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The effect of the nozzle hole geometry on the fuel spray shape and the quality of the fuel atomisation

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This paper presents the investigation results of the influence of a nozzle hole length on a shape and atomisation quality of fuel during injection in combustion engines. The method of the endoscopic investigations of the fuel injection performance in an open injection chamber specially arranged has been presented. The investigations have been performed for the multi-hole nozzle and different length of nozzle holes. On a basis of the results of the performed examinations an approach to evaluate a quality of fuel atomisation through the analysis of the fuel spray parameters has been done. In order to perform the relevant analysis of fuel spray a programme for digital processing of the images obtained during the endoscopic investigations has been used.

1. Introduction

The rigorous requirements concerning the cleanliness of exhaust gas have stimulated the searching for new methods of lowering the emission of exhaust gas toxic components. The emission is mainly determined by the characteristics of the combustion process being performed in the cylinder of the engine. In case of the compression-ignition engines the preparation of fuel charge i.e. swirl of air and atomisation of the injected fuel, is decisive for the combustion process. The reduction of emission can be obtained in two possible ways.

Avoiding any interference into the combustion process it is possible to lower the emission of toxic components in exhaust gas by use of the catalitic reduction in the engine exhaust system. The second method is based on limiting the formation of toxic compounds at the very origin of their creation by interfering into the combustion process.

In diesel engines the mechanism of fuel atomisation is strongly influenced by three following factors, namely: velocity of fuel flowing out from the nozzle holes, the coupled effect of nozzle hole walls on fuel spray, and the influence of medium which the spray is directed to.

The fuel outlet velocity results directly from the difference of sac hole and combustion chamber pressures existing during the fuel injection. In order to comply with the exhaust gas emission standards there is a tendency to obtain the possible highest values of fuel injection pressure. The injection pressure values ranging from 150 to 200 MPa are commonly used in the modern diesel engines. For obtaining such values some very strict material, design and process requirements must be met by the injection system, and injection nozzles in particular, what can be also seen reflected by the increased costs of production. The influence of medium, which the spray is directed to, is mainly connected with a density of air charge in a cylinder, i.e. compression ratio ε, and its proper swirl obtained by the optimisation of shape of the inlet channels and combustion chamber.

In future the factors presented above can appear not to be sufficient to keep the cleanliness of exhaust gas at level which enables fulfilling the emission standards, especially in case of the particle matters (PM) and hydrocarbons (HC) emissions as well. For these components the emission is decided by the structure of atomisation, mainly by the diameter of drops.

In such a situation some efforts to analyse the problem of the toxic compounds emission limitation, which are being formed during the combustion process, by means of the improvement of the injected fuel spray atomisation have been undertaken.

The improvement of atomisation involves mainly a decrease of droplets diameter and an increase of the atomised spray jet angle. The nozzles are characterized by delivering droplets of different diameter sizes. In cross section of a fuel spray a number of droplets, as a function of their diameters, is distributed in accordance with the Gaussian-similar distribution (e.g. Rosin — Rammler distribution). Therefore for comparison reasons a term of an equivalent droletp is used in the relevant bibliography. In analyses the mean equivalent diameter SMD (Sauter Mean Diameter) is generally used. Its value can be calculated on a basis of various empirical formulas, for example according to the Knight's formula of the following form (equation (1.1)) [1]:

$$\mathrm{SMD} = 76.96(p_w - p)^{-0.458} q_m^{\;0.209} \nu^{0.215} \left(\frac{F}{\mu F}\right), \quad [\mu\mathrm{m}] \tag{1.1}$$

where p_w — injection pressure [kG/cm^2], p — pressure of the medium, which the injection is performed to [kG/cm^2], q_m — outlet fuel spray [kg/h], F — section area of nozzle hole [m^2], ν — kinematical viscosity of fuel [cSt], μ — flow coefficient [–], calculated according to the following formula (equation (1.2)):

$$\mu = \left(1.23 + \frac{58}{\mathrm{Re}} \cdot \frac{l}{d_o}\right)^{-1} \quad [-] \tag{1.2}$$

and l — length of nozzle hole [m], d_o — hole diameter [m], Re — Reynolds number [–], In this formula, in addition to such parameters like a difference of pressures existing in the sac hole and in combustion chamber, and the fuel viscosity, there are some design parameters of spray nozzle, presented both in an evident or hidden way, namely diameter of nozzle hole and its length. If it is assumed, that the dose of the injected fuel is constant, the reduction of l and d_o values results in the reduction of SMD value. However, if it is assumed, that for the technological process reasons other possibilities of reduction of d_o have been used, the length of a nozzle hole is the only design parameter which can make SMD value to be lowered.

