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Assessment of fuel spraying using schlieren system

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Abstract: *Assessment of fuel spraying using schlieren system.* This paper presents results of research on spraying a diesel oil, bioester, alternative fuel, which can be rapeseed oil and mixtures of fuels that can be used to fire engines with compression ignition. The fuels were sprayed using an injector with a pintile spray tip. This type of an injector is used in engines of older construction with indirect injection, which commonly utilize alternative fuels. In order to visualize the jets a schlieren system was utilized. The collected photos were used to determine the cone angle of the jet. Among the fuels tested the rapeseed oil was characterized by the worse spraying characteristics. The average value of the angle for jets of this type of an oil significantly deviated from the average angles of the remaining fuels. Bioester, obtained from a process of transesterification of the rapeseed oil, was characterized by a very good spray angle. Its average cone angle was very high. The differences in angles were mostly due to the viscosity of different fuels. Average jet angles of the sprayed fuel for the rapeseed oil after it was supplemented with fuels of lower viscosity – ethylene and ethyl alcohol in an amount of 15% – increased however the difference between the angles proved statistically insignificant.

Key words: bio-diesel, bio-fuel, diesel, rapeseed oil, schlieren

INTRODUCTION

Until recently most automotive research, in specificity, research on combustion engines was focused on minimizing the fuel consumption and reduction of toxic compounds in exhaust gasses while maintaining or increasing the performance of the drive units [Nikolaewicz Kartashevich and Belousow 2009]. Among the many factors impacting the fuel consumption and exhaust gasses emission levels for both the positive and compression ignition is the spraying of fuel injected into the combustion chamber. The basic parameters that describe the jet of the injected fuel, which at the same time characterize the quality of the fuel spraying are: cone angle of jet, its range, distribution of the droplets' diameter, change in droplets' diameter during injection and the speed at which the jet spreads [Idzior and Lijewski 2001]. Idzior and Lijewski [2001, 2002], by using methods of visualization of the injected fuel jet, have proven that the construction of the injector is of key importance for the cone angle of the schlieren and its range. Their research was however focused on spraying just one type of fuel – diesel oil.

The limited character and decreasing reserves of crude oil makes the availability of gasoline and diesel oil limited. This results in vigorous research activities on adjusting the combustion engine to utilize plant-based fuels [Bocheński 2003, He i Bao 2003, Czechlowski et al. 2006, Dzieniszewski 2008]. This is, in a way, going back to the roots, as Rudolf Diesel, the creator of compression ignition engine, proposed peanut oil as fuel [Knothe et al. 2005]. The main advantages of plant-based oils utilized as fuels are: sustainable sourcing, a relatively low price (unprocessed oils) and high availability. The disadvantages of unprocessed plant-oils are: inconsistent chemical and phase composition, high molar mass of components, quick physical, chemical and biological decay and high variability of characteristics between oils of different kinds and within the same kind, dependent on, e.g. natural conditions during growth, the way the material was collected, produced or stored. In case of processed oils (depending on the processing level, e.g. esterification) the main disadvantages are: inconsistent chemical and phase composition, increased production cost (which in many cases makes production unprofitable) and high variability of properties between materials of different types with small variability of properties between oils of the same type [Bocheński 2003, Cieślikowski and Ślipek 2006, Jóźwiak and Szlęk 2006].

Out of many available plant-based oils the one that is most popular as alternative fuel is the rapeseed oil and its esters [Heneman and Červinka 2007, Kovalyshyn 2010]. Due to the above, the authors have considered it justified to test the process of injection of fuel in form of rapeseed oil in its unprocessed form, its esters and fuel mixtures. The characteristics of the fuel spray were analyzed using high speed photography allowing for imaging and measurement of the parameters of the sprayed fuel.

RESEARCH METHODOLOGY

The bench testing utilized a schlieren system – Figure 1 [Settles 2001]. This allowed for visualization of the fuel injection process by the injector in form of videos and photos of the sprayed jet with its external envelope and to measure the cone angle that the jet generated. The angle calculation was realized using the AutoCAD software developed by Autodesk. The utilized injector was equipped with a pintile spray tip produced by Warszaw-

