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The Impact of Rapeseed Oil Methyl Esters on Fuel Injection Parameters in a Diesel Engine Equipped with the Common Rail Injection System

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ABSTRACT
In the global fuel economy, new challenges concerning the use of alternative (vegetable) fuels in the internal combustion engines are starting to arise. The important issue is to meet the new limits on four main pollutant emissions from a diesel engines: CO (carbon monoxide), NO_x (nitrogen oxides), HC (hydrocarbons) and PM (particulate matter). The design of a modern engine must be characterized by high efficiency, its dynamics of movement and durability. Dynamic development of plant fuels is forced by the new strategy of the global fight against the global warming. For these reasons, it is necessary to do research concerning the effects of the use of biofuels, including methyl esters, higher fatty acids of rapeseed oil for self- ignition engines. The current tests must concern the engines equipped with the latest Common Rail fuel injection systems. In the publication, the above-mentioned issues have been analyzed, and the results of tests of the basic injection process parameters have been presented. The AVL5402 engine was fueled with mixtures of diesel oil with RME ester of rapeseed oil produced by ORLEN Południe S.A. in Trzebinia. The impact of the RME content in the mixture with diesel fuel (DF) on the injection process parameters such as: initial velocity of the injected fuel, critical speed of secondary fuel breakup, critical droplet diameter, microstructure of the fuel stream, droplet Sauter mean diameter, vertical angle of the fuel stream, have been justified. The impact of the RME content in the mixture with diesel fuel on the above-mentioned parameters has been proved. During the tests, the engine worked on the load characteristics.

Keywords: self-ignition engines, vegetable fuels, rapeseed oil methyl esters, Common Rail injection system, fuel stream.

INTRODUCTION

Contemporary internal combustion engines are subject to current design solutions concerning the requirements of environmental protection standards. More and more perfect crude oil processing technologies, new fuel additives and alternative fuels meet the requirements set for them

In fact, the important thing is to meet the new, increasingly stricter EURO 6d standards in terms of emission of the most common pollutants (CO, HC, NO_x, PM), while maintaining high efficiency of the engine, its dynamics of movement and high durability.

In the mid-1920s, the growing availability of new crude oil resources and its lower price effectively blocked the development of the economy for new alternative fuels, including plant origin engine biofuels [29].

When using them, special attention is paid to their biodegradation and impact on human health. The economic crisis of the 1980s and the political situation in the Persian Gulf countries contributed to the interest in plant fuels. The direction of research on the use of biofuels for diesel engines as less sensitive to changes in the physicochemical properties of these fuels was selected then.

The concept of the development of these fuels fit in the global fight against the global warming of the Earth's climate adopted at the international climate conference in Kyoto in 1997. One of the findings of this conference were decisions to reduce greenhouse gas emissions into the atmosphere by, among others, limiting the consumption of fossil fuels, including those derived from crude oil. It has been recognized that carbon dioxide, which blocks the radiation of heat into the atmosphere, plays a decisive role in the global warming.

From the point of view of ecologists, cultivated plants take up carbon dioxide from the atmosphere, which is then used in the process of photosynthesis. With some simplification, it can be assumed that we are dealing with a closed CO_2 cycle, namely: engine exhaust fumes-atmosphere-plants. Vegetable fuels are said to be carbon neutral.

The concept of using vegetable fuels was patented by Rudolf Diesel at the World Exhibition in Paris in 1900 when his diesel engine was fed with peanut oil.

In Poland, there are perfect conditions for growing rapeseed plants. In the RME production process, transesterification reactions are used and the obtained ester viscosity is comparable to that of diesel [32].

This process takes place when methyl alcohol is used in the presence of a selected catalyst: sodium or potassium hydroxide. As a result of this reaction, the chemical particle is restructured and a glycerol group is replaced with an alcohol group. With different acid residues in triglyceride, a mixture of vegetable oil methyl esters is formed. It can be used as diesel fuel as well as glycerin. The latter is most often used in the pharmaceutical industry. Meeting the above-mentioned expectations in relation to vegetable fuels requires the involvement of numerous research centers in order to adapt them to diesel engines without structural changes. The parameters of the injection and combustion process in the engine, the emission of the most common pollutants while maintaining the required engine performance are tested.

PURPOSE AND SCOPE OF THE STUDY

The aim of the research was to perform the required measurements on an engine dynamometer equipped with a supercharged single-cylinder AVL 5402 diesel research engine, with the Common Rail fuel injection system.