The Knight's formula is not precise from the theoretical point of view. Therefore it has been decided to verify experimentally the above statement by performing some test bench examinations in order to determine the influence of the modification of the nozzle hole length on the quality of atomisation of the fuel spray.

2. Methods of investigation

2.1. Methods of investigation and object of testing

To evaluate the quality of fuel atomisation some selected parameters are normally used. The basic parameters are: the structure of atomisation (diameter of droplets, and their distribution in the cross-section relative to its axis), velocity of spray propagation, range of propagation and jet angle [1, 2, 3]. The selection of parameters is usually determined by the measuring abilities. In the discussed case digital video system was available and the observation of spray „from outside" was possible. Owing to low frequency of taking the picture the observations were performed by a stroboscopic method, which made possible the precise measuring step (even at 0.2^0 c.a. intervals). Therefore, for evaluation of the atomisation quality the parameters which can be taken directly from the recorded pictures and some intermediate parameter informing on the modifications occurring in the structure of atomisation have been taken into consideration. The extent and velocity of spray face belong to the first group of parameters. The spray area being calculated after the picture has been digitally processed, is the intermediate parameter.

The digital camera of the video system records a picture in a pixel form. Each pixel is determined by three parameters, used in an abbreviated form as HSL (Hue, Saturation, Luminance) parameters [4, 5]. The HSL can be considered as a vector of visual information on the recorded point of a space. In this situation it can be expected, that the similar values of such a vector recorded in a space will prove that in their spaces the structure of atomisation should be similar. The parameter L (Luminance) is proportional to the intensity of reflected light recorded by a camera. The luminance of picture in the selected area is dependent on the concentration of fuel in this area and the structure of atomisation. For such a reason that parameter was modified during the performed analysis. However, the parameters H and S had such desired values, that they covered the complete spray area. The digital form of picture is very convenient to be digitally processed as using the computer in a desired way the discretisation of the recorded information can be performed. In the discussed case the problem concerns the determination of such segments of the spray area, which can be characterized by the similar values of the HSL parameters. By use of contour lines of the recorded parameters the picture of the fuel spray can be divided into sub-areas, which are characterized by the similar values of atomisation. The picture of such sub-areas and their change resulting from the design modification of the nozzle in particular, indirectly inform on the variations of atomisation, which are occurring there. To assign the desired contour lines of the HSL vector to the created sub-areas of spray, and to calculate their areas as well, the PatEV[1] programme has been used.

Taking the above into consideration, the desired analysis of the atomisation quality have been performed in the following way:

1) pictures of spray of fuel injected into an open space were recorded,

2) measurement of extent of the atomised spray as a function of the injection pump camshaft angle position was taken; that measurement made also possible the determination of velocity of propagation of the spray face;

3) the research material obtained in a form of video sequences (bmp-files) was subject to the digital processing which consisted in presenting the spray area by means of contour lines and calculating the area for each of them also as a function of fuel injection pump camshaft angle position.

The evaluation of the effect of the nozzle hole length on the quality of atomisation was done on a basis of the obtained test results. The modification of length of the nozzle holes was performed by grinding the outer surface of the nozzle tip of the tested nozzle to the desired size, as shown in Figure1. Beginning from the initial value of 1.1 mm the hole length was gradually reduced by step of 0.4 mm forming a sequence of values of length of 1.1, 0.7 and 0.3 mm. When performing the given set of examinations all values of settings were identical for each length of the nozzle hole. The operation conditions of the injection system should be included into the programme of examination of the injection system in order to make possible the complete evaluation of the effect of length of the nozzle holes on the quality of atomisation. This programme has been accepted after completing the test examinations. It was decided to take measurements for each nozzle hole length at settings of the fuel injection pump, which are presented in Table 1. The ambient parameters recorded during the examinations are also presented in this table. The step of 0.50 of pump shaft rotation angle between two successive pictures and period of observation were selected. The observation was commenced at the angle of 1^0 injection pump shaft revolutions before the spray had appeared and it was finished at the angle of 10^0 injection pump shaft revolutions after the injection had been completed.