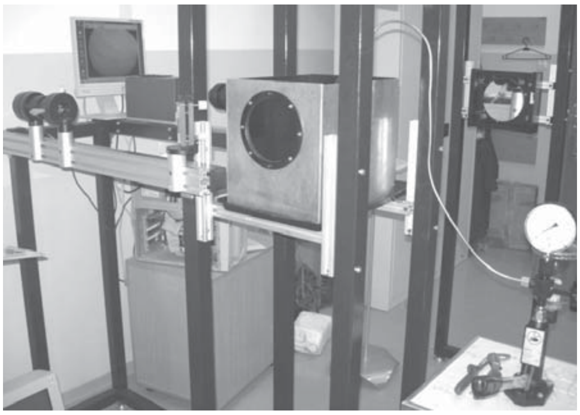

FIGURE 1. Bench-schlieren system with the test chamber and injector probe (to the right) during tests (author's photo)

skie Zakłady Mechaniczne WUZETEM, which is used in the Ursus agricultural tractors. Such injectors create a jet dependent on the geometry of the pintile tip. Injectors equipped with pintile tip create a jet with a cone angle of up to 30° (when spraying diesel oil), and cylindrical tips create narrow jets with long range and small cone angle [Wardziński 1988, Dong et al. 2013]. The realized study utilized a pintile injector tip.

The device used as an injection pump was an injection probe type EFEP 60H (Fig. 1). Such probes are used for periodic maintenance of injectors. They allow for statistical tests, e.g. testing tightness of joints between the injector's parts, or dynamic testing, e.g. testing the opening pressure – injection, proper movement of the pin and the parameters of the jet. During the research utilized was injection pressure of 12 MPa which is recommended for many engines with indirect injection.

It should be noted that the realized bench tests differ from the actual working conditions of an injector:

- lower pressure in the test chamber in relation to the combustion chamber of an engine – measurements realized at atmospheric pressure;
- lower temperature in the chamber – tests realized at ambient temperature;
- lower speed of pumping.

The tests and result analysis were realized taking into consideration the above differences due to the difficulty in realizing tests covering the same research scope under realistic or simulated conditions. The authors agree that in the longer perspective, the research should be continued under conditions that would be more realistic and that would better represent actual operating conditions of an engine.

The tests covered the following fuels: diesel oil – summer type (DO) provided by PKN Orlen, refined rapeseed oil (RO) provided by Basic Components Sp. z o.o., bioester BIO100 – fatty acid methyl esters obtained via transesterification of rapeseed oil (RME) provided by PKN Orlen, a mixture of rapeseed oil and 15% vol. ethylene 95 (R15G) (ethylene provided by PKN Orlen) and mixture of rapeseed oil and 15% vol. of commercial grade ethyl alcohol (96% vol.), (R15E). The mixtures were created by the researches from the components provided. The properties of the mixtures were realized in the fuel quality laboratory of PKN Orlen. The parameters of the fuel mixtures components (ethylene and alcohol) are provided in Tables 1 and 2 present the chosen properties of the tested fuels.

In case of mixtures of rapeseed oil and ethylene 95 and ethanol some of the

TABLE 1. Properties of fuel mix components (own deliberation)

Parameter	Standard tests	Unit	Component	
			petrol 95	ethanol
Density at 15°C	PN-EN ISO 12185	$kg{\cdot}m^{-3}$	746	810
Kinematic viscosity at 40°C	PN-EN 3104	$mm^2{\cdot}s^{-1}$	0.7	1.0
Flashpoint	EN 22719	°C	67	12

TABLE 2. Properties of tested fuels (own deliberation)

Parameter	Standard tests	Unit	Fuel			
			DO	RO	RME	R15G
Density at 15°C	PN-EN ISO 12185	$kg \cdot m^{-3}$	836	920	882	–
Kinematic viscosity at 40°C	PN-EN 3104	$mm^2 \cdot s^{-1}$	2.87	36.7	4.52	15.88
Cold filter plugging (CFPP)	PN-EN 116	°C	–25	–	–10	–
Flashpoint	EN 22719	°C	67	>250	166	–

parameters cannot be measures due to total or partial distribution into separate phases.

The statistic analysis of the collected data was realized using the Statistica 8.0.725 software developed by Statsoft. In order to assess the test environment (bench), i.e. the repeatability of testing, a statistical test of Wald-Wolfowitz was performed and the statistical analysis of test results was performed using the Kruskal-Wallis test.

RESULTS

Figure 2 presents exemplary visualization photos for spraying of fuel jets using the schlieren system.

In order to ensure repeatability of tests the Wald-Wolfowitz statistical test was utilized (Table 3). The test assumed a null hypothesis that two independent samples (groups I and II) are from the same population. The test was realized for results obtained for the diesel oil and rapeseed oil.