The engine was powered by mixtures of diesel fuel (DF) with methyl esters of rapeseed oil fatty acids RME, as well as self-contained DF and RME ester. The engine will run on the load characteristics.

The following mixtures of ON and RME have been selected for the tests: 10 RME, 20 RME, 30 RME, 40 RME, 50 RME, DF and RME. The number denotes the volume fraction (v/v) of RME in diesel oil. The basic physicochemical properties of these fuels will be determined.

Necessary quantities for determining the parameters of the fuel stream will be registered. Due to the growing proportion of DF and RME in the mixture, the physicochemical properties of these fuels are changing. In traditional fuel supply systems of these engines (in-line fuel injection pumps, injection pumps, unit injectors), due to the interaction of opposing, different factors in the injection system (sealing clearance, flow resistance), they may cause changes in the beginning of fuel injection. This moment is closely related to the preparation of the combustion process. Next, it influences the organization of combustion and, consequently, the emissions of the four common pollutants [13, 27, 30]. These phenomena are interesting because the AVL 5402 engine is equipped with a new generation Common Rail fuel supply system. The development of research and production of methyl esters for diesel engines will be presented.

The main purpose of the research is to determine the impact of the content (v/v) of RME fuel on the injection process parameters of the engine equipped with the Common Rail injection system. The assessment of the impact of the tested fuels on the formation of a combustible mixture will be analyzed in detail. The following things are taken into consideration:

- the initial velocity of the fuel stream injected into the combustion chamber,
- critical speed of secondary fuel droplet breakup,
- value of the critical droplet diameter,
- the microstructure of the fuel stream, droplet Sauter mean diameter,
- vertical angle of the injected fuel.

DEVELOPMENT OF RESEARCH AND PRODUCTION OF METHYL ESTERS FOR DIESEL ENGINES

Rapeseed oil fatty acid methyl ester mixtures were referred to in the western literature as biodiesel and were marked RME - rapeseed methyl ester or marked as FAME – fatty acid methyl esters, Fatty acids, C 16-18 and C C 18 unsadt., Me esters. Earlier in Poland they were marked as EMKOR - methyl esters of rapeseed oil fatty acids.

Currently, according to EU standards, the name FAME appears on the domestic market as " Fatty acids C-16-18 and C 18 unsadt., Me esters and RME esters, but "higher fatty acids" were added to their full name in both cases. According to the EU standard, the current name of RME according to the Fuel Safety Data Sheet prepared in accordance with EU Regulation 830/2015 with the update of 16/08/2018 is: methyl esters of higher fatty acids "RME (methyl ester of higher fatty acids)" [35, 36].

This fuel is intended for the use as a standalone fuel for self-ignition engines or as a biocomponent in the production of conventional diesel oil that meets the requirements of PN-EN 590 standard [38].

Austria was the first European country to conduct a research program on the use of rapeseed oil as a fuel in a diesel engine (Piloproject Bio-Diesel) in 1987 [16]. Subsequently, Biodiesel was produced in England, Belgium, the Czech Republic, France, Germany, Slovakia, Hungary, Italy and the USA [8, 26, 32, 33]. It was possible to buy pure RME esters as well as their mixtures with diesel fuel at petrol stations. The fuel market in Germany developed particularly dynamically at that time. According to UFOP (Union zur Fårderung von Oel - und Proteinpflanzen E.V.) sources, there were three main producers of Biodiesel [34].

In the end of the 1980s, in Poland, in the Chemical Plant ROKITA in Brzeg Dolny, methyl esters of rapeseed oil fatty acids under the name EMKOR ROKMET were produced. A little bit later, these esters were produced at Zakłady Azotowe Kędzierzyn, and then at the Agrorafineria in Mochełek.

In 1987, Polish technology for the production of rapeseed oil fatty acid esters was developed at Kazimierz Pulaski Higher School of Engineering in Radom.

There, the first research works in Poland on the use of these esters to power diesel engines in Tarpan cars, were also undertaken.

Until now, under the supervision of the author, the research works have been continued both in steady and transient states of engine operation. They mainly concern the processes of injection and combustion of biofuels [19, 20, 21, 22, 23].

Numerous research works on the use of rapeseed oil and its esters to power diesel engines were carried out in several centres in the country, including among others: Cracow University of Technology, Lublin University of Technology, Poznań University of Technology, Szczecin University of Technology, Military University of Land Forces in Wrocław, Industrial Institute of Agricultural Engineering (PIMR) in Poznań, Institute of Aviation in Warsaw.

