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THE INFLUENCE OF DIESEL OIL IMPROVERS ON INDICES OF ATOMISATION AND COMBUSTION IN HIGH-EFFICIENCY ENGINES

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ABSTRACT

The process of fuel combustion in a diesel engine is determined by factors existing during liquid fuel injection and atomisation. The physicochemical properties of the fuel to a large extent decide upon the quality of this phase of cylinder fuelling. So it is important to ensure appropriate properties of a fuel affecting its atomisation and, as a result, combustion. The paper deals with the topic of diesel oil improvers and the analysis of their influence on atomisation and combustion indices. In the studies base diesel oil and a diesel fuel improved by a package of additives, were used. The process of conventional and improved fuel injection was analysed by using optical examinations. The amount of released heat was evaluated during the studies carried out on combustion. Significant aspects of the applied improvers in relation to fuel injection and its combustion have been indicated.

Keywords: diesel oil,diesel engine,improvers,fuel injection,fuel combustion

INTRODUCTION

The development of diesel engines is determined mainly by the fuel injection system and combustion system. Because of the low diversification of combustion systems, possibilities to increase the engines' efficiency are sought to be made through modifications of the fuelling system. A multiple division of fuel charge is used here and – by utilising a missing division – so-called rate shaping (a change of nozzle needle lift during the fuel injection) [5,8,10]. The use of substitute fuels or conventional fuel additives are the next possibilities to change the combustion process parameters.

Based on the research of different fuels, Lamas et al. [7] concluded that natural gas is the best alternative fuel for marine engines due to its low cost and high availability. However, the main disadvantage of this fuel is the knock risk. Research conducted by Kowalski [6] showed an increase in exhaust gas temperature when injector nozzle holes are damaged (increased cross-section) and require recalibration. Blocked (clogged) injector holes cause a drop in combustion pressure, and increase CO emissions by more than 70% with an average engine load [6]. In addition, these studies reported that amounts of nitrogen oxides emission increased at low loads by more than 30% [6]. The reason of this may be contamination of fuel or lack of cleaning substances in the diesel fuel [1, 16], petrol fuel [4] and oil [12]. This paper deals with the issue of diesel fuel improvers.

ANALYSIS OF THE STATE OF KNOWLEDGE

Diesel fuel is improved mainly by oxygen and detergent additives. The application of the first method, e.g. in the form of fatty acid methyl esters (FAME), results in improvement in fuel combustion and in the reduction of harmful pollutant emission into the atmosphere. Ethanol is used here as an additive to diesel fuel. The literature analyses presented by Burnus [3] do not show the occurrence of positive effects of such fuel. It was shown that despite a small drop in power, the emission of all toxic flue gas components was not limited.

The study carried out by Rodríguez-Fernández et al. [15] shows that the use of an e-diesel fuel (10% of ethanol addition) increases the possibilities of smooth oxidation in the DPF (diesel particulate filter). The higher chemical activity of the modified fuel (this activity is related mainly to the alcohol group) is the reason.

Detergent-dispersing improvers are the second group of additives. Beck et al. [2], in a study on improvers, showed that detergent-dispersing additives can be used to improve the oxidation resistance of pure diesel oil and bio-diesel mixtures with diesel oil. In the case of the studied fuel samples – biodiesel, diesel fuel and their mixtures, the reduced oxidation stability due to long-term storage may be partly offset by the application of selected detergent-dispersing additives. Such additives prevent from the formation of free radicals and neutralise carboxylic acids, and therefore increase the sample's oxidation stability.

Żak et al. [17], when analysing the influence of detergent-dispersing additives, showed that they have a significant impact both on the state of diesel engines' fuelling systems and the reduction of the flue gas emission (mainly particulate matter).

The review of the subject literature is related primarily to influence of the fuel additives on the effects of combustion engine operation. This paper particularly emphasises the initial stages of engine fuelling: injection and atomisation of various fuels (without and with additives) were analysed, including the additives' impact on combustion.

