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Experimental study of spray generated by a new type of injector with rotary swinging needle

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1. Introduction

Numerous papers have indicated that the present standard systems of injecting fuel directly into the combustion chamber, in the most economical, direct-injection diesel engines, have reached the limits of development. In order to maintain the emission of toxic components of exhaust gases within the ranges defined by both EURO V and projected EURO VI standards, various modifications to the combustion system will be necessary. It is known that injection through a conventional multi-hole nozzle, in combination with induced swirl in the air in the chamber, does not ensure that particulates and oxides of nitrogen are not formed. These toxic components are among the most difficult to subsequently remove from the exhaust gases (Hiroyasu & Arai, 1990; Peake, 1997; Kuszewski & Lejda, 2009). Effective limitation of NO_X and PM emission can be achieved by providing proper macro structure parameters of the spray. First of all, it is very important to distribute fuel effectively in the combustion chamber, considering the rotary motion of the air and the spray shape (Beck et al., 1988; Dürnholz & Krüger, 1997; Kollmann & Bargende, 1997). Next, a larger range of the spray front and apex angle of spray is needed (Kollmann & Bargende, 1997; Kuszewski & Lejda, 2009). Moreover, it is important to know the distribution of fuel in the spray, because then it is possible to select the correct rotary motion of the charge in the cylinder, which will guarantee as effective a mix of the air and the fuel as is possible. A fuel spray with a different macro structure might have an important effect on these processes; however it is necessary to use a different type of injector, a new type of construction and modus operandum (Varde and Popa, 1983; Kuszewski, 2002). The design for such a device forms the subject of this paper (Metz & Seika, 1998; Szlachta & Kuszewski, 2002; Szymański & Zabłocki, 1992). The special feature of the spray nozzle of this injector is the variability of the fuel-spraying holes during injection. The variability of the cross-sections of these holes is achieved by the rotary swinging movement of the needle (RSN injector). The results of investigations described below show that a spray generated by this injector design has macro-structural parameters that differ from those of a standard traditional injector.

2. The construction and principle of operation of an injector with rotary swinging needle movement

The construction of an injector with a rotary swinging needle movement is shown in Fig. 1. Fuel is supplied through a high-pressure tube to the upper part of the injector body. The fuel pressure acts on the working area 'b' of a piston, 7, joined by a pin, 13, to an injector needle driver, 14. This causes the driver to rotate simultaneously with the rotation of the needle, 17, which is joined to the driver.
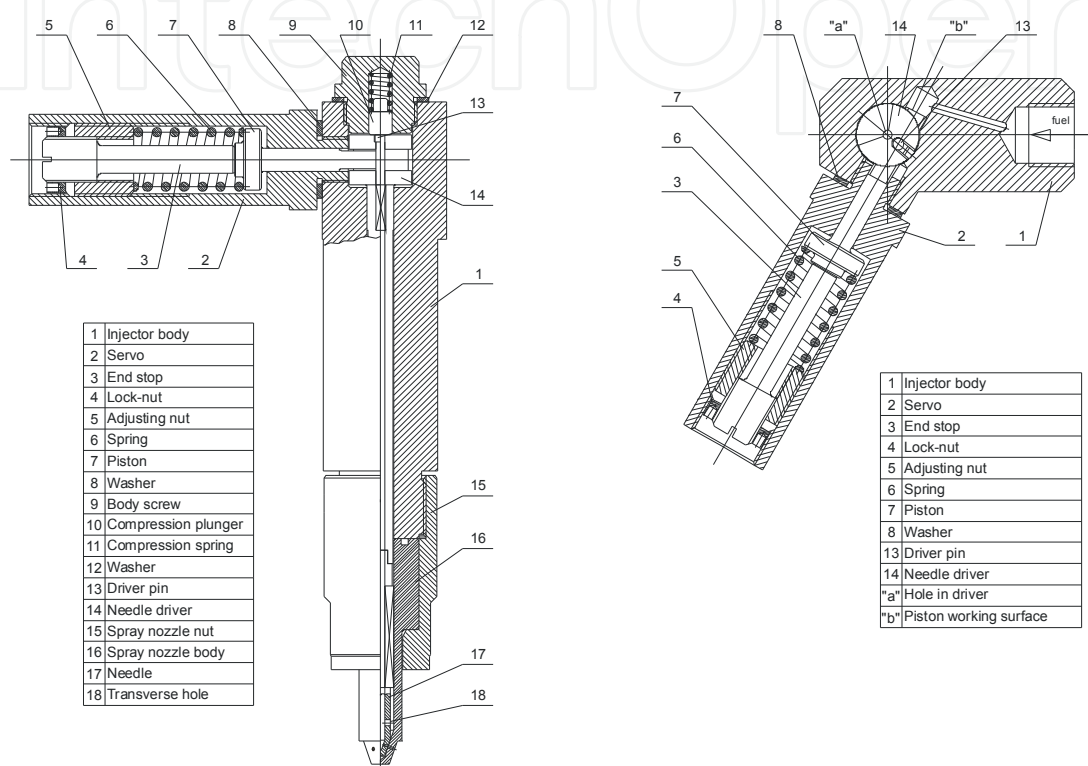

1	Injector body
2	Servo
3	End stop
4	Lock-nut
5	Adjusting nut
6	Spring
7	Piston
8	Washer
9	Body screw
10	Compression plunger
11	Compression spring
12	Washer
13	Driver pin
14	Needle driver
15	Spray nozzle nut
16	Spray nozzle body
17	Needle
18	Transverse hole

1	Injector body
2	Servo
3	End stop
4	Lock-nut
5	Adjusting nut
6	Spring
7	Piston
8	Washer
13	Driver pin
14	Needle driver
"a"	Hole in driver
"b"	Piston working surface

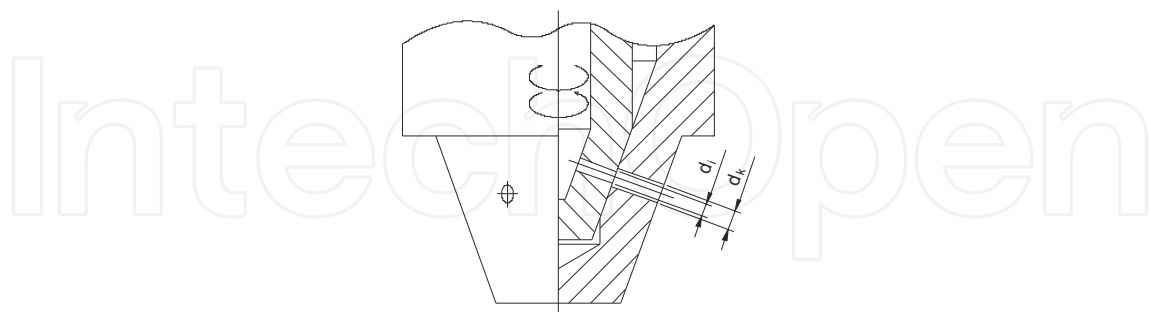Fig. 1. The construction of an RSN injector

Fig. 2. Magnified part of RSN spray nozzle, d_k: outlet hole diameter in the spray nozzle body; d_i: outlet hole diameter in the needle

Fuel flows to the needle through a hole 'a', in the needle driver and through a fissure between the driver and the injector body. From there the fuel flows through an axially-symmetrical hole in the needle, both to the holes in the needle (spraying holes) and in the injector body (outlet holes), on the cone side surface which seals the needle (Fig. 2). The release of fuel from the sprayer starts when the needle-performing a rotary swinging

