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EVALUATION OF THE INJECTORS OPERATIONAL WEAR PROCESS BASED ON OPTICAL FUEL SPRAY ANALYSIS

OCENA EKSPLOATACYJNEGO ZUŻYCIA WTRYSKIWACZY NA PODSTAWIE ANALIZY OPTYCZNEJ ROZPYLENIA PALIWA*

The diagnostics of combustion engine components currently requires the integration of many technical and scientific fields in order to quickly and accurately locate faults or pinpoint the causes of malfunction. This article analyzes the wear of injectors based on the geometric indicators of the fuel spray. Using a number of available parameter data, a selection has been made to best judge the wear of injectors in their operating conditions. Optical fuel spray tests were used to assess the injector wear. Various geometric indicators of the fuel stream have been presented, indicating their diagnostic utility and applicability. In conclusion, it was found that the current injection systems require the combination of mechanical injector diagnostics and advanced optical fuel spray diagnostics.

Keywords: *fuel injection, fuel spray, fuel jet cone angle, optical diagnostics.*

Diagnostyka elementów silnika spalinowego wymaga obecnie integracji wielu dziedzin techniki i nauki w celu szybkiej i trafnej lokalizacji uszkodzenia lub poszukiwania przyczyn niesprawności. Artykuł dotyczy analizy zużycia wtryskiwaczy na podstawie wskaźników geometrycznych strugi rozpylanego paliwa. Na podstawie kilku dostępnych wielkości badawczych dokonano wyboru pozwalającego najlepiej ocenić zużycie wtryskiwaczy w warunkach ich eksploatacji. Do oceny diagnostycznej zużycia wtryskiwaczy wykorzystano badania optyczne rozpylenia paliwa. Przedstawiono różne wskaźniki geometryczne strugi paliwa, wskazując na ich użyteczność diagnostyczną oraz możliwość zastosowania. W podsumowaniu stwierdzono, że badania obecnych układów wtryskowych wymagają połączenia mechanicznych metod diagnostyki wtryskiwaczy oraz zaawansowanej diagnostyki optycznej rozpylenia paliwa.

Słowa kluczowe: *wtrysk paliwa, rozpylenie paliwa, kąt stożka strugi, badania optyczne.*

1. Introduction

The diagnostics of combustion engine components currently requires the integration of many technical and scientific fields in order to quickly and accurately locate faults or pinpoint the causes of malfunction. The injection system is one of the most sensitive engine systems, which in compression-ignition engines requires more rigorous performance and fit regimes than in spark ignition engines. Evaluation of the injection system components and in particular of the injectors is carried out by analyzing the degree of their contamination by external or internal deposits resulting from the combustion of fuels and lubricating oil [16].

The use of additives for diesel fuels aims to limit the formation of such deposits.

Studies on the use of detergent-dispersant additives were conducted by Beck et al. [1]. They have shown that these additives are suitable for increasing the oxidation resistance of pure diesel and biodiesel blends. With respect to the fuel samples tested - biodiesel, diesel and their mixtures, the reduction of oxidation stability due to prolonged shelf life may be partially compensated by the use of selected dispersant-detergent additives. Additives prevent the formation of radicals and neutralize carboxylic acids and thus increase the oxidation stability of the fuel samples.

When analyzing the effects of detergent-dispersant additives Żak et al. [19] have shown that they have a significant effect both on the state of the compression-ignition combustion engine fuel supply equipment as well as on the reduction of exhaust gas emissions (mainly for particulate matter).

Khalife et al. [5] analyzed the effects of various additives on fuel consumption and emissions, and showed that oxidation additives have the most significant impact on these values. They increase fuel consumption while reducing CO, HC and PM emissions, while slightly increasing NO_x emissions. It has also been shown that non-metallic additives (such as carbon nanotubes) have the least notable impact on these values.