Also in Europe, extensive research was conducted by such centres as: Institute of Internal Combustion Engines in Graz, Austria, French Environment and Energy Management Agency, French Institute of Oil Technology, DMS Diesel-Motoren und Gerätebau Schönebeck in Germany, Same - Lamborghini in Italy, VTT Technical Research Centre of Finland, Porsche Research and Development Centre in Germany and others. The results of these studies were the engine adjustment for vegetable oil combustion, multi-fuel engines and a new engine design developed in 1964 by Elsbett [11, 16].

The aforementioned aspects of limiting the access to crude oil resources and the problems with the global warming make the issues of biofuels very interesting almost all over the world. Currently, very intensive research is being carried out on their application to diesel engines for various means of transport. Research is being conducted on the use of more and more various seeds to obtain vegetable oils, e.g. jatropha plant grown in Mexico, Central America, Brazil, Bolivia, Argentina, Paraguay. Currently, jatropha biodiesel is produced in the Philippines, Pakistan and Brazil.

Another source for obtaining fuel is karanja, grown in India, China and Japan. Currently, research on the use of various vegetable and animal esters as additives in diesel fuel is carried out in the form of simulation [5, 12, 14, 24] and experimental tests [3, 6, 10, 12] in order to optimize the parameters of the injection and combustion of exhaust emissions as well as engine performance with the use of the latest numerical modelling methods. However, research on real objects [2, 6, 10, 14, 17, 24, 28, 31] are the major part of the tests.

The additives to the mixture containing diesel oil are most often fatty acid esters of rapeseed oil [16, 26], palm oil [4, 9], karanja oil [2, 18], sunflower oil [10, 25], algae oil [7], neem oil [25], animal fats, catering waste [3, 24], soybean oil, rubber seed oil [25].

CHARACTERISTICS OF THE RESEARCH OBJECT AND FUELS

A single-cylinder supercharged diesel engine AVL5402 has been selected for the tests. It is a typical engine for research on the development of new engine prototypes at the Institute of Prof. List in Graz, Austria. It is an engine design with variable compression ratio, with the latest Common Rail fuel injection system. The injection system enables the use of 1 ÷ 4 pilot doses of the injected fuel. Two pilot fuel doses were used in the tests. The engine was supercharged with the pressure of the compressor. A general view of the test stand is shown in Figure 1.

The main components of this stand were: AVL 5402 engine, AVL eddy-current brake, air and fuel conditioning systems, fuel weight, Atlas Copco rotary screw compressor, air temperature control system, automated supply system for the AVL + EC stand, test stand for: CO, NO_x, and PM measurement. Figure 2 shows the control and recording systems of the test stand.

Measurement procedures, availability of engine operating parameters and their edition is possible thanks to computers equipped with PUMA Open V1.5.3 software. and AVL INDICOM V2H.

The Microsoft Windows 7 (32/64 Bit) operating system is used to operate the AVL PUMA Open software. In addition, the AVL Indi Com system is used to analyze the engine operating parameters.

The measuring apparatus used for the tests was in conformity with the requirements of the following normative documents: Directive 1999/96/EC of the European Parliament and of the Council of

Fig. 1. General view of the test stand equipped with AVL 5402 research engine

Fig. 2. Control systems and test records

13 December 1999, Regulation (EC) No. 715/2007 of the European Parliament and of the Council of 20 June 2007, and Commission Regulation (EC) No. 692/2008 of 18 July 2008.

Basic technical characteristics of the AVL 5402 engine: a single – cylinder engine wit diameter 85.01 mm, stroke 90 mm, displacement - 511.0 cm^3, combustion type – compression ignition, compression ratio – 17.0÷17.5, fueling system - direct injection, single injector, Common Rail system, maximum effective power with supercharging - 16 kW, rated engine speed - 4200 min^{-1}, injection pressure – 110.0 MPa.

The following fuels were tested: diesel fuel without DF additives and methyl esters of higher fatty acids of RME rapeseed oil produced by ORLEN Południe S.A. in Trzebinia as mixtures with diesel fuel with respectively 10% RME in a mixture, 20%, 30%, 40% and 50%. They were marked as 10RME_DF, 20RME_DF, 50RME_DF. Selected physicochemical properties of the tested fuels are presented in Table 1 in accordance with the data for diesel fuel based on the quality certificate no. 21BMK/A/321 PKN ORLEN S.A.Płock, of 6th February 6, 2021 and for RME presented by PKN ORLEN Południe S.A. Trzebinia Certificate of Quality no. 21TBIO/A/41 of 2nd March 2021 [37].

