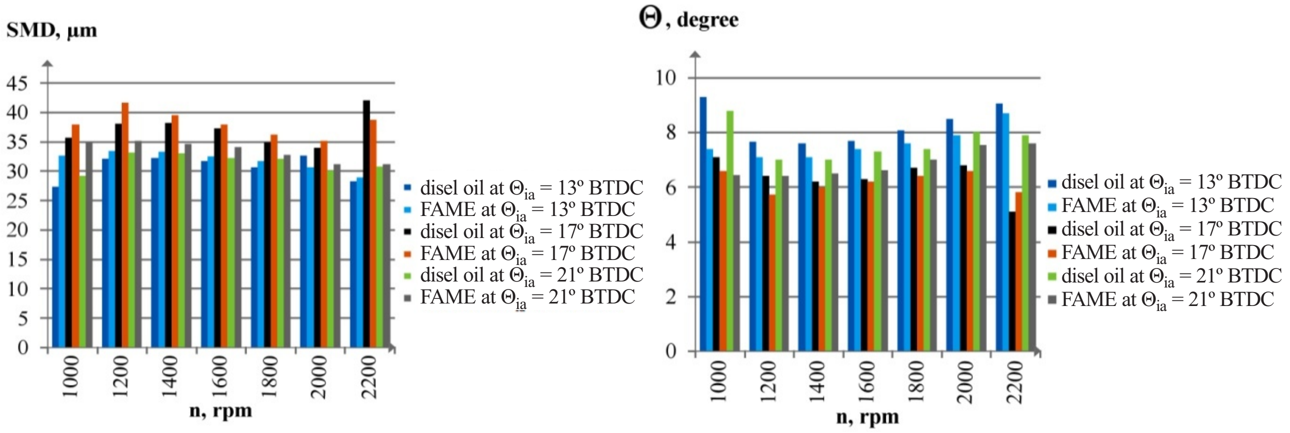


Fig. 6. The Sauter mean diameters, SMDs, and the spray angle for engine operating under full loading, being fed with diesel oil and FAME, at the injection advance angles tested.

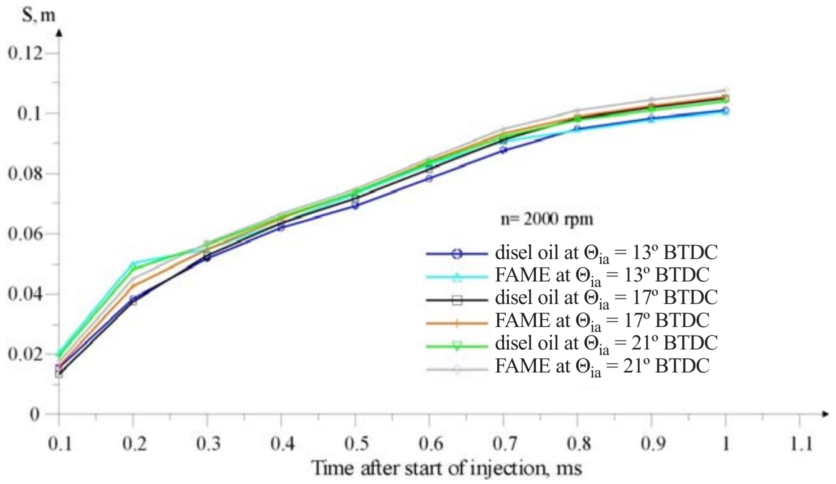


Fig. 7. The spray tip penetration for engine operating under full loading and at n=2000 rpm, being fed with diesel oil and FAME, at the injection advance angles tested.