Nano-additives to fuels are becoming increasingly important. Shaafi et al. presented their full characteristic in [15]. This revealed the impact of the use of metal nano-additives, metal oxides, magnetic fluids, carbon nanotubes and mixtures thereof on engine performance and emissions. It has been found that using mixtures of nano-additives into pure diesel fuel increases nitrogen oxide emissions, due to the increase in the combustion chamber maximum temperature. It has been shown that emulsification (the use of water) is the best way to reduce NO_x emissions, but also limits the engine performance.

Reducing the buildup of residues can lead to changes in fuel spraying and combustion in the combustion chamber. Hence the need to study the fuel stream geometric parameters, not only as a result of

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** the engine operation of the wear of components, but also as a result of using fuel additives.

Fuel stream research is used mainly to determine the main spray indicators, such as the stream range, the area of the jet (defined as flat image exposure) and the jet incidence angle. Many studies employ fixed volume chambers to study these quantities using halogen lamps [13], LED [7] or laser light [18].

The study of fuel streams geometric indicators is usually performed using optical methods. They allow for precise determination of the stream range in different temperature conditions of the medium. They also often include images from varying view angles to allow for corrections in determining the stream. Flat image exposure is used to determine the area of the fuel stream. There are methods of masking each stream to individually determine their parameters. The stream cone angle is determined using several methods. The basic methods allow to determine it at any distance from the atomizer, analyzing the width of the stream in a given cross section [8]. Others are based on the averaging of such magnitudes after taking into account several stream width values. The latest method, which allows for some level of automation, was devised by Naber and Siebers [8]. It enables determining the cone angle based on the knowledge of the stream surface area and its range [10]. So, to determine the stream cone angle, it is necessary to know the value of these several parameters.

Ghahremani et al. [2] determined the geometry of the fuel stream based on experimental studies. Equations describing the range and surface area of the stream were determined (fuel and medium density, kinematic viscosity and surface tension of fuel) using the physical and chemical properties of the fuel (bio-diesel). The maximum range error was 9% and for the area it was 12%.

2. Research motivation

Studies of fuel spray indicators conducted with respect to injectors in compression-ignition engines are primarily concerned with the assessment of changes in the stream geometric parameters resulting from their operation. The aim of this article was to determine the influence of different fuels on these indicators in addition to obtaining the indicator values themselves. Another issue was the estimation of fuel atomization time, with which it is possible to determine the described changes in geometric parameters.

3. Research methodology

3.1. Test objects

The study of the fuel stream geometric parameters for different fuels was performed using three groups of injectors and two types of fuel. New injectors (designated n1) and injectors previously used in vehicles (designated u1 and u2) were used. Their characteristics are shown in Table 1. The tested injectors were characterized by an 8-pore atomizer with a 162° angle between the fuel jets.

Base diesel fuel (B7 fuel labeled as #1) and diesel fuel with a set of additives (labeled #2) are included in the study.

Table 1. Characteristics of the injectors used in the tests

Injector	Fuel	Notes	Injector mileage [km]
n1	#1	New injector	0
n1	#2	New injector	0
u1	#1	Used injector/vehicle 1	80 000
u2	#2	Used injector/vehicle 2	80 000

Table 2. Selected properties of the base and modified diesel fuel

Test type	Unit	Result	
		Diesel oil B7	Diesel oil with INIG additives
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 polycyclic aromatic hydrocarbons	% (m/m)	1.1	
Sulfur content	mg/kg	below 5	below 3.0
Ignition temperature	°C	88	87.5
Coking residue (with 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
Impurities content	mg/kg	2.1	6.7
Corrosion test on steel (3 h, in the temperature of 38°C)	corrosion degree	trace B^{++}	corrosion trace
Fatty acids methyl esters (FAME)	% (V/V)	5.6	–
Oxidation resistance	hg/m^3	35.97	2.0
Lubricity, corrected average wear trace diameter (WS 1.4) at 60°C	µm	180	337
Kinematic viscosity at 40°C	mm^2/s	2.7175	2.711
Fractional composition at temperature up to 250°C distills at temperature up to 350°C distills 95% (V/V) distills at temperature	 % (V/V) % (V/V) °C	 27.3 97.7 333.0	 26.3 97.2 328.0