movement-causes a misalignment of the spray and the outlet holes, so that they are momentarily occluded, resulting in a non-circular area of flow (Fig. 3). This area increases in proportion to the increasing angle of needle rotation. It should be mentioned that during the initial phase (low rotary angle), the needle has a 'dead' movement, which prevents increase of the flow area. The rotation of the needle in one direction continues so long as the axes of the spraying and outlet holes overlap. In this position, the piston of the driver rests on the end stop, 3, which acts as a regulatory element, limiting needle movement. The release of fuel causes a decrease in fuel pressure, which causes the spring, 6, to move the piston, 7 (moving in the servo, 2), screwed into the injector body, until it reaches a position corresponding to the closure of the injector. During this movement the flow area from the injector decreases to zero. The unique feature which distinguishes the new construction from the standard construction is that fuel flows out through a non-circular area, quasi-lenticular in shape, during the beginning and end phases of injection. During injection, fuel is throttled only in this non-circular area.
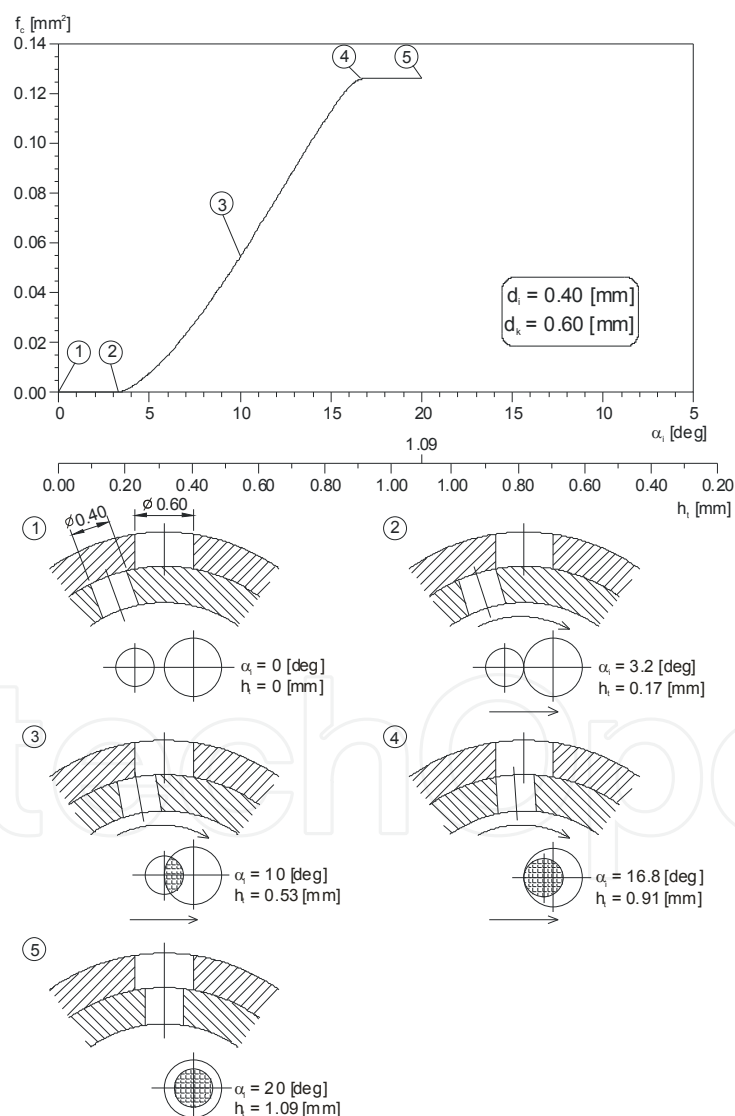

Fig. 3. The diagram of outlet hole in the spray nozzle body and outlet hole in the needle position and growing of geometrical flow area, f_c: geometrical flow area; α_i: angle of needle rotation (part 17 on Figure 1); h_t: piston stroke (part 7 on Figure 1).

3. Method of investigations

The parameters of the macrostructure of the stream of sprayed fuel were determined on the basis of measurements carried out using specially constructed equipment, which enabled both the direct observation of the development of the spray during the fuel injection to a chamber of fixed volume (Metz & Seika, 1998; Szlachta & Kuszewski, 2002; Szymański & Zabłocki, 1992) and the measurement of the fuel distribution within the spray of droplets. The scheme of test stand for visual studies is shown in Fig. 4.
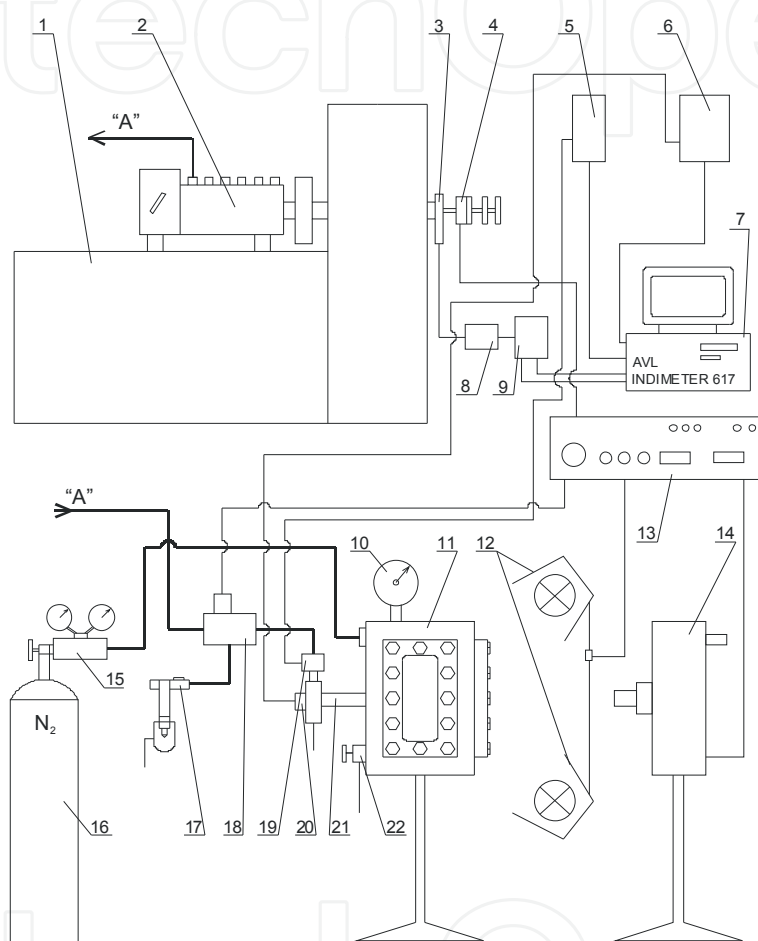
Fig. 4. Scheme of test stand for visual studies, 1: test bench Hansmann EFH 5008; 2: injection pump P56-01; 3: position and rotational speed sensor of pump shaft AVL; 4: synchronizing plates; 5: charge amplifiers AVL 3056; 6: tensometric bridge; 7: computer with data acquisition device for high-speed courses recording AVL Indimeter 617; 8: signals decoder; 9: feeder; 10: manometer; 11: visualization chamber of constant volume; 12: lights; 13: driver of high-speed camera; 14: high-speed camera; 15: pressure regulator with manometers; 16: nitrogen cylinder; 17: auxiliary injector; 18: switching valve; 19: piezoquartz pressure sensor AVL 5QP6002; 20: inductive position sensor of injector piston (or needle); 21: tested injector; 22: release valve

The essential elements of test stand were: visualization chamber of constant volume, where a fuel was injected by using tested injector, 21, test bench ,1, injection pump, 2, for pumping the fuel to injector, the high-speed camera, 14, with driver, 13, and the computer with data

acquisition devices for high-speed courses recording 7. Inside the chamber to which fuel was injected, there was fixed backpressure verified with manometer, 10. For safety reasons, gas filling the chamber was nitrogen, passed from the cylinder 16. The fuel for tested injector, 21, was supplied from the injection pump, 2, driven by an electric motor of test bench, 1. Switching valve, 18, referred fuel from injection pump to the tested injector, 21, (at the time of visualization test of stream development) or to the auxiliary injector, 17, (in the intervals between fundamental tests). To record of fuel stream images, it was necessary to synchronize the work of high-speed camera, 14, the test bench, 1, the lights, 12, and switching valve, 18. It was obtained using a special camera driver, 13, co-operating with synchronizing plates, 4, fixed to the driving shaft of the test bench engine. Additionally, during work of the high-speed camera, using piezoquartz pressure sensor, 19, the values of pressure before the injector were recorded. Furthermore, using inductive position sensor, 20, it was recorded displacement of injector needle (or a piston in the injector of new type) and using an optical rotation speed sensor, 3, – it was recorded rotational speed of injection pump camshaft. The record of these parameters was possible thanks to the computer, 7, with a special data acquisition device. The stream images were recorded at a speed of 5000 fps. The successive images of a developing fuel stream were recorded every 0.0002 s (0.2 ms). Next, the films of width 16 mm were scanning and digital images were analyzed using a computer.
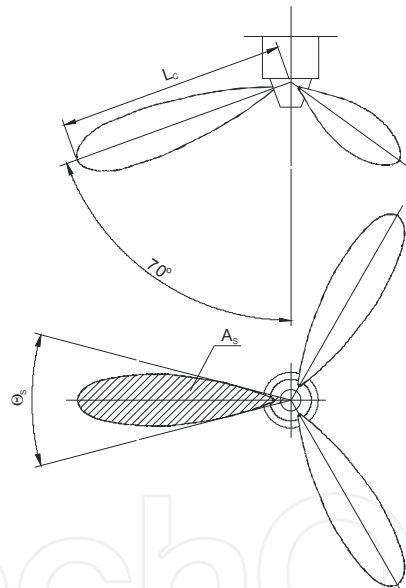