Currently, fuel stations in Poland sell diesel fuel with an addition of 7% (v/v) FAME or RME. The RME and FAME product quality certificates show that both of these esters are characterized by the same basic physicochemical parameters [35, 36].

In order to determine the parameters of the formation of a combustible mixture (fuel stream), it is necessary to know the density, viscosity and surface tension of the tested fuels. These values are given in Figure 3, 4, 5, respectively.

TEST RESULTS AND THEIR ANALYSIS

Selected parameters of the fuel stream injected into the combustion chamber of the AVL 5402 engine, calculated and obtained from the tests, will be presented below.

Table 1. Selected physicochemical properties of the tested fuels

Properties	Unit	Limits	Fuel type						
			DF	RME	10 RME	20 RME	30 RME	40 RME	50 RME
			Result						
Content RME	% (v/v)	-	-	100.0	10.0	20.0	30.0	40.0	50.0
Density at temp. 15 °C	kg/m	860 ¸ 900	825.3	882.7	831.2	836.6	841.7	846.5	852.6
Kinematic viscosity at temp. 40 °C	mm²/s	3.5 ¸ 5.0	2.50	4.47	2.659	2.832	3.129	3.237	3.400
Surface tension at temp. 20 °C	mN/m	-	27.32	31.45	27.29	27.38	27.70	27.79	28.77

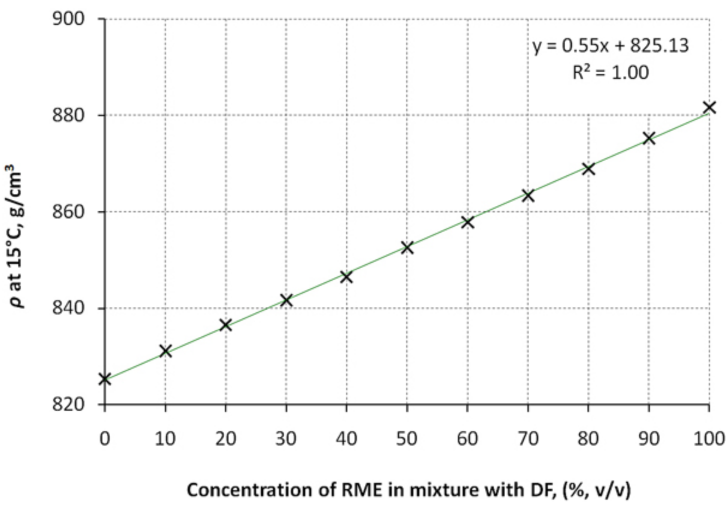

Fig. 3. The effect of the RME concentration in diesel fuel on the mixture viscosity on the mixture density

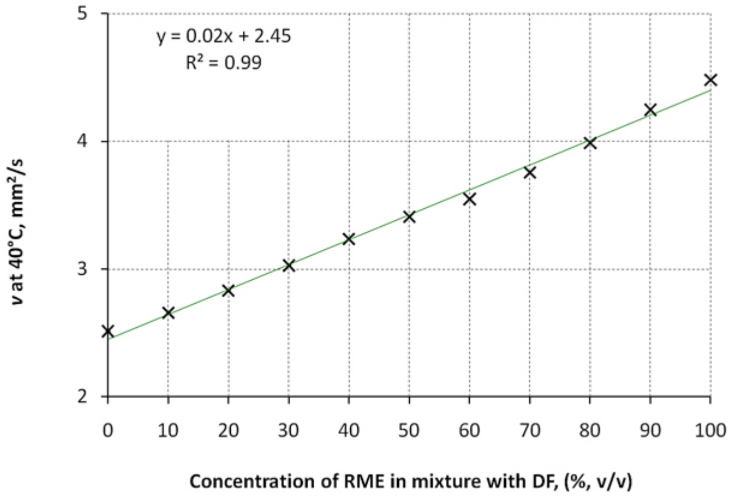

Fig. 4. The effect of the RME concentration in diesel fuel on the mixture viscosity on the mixture viscosity