3.2. Research apparatus

A fixed volume chamber with a set backpressure value was used to determine the fuel stream geometry, using a diesel fuel injection (the exact description of the chamber can be found in [14]). Fuel injection at 35 MPa (corresponding to idle and low load conditions) and injection time of 0.3 ms were used in the research. For these conditions it is possible to accurately determine the stream geometric parameters. At the same time it also becomes possible to determine the effect of the injectors used on the change of the spray parameters. High fuel pressure values result in high flow rates, which results in fewer data records being recorded in a given measurement range. The measurement range is due to the size of the video window of the fixed

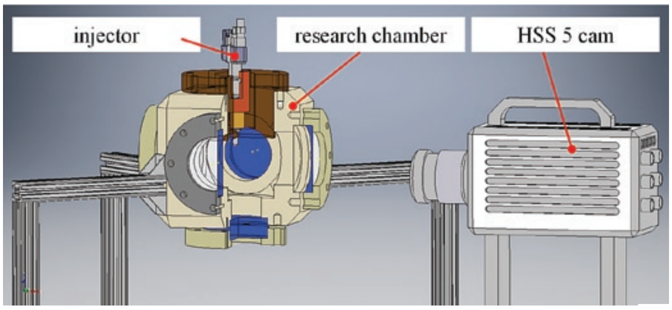

Fig. 1. Test bench

volume chamber [13]. The size of the quartz window used was 90 mm – Fig. 1.

Fuel injection into a fixed volume chamber was performed using an oil injection system along with its conditioning – STPiW3 from Mechatronics. The system uses a CP4.1 pump with a maximum fuel injection pressure of 200 MPa. In order to provide comparable testing conditions, the fuel temperature was maintained at 42°C.

The optical analysis of the fuel injection and atomization process was carried out using LaVision's high speed, monochrome HSS5 camera, with the 10 kHz ($\Delta t = 100$ µs) frequencies at a resolution of 512 × 512 pixels (examples are shown in [12]). The work area was 410 pixels, which, at the size of the measuring window (90 mm), allows for a 1 pixel = 220 µm imaging (or 1 mm = 4.55 pixels). This value is sufficient to carry out accurate analyzes of the fuel stream geometric parameters.

3.3. Results analysis

The recorded images were further processed to obtain fuel injection indicators from injectors with different mileage (new and used).

The study of injection indicators was carried out independently for each of the eight fuel sprays and the parameters determined included:

a) stream range; it is defined as the maximum distance from the atomizer to the adopted luminance boundary of the fuel stream image. Preparation of the images to evaluate the fuel stream range consisted of selecting the test area (applying masking of the image) and subtracting the background (measured noise). The fuel stream range was determined individually for each stream.
b) fuel stream area; it is defined as the number of pixels within the specified luminance intensity range. These tests were performed by determining the coordinates of triangles on each of the fuel streams.
c) the fuel stream cone angle; this value was determined using the method devised by Naber and Siebers [8]. It is possible to use typical algorithms to search for the stream cone based on the edges of the fuel jet streams, but this method is used increasingly less often due to the low accuracy and lack of precise guidelines for determining the rules of such methods. The Naber and Siebers method can be used for any injector in compression-ignition engines with different fuel outflow angles [9]. This algorithm requires determining the range of the fuel stream and then using half of that value and determining the fuel stream area for that range value. With this method it is possible to determine half of the stream cone angle value:

$$tg\left(\frac{\alpha}{2}\right) = \frac{P_\Delta}{(S/2)^2}$$

where: α – fuel stream cone angle, P_Δ – triangle surface area, S – maximum fuel stream range (Fig. 2).