METHODOLOGY

STUDIED FUELS

Base diesel oil (B7) and a diesel fuel improved by a package of additives were used in the studies.

The second diesel fuel was improved by a package of additives (by dosing about 300 mg of additive per 1 kg of fuel), containing a detergent-dispersing additive with an alkene-succinate-imide-amide structure synthesised at the INiG–PIB and the following commercial additives: demulsifiers, a defoamer, an anti-corrosive additive, a biocide and a solvent (the package composition was protected at the Patent Office, application No P.413866). Tab. 1 presents the properties of both diesel oil types.

Tab. 1. Selected properties of the base and modified diesel oils

Test type	Unit	Test result	
		B7 DO	Improved DO INIG
Cetane index	–	57.6	57.8
Cetane number	–	53.3	54.7
Density at 15 °C	kg/m^3	828.7	828.6
Content of polynuclear aromatic hydrocarbons	% (m/m)	1.1	
Sulphur content	mg/kg	less than 5	less than 3.0
Ignition temperature	°C	88	87.5
Coking residue (of 10% distillation residue)	% (m/m)	0.062	0.074
Incineration residue	% (m/m)	0.001	0.004
Water content	% (m/m)	0.005	0.0005
Pollutant content	mg/kg	2.1	6.7
Test of corrosive effect on steel (3 h at 38°C)	degree of corrosion	trace B++	corrosion trace
Test of corrosive effect on copper (3 h at 50°C)	class	1a	1a
Fatty acid methyl esters (FAME)	% (V/V)	5.6	–
Oxidation resistance	h g/m^3	35.9 7	2.0
Lubricity, adjusted diameter of the wear trace (WS 1.4) at 60°C	µm	180	337
Kinematic viscosity at 40°C	mm^2/s	2.7175	2.711
Fractional composition up to 250 °C distils up to 350 °C distils 95% (V/V) distils up to	% (V/V) % (V/V) °C	27.3 97.7 333.0	26.3 97.2 328.0

RESEARCH INSTRUMENTS

A number of experiments were applied to comparative analysis of the used fuels, aimed at describing basic practical parameters crucial from a combustion engine operation point of view. Scope of the experiment comprised two main parts: fuel injection and atomisation, and combustion. For each test point 3 iterations were carried out during the first and the second phases to eliminate a gross error from the obtained results.

The first phase of the experiment, related to characteristic parameters of the fuel spray and chamber filling with it, was carried out by using a fast LaVision HSS5 camera working with DaVis software of the same company. A constant volume chamber (CVC) was used as the space being registered [9,13,14], which allowed the setting of a backpressure, thereby simulating conditions existing in the combustion chamber during injection in a diesel engine (2 MPa backpressure). Optical access to the chamber combined with halogen lighting enabled the registration of drops. The same injector which featured an 8-nozzle sprayer with an angle of spray flare of 162° was used for both fuels. Tests were carried out at working points occurring in a combustion engine. The first point featured 35 MPa injection pressure of and 0.5 ms time of injector opening. The second point was described by the values of 100 MPa and 0.3 ms, respectively. The recorded images were subject to software processing and analysis. On this basis parameters of the fuel spray were determined by using proprietary subroutines.

The second phase of the experiment consisted in using a Rapid Compression Machine (RCM) [13] to carry out combustion of both fuels. The machine allows to carry out one combustion cycle simulating the combustion cycle in a combustion engine. The piston (diameter = 80 mm and stroke = 81 mm) is pneumatically driven, and a combustion pressure gauge is installed in the direct injection combustion chamber (displacement volume is 407 cm^3). The AVL instrument for quickly varying measurements was used for recording. The instrument was working with the AVL IndiCom software, and the AVL Concerto software was used to analyse course of the obtained values.