[1] PatEV — Picture Analysis and Transformation for Engine Video-Observations [6]

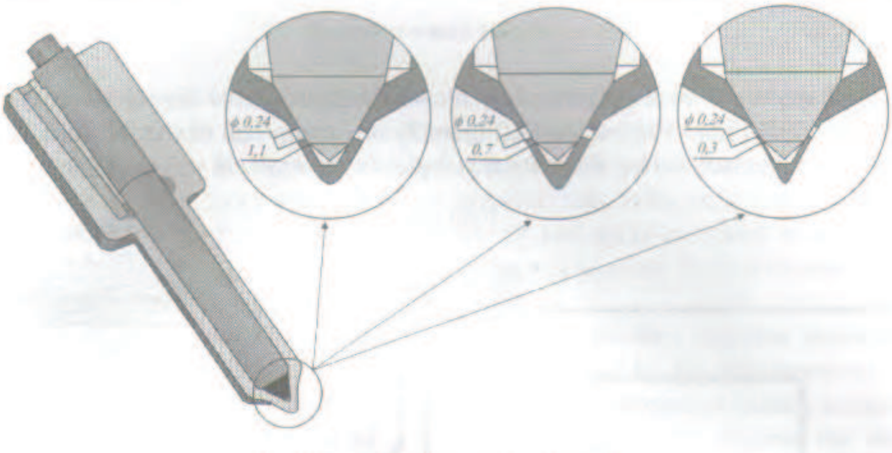


Fig 1. The tips of the examined nozzles.
Rys. 1. Końcówki badanych rozpylaczy.

Table 1. Conditions of examinations of the fuel injection into open space.
Tablica 1. Warunki badań wtrysku do otwartej przestrzeni.

No.	Fuel charge q [mm^3/100 cycle]	Rotational speed of injection pump shaft n [rpm]	Length of nozzle hole l_o [mm]	l_o/d_o ratio [–]	Opening pressure of spray nozzle P_{on} [bar]	Ambient temperature t_{ot} [°C]
1	5.2	600	1.1	4.58	307	16
2		800				
3		1000				
4	5.2	600	0.7	2.92	310	16
5		800				
6		1000				
7	5.2	600	0.3	1. 25	305	16
8		800				
9		1000				
10	9.2	600	1.1	4.58	307	16
11		800				
12		1000				
13	9.2	600	0.7	2.92	310	16
14		800				
15		1000				
16	9.2	600	0.3	1.25	305	16
17		800				
18		1000				

2.2 Test stand

The observations were performed by use of the professional digital video system of AVL type 513D [7,8]. The test stand (Figure 2) was composed of the injection chamber in which the pressure during the tests was equal to the ambient pressure.

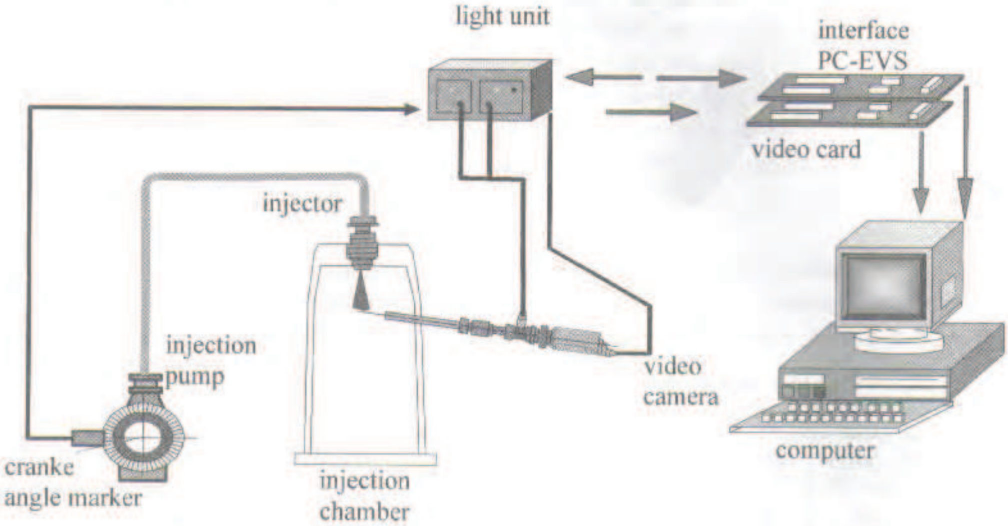


Fig. 2. Scheme of system to course of injection visualization.
Rys. 2. Schemat układu do wizualizacji przebiegu wtrysku.