The method of image processing and determination of individual spray indicators is shown in Fig. 3. The results obtained with this method (for each stream and for the full atomization time) mean that the results of initial values obtained for the fuel stream development will be subject to a large error resulting from the small developed fuel stream area value. With the development of the stream, the value of the resulting cone angle of the stream should be constant.

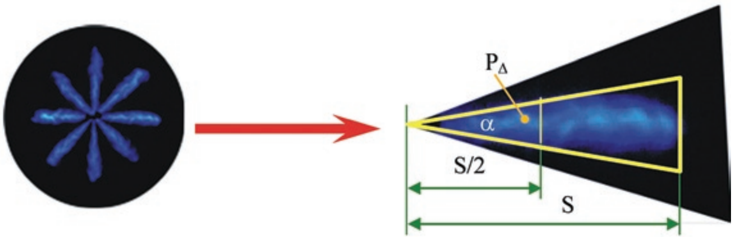

Fig. 2. Method for determining the fuel stream cone angle

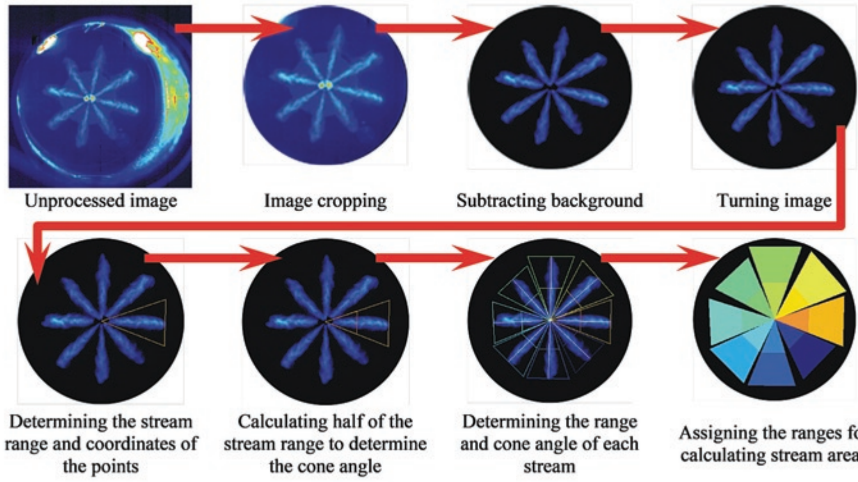

Fig. 3. Image processing and determining the geometric indicators of the fuel stream

4. Analysis of fuel spray geometric parameters and selection of the comparative index

4.1. Assessment of individual fuel spray indicator values

The methodology described above was used to determine the range of individual fuel streams. An average of these values was calculated, and presented in the form of lines without any visible measured points (Fig. 4a). Conducted research indicates the similarity of the range of individual fuel streams. It can also be concluded that analyzing each of the streams individually is necessary, since the arbitrary choice of one fuel stream does not permit full analysis of such atomization. Representative streams can be indicated in the analyzed results – similar to the average values. However, this selection is possible only after individual stream analysis. There were no significant differences in the range of individual fuel streams using standard fuel (diesel). In the analysis of the modified fuel range, however, it was found that there are two streams that differ significantly from the others. Such cases occurred during the stream range analysis of both, the new and the used injectors. It is not possible to deduce the difference in the wear level of the injectors or to change this value by using different fuels based on the analysis of individual stream ranges.

Analysis of the injected fuel stream surface area indicates the existence of significant differences when determining this value. Using this indicator, it is possible to assess the operational wear of the injector, as the stream surface area is significantly smaller (Figure 4b). It was thus also found that the analysis results of only one fuel stream could not be representative of the injectors operational changes.

The assessment of the fuel stream cone angle (Fig. 4c) indicates the existence of the lowest scatter values (spread at t = 1.6 ms between the new injectors is 4 percentage points). Analyzing this angle indicates a high repeatability of this measurement for each fuel stream. It is also possible to determine the injector wear, since as the injector mileage increases the fuel stream cone angle decreases.