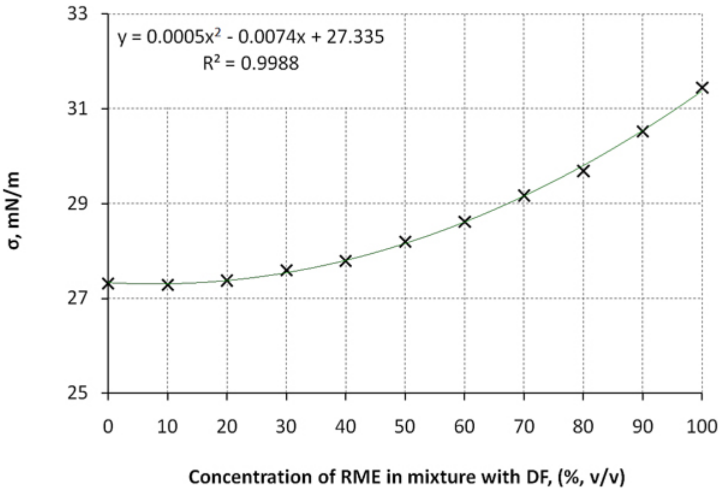

Fig. 5. The effect of the RME concentration in diesel fuel on the mixture viscosity on the mixture surface tension

INITIAL VELOCITY OF FUEL INJECTION

In a compression-ignition engine, pressure changes are essential for the process of creating a fuel-air mixture in the combustion chamber. They are understood as the difference between the fuel injection pressure and the gas pressure prevailing in the chamber at the moment and defined as ΔP. An example of these changes for the selected engine load as well as for the fuel is shown in Figure 6.

During the process of fuel injection into the combustion chamber, secondary breakup of droplets occurs. To analyze this phenomenon, the knowledge of the critical speed of w_{kr} fuel is used, when exceeded, their secondary breakup occurs. The initial velocity of the fuel stream injected into the combustion chamber can be calculated from the formula:

$$w_p = \mu \sqrt{\frac{2\Delta P}{\rho_p}} \; [m/s] \tag{1}$$

where: ΔP – the difference between the injection pressure and the pressure in the combustion chamber (injection overpressure), ρ_p – fuel density, μ – an impact factor of 0.7 was taken from the literature.

On the basis of the determined values of ΔP for the tested fuels, the initial speed of the fuel flow from the injector was calculated for the AVL 5402 engines operating on the load characteristic (at n = 1700 rpm, M_o = 30 Nm). Results are expressed in Table 2.

The injection pressure is mainly decisive for the speed of fuel spurt from the nozzle orifices. As the speed of fuel spurt increases, the accuracy and uniformity of the stream are improved. As the fuel injection overpressure of 50 RME decreased slightly in relation to diesel fuel, the initial stream speed decreased about 3%. In this case, the increase in the density and viscosity of RME with DF mixtures resulted in a very slight decrease in

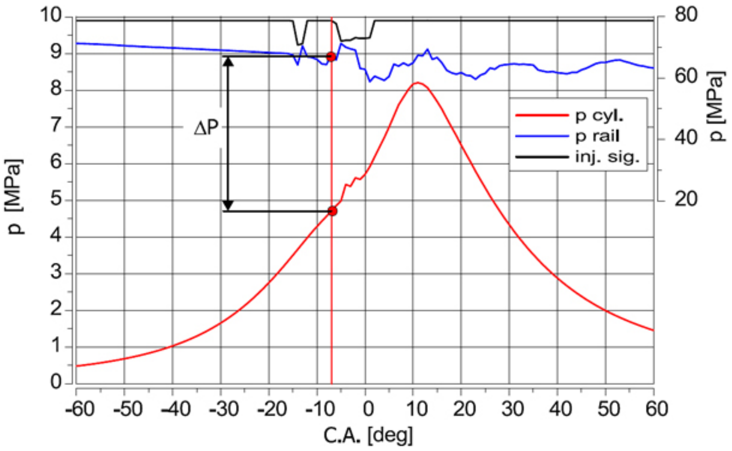

Fig. 6. Maximum overpressure definition before starting the injector in the combustion chamber

Table 2. The impact of the content of rapeseed oil methyl esters in a mixture with diesel oil on the initial velocity of the injected fuel stream of the AVL 5402 engine (n = 1700 rpm, M_o = 30 Nm)

Fuel type [%, v/v] RME	Injection overpressure, ΔP [MPa]	Initial velocity of fuel stream, w_p [m/s]
DF	63.10	273.71
10 RME	63.17	272.90
20 RME	62.00	269.49
30 RME	62.02	268.72
40 RME	61.98	267.89
50 RME	61.70	265.37

the injection overpressure and the temperature in the combustion chamber, from 760 ÷ 783 K.