Fig. 5. The method of determining the values of the parameters of the fuel spray, L_C: range of the spray front; Θ_S: apex angle of the spray; A_S: area of the spray projection in a plane perpendicular to the injector axis

The visual studies enabled the following to be analysed: the range of the spray front – L_C, the apex angle of the spray – Θ_S, and the area of the spray projection in a plane perpendicular to the injector axis – A_S. The last criterion of the spray macrostructure estimation was introduced because of the irregular shape of the spray generated by the RSN injector. The method of determination of the values of the analysed parameters of the spray of injected fuel is depicted in Fig. 5. A standard injector with a D1LMK 140/M2 pattern sprayer, and the new RSN injector were compared. Both sprayers had three outlet holes, the diameter of the holes in the standard injector body and the RSN type being equal.
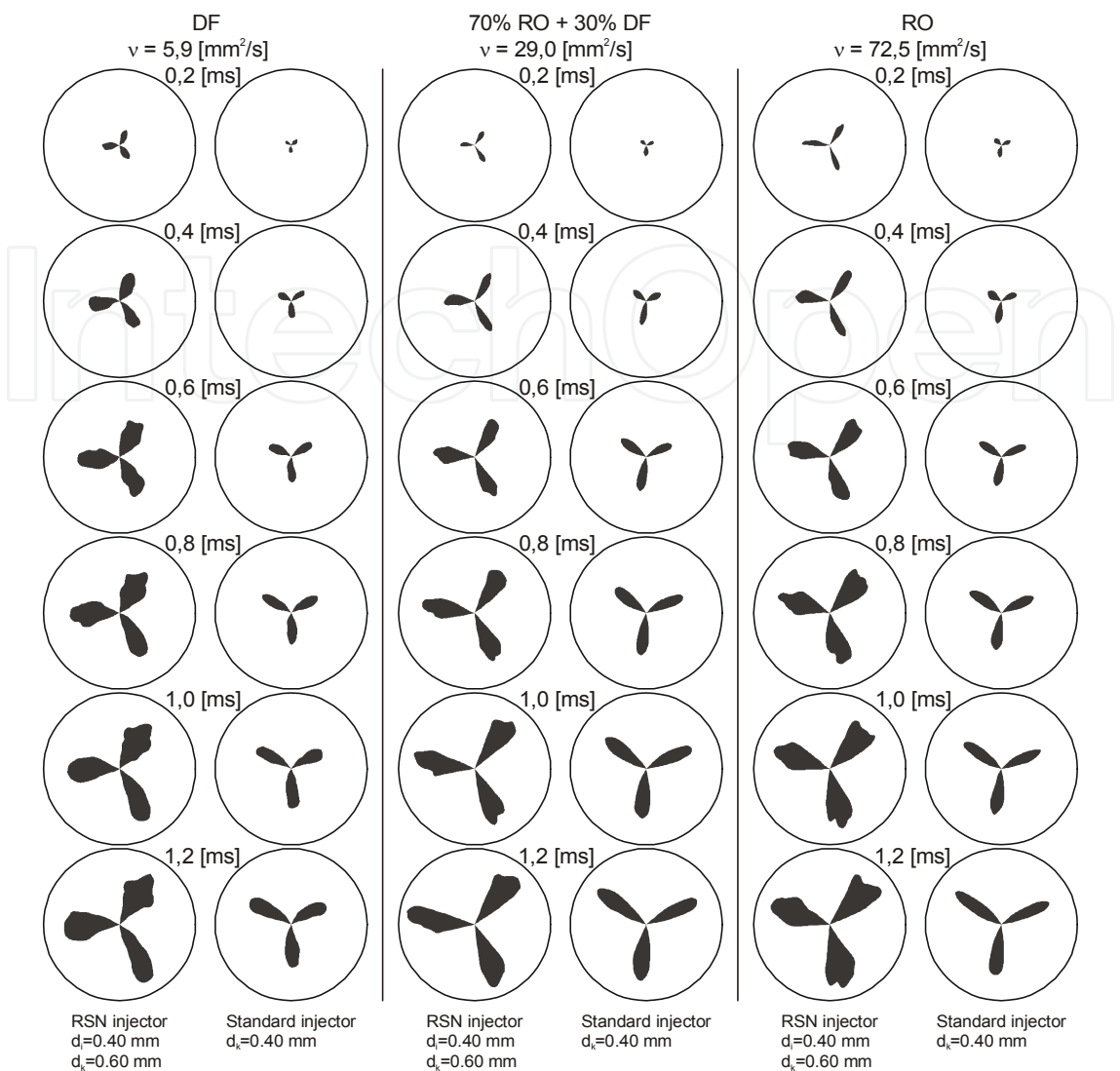
Fig. 6. Pictures of fuel spray propagation obtained at use three-hole spray nozzle with rotary swinging needle movement and standard (p_o = 170 bar, p_b = 20 bar, q = 130 mm³/injection, n_p = 600 rpm, fuel: DF, 70% RO + 30% DF, RO), d_k: outlet hole diameter in the spray nozzle body; d_i: outlet hole diameter in the needle; v: kinematic viscosity; DF: diesel fuel; RO: rape oil

In Fig. 6 the pictures of fuel spray propagation obtained at use three-hole spray nozzle with rotary swinging needle movement and standard are shown. From the figure 6 it is clear that the spray generated by injector with rotary swinging movement of the needle is developing in a different way than in the standard nozzle. It causes differences in values of used parameters to assess the macrostructure of fuel spray. In particular it is clear, that the spray forming by injector with a rotary swinging needle movement is irregular in shape, and its area (area of the spray projection in a plane perpendicular to the injector axis), the apex angle of the spray and the front range are usually significantly higher compared to the classical sprayer. Particularly noteworthy are the results presented in Figure 6 concerning rape oil, which is characterized by a high value of kinematic viscosity (v = 72.5 mm²/s). As we can see, the area occupied by rape oil spray from the RSN needle movement is much larger than achieved for classical sprayer.

4. The range of the spray front

In both injectors the following values were set, being the same for each type: line pressure at the opening of the sprayer p_o = 170 bar, fuel dose q = 130 mm³/injection and rotary velocity of the camshaft of the injection pump n_p = 600 rpm. Fuels of different viscosity (Diesel Fuel (DF), Rape Oil (RO), and 70/30 RO/DF mixture), were injected into the observation chamber, which was filled with nitrogen at pressures of 15, 20, and 25 bar. During all investigations of the range of the spray front, the apex angle and surface area of the spray, a time scale of 0–1.4 ms was chosen. Beyond this range, for some injection parameters, the spray front reached the walls of the observation chamber. The range of the spray front for DF, formed by the RSN sprayer under various values of the background pressure in the observation chamber, is presented in Fig. 7. For RSN injector, it can be seen that an increase of nitrogen pressure in the observation chamber caused – as was expected – a reduction in the range of the spray front. This phenomenon is characteristic of standard sprayers, and may be ascribed to the effect of the aerodynamic resistance on droplets of variable size. An increase in the background pressure (gas density), causes an increase in aerodynamic resistance, and reduced dynamic pressure of the gas into which the injection is made, creating adverse conditions for the disintegration of secondary droplets. Therefore, larger droplets with greater penetrative capability are formed (obviously a larger droplet has greater kinetic energy and will therefore travel further).
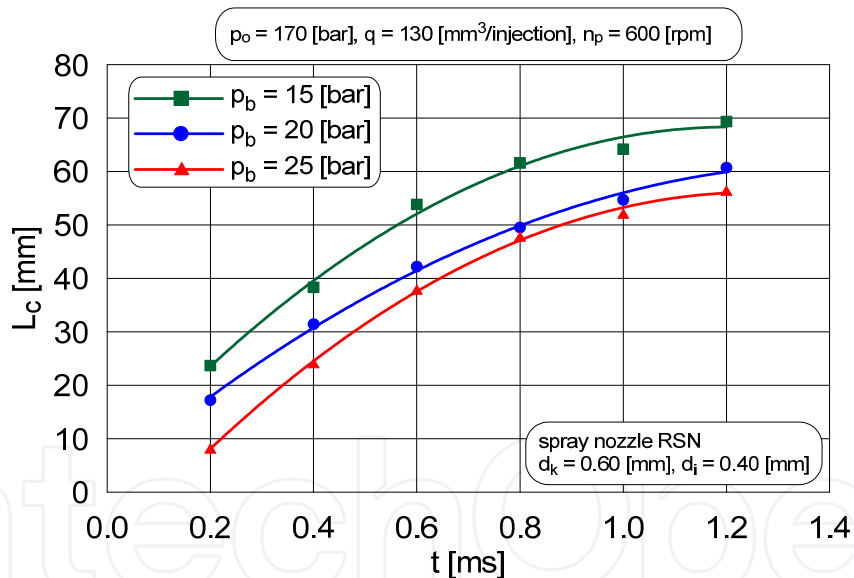
Fig. 7. The range of the Diesel Fuel spray front formed by the RSN type, at various background pressures in the observation chamber