The test shows that samples from groups I and II for diesel oil and the rapeseed oil belong to the same population. The null hypothesis was confirmed. This allowed for an assumption that the testing bench ensured repeatability of results with materiality level of 0.732 for diesel oil and 0.254 for the rapeseed oil.

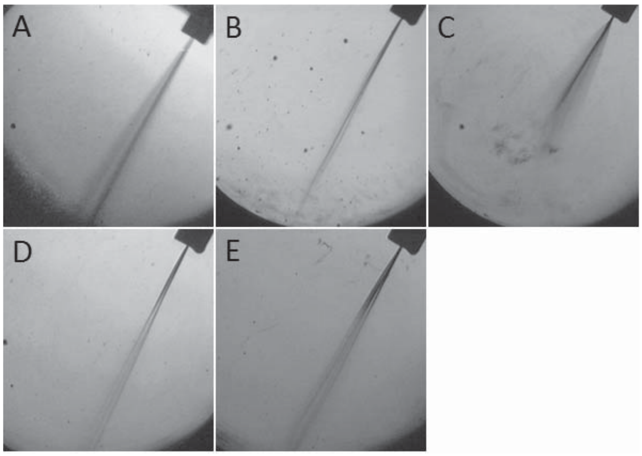

FIGURE 2. Image of the sprayed jet of: A – diesel fuel (DO); B – rapeseed oil (RO); C – bioester (RME); D – mixture of rapeseed oil and 15% vol. ethylene 95 (R15G); E – mixutre of rapeseed oil and 15% vol. ethanol (R15E) registered using a schlieren system (own deliberation)

TABLE 3. Wald-Wolfowitz test results for variable: fuel type (own deliberation)

Diesel oil										
Variable	N impor-tant. Group I	N impor-tant. Group II	Avera-ge Group I	Avera-ge Group II	Z	Level P	Z correc-ted	Le-vel P	Num-ber of series	Num-ber of linked
Angle	38	39	9.92	10.26	–0.34	0.73	0.23	0.81	38	33
Rapeseed oil										
Variable	N impor-tant. Group I	N impor-tant. Group II	Avera-ge Group I	Avera-ge Group II	Z	Level P	Z correc-ted	Le-vel P	Num-ber of series	Num-ber of linked
Angle	66	65	3.35	2.95	1.14	0.25	1.05	0.29	73	65

Table 4 presents the minimal and maximal cone angles for the oil jet, the standard deviations and number of tests for every oil type.

Cone angle is one of significant geometric parameters determining quality of spraying (injection). Figure 3 presents the average values of cone angles of injected fuel and their differentiation. Among the fuels tested the rapeseed oil was characterized by the worse spraying characteristics. The average value of the angle for jets of this type of oil significantly deviates from the average angles of the other fuels. The differences were mostly due to the viscosity of different fluids. The parameters of injection (spraying) of rapeseed oil were modified (improved) by mixing it with fuels of lower viscosity. On the other hand, bioester obtained from a process of transesterification of the rapeseed oil was characterized by a very good spray angle. The average cone angle for the jet of this type of fuel was very wide.

TABLE 4. Descriptive statistics concerning cone angles of sprayed oil jet (own deliberation)

Fuel	Min.	Max.	Average	Standard deviation	Number of attempts N important
DO	6	17	10.09	2.18	77
RO	0	8	3.15	2.25	131
RME	9	25	14.16	4.00	85
R15G	2	8	4.33	1.76	12
R15E	1	10	5.06	2.61	32

The statistical significance of observed differences between the cone angles of injected fuels was tested using the Kruskal-Wallis test (Table 5). Verified was the null hypothesis that the compared samples were from the same population with the same distribution or distributions with the same median. The test showed that the samples of the rapeseed oil and the samples of the rapeseed oil with admixtures were of the same population. The samples of diesel oil and the bioester are significantly different