The important thing is that when the engine is powered with the Common Rail injection system, the initial velocity of the fuel flow has increased almost twice in relation to the AD3.152 engine with the CAV distributor injection pump. This significantly improves the parameters of the fuel injection process.

The velocity of the fuel spurt from the nozzle can give the fuel stream a different shape. Moreover, the nature of the stream is determined by fuel viscosity, air bubbles in the fuel, compressibility and surface tension. Vortices are created when the fuel spurts from the nozzle. The orifice edges as well as their smoothness contribute to their formation. They are rounded on the inner side of the orifice.

CRITICAL VELOCITY FOR THE SECONDARY BREAKUP OF FUEL DROPLETS

The vortices formed just behind the nozzle orifice cause a turbulent pulsation of the fuel. Waves of increasing amplitude are formed on the surface of the flowing out stream. These disturbances cause the primary breakup of the stream into drops. The similarity of the stream decay is determined by four criterial numbers, including the Weber number, which is crucial.

The Weber number (w_e) is proportional to the ratio of the aerodynamic drag forces of the droplet and the surface tension force that is responsible for its shape. At the moment of the fuel stream breakup, the Weber number (w_e) reaches a critical value. It depends mainly on the viscosity of the liquid (not explicitly defining the Weber number). When the aerodynamic force is greater than the surface tension force of a droplet, the secondary droplet breakup occurs. The criterion for this phenomenon is the value of $(w_e)_{kr}$.

For the critical value of the Weber number, it is possible to determine the maximum speed of a droplet (in a stationary gaseous medium), with a strictly defined diameter. In case the diameter is bigger, the droplet breakup takes place:

$$w_{kr} = \sqrt{\frac{(W_e)_{kr}\sigma_p}{\rho_g d}} \tag{2}$$

where: σ_p – surface tension of the fuel, d – defined diameter of the droplet, ρ_g – density of the gaseous medium in the cylinder.

The Weber number was assumed to be 10 and additional conditions were specified: pressure, density and gas temperatures in the combustion chamber. For the load of the engine AVL5402 , M_o = 30 Nm and n = 1700 rpm. The supplied air density in the cylinder was calculated as 21.2 kg/m^3.

The measured pressure was 4.6 hPa and the temperature was 764 K. Previously, the surface tensions, shown in Figure 5, were measured.

The range of 10 ÷ 150 μm of fuel droplet diameters was also assumed, and the critical speeds of their breakup, for the tested fuels, were calculated. The results were shown in Table 3.

The assessment of the w_{kr} values contained in the Table 3 shows that the critical speeds of the droplets when the secondary breakup occurs increase together with the increase of the amount of RME fuel in the mixture with DF. Their greater surface tension is responsible for this.

THE CRITICAL DIAMETER OF THE FUEL DROPLETS

Secondary breakup of fuel droplets takes place due to the aerodynamic force in a medium in which an increased dynamic gas pressure occurs. This pressure increases with increasing gas density, and especially when the relative velocity (w) of gas and droplets increases. If the aerodynamic force exceeds the surface tension, the droplet disintegrates. The deformation criterion is the Weber number $(We)_{kr}$. The primary droplet breakup takes place already in the outlet cross-section of the nozzle orifice [39]. That is why the role of the injection pressure and the nozzle orifice diameter are so important. This justifies modern solutions of Common Rail systems, where the pressures are 15–35 MPa in the AVL 5402 engine, and the diameter of the nozzle orifice is 0.12-0.20 mm [39].

Calculations of the diameter d_{kr} of the tested fuels and the four ‘’w’’ relative velocities were calculated from the formula:

$$d_{kr} = \frac{\sigma_p (W_e)_{kr}}{\rho_g w^2} \tag{3}$$

where: ρ_g – gas density in the chamber at M_O = 30 Nm and n = 1700 rpm and temp. = 764 K, σ_p – surface tension of fuels, $(We)_{kr}$ – critical value of Weber number equals 10.0, w – selected critical droplet velocities.

The speed of sound which equal 340 m/s and other selected fuel speeds equal ½, ¼, 1/8 of this value, were considered for the calculations. The obtained results were summarized in Table 4.