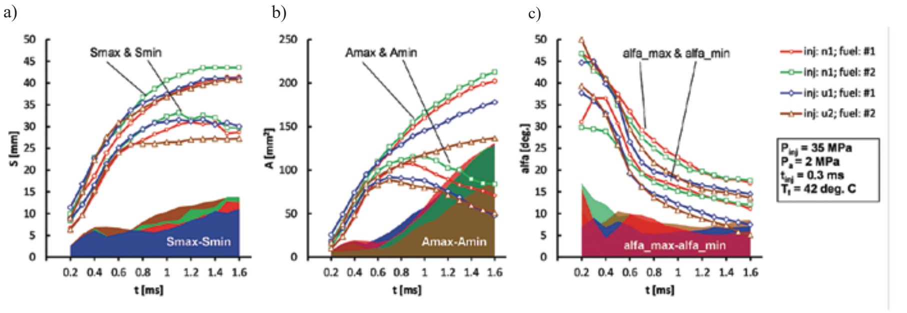

Fig. 5. Evaluation of limit values and differences of these values during fuel injection: a) stream range – S, b) stream surface area – A, c) stream cone angle – alpha

4.2. Assessment of fuel spray indicators limits

Due to the discrepancies in the fuel spray indicators of different streams mentioned previously, their limit values were determined. Stream range analysis indicates an increase in the differences with the streams development. The fuel spray limit values are similar (Figure 5a). At time up to 0.6 ms, the differences in the stream ranges are small and are about 14.9% for new injectors regardless of fuel type. After this time, however, these values increase to 30.5% for the injection of both fuels (at atomization time t = 1.6 ms after injection start time). The spread of values obtained for the used injectors #1 and #2 are: 17.5% and 22% respectively (0.6 ms after injection start) and 26.9% and 33% (at 1.6 ms) respectively.

The boundary values of the stream surface areas vary more significantly (Figure 5b). The investigations of new injectors indicate a much smaller spread between them than observed for the used injectors. However, the absolute value analysis allows to conclude that the differences in this case are smaller (between used injectors fed with different fuels). The smaller fuel stream surface area is caused by injector wear and tear (smoldering of atomizer holes), the smaller differences in values are due to the same level of injector wear. New injectors were characterized by increased differences in manufacturing and machining and were not subjected to several hours of operation. Up until 0.6 ms time the stream surface area differences were small and amounted to 15–19%. In both cases, the final stream surface area values (at t = 1.6 ms after injection start) were found to be in the range of 60–75%. This result may be due to the different manufacturing accuracy of the injector holes. The change in the range of stream area value analysis (t = 1.6 ms) does not exceed 5 percentage points (new