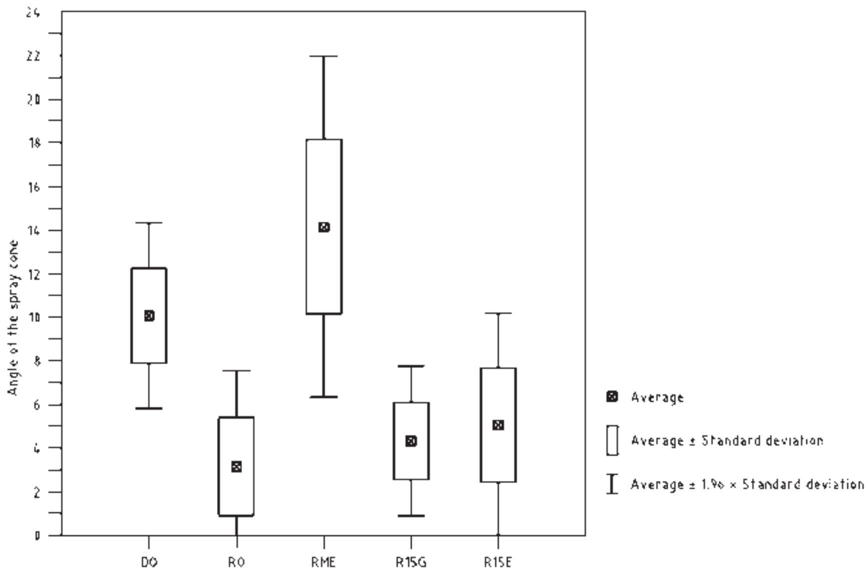

FIGURE 3. Graphical representation of average cone angle values for the jet and its variability for the tested fuels (own deliberation)

TABLE 5. Results of the Kruskal-Wallis test (own deliberation)

The type of fuel	Code	N important	Total ranks		
DO	101	77	17,378.0		
R15G	102	12	1,253.0		
R15E	103	32	3,826.5		
RO	104	131	10,592.5		
RME	105	85	23,903.0		
The level of significance of p for bilateral comparisons					
The type of oil	DO R:225.69	R15G R:104.42	R15E R:119.58	RO R:80.86	RME R:281.21
DO	–	$6.05 \cdot 10^{-4}$	$2 \cdot 10^{-6}$	0	$2.92 \cdot 10^{-3}$
R15G	$6.05 \cdot 10^{-4}$	–	1	1	0
R15E	$2 \cdot 10^{-6}$	1	–	0.44	0
RO	0	1	0.44	–	0
RME	$2.92 \cdot 10^{-3}$	0	0	0	–

The independent variable: the type of fuel, the dependent variable: the cone angle of the jet.

from one another and from the remaining samples.

SUMMARY

The obtained results prove the usability of the schlieren system for analysis of jet's cone angle.

On basis of the statistical analysis performed we can state that the jet cone angles of diesel oil, rapeseed oil and bio-diesel are significantly different and that adding a 15% vol. of ethylene or ethyl alcohol did not result in a significant change in the jet cone angle of the rapeseed oil.

The quality of the oil jet is mostly dependent on its type and characteristics (most notably viscosity). In consequence, on basis of the tests realized and the literature sources [Idzior and Lijewski 2001, 2002], it can be justifiably stated that there are no universal fuel injectors that would ensure proper quality of the fuel jet regardless of the type of fuel used. This means that if a given engine is to utilize hybrid fuels of different types, e.g. interchangeably the diesel fuel and plant-based fuels, it should be equipped with a fuel injection system able to adjust to different fuel types, e.g. injectors of variable geometry or a system allowing for decreasing the viscosity of the fuel by e.g. pre-heating of the fuel.

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Streszczenie: *Ocena rozpylania paliwa metodą smugoskopii.* W pracy przedstawiono wyniki badań rozpylania oleju napędowego, bioestru, alternatywnego paliwa, jakim może być olej rzepakowy oraz mieszanina paliw, które mogą służyć do zasilania silników z zapłonem samoczynnym. Paliwa rozpylano, stosując wtryskiwacz z rozpylaczem czopikowym. Ten rodzaj rozpylacza stosowany jest w starszych konstrukcjach silników z wtryskiem pośrednim, które w warunkach eksploatacji często zasilane są paliwami alternatywnymi. Do wizualizacji strug zastosowano smugoskop wyposażony w kamerę. Uzyskane zdjęcia posłużyły do wyznaczenia kątów wierzchołkowych stożków strug. Spośród badanych paliw najgorzej rozpylany był olej rzepakowy. Wartość średniego kąta strugi tego oleju zdecydowanie odbiegała od wartości średnich kątów dla pozostałych paliw. Bioester, uzyskany z procesu transestryfikacji oleju rzepakowego, charakteryzował się zaś bardzo dobrym rozpyleniem. Jego średni kąt wierzchołkowy przyjmował duże wartości. Różnice w kątach wynikały głównie z różnic w lepkościach poszczególnych paliw. Średnie kąty strug rozpylonego paliwa uzyskane dla oleju rzepakowego po dodaniu do niego paliw o mniejszej lepkości etyliny oraz alkoholu etylowego w ilości 15% uległy zwiększeniu, lecz różnice w kątach okazały się statystycznie nieistotne.

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