Table 3. The impact of the content of rapeseed oil methyl esters in mixtures with diesel oil on velocities above which their secondary breakup occurs in the AVL5402 engine (n = 1700 rpm, M_o = 30 Nm)

Fuel type	Surface tension at temp. 20°C	Droplet diameter [μm]						
		10	20	30	50	75	100	150
		Critical velocities of fuel droplets, w_{kr} [m/s]						
DF	27.32	35.89	25.38	20.72	16.05	13.10	11.35	9.26
10 RME	27.29	35.87	25.36	20.71	16.04	13.10	11.34	9.26
20 RME	27.38	35.93	25.41	20.74	16.07	13.12	11.36	9.27
30 RME	27.70	36.14	25.55	20.86	16.16	13.19	11.43	9.33
40 RME	27.79	36.20	25.66	20.90	16.19	13.22	11.44	9.34
50 RME	28.77	36.83	26.04	21.26	16.47	13.45	11.64	9.51
100 RME	31.45	38.51	27.23	22.23	17.22	14.06	12.17	9.94

Table 4. Critical diameters dkr of diesel fuel DF droplets and their mixtures with RME

Droplet relative velocity, w_{kr} [m/s]		Fuel type					
		DF	10 RME	20 RME	30 RME	40 RME	50 RME
	w [m/s]	Critical velocities of fuel droplets, d_{kr} [μm]					
1	340.0	3.36	3.39	3.41	3.43	3.45	3.47
1/2	170.0	13.47	13.56	13.65	13.73	13.81	13.91
1/4	86.0	59.34	59.75	60.14	60.51	60.85	61.29
1/8	43.0	217.50	212.04	213.42	214.72	215.95	217.50

From the results shown in Table 4, it is clear that the differences in the critical values of the droplet diameters of diesel fuel as well as RME and DF mixtures decrease with the increase of the relative velocity between the fuel droplet and the gaseous medium in the combustion chamber. Within the same of the four relative velocities, differences in the impact on the droplet diameters with different physicochemical properties of the tested fuels do not show significant changes.

THE MICROSTRUCTURE OF THE FUEL STREAM

Conventional, alternative fuel droplet diameters constitute a fairly convenient criterion in the evaluation of the spray droplet size spectrum due to specific comparative processes of injection parameters of different fuels. They include the mean diameter of fuel drops according to Sauter d_{32}. Semi-empirical formulas are used to calculate the mean diameter of the droplets in the stream of the injected fuel. Some of them are quite troublesome to use. A relatively simple formula was proposed by Hiroyasu and Kadata [15].

$$d_{32} = A(\Delta P)^{-0.135}\rho_g^{0.121}V_{pj}^{0.131}[\mu m] \quad (4)$$

where: ΔP – injection overpressure, ρ_g – density of the gaseous medium in the chamber is 21.2 kg/m^3, V_{pj} – unit dose of fuel per cycle, A – the constant of the open injector is 23.9.

The results of calculations of droplet Sauter d_{32} mean diameter tested with mixtures of RME with diesel fuel were presented in Table 5. The AVL 5402 engine worked under the load M_o = 30 Nm and n = 1700 rpm on the external characteristics.

The analysis of the data in Table 5 shows that for a group of tested fuels, Sauter mean diameters of droplets differ slightly. With the increase in the share of RME in the mixture with DF, the fuel dose increased slightly. The increase in surface tension for fuel mixtures with a higher proportion of RME can be an explanation.

VERTICAL ANGLE OF THE FUEL STREAM

As the physicochemical properties of the tested RME and DF fuel mixtures differ from each other, they have an impact on the microstructure of the fuel stream. Therefore, it was decided to test their impact on the vertical angle of the injected fuel stream. Apart from the fuel type, other parameters have also an impact on this vertical angle. They are:

- fuel injection pressure,
- gas density in the combustion chamber,
- type of the injector design,
- ratio of the nozzle orifice length to its diameter.

Three empirical relationships are most often used in the tests to determine the vertical angle of fuel atomization:

– spray angle according to Abramowicz [1]:

$$tg\left(\frac{\Theta}{2}\right) = 0.13\left[1 + \left(\frac{\rho_g}{\rho_p}\right)\right] \quad (5)$$

– spray angle according to Bracco et al. [15]:

$$tg\left(\frac{\Theta}{2}\right) = 2\frac{\pi}{\sqrt{3}}\frac{1}{A}\left(\frac{\rho_g}{\rho_p}\right)^{0.5} \quad (6)$$

– spray angle according to Heywood [15]:

$$tg\left(\frac{\Theta}{2}\right) = \frac{1}{A}4\pi\left(\frac{\rho_g}{\rho_p}\right)^{0.5}\frac{\sqrt{3}}{6} \quad (7)$$

where: ρ_g – gas density in the combustion chamber at the time of fuel injection [kg/m^3], ρ_p – fuel density [kg/m^3], A – nozzle constant for a given design calculated from the dependence, l_w – nozzle orifice length 1.0 [mm], d_w – diameter of the nozzle orifice 0.2 [mm].