STUDIES ON FUEL INJECTION AND ATOMISATION

Fuel atomisation in the form of atomised fuel sprays was analysed basing on video material recorded at the frequency f = 10 kHz. Studies carried out at two values of fuel pressure and different injection times are presented in Tab. 2.

Such analysis does not allow to fully identify the video material at simultaneous shortage of quantitative data on changes in the structure of fuel atomisation. Therefore, by using macros created in the DaVis 7 Command Language editor, the range of individual fuel sprays (based on paper [11]) and their surface areas were analysed (Fig. 1). Determination of such area is based on assuming a flat exposure represented by the recorded image.

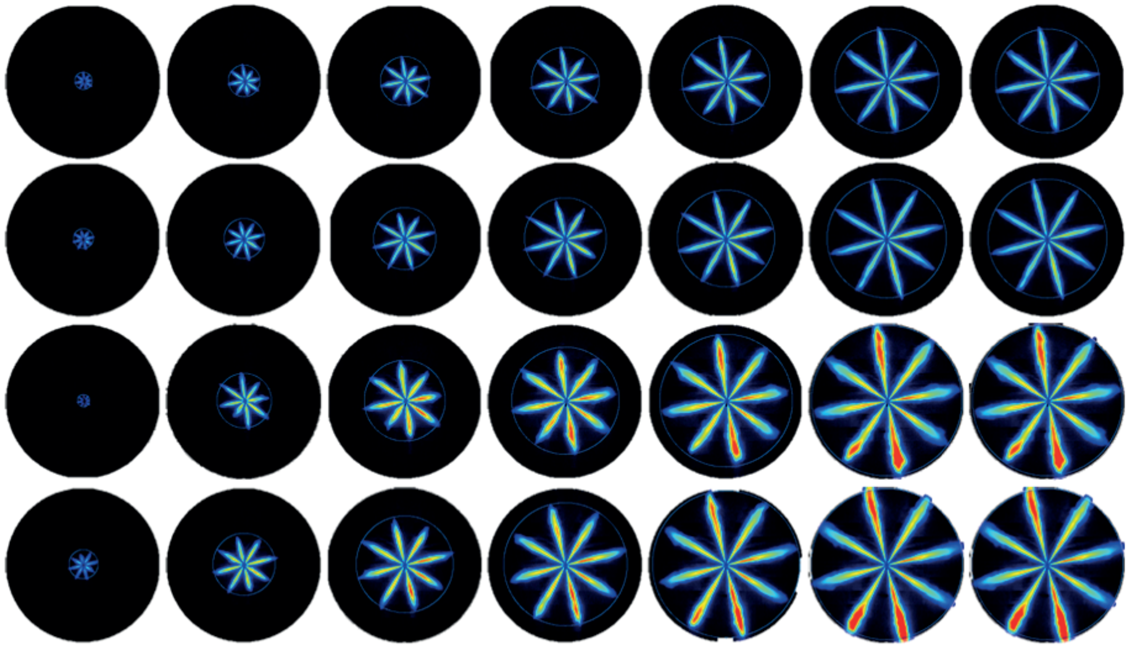
Based on the video material processing, quantitative information was obtained, allowing to perform evaluation of the fuel atomisation indices. Because of small deviations of individual fuel spray ranges, the average range and surface area of spray was analysed (Fig. 2). At the same time value of the coefficient of variation (CoV) was determined – Fig. 3, defined as:

$$\mathrm{CoV(S)} = \frac{\sigma}{S_{av}} \tag{1}$$

where: S_{av} – average value of range in the given time t, ? – standard deviation of the sample mean.

Determination of the range variability shows the fact that the value achieves its maximum value at the beginning of atomisation (errors resulting from processing the image with a small spray range), and then gradually diminishes to around 5–6%. This is the value that allows to use the mean range of the spray and the average value of the spray surface area in the further part of the paper.