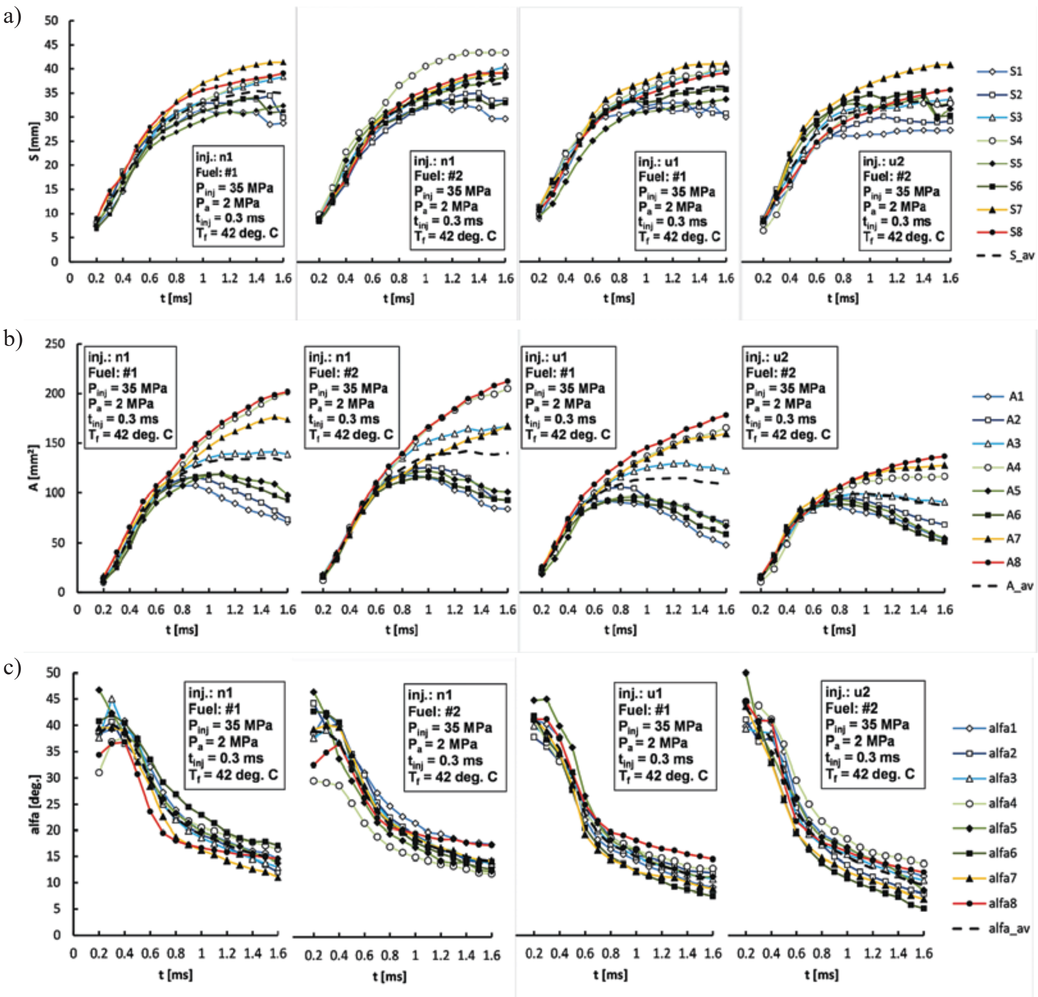

Fig. 4. Results of fuel spray indicator tests: a) fuel stream range – S, b) fuel stream area – A, c) stream cone angle – alpha

injectors) and 11 percentage points when analyzing injectors previously used.

Changes in the fuel stream cone angle are quite uniform throughout the injection period. The initial large angle values are due to the low corresponding fuel range value. Later on in fuel injection, similar changes for each test are observed. Up to 0.68 ms the difference in the stream range values is about 30%. After this time the values are still around 30% (at time t = 1.6 ms). Thus it can be stated, that this indicator is characterized by limited value changes with the time after injection. But also, for all the performed tests, the stream cone angle value spread decreases, resulting in a steady values after about 1 ms (range of angle between streams less than 10 degrees).

4.3. Average fuel spray rate evaluation

Due to the described discrepancies in the individual stream spray indicators, their averaged values were determined (Fig. 6).

Fuel injection using the new injectors indicates a greater stream range is obtained by fuel with additives (5% greater range). The operating conditions produce ambiguous results (Figure 6a). The stream range for injectors using base diesel fuel increased by 6%, while for diesel fuel with additives the range decreased by 11%. As can be seen from the above results, there is no clear conclusion, which indicates the need for additional fuel stream geometry analyzes to determine the fuel atomization differences between the various injectors and the use of different fuels.

The mean fuel stream area values analysis indicates the possibility of evaluating both the injectors wear degree as well as the fuel type used (Figure 6b). This is due to significant changes in the analyzed quantities. Larger fuel stream areas are observed for new injectors (regardless of the fuel type used). These values are higher by 20% (fuel #1) and 60% (fuel #2) compared to used injectors. Larger spray values (6%) were achieved with fuel #2 for new injectors. In the case of used injectors, the larger stream area was observed for fuel #1 – by 24%. Inclusion of the stream surface area in the fuel stream geometric analysis is a measure that allows the identification of the mileage and wear of the injectors as well as to determine the differences when spraying different types of fuels.