For atomisation of fuel the injection valve of Bosch KBL140 type equipped with a five-hole nozzle of DSLA134P604 type, manufactured by WZM Warszawa, with a nozzle whole length l_o of 1.1 mm and diameter d_o of 0.24 mm were used. The injection valve was fuelled by the in-line injection pump mounted on a test table. The pumps shaft angle was measured by means of an optical sensing element. The atomisation process was recorded by means of the digital camera of TMC-9700 type, equipped with lens with a focal length of 25 mm. The camera picture resolution is 768×484 pixels. In order to improve the quality (Luminance) of the video sequences, in the injection chamber for lighting the fuel sprays an additional source of flash light, supplied by the lighting endoscope, was installed.

The endoscope was supplied by a stroboscopic module, via — a light guide, which made possible to synchronise a moment of lighting the spray with a moment of taking the picture by the camera. The stroboscopic module was combined with a marker of angle and owing to it the light flash was stimulated for the right moment of the pump shaft rotation. Inside the injection chamber a square of 20×20 mm was placed as a reference for vertical and horizontal dimensions. As a synchronizing chart for a camera-stroboscopic-module-marker of angle unit the PC-EVS interface was used. The measuring settings, namely: the start and the end angles, phase shift between the successive pictures and recurrence number of records taken at the same injection angle (in order to take into consideration the fact of non-repeatability of the injection process) were loaded into the Video-Scope control programme.

2.3. Discussion of examination results

The results of performed examinations are obtained in a form of a sequence of the successive pictures of fuel spray recorded in a computer memory and shifted by a desired phase angle. Each picture includes the images of all fuel sprays (five-hole nozzle). Only that fuel spray which axis was perpendicular to the axis of the camera was subject to the performed analysis. The selection of fuel spray consisted in marking the area of the picture in which the selected fuel spray was situated. Such area was analysed by means of the PatEV programme.

There were two stages of the performed analysis. In the first stage the shape of fuel spray recorded on the successive pictures was evaluated by the measurement of its total area A and the extent of the fuel spray face L. Those measured values, assigned to the relevant angle α of rotation of the injection pump shaft, formed the desired functions $A(\alpha)$ and $L(\alpha)$. The product of ΔL and $\Delta\alpha$ values (variation of fuel spray extent which occurred for step $\Delta\alpha$) determines the velocity of the fuel spray face propagation.

The effect of nozzle hole length on the shape of fuel spray is shown on the example of three selected pictures, which are presented in Figure 3. The method for measuring of spray propagation L is also shown in this figure.