Tab. 2. Picture sequences of fuel atomisation for the analysed injectors



t_{inj} [ms]		0	0.1	0.2	0.3	0.4	0.5	0.6
P_{inj} = 35 MPa t_{inj} [ms] = 0.5 ms	DO							
	INIG							
P_{inj} = 100 MPa t_{inj} [ms] = 0.3 ms	DO							
	INIG							

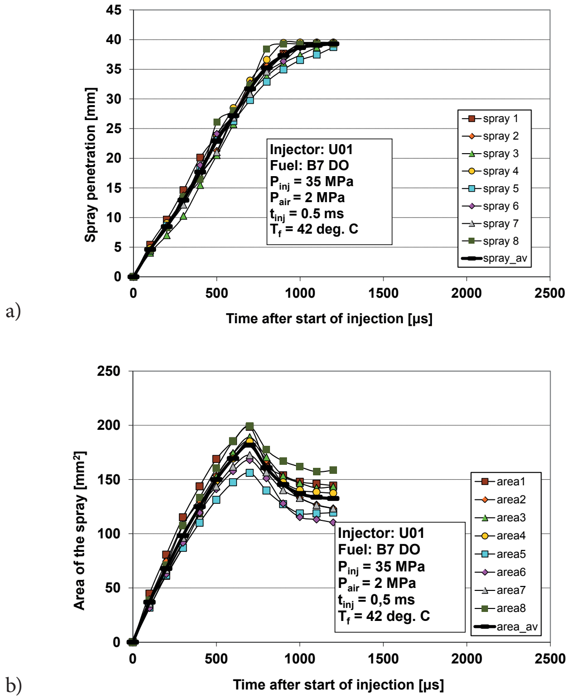


Fig. 1. Determination of values of fuel injection characteristics : a) values of each fuel spray range, b) values of each fuel spray area

The stream range observed in Fig. 2 reaches 40 mm in a linear manner. It is clear that a significant slowdown in the stream development process occurs after 1 ms, indicating the stream's limitation. However, the value of the resulting area indicates that a steep development of the stream (surface area increase) occurs up until 0.6 ms, but after this time a decrease in surface area is observed, which indicates an increase in evaporation.

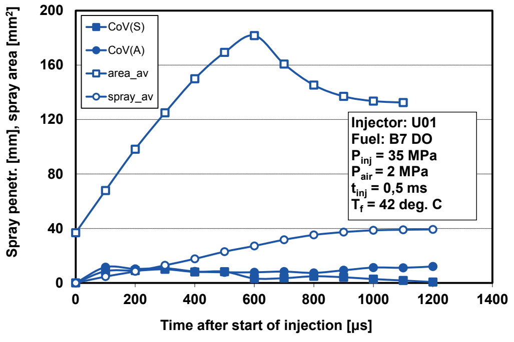


Fig. 2. Determination of values of fuel injection spray characteristics : average values and values of coefficient of variation

By using the presented analyses, the mean ranges of the fuel spray during its injection into a chamber of constant backpressure value, were compared (Fig. 3).

The analysis of the data from Fig. 3 shows the fact that slightly different values of range of the analysed fuels occur.