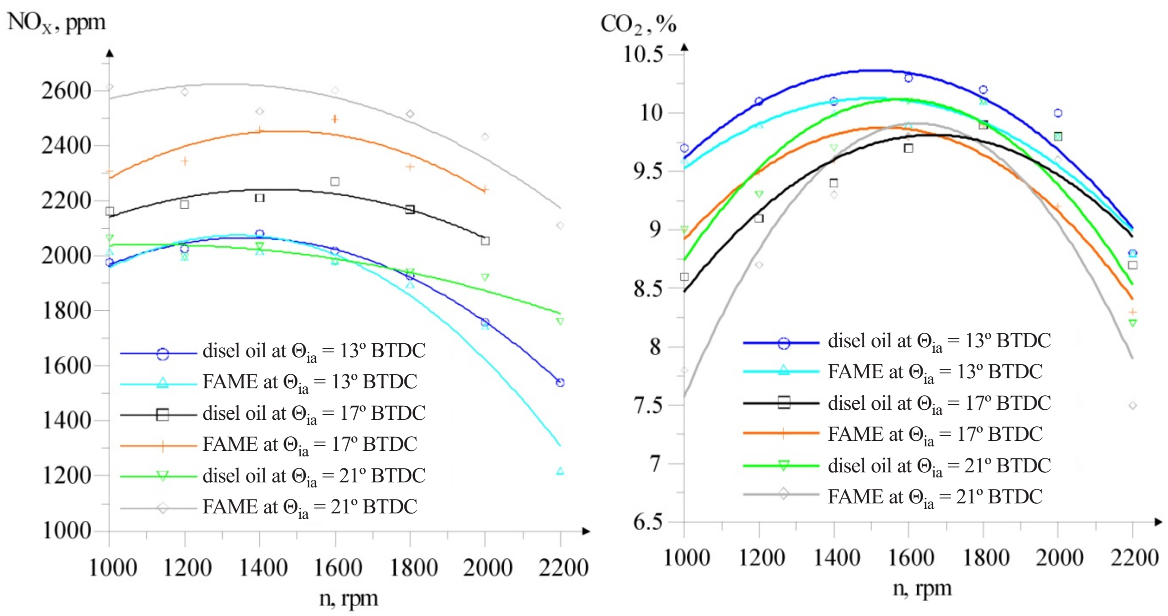


Fig. 8. Concentrations of nitrogen oxides and carbon dioxide for engine operating under full loading, fed with diesel oil and FAME, and at the injection advance angle settings tested.

advance angle and with the engine operating under full loading, and fed with diesel oil, the lowest carbon dioxide concentration was obtained for the engine operating at rotational speeds smaller than n=1600 rpm. Above this crankshaft rotational speed, the concentration of carbon dioxide was higher.

Conclusions

From the performed analysis of the obtained investigation results, the following conclusions can be drawn:

1. Higher maximum effective power at a rotational speed of n=2,000 rpm was obtained for feeding the engine with diesel oil. That is due to the higher calorific value of diesel oil compared with the FAME fuel.
2. Larger fuel doses per single operation cycle for the engine operating under full loading were obtained for the engine fed with the FAME fuel.
3. The full opening of the sprayer needle takes place earlier for the FAME fuel. This is due to the greater viscosity, and thus better self-sealing of the injection system.
4. For the engine fed with the FAME fuel, greater pressure magnitudes occur in the injection line. They cause greater spray tip penetration of the fuel injected to the cylinder.
5. The physicochemical properties of the FAME fuel, being different from those of the diesel oil fuel, cause the former to be sprayed less effectively. For feeding the engine with the FAME fuel, larger SMD droplet diameters, greater spray tip penetration, and smaller spray angles of the sprayed fuel were obtained. Using the FAME fuel contributes to greater spray inhomogeneity, and the occurrence of an earlier time of the injection beginning delay.
6. Higher nitrogen oxide concentrations were obtained for the engine fed with the FAME fuel.
7. For the engine being fed with diesel oil, and operating at a rotational speed of up to n=1,800 rpm, at the injection advance angles tested, the nitrogen oxide concentrations were comparable. At a rotational speed above 2,000 rpm, and an injection advance angle of 21° CA, the nitrogen oxide concentrations increased dramatically.
8. At the injection advance angles of 13° and 21° CA, a lower carbon dioxide concentration was obtained for feeding the engine with the FAME fuel than with the diesel oil fuel. At an injection advance angle of 17° CA, and for the engine operating under full loading, up to a rotational speed of n=1,600 rpm, a higher CO_2 emission was obtained for feeding the engine with the FAME fuel. Above the rotational speed of n=1,600 rpm, the CO_2 emission is lower for feeding with FAME than with diesel oil.

In order to optimize the combustion process when feeding diesel engines with plant fuels, changes to the factory settings of the injection apparatus should be made.

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