The greatest range of the front of the DF spray formed by both the standard injector (Fig. 8) and the RSN injector, was observed at p_b = 15 bar. However, at p_b = 20 bar, the range of the front was less than at p_b = 25 bar. Most probably this was because during the analysed (single) injection, at p_b = 25 bar, the initial velocity of fuel at the sprayer outlet was higher than that at p_b = 20 bar. This was caused by the greater difference between the line pressure and the pressure in the observation chamber. Therefore, the greater kinetic energy of the spray at p_b = 25 bar, had a stronger influence on the movement of the front of the spray than the enhanced aerodynamic resistance of the environment. A comparison of Fig. 7 and 8

shows that, generally, the range of the front of the spray generated by the RSN sprayer is greater than that of the standard injector.
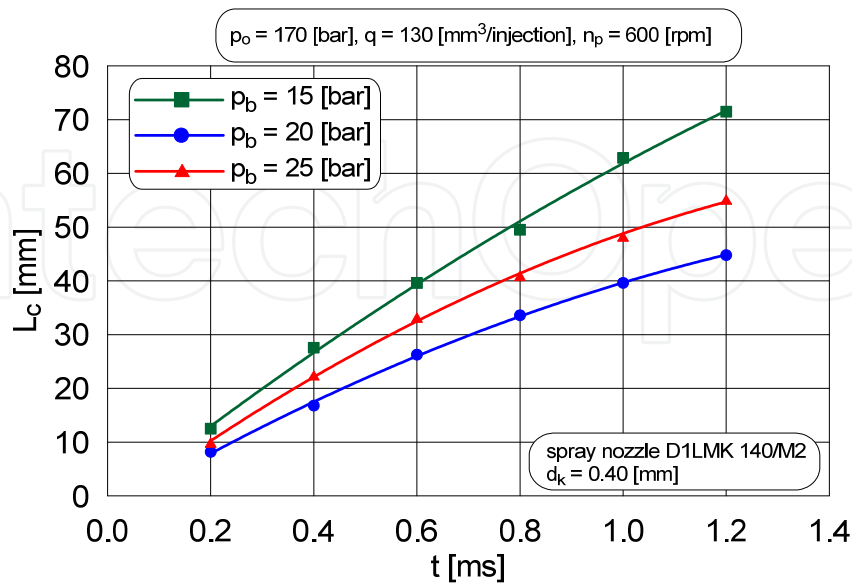

Fig. 8. The range of the Diesel Fuel spray front formed by the standard injector, at various background pressures in the observation chamber
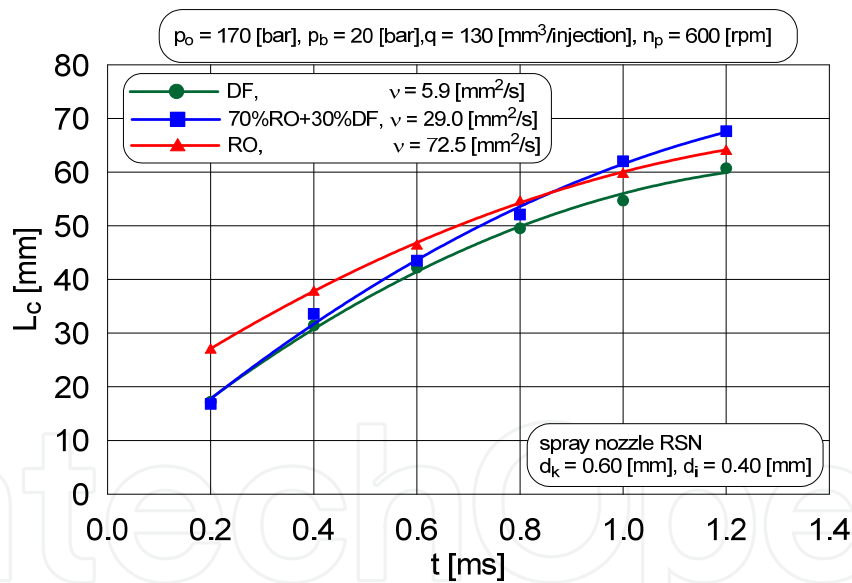

Fig. 9. The range of the front of the spray, formed by the RSN injector for fuels differing in physical properties

As could be expected, the use of fuels of considerably greater viscosity affected both types of injectors by considerably increasing the injection pressures. This was caused by a reduction in the value of the index of fuel outflow from the sprayer holes. These changes were the main contributors to the increased spray front range for fuels of increased viscosity (RO – $v = 72.5$ mm²/s; 70/30 RO/DF – $v = 29.0$ mm²/s), in relation to (DF – $v = 5.9$ mm²/s) – see Figures 9 and 10. An additional reason for the increased range of the spray front when using higher viscosity fuels (observed for both types of injectors), was probably due to the increase in droplet size, when conditions conducive to their disintegration became worse.

From a comparison of Fig. 9 and 10, it may be seen that – as in the case of DF – the spray range of other fuels was greater for the RSN injector over the entire time of spray development.
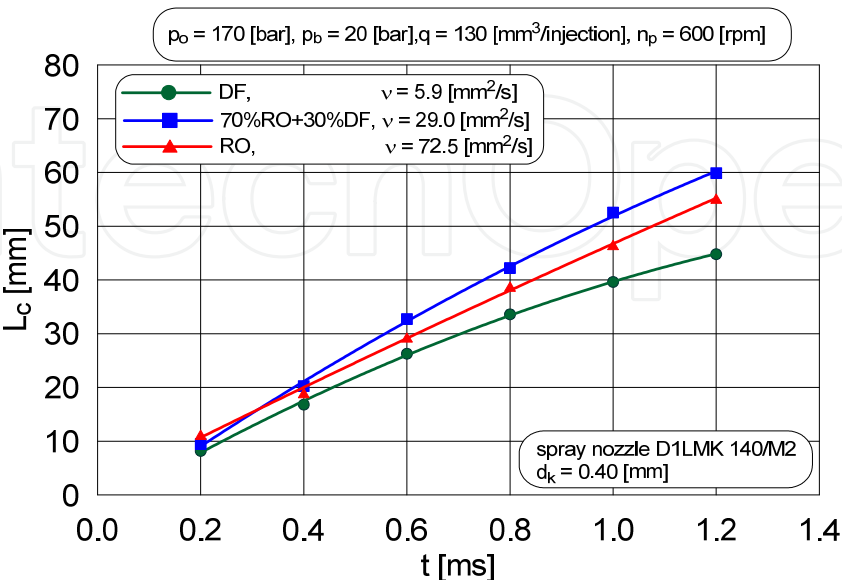

Fig. 10. The range of the front of the spray, formed by the classical injector for fuels differing in physical properties

5. The apex angle and surface area of the spray

In Fig. 11 it may be seen that, in the case of the RSN sprayer, a change in background pressure did not significantly affect the values of the apex angles of the spray over the whole period of its development. However, the spray surface area varied, the greatest area being observed for p_b = 15 bar, i.e., at the background pressure at which the range of the spray was greatest.

Conversely, in the case of the standard injector, the effect of p_b on the apex angle Θ_S was more visible – cp. Fig. 12. As could be expected, the largest apex angles occurred at maximum background pressure. The values of the apex angles of the spray diminished during its development, i.e., the penetration of the spray in a direction perpendicular to its axis was reduced; this has a negative effect on mixing. It may be only partly compensated by the fact that the spray surface area increases with its development. The smallest surface area of the spray was recorded during the intermediate background pressure, p_b = 20 bar, i.e., for a value corresponding to the shortest range of the spray front.