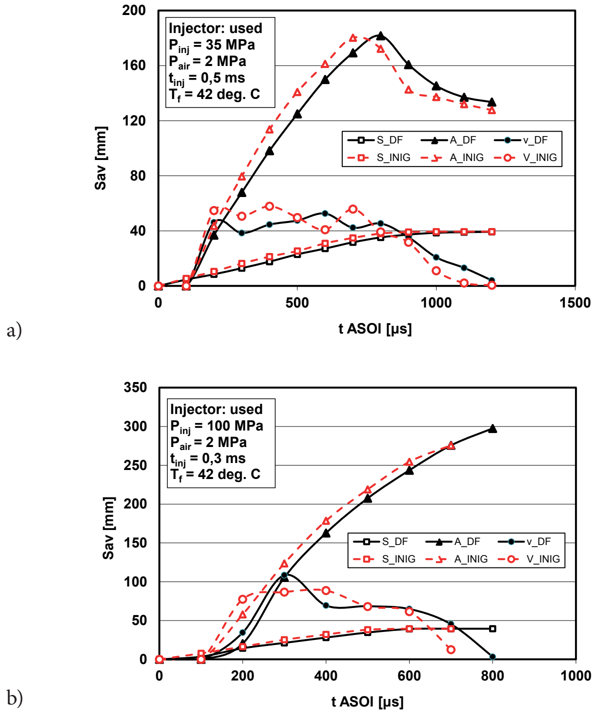
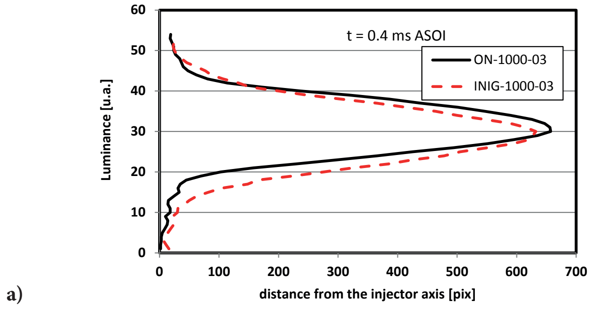
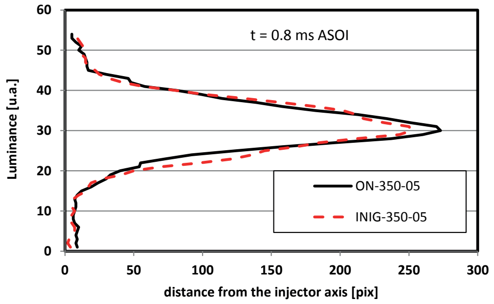


Fig. 3. Geometrical indices of a (mean) fuel spray from the operating injectors fuelled with DF and INIG fuels at: a) P_{inj} = 35 MPa and t_{inj} = 0.5 ms, b) P_{inj} = 100 MPa and t_{inj} = 0.3 ms

INIG fuel has a slightly longer range and larger spray area. The increase in the spray area in not directly a result of the lower density of this fuel since the densities of the fuels, as shown in Tab. 1, have similar values. Therefore this result comes from the used fuel additives. Higher fuel spray values were noted at lower fuel pressure values, i.e. within the range of small loads and low engine speeds. This indicates the potential benefit of using the considered fuel in low speed engine systems at relatively low injection pressure values.

The observation encouraged the authors to look for further differences in the fuels' atomisation. Further on – based on recorded images – a cross-section of the selected fuel spray was made perpendicularly to the spray axis. The distribution of luminance (spray brightness) was this way determined for both fuels at different injection pressures of them (Fig. 4 and Fig. 5).



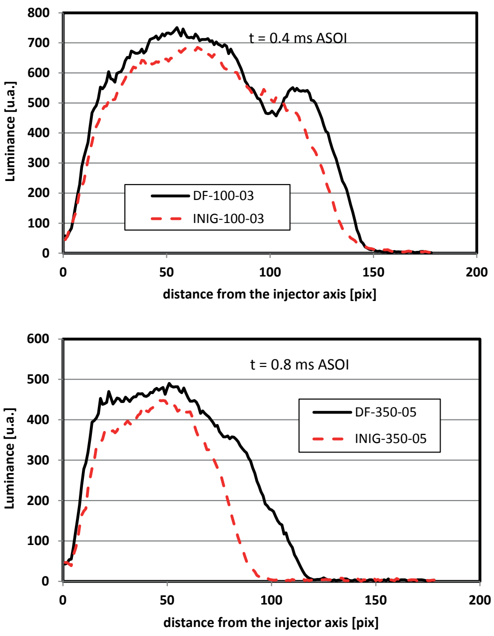


b)