To verify these methods, the calculation of the fuel stream vertical angle was performed using Abramowicz, Bracco and Heywood's method. The obtained results were presented in Table 6.

The analysis of three formulas adopted to determine the vertical angle of the injected fuel

Table 5. The impact of the RME content in a mixture with DF on droplet Sauter mean diameter for AVL5402 engine (n = 1700 rpm, M_o = 30 Nm)

Parameter name	Fuel type					
	DF	10 RME	20 RME	30 RME	40 RME	50 RME
Fuel dose, V_{pj} [mg/cycle]	22.90	26.10	26.20	26.30	27.00	27.20
Injection overpressure, ΔP [MPa]	63.10	63.17	62.00	62.02	61.98	61.70
Sauter mean diameter, d_{32} [μm]	29.78	30.30	30.39	30.40	30.51	30.56

Table 6. Impact of the type of the tested fuel on the vertical angle of the stream injection into the AVL5402 engine at M_o = 30 Nm and n = 1700 rpm

Fuel type	Density at temp. 15 °C [kg/cm³]	Vertical angle values according to the formulas:		
		Abramowicz [1]	Bracco [15]	Heywood [15]
DF	825.4	15.188	15.044	15.044
10 RME	831.2	15.186	14.992	14.992
20 RME	836.6	15.184	14.944	14.944
30 RME	841.7	15.182	14.900	14.900
40 RME	846.5	15.182	14.858	14.858
50 RME	852.6	15.176	14.806	14.806

stream shows that according to Abramowicz's formula [1] the size of this angle is not influenced by the design parameters of the atomizer/nozzle (the orifice diameter and length), but only by the ratio of the gas density in the combustion chamber to the fuel density. On the other hand, Bracco and Heywood's formulas [15] take into account the design parameter in the form of the indicator A (formula 7). The previous research shows that the vertical angle of the fuel stream increases for nozzles with a small ratio of the length to the orifice diameter [32]. It can be assumed that according to Bracco and Heywood's formula, identical values of angles were obtained. They were lower by about 1% in relation to the results obtained according to Abramowicz's formula. Table 6 shows that as the density of the tested fuels decreased (Fig. 3), the vertical angle of the injection increased slightly. This confirms the existing general opinion that the fuel spray angle increases with the increasing ratio of gas density in the combustion chamber to fuel density. Higher viscosity of RME with DF mixtures (Fig. 4) affects the macrostructure of the fuel stream, limiting its disturbances and hindering the fuel droplet breakup. Consequently, the stream is more continuous when the vertical angle is smaller.

CONCLUSIONS

It should be emphasized that the fuel tests were carried out for constant injection parameters: the injection start angle of both the pilot dose and the main dose fuel as well as the size of the pilot dose. During the tests, only the basic dose for the tested mixtures of RME with diesel fuel changed when constant rotational velocities were: n = 1700; 2200 and 2700 rpm and the corresponding constant torques M_o = 5; 10; 15; twenty; 25; thirty; 35; Nm. Such rules are necessary when testing comparative parameters of the fuel injection process when fuels have different physicochemical properties.

An important thing in the tests on mixtures of RME rapeseed oil methyl esters with diesel was the fact that a research engine equipped with a Common Rail fuel supply system, high injection pressures and an engine controller with a load map were used for this purpose. The engine load characteristics were made and the basic parameters of the injection process were measured for them. They were used to calculate the following values:

- initial velocities of the injected fuel,
- critical velocities of fuel secondary breakup,
- critical diameter of fuel droplets,
- stream microstructure,
- vertical angle of the injected fuel stream.

The impact of the physicochemical properties of these fuels on the mentioned parameters of the injection process was analyzed.

The test results confirmed the improvement of parameters for the combustion process, mainly due to the new engine power supply system.

Earlier design solutions were not able to meet the requirements set for them. Both the author's own research carried out for many years and the results of previous and modern research centers confirm that vegetable oils and especially their esters, still seem to be a promising fuel for diesel engines. Renewable fuels are of great importance in the world, and biodiesel made from vegetable and animal oils reduces the emission of exhaust components into the atmosphere by diesel engines.

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