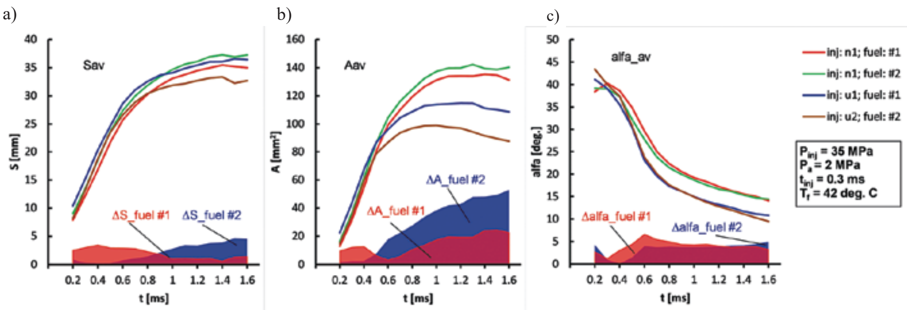

Fig. 6. Evaluation of average fuel spray indicators with limit values and value ranges: a) stream range – S, b) stream surface area – A, c) stream cone angle – alpha

Analysis of the average stream cone angle values indicates the high usefulness of this indicator for evaluating fuel spray of the operating injectors (Figure 6c). This analysis of the average stream cone angle reveals significant differences in the evaluation of new and used injectors. Operating conditions deteriorate the performance of the injectors (sintering and coking of the injector holes), resulting in a reduced stream cone angle. The difference between new and used injectors is about 30%. It can be noted that after some time (about 0.8 ms from the start of the injection) the values of these differences are constant. In the case of tested fuels it is not possible to effectively distinguish the difference in fuel spray from new or used injectors (the difference in spray angle for used injectors is only about 5% higher). The results of the fuel stream cone angle analysis by this method are convergent (with respect to the trend of changes during injection and atomization) with the results obtained in the studies of the mixture of n-pentanol and diesel oil by Ma et al. [7].

5. Selection of test conditions for the assessment of fuel spray indicators

Using the average fuel spray indicator values obtained, the coefficient of variation (as the standard deviation of the mean value) was determined for each fuel injection time. Because the value of the standard deviation itself depends on the mean value, this means that as the stream range increases, this value will also increase, an indicator that is independent of the mean has been selected. Thus it became possible to determine the time after which indicator value only increases. In combustion engine studies, it is assumed that the value of the coefficient of variation compared to the average indicated pressure should not exceed 3.5%–5% [6, 17] or the value of 10% [4]. Due to the much lower repeatability of the stream cone angle measurement results, it is assumed that in such tests it can reach values of up to 40% [3]. Taking these assumptions into account, an analysis is presented, including the determination of the minimum coefficient of variation value. It has been shown that there is a time after which the value of a given fuel geometry indicator only increases (Figure 7). With these assumptions, it is assumed that the minimum fuel spray analysis time, after which it is possible to determine the difference in the fuel atomization method, is 0.6 ms from the start of the injection. Only after such a time, changes in the range of the stream, the stream surface area and the stream cone angle are visible. Adopting a higher time value makes it valid, but the best form of evaluation consists of the knowledge of the whole fuel spray pattern.