From a comparison of Fig. 11 and 12 it will be seen that the values A_S, achieved by the RSN injector, were greater than for the standard injector. It may also indicate the superior properties of the spray from the RSN injector, due to improved air/fuel mixing processes. The larger area of the spray allows distribution of the fuel around the combustion chamber of DI engine much effectively. In this case it is possible to reduce a rotary motion of the charge. Too strong rotary motion of the charge can lead to sprays overlapping and can cause the coalescence of fuel drops. It is unfavourable on account of PM formation.
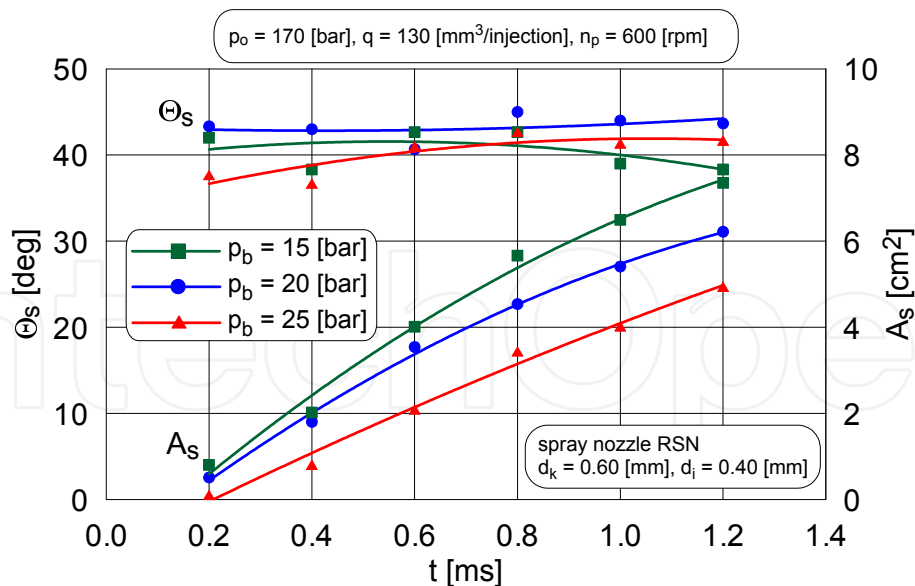
Fig. 11. The apex angle and surface area of the spray formed by the RSN type at various background pressures levels
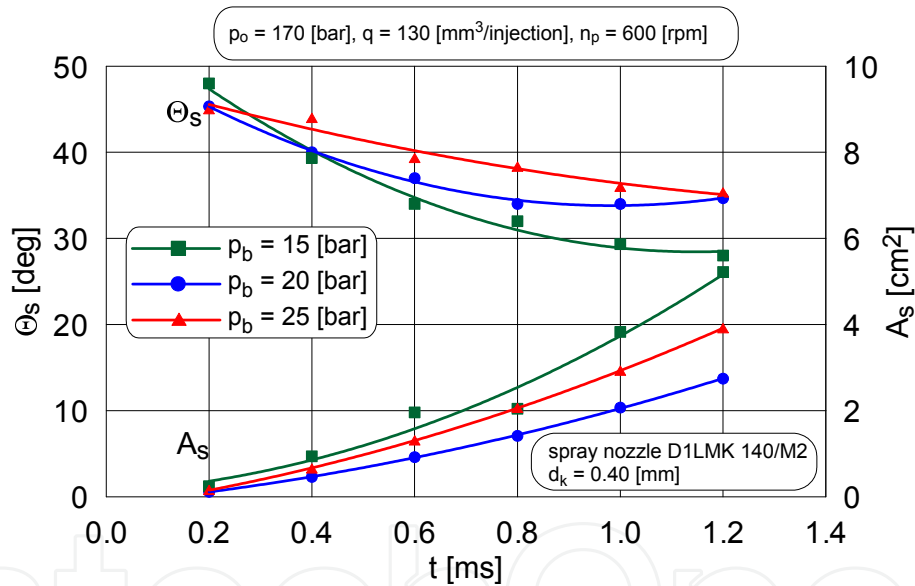

Fig. 12. The apex angle and surface area of the spray formed by the classical injector at various background pressures levels

The application of fuels with increased kinematic viscosity had little effect on the surface area of the spray, A_S (Fig. 13 and 14). At the same time, it may be noted that the dimensions of this area are much greater for the RSN-type than for the standard injector.

The value of the spray angles generated by the standard injector decreased inversely as the sprays developed. The value of the angle was virtually independent of the type of fuel used. On the other hand, in the case of the RSN sprayer, the apex angle of the spray was dependent not only on the time of the spray development, but also on the type of fuel. It is significant that the largest values of these angles were found in fuels with the lowest viscosities and surface tension (DF). They did not change during the spray development period. It is very likely that the smaller drops deviated more acutely towards outside the
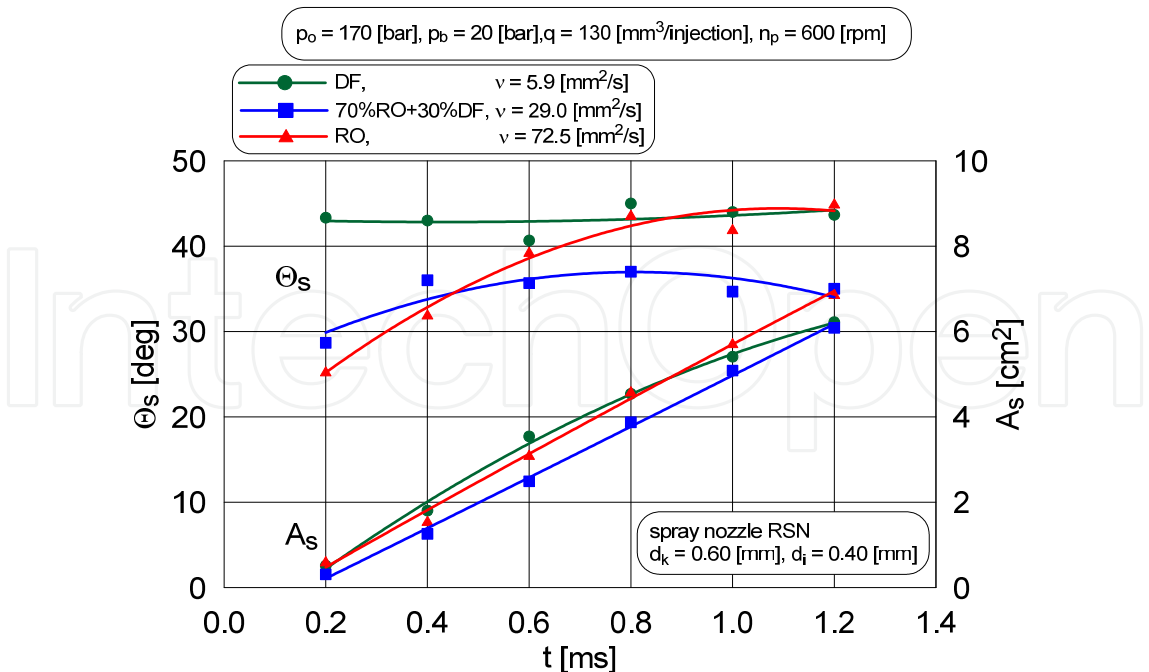
Fig. 13. Apex angle and surface area of spray formed by the RSN model when spraying fuels differing in physical properties
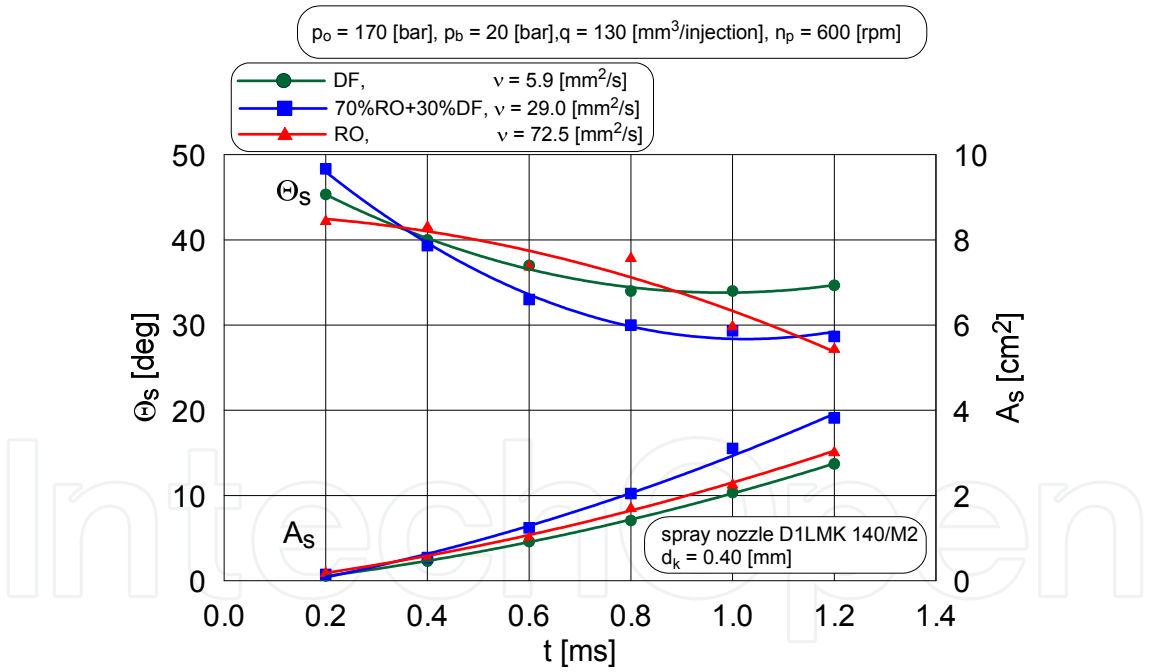

Fig. 14. Apex angle and surface area of spray formed by the standard injector, spraying fuels with different physical properties

spray. RO, with the highest viscosity, behaved differently. The apex angle of the spray increased steadily, and for time t = 1.2 ms (the end of the analysed fuel injection), it was greater than for DF. Presumably, in this case the apex angle of the spray resulted from the additional factor which increased the turbulence of outflow from the sprayer, caused by the variability of cross-sections of the spraying holes, and the resulting permanent change in the ratio of the length of the outlet hole to its sectional area.
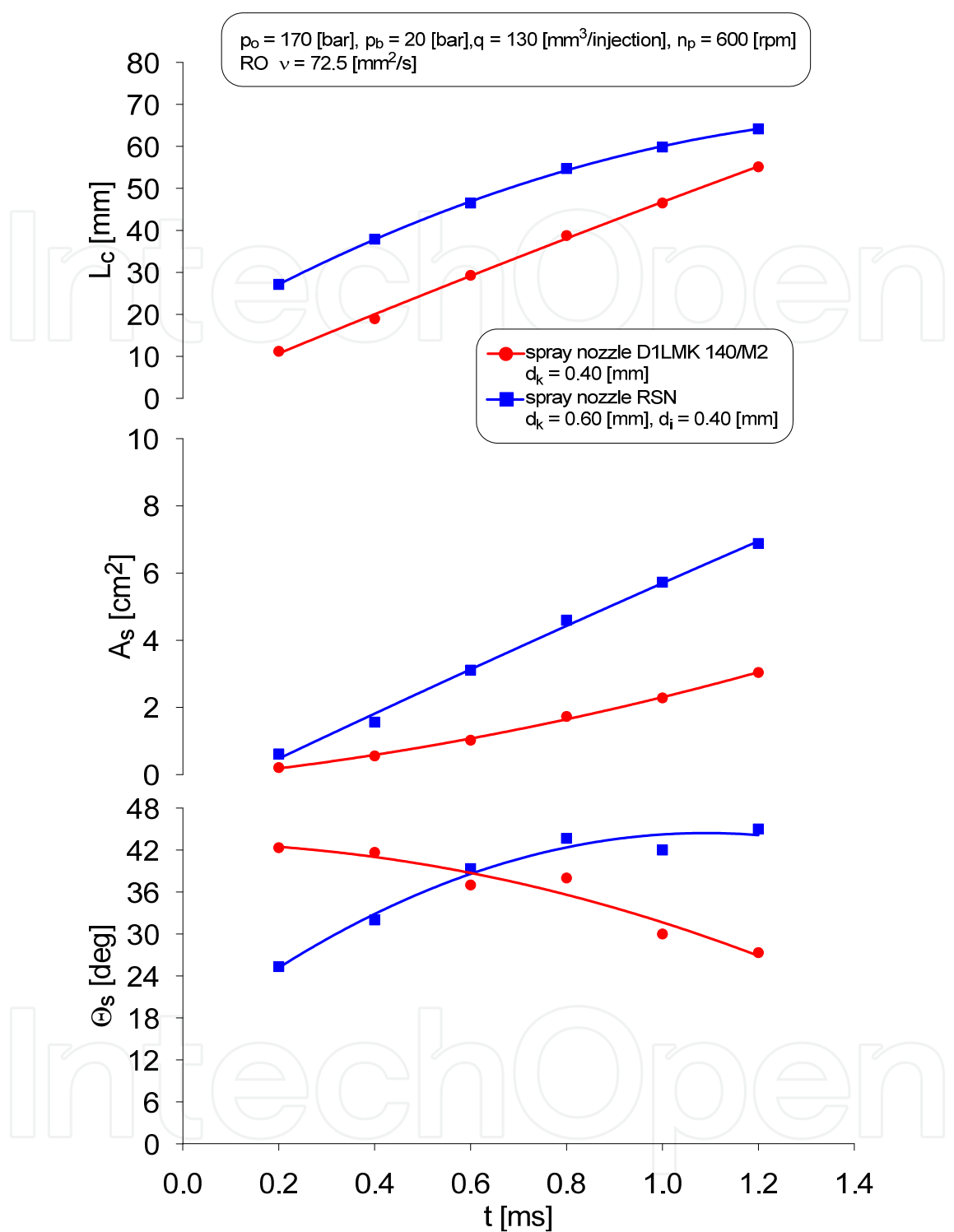
Fig. 15. The comparison of the apex angle, surface area, and the front-range of the spray generated by the classical injector and the RSN type when spraying RO

In Fig. 15, an additional comparison of the surface area, apex angle and range of the spray front for a spray of RO through a triple-hole standard injector and the RSN injector type, is depicted. The studies were carried out at p_b = 20 bar and a line pressure at injector opening p_o = 170 bar. The fuel dose was set at q = 130 mm³/injection, and the rotary velocity of the

camshaft of the injection pump was $n_p = 600$ rpm. Despite the fact that smaller values of injection pressures were noted for the RSN injector ($p_{wmax} = 300$ bar, $p_{wav} = 189$ bar, and for the classical injector 376 bar and 236 bar, respectively), the surface area and range of the spray front were much greater in this case. Only the apex angle of the spray in the initial phase of the injection had a lower value for the spray generated by this injector (RSN type). Later in the cycle, however, this angle increased rapidly and at the end of the analysed period of spray development, the angle was greater by about 18 deg. Greater values of the parameters A_S, Θ_S, and L_C for the RSN injector probably resulted not only from the lack of throttling of the fuel flow in the needle seat, but also from the mechanical action of the outlet holes in the spray nozzle on the spray.

6. Radial distribution of fuel in spray drops generated by standard and RSN injectors

Investigations of fuel distribution were carried out using both injectors in a spray of droplets, at a constant injection pump speed of $n_p = 600$ rpm. The fuel dose was adjusted to 130 mm^3/injection and the line pressure at the injector was $p_o = 170$ bar. Fuel was injected into a background atmospheric of $p_b = 1$ bar; the fuel level H_p in the measuring vessels was read after each 1000-cycle period. The radial distribution of fuel in a spray was measured by directing the sprayed fuel into a series of standing measuring vessels. The inlet openings of the vessels were perpendicular to the axis of the spraying hole. Fuel distribution in a spray was investigated by placing the inlets of the measuring vessels at several distances from the edge of the inlet hole of the sprayer body – S_r. These were: 75, 150 and 210 mm. In addition, for each distance, the series of vessels was rotated by 45 deg, which enabled determination of the fuel distribution in four planes, mutually inclined at angles of 45 deg. Fig. 17 and 18 have the following legend: 'Position 90 deg', denoting the axis '–x + x' and the axis of a sprayer in one plane. 'Position 45 deg' denotes that the series of vessels had been turned through 45 deg in relation to position 90 deg.
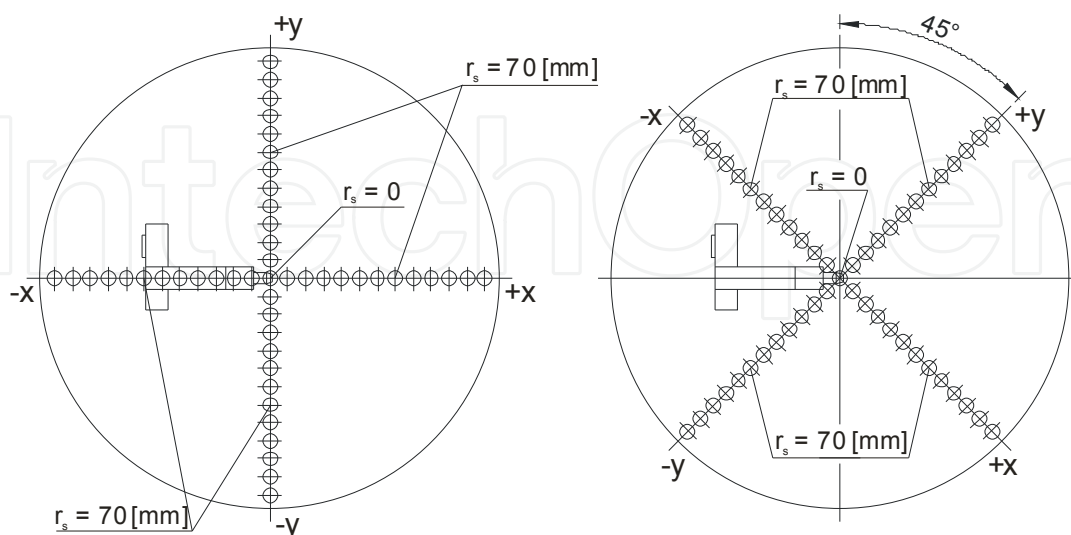

Fig. 16. A series of cylindrical measuring vessels used in determining fuel distribution in a spray of drops (top view)

The height of fuel in the measuring vessels was adopted (denoted by H_p) as a comparative measure to ascertain the fuel distribution in a spray of droplets. A radius at which a chosen fuel column was located, i.e., the radial distance from the theoretical axis of a spray, was denoted by r_s (Fig. 16). 'Direction x' and 'direction y' (legends on figures), denote vessels placed on the '–x + x' and '–y + y' axes, respectively, in Fig. 16.

Similar to the case of the direct observation studies – the standard injector with a D1LMK 140/M2 sprayer, and the new type injector – denoted as RSN, were studied.
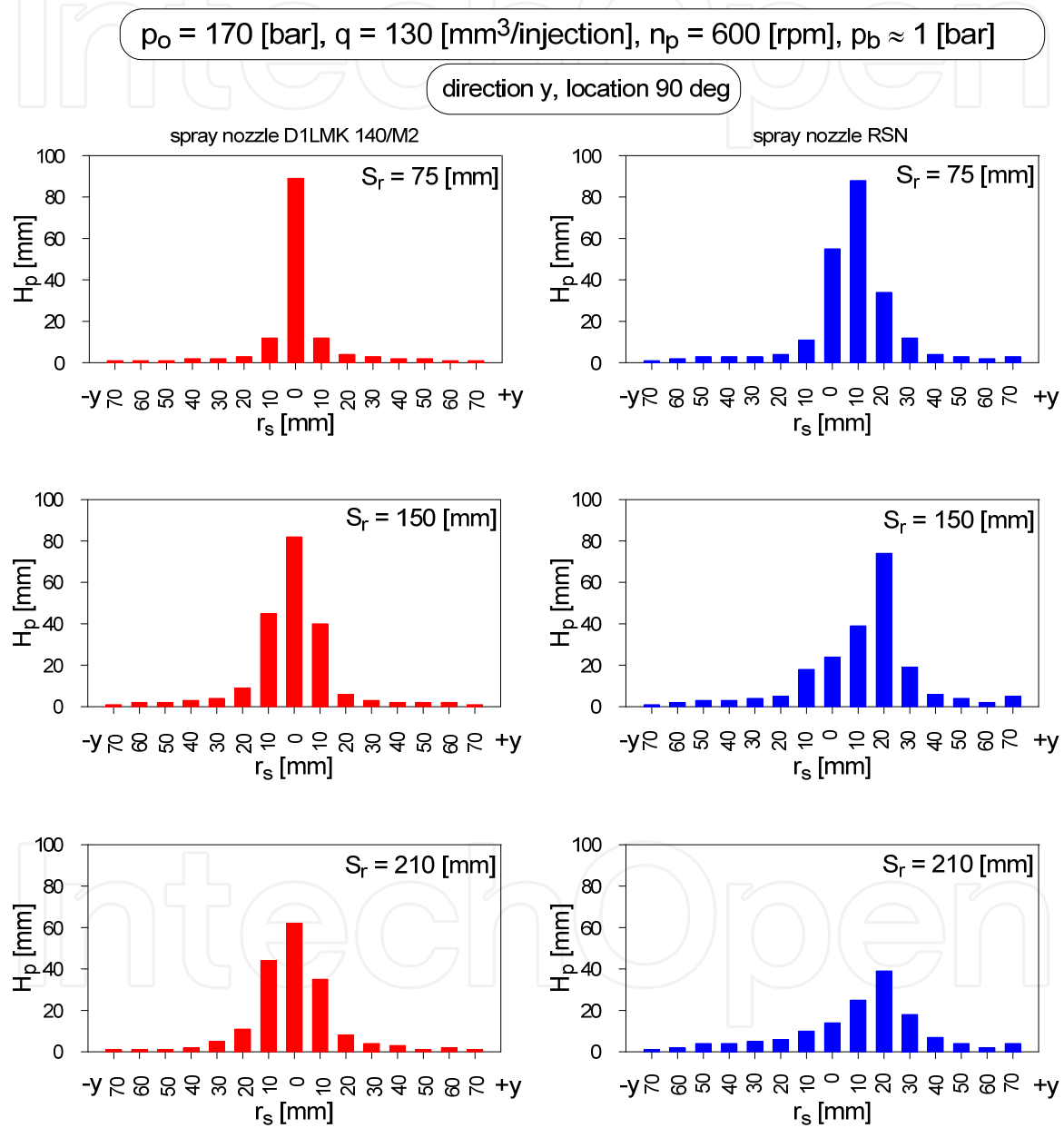

Fig. 17. Comparison of the radial distribution of fuel in a spray in the 'y' direction for the standard injector and the RSN type

Using histograms, Fig. 17 and 18 show the results of studies of the radial distribution of fuel in a spray of drops, formed by the standard injector (D1LMK 140/M2) and the RSN type. For simplicity, particular values of the radius r_s are plotted against the measured heights of fuel columns in the measuring vessels, H_p, rather than the related values of the spray density.

As seen in the standard injector, the usual situation prevailed, and the highest concentration of fuel lay at the core of the spray, i.e., the density of a unit spray has a maximum value at the spray axis, where large diameter droplets are most numerous, as stated earlier. A characteristic feature of fuel distribution in the standard spray is its symmetry around the spray axis (the axis in line with the axis of symmetry of the outlet hole), and the levelling off of the distribution as the distance from the sprayer increases (H_p values diminish in the centre and increase slightly towards the outside).

$p_O = 170$ [bar], $q = 130$ [mm^3/injection], $n_p = 600$ [rpm], $p_b \approx 1$ [bar]

direction x, location 45 deg

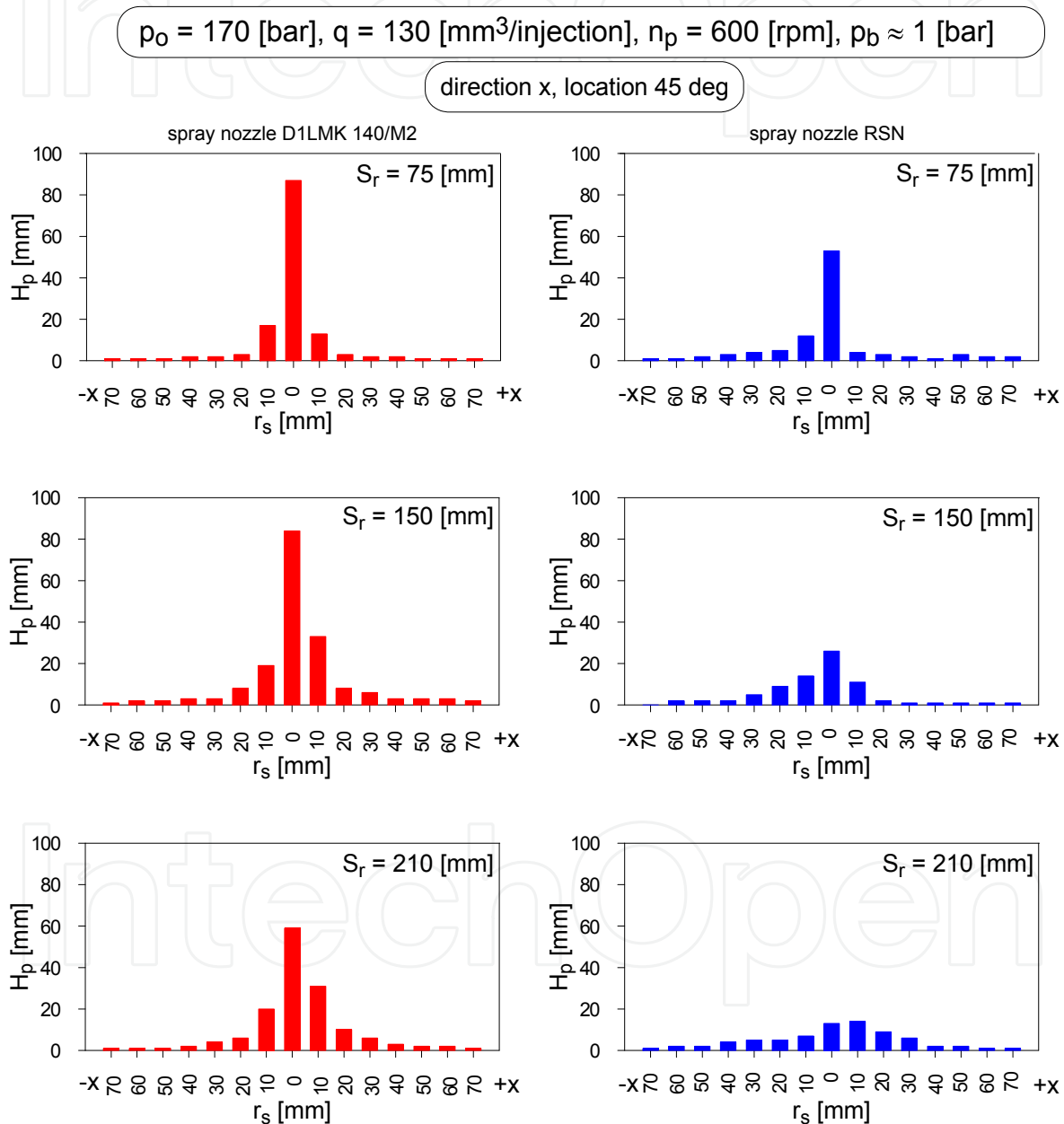spray nozzle D1LMK 140/M2   spray nozzle RSN

Fig. 18. Comparison of the radial distribution of fuel in a spray in the 'x' direction for the standard injector and the RSN type

The levelling off of the fuel distribution in a spray as the distance from the sprayer increases is caused by the size reduction of the droplets and the damping of their movement. Additionally, the turbulent movements in a spray tend to carry fuel towards the outer layers

of the spray, and the distribution becomes more equal (Metz and Seika, 1998). This phenomenon is related to the fuel movement in the later phase of injection and it is also observed in the spray formed by the RSN-type injector. The levelling off of the fuel distribution with increased distance from the sprayer seems to be a phenomenon shared among sprays generated by both injector types.

A spray of fuel generated by the RSN sprayer shows asymmetry; the distribution in the 'x' direction differs from that in the 'y' direction. In the 'y' direction particularly, the concentration of fuel is considerably larger (also when the series of vessels is rotated through 45 deg). Moreover, in the 'y' direction a greater shift of the area of the maximum fuel concentration (core of a spray) may be observed in comparison to the 'x' direction. This leads to the conclusion that the fuel distribution in the spray formed by the RSN sprayer does not show any symmetry in relation to the theoretical axis of the spray.

The largest shift of the spray core from the theoretical axis for the RSN sprayer was observed in the 'y' direction. This effect appeared when the axis of the sprayer was in one plane with the axis at –x + x. In this position the axis of the needle rotation was perpendicular to the 'y' direction. The asymmetry of the core of the spray generated by the RSN sprayer may be explained by the change of the cross-sections of the outlet holes and the resulting mechanical action of the surface of the hole in the sprayer body on the fuel being discharged. The fuel, flowing through the spraying hole (particularly in the opening phase), hit the surface of the outlet hole. This changed the direction of the flow, which caused variations in the position of the core in the cross-section of the spray.

The spray generated by standard injector is axially symmetric. More fuel saturation in the spray core causes a different value of combustion air factor. This is unfavourable, because soot is usually produced in the rich mixture area (local deficiency of air) at a sufficiently high temperature (800–1400 K). This happens mainly in the core of the fuel spray and at its rear, where the concentration of fuel droplets is often higher.

Executed investigations of radial distribution of fuel in spray confirm that the spray generated by RSN injector is not symmetrical. The shift of the spray core outside (as effect of needle rotary) can be favourable on account of the possibly stronger impact of gas medium on spray zone, where the concentration of the fuel is higher. In this case, the secondary drop break-up will be more intensive. Smaller diameters of drops are obviously favourable with regard to soot and PM formation.

7. Conclusions

The parameters of the injection system have a decisive effect on the rate of combustion in the diesel engine, because of the influence on quality of formed air-fuel mixture. However, the optimal macrostructure of the spray, which is distributed in the cylinder volume, depends on the type and construction of the injector. On braking, the fuel stream in drops increases the area of contact between the fuel and air. It causes, first of all, fuel vaporisation and, then, its diffusion into air. The pressure energy generated by the injection system is consumed on spraying of the fuel stream which, together with the phenomena of physical and chemical parts of self-ignition delay, leads to fast increase in mixture entropy.

A better quality of fuel spraying guarantees RSN injector, which was confirmed by model investigations. The selected results have been presented in the paper.

The results of these investigations show that fuel sprays formed by using a RSN type injector differ from those generated by a standard injector. In particular, the parameters analysed, i.e., the range of the spray-front, the apex angle of the spray and its surface area, reach greater values for a spray formed by the new RSN type of sprayer; this may positively affect the ecological impact as well as the performance of engines fitted with injectors of this type.

Variation in the conditions of injection (pressure changes in the gaseous medium into which fuel is injected, change due to use of fuels of differing viscosity), affects the macrostructure of sprays generated differently by each type of injector. The best example may be the variance in the apex angle of the spray while spraying RO. In the standard injector, it was found that this angle diminished as the spray developed, while in the RSN injector the opposite tendency was observed.

The investigations of fuel distribution in a spray of droplets confirm that the spray generated by the RSN-type injector develops in a different way from that generated by the standard injector. In particular, the results of these studies show the asymmetry of the spray formed by the new type of injector.

More favourable parameters of the macrostructure of the spray generated by the RSN injector allow the air-fuel mixture to burn more completely. Next, it provides reducing of emission of toxic components from exhaust gases. However, for using a new type of injector, modification of the combustion chamber is needed. This modification has to consider higher values of spray macrostructure parameters. For example, a confirmed larger range of the spray formed by a new type of injector can be served. At injection into the combustion chamber without modification, the spray can settle on the walls of combustion chamber which can cause increase in PM emission. The authors conducted investigations in this range and intend to publish them in the subsequent papers.

8. Nomenclature

The Table 1 shows the parameters for the atomization of fuel, which were used in the study. Additionally, there are used description of parameters, if required.

Quantity	Unit	Specification
A_S	[cm²]	Surface of view of fuel spray on perpendicular plane to spray nozzle axis
L_C	[mm]	Tip penetration of fuel spray
Θ_S	[deg]	Apex angle of fuel spray
H_p	[mm]	Fuel level (at measuring of the fuel radial distribution in a spray)
S_r	[mm]	Distance of an inlet area of the measuring vessel from the edge of outlet hole in spray nozzle body (measuring fuel radial distribution in a spray)
r_s	[mm]	Distance measuring point from the theoretical axis spray (measuring fuel radial distribution in a spray)
d_k	[mm]	Outlet hole diameter in a needle
d_i	[mm]	Outlet hole diameter in a spray nozzle body

Table 1. Description of parameters used in the study

The continuation of Table 1

Quantity	Unit	Specification
h_t	[mm]	Piston stroke of injector
α_i	[deg]	Angle of needle rotation
f_c	[mm²]	Geometrical flow area
q	[mm³/injection]	Fuel dose
t	[ms]	Time
n_p	[rpm]	Rotational speed of injection pump camshaft
p_o	[bar]	Static opening pressure of injector
p_b	[bar]	Background pressure
p_{wmax}	[bar]	Maximum fuel injection pressure
p_{wav}	[bar