Fig. 4. Analysis of cross-section of fuel sprays at a distance of 30 mm from the injector axis for various times from the injection start at constant value of fuel pressure P_{inj} = 100 MPa and t_{inj} = 0.3 ms: a) for time t = 0.4 ms after start of injection, b) for t = 0.8 ms after start of injection

The initial atomisation of INIG fuel spray (for t = 0.4 ms after the injection start – Fig. 4a) results in its larger width, resulting from a smaller fuel concentration in the spray core. This means easier evaporation and may prove to have a larger spray surface area. The observed trend disappears during the spray development (Fig. 4b). It may be related to the evaporation of lighter fuel fractions. Such situation means that the images are similar and the algorithm computing the spray areas calculates a similar number of pixels of present luminance (light intensity).

The analysis of the longitudinal cross-section of the spray confirms the previous conclusions on the faster evaporation of the INIG fuel. The spray luminance in the longitudinal cross-section (Fig. 5) shows its smaller intensity during the INIG fuel analysis. This indicates that the considered fuel has a slightly larger spray cone because concentration in the core is smaller. The observed trend is also confirmed during a larger development of fuel spray (Fig. 6b for time t = 0.8 s after the start of fuel injection).



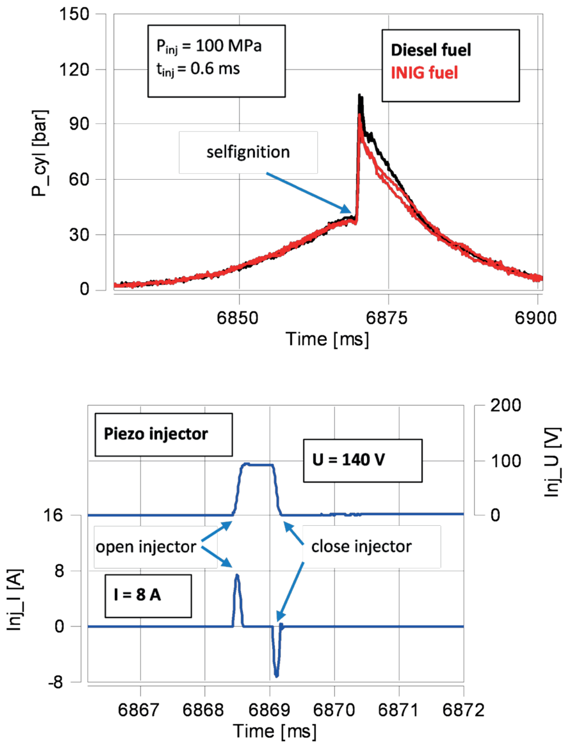
a)

b)

Fig. 5. Analysis of longitudinal cross-section in the fuel spray axis for various times from the start of injection at constant value of fuel pressure P_{inj} = 100 MPa and t_{inj} = 0.3 ms: a) for time t = 0.4 ms after start of injection, b) for t = 0.8 ms after start of injection

STUDIES ON THE COMBUSTION PROCESS

Studies on the combustion process were carried out at the pressure of 100 MPa and injection time of a piezoelectric injector, equal to t_{inj} = 0.6 ms. This is the time at which it is possible to obtain a large fuel dose, and the process course can indicate significant changes during the analysis. Short injection times and low pressures implemented during studies in a constant volume chamber are not applicable during combustion. The INIG fuel combustion features lower maximum pressures of the process. To obtain correct combustion, trials were repeated twice. Fig. 6a shows repetitions which are identical during the combustion of a standard diesel oil. Small differences were recorded during the INIG fuel combustion. However, they are related to the combustion and expansion phase.



a)

b)

Fig. 6. Combustion pressure (during two combustion trials) (a) ; and conditions of electric signals course during this process (b)

Fig. 6b presents the conditions of injector operation, specifying the value of control voltage (140 V) and a characteristic course of a piezoelectric injector with 8 A peal [=peak?] value.