6. Conclusions

Conducting research on the fuel streams geometry requires the use of optical tests in which it is important to consider several different parameters. Determining the geometric indicators of the fuel stream requires the use of procedures that determine the parameters of each stream separately and then averaging the results. It is necessary to analyze each stream individually, because choosing one stream for analysis does not allow for a full fuel spray and atomization analysis. Because of the large variation between

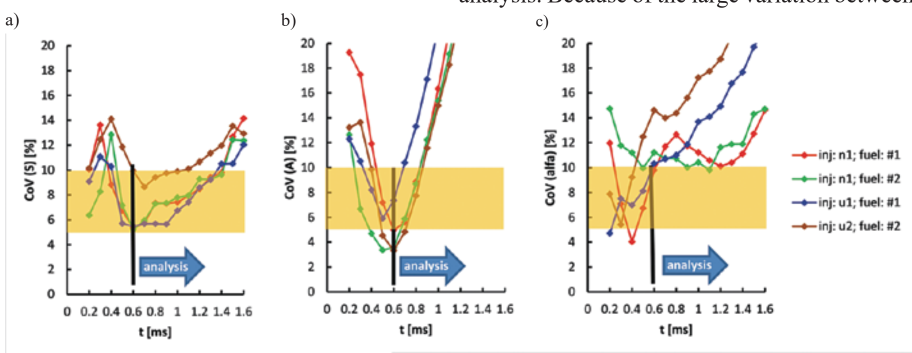

Fig. 7. Choice of analysis time for fuel spray coefficients based on the coefficient of variation: a) stream range – CoV (S), b) stream surface area – CoV (A), c) stream cone angle – CoV (alpha)

the different atomizer holes, the atomized fuel parameter values can vary greatly for each fuel stream.

In order to determine the effect of the fuel type used for the same injectors, it is necessary to determine the surface area occupied by the fuel stream as well as the stream cone angle. Due to the close similarity of the physical characteristics of the tested fuels, the range of the fuel stream does not indicate any changes that would allow to differentiate the fuel used based on the observed values.

Evaluation of the injectors wear level requires knowledge of the fuel stream surface area and the stream cone angle. In this case, the cone angle of the injected fuel stream is a significant indicator of the stream geometry, whose changes can be observed as a result of the operation and wear of the injector.

Detailed conclusions on the fuel stream geometric indicators were formulated in relation to the mean values obtained from the analysis of each stream:

1) in terms of stream range:
   a) the similarity in the physical characteristics of the analyzed fuels causes the differences in stream range from the new injectors to be small reaching about 5% in favor of the additive-rich fuel,
   b) during the analysis of the used injectors, different results were obtained: fuel injection using base diesel fuel increased the stream range by 6%, while using diesel fuel with additives led to a range decrease of 11%,
   c) the fuel injection characteristics and operational changes of the injectors cannot be evaluated or tested using the values of fuel stream range.
2) in terms of fuel stream surface area:
   a) new injectors (regardless of the fuel used) have a much larger stream area than the used injectors; which had a mileage of 80,000 km, the area has decreased both during base diesel fuel injection (20%) and during the additive-rich fuel injection (60%),
   b) when fuel is injected using the new injectors, the stream area is slightly larger for fuel with additives (by 6%); it is significantly smaller for base diesel fuel (by 24%) when using the already worn out injectors,
   c) the analysis of the mean stream area values indicates the applicability of this indicator, both to the assessment of the injectors wear and mileage and to identify the injection of different fuels (even with similar physical characteristics); this is due to significant changes in the values of analyzed parameters,
3) in terms of fuel stream cone angle:
   a) the difference between new and used injectors is about 30%,
   b) in the case of the tested fuels, it is not possible to determine the difference of fuel spray from new or used injectors (the difference in stream cone angle for used injectors reaches only up to 5%),
   c) the analysis of the results indicates the usefulness of this indicator for assessing the fuel atomization for the analysis of both new and used injectors.

The results of the conducted research indicate very high possibility of evaluating the degree of wear of the injectors. However, full analysis of the impact of different fuels on their geometric indicators should be complemented with combustion studies. Such studies, which are the next planned stage in the authors research, on the recognition of the various fuels injection effects, should be used to supplement the knowledge on the possibility of evaluating different fuel types, in the aspect of their effect on the operation of injectors, in compression-ignition engines.

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