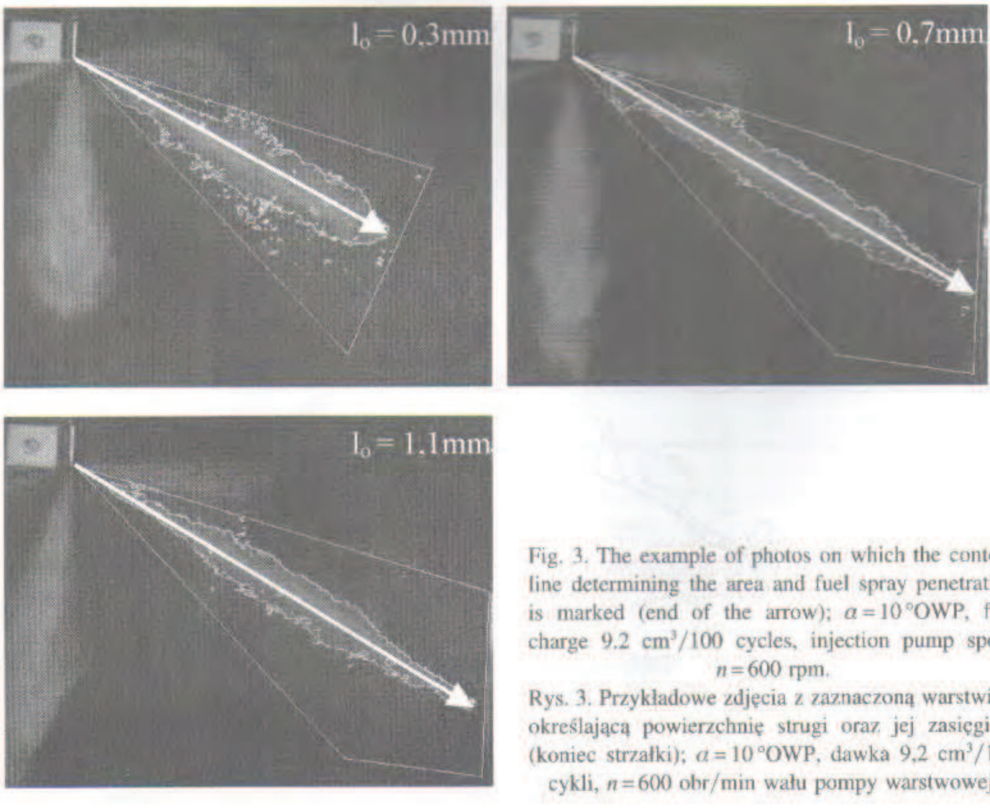


Fig. 3. The example of photos on which the contour line determining the area and fuel spray penetration is marked (end of the arrow); $\alpha = 10$ °OWP, fuel charge 9.2 $cm^3/100$ cycles, injection pump speed $n = 600$ rpm.

Rys. 3. Przykładowe zdjęcia z zaznaczoną warstwicą, określającą powierzchnię strugi oraz jej zasięgiem (koniec strzałki); $\alpha = 10$ °OWP, dawka 9,2 $cm^3/100$ cykli, $n = 600$ obr/min wału pompy warstwowej.

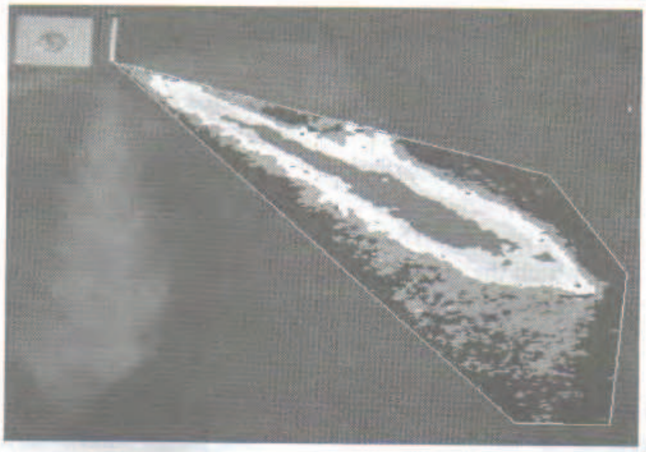
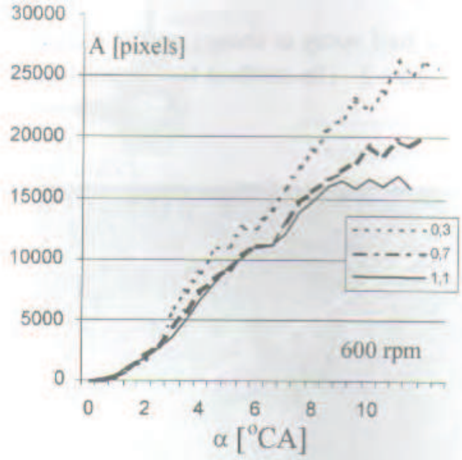
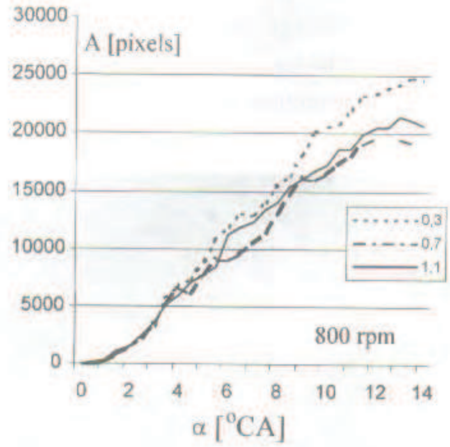


Fig. 4. The example of fuel spray divided by contour lines: $l_o=0.3$ mm.
Rys. 4. Przykład podziału powierzchni strugi na warstwice: $l_o=0{,}3$ mm.





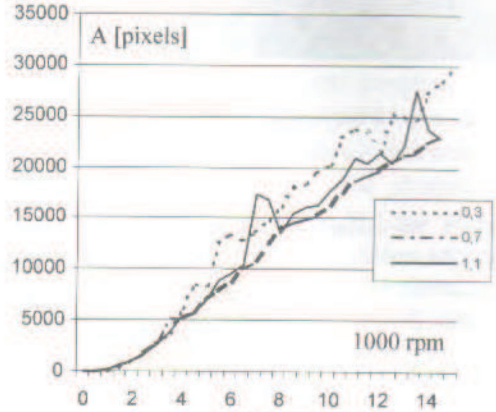
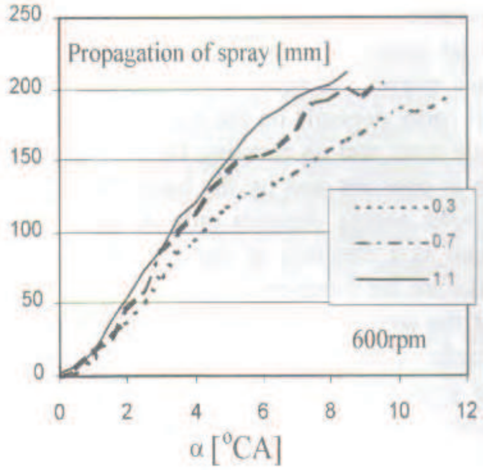
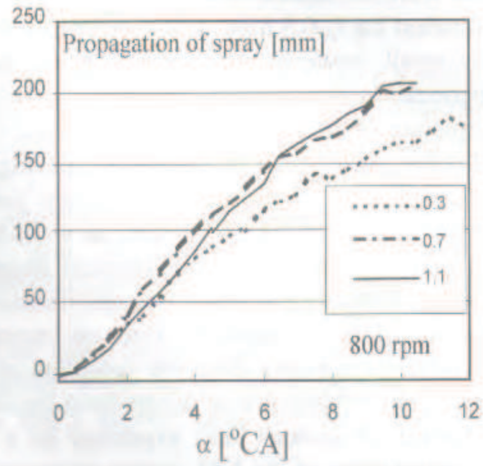


Fig. 5. Area of atomised fuel spray as a function of injection pump shaft speed for different nozzle hole length.
Rys. 5. Powierzchnia rozpylonej strugi w funkcji obrotu wału pompy wtryskowej dla różnych długości otworków rozpylacza.

The analysis in the second stage was performed on a basis of contour lines defined in the PatEV programme by use of the pixel HSL parameters. In such a way the considered fuel spray was divided into sub-areas respectively to the created contour lines. The set of contour lines obtained after completing the digital processing is shown on the example photo, presented in Figure 4, taken for the nozzle hole length of 0.3 mm. Straight lines frame the selected fuel spray. The contour lines are the lines, which result from the assumed classification of HSL parameters. The variation of total fuel spray area for the examined nozzles as a function of the rotation angle of the fuel injection pump shaft is presented in Figure 5. The spray area (A) was calculated as a sum of all pixels inside the contour ine. The results of measurements of the fuel spray penetration are shown in Figure 6.





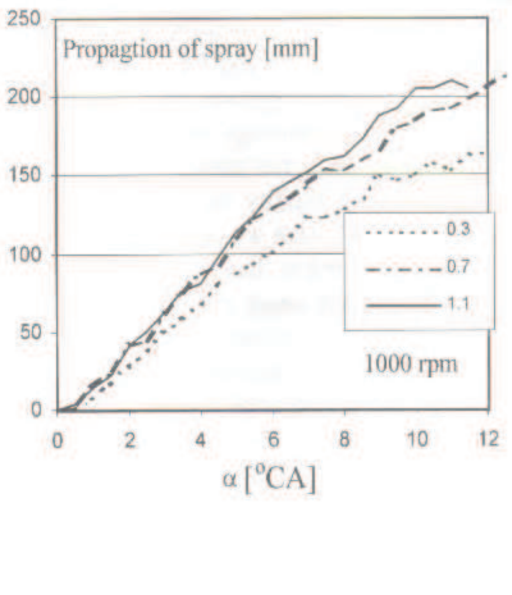


Fig. 6. Propagation of atomised fuel spray as a function of injection pump shaft speed for different nozzle hole length.

Fig. 6. Zasięgu rozpylonej strugi w funkcji obrotu wału pompy wtryskowej dla różnych długości otworków rozpylacza.

The total area of the atomised fuel spray is the largest for the nozzle tip with a hole length of l_o=0.3 mm as it results from Figure 5. In relation to other hole length the increase of area of the atomised spray at the end of the injection process is about 20%. Such dependence was noticed both for all speeds of the injection pump shaft and fuel charges, at which the investigations were performed.

For length of nozzle holes of 1.1 mm and 0.7 mm no unambiguous changes of the total spray area were noticed. This observation can be confirmed by the previous observations of the fuel sprays carried out for nozzle hole length of 0.9 and 0.5 mm, but they were carried out for another piece of nozzle, so they were not included in this paper. However, the relevant conclusions from those examinations were taken into consideration. Starting from l_o=0.5 mm the noticeable change of area was noticed.

The measured penetration of fuel spray is the greatest in case of a fuel spray flowing out from the nozzle with l_o=1.1 mm, and it is almost identical for l_o=0.7 mm but the smallest for l_o 0.3 mm. At the same time the decrease of the hole length is accompanied by small, however noticeable, increase of the jet angle. The fact, that the fuel spray penetration decreases as its total area increases proves changes, which occur in the structure of atomisation. The penetration of fuel spray depends on the kinetic energy of droplets, at the time when they are leaving nozzle hole, and on resisting force caused by the ambient condition. If the injection pressure is constant and by the same the initial velocity of a droplet is constant as well, the kinetic energy depends only on mass. For droplets having an almost spherical shape, mass is a function of the third power of diameter but the resisting force and friction works are the functions of the approximately second power of diameter. Thus, an increase of the area of spray and a decrease of the penetration informs about the reduction of diameter of droplet of the atomised fuel.

A similar conclusion results from the second stage of performed analysis. The values of areas of contour lines expressed by a number of pixels according to the assumed differentiation of the HSL vector are presented in Figure 7. The brightest element of the spray is located in its centre. When approaching the centre parts of the spray the recorded luminance decreases. The camera collects light, which is reflected by droplets of fuel. Since the fuel spray is being observed from „the outside" and the atomised fuel is distributed in a space similar to a circular cone, it becomes obvious, that the central part of the fuel spray must reflect most of light as the concentration of fuel in this region is the highest. The most outer contour line, marked with w6 is the darkest one.

Though, the video system itself does not provide any facility for taking a direct measurement of diameter of droplets, the evaluation of their size was carried out in the indirect way. For safety reason a tank, which fuel was injected to, has been connected to a fume cupboard owing to in the observed space appeared small (hardly noticeable) convection directed towards the tank bottom. The influence of convection on a fuel spray was clearly noticeable only for the hole length l_o=0.3 mm in a form of „a tail" of fuel droplets situating in a lower part of fuel spray. The effect of air convection is the greatest for the smallest droplets. Thus in a region of this contour line the droplets of the smallest diameter must be met. Therefore the area and shape of this contour line are the most essential for comparing the size of droplets. On a basis of such a comparison it can be admittedly concluded, that the best atomisation is obtained for l_o=0.3 mm.

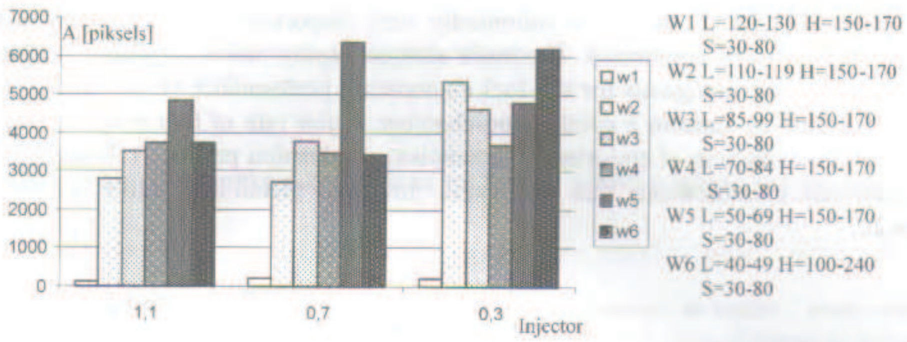


Fig. 7. The values of areas for individual contour lines.
Rys. 7. Wartości powierzchni dla poszczególnych warstwic.

This conclusion is supported by the analysis of luminance performed in a radial direction along the line perpendicular to the spray axis, as it is shown in Figure 8 for the selected case. In case of fuel spray from the nozzle with the hole length $l_o = 0.3$ mm the distribution of pixels of the similar values of L (Luminance) parameters is the most uniform and wide. There is no peak value of luminance for this case like the one which was observed for the hole length of 1.1 and 0.7 mm. The form of distribution allows to state, that there must be any relationship between brightening the spray and radial density distribution [2].

The presented analysis obtained by use of the video system allows to state that after reaching the certain threshold value the reduction of the nozzle hole length results in getting the spray which is wider and which has a shorter range and more uniform

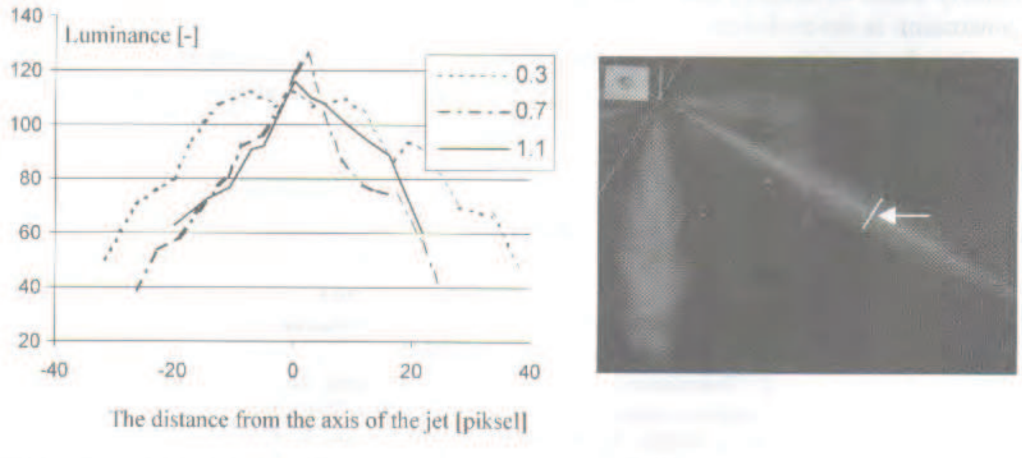


Fig. 8. The analysis of pixels luminance as a function of a distance from the spray axis, performed for a spray section distant by 300 pixel (e.q., see photos on right).
Rys. 8. Analiza jasności pikseli w zależności od odległości od osi strugi, wykonana w przekroju strugi odległym o 300 pikseli (przykład zdjęcia po prawej stronie).

distribution of mass of fuel. It is admittedly very important when preparing a fuel charge, which is to be combusted. The more atomised spray makes air easier get inside, and this is very advantageous for the fuel combustion performance (more similar local values of excess air ratio in a combustion chamber, better rate of fuel evaporation and, as a result, the reduction of emission of incomplete combustion products). It results from the performed measurements that the length threshold mentioned above appears for $l_o/d_o \approx 2$.

3. Conclusions

The analysis presented in this paper proves the usability of the visualisation method in the applied research on the atomised fuel structure. The obtained unambiguous determination of the atomisation quality should demand the discussed method to be confronted with the results of measurements of fuel spray droplets diameter and their velocities and with the results of the engine stand tests.

The visualisation method presented here can be used in order to perform the evaluation of the geometrical parameters of the fuel spray, namely its penetration and atomisation jet angle which important in case of the compression-ignition engines (ZS DI). At the same time this method offers some possibilities of the instant evaluation of the atomisation quality and selection of the right nozzle for the engine, if needed. The performed investigations proved the relation between the nozzle hole length and the atomisation. The best atomisation was obtained in case of the nozzle with a hole length of 0.3 mm. A short penetration, a large atomisation jet angle and the greatest area can characterize its fuel spray. In such situation it can be supposed, that in the discussed case small droplets of fuel are obtained since a small mass droplet moving in inertia medium quickly losses its velocity and — due to a significant loss of momentum — its attainable penetration is never distant.

On a basis of the performed investigations and their analyses it can be assumed, that there is a relation between the obtained video images of the atomised spray and its microstructure.

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Wpływ geometrii otworków rozpylacza na kształt strugi i jakość rozpylenia paliwa

Streszczenie

Artykuł przedstawia badania wpływu długości otworka rozpylającego na kształt i jakość rozpylenia paliwa. Zaprezentowano metodę badań wizualizacyjnych przebiegu wtrysku paliwa do specjalnie przygotowanej komory otwartej. Badania wykonano dla rozpylaczy wielootworkowych o różnych długościach otworków rozpylających. Na podstawie przeprowadzonych badań dokonano próby oceny jakości rozpylenia poprzez analizę parametrów strugi. Do analizy strugi wykorzystano program służący do cyfrowej obróbki obrazu uzyskanego podczas badań wizualizacyjnych.