The analysis of the combustion process shows a similar course of pressure growth after spontaneous ignition (Fig. 7a) but a slightly smaller value of the maximum released heat (Fig. 7b). This may prove a slightly worse combustion or slightly lower calorific value of the new fuel.

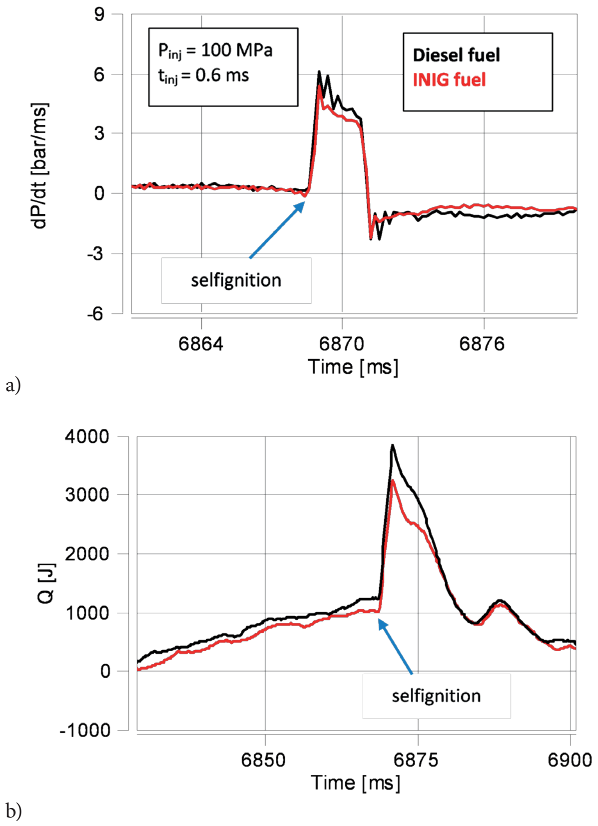


Fig. 7. Thermodynamic parameters of the combustion : a) rate of pressure change in the cylinder, b) amount of heat released during combustion

SUMMARY

The studies on comparison of fuels selected by the authors were carried out in the form of characteristics trials, providing the grounds for the assessment of the injection system, combustion system, and the fuel properties. Because of the nature of individual analyses, the conclusions were divided - in accordance with the aim of the carried out studies- into those dealing with blend [= mixture?] preparation and combustion.

The studies on fuel-air mixture ? preparation in a constant volume chamber showed no visible differences during standard analysis. The extension of the analysis scope by means of direct image comparisons allowed to indicate conditions for the blend preparation of a new fuel. A larger exposure area proves a potential for faster evaporation due to a greater filling of the analysed area and facilitation of substances mixing. The luminance-based analysis of liquid phase concentration within the spray became the argument confirming this thesis. It showed a greater share of gaseous fuel fraction combined with a better spatial distribution.

The second group of conclusions applies to combustion, showing slightly smaller values of pressure change rates inside the cylinder. Compared to the commercial diesel fuel, the course of dP/dt indicates less deflagration and thereby a smaller share of kinetic combustion phase.

These observations allow to determine the new fuel's potential:

- it is expected to reduce fuel consumption due to the increase in the spray rate values in the area occupied by the fuel stream. This beneficially affects its evaporation, that in consequence leads to a reduction in the injected fuel weight,
- it is possible to reduce the emission of HC and CO components as better spraying and faster evaporation will lead to partial elimination of incomplete combustion (reduced combustion losses). The negative effect of using this fuel may be an increase in the emission of nitrogen oxides (improvement of the fuel-air mixture preparation process), which could be corrected by changing the injection timing setting.

Reduced fuel consumption and increased combustion efficiency can be achieved not only through the search for new alternative fuels, but also by using suitable fuel additives to increase the charge preparation process indicators and controlling the course of the combustion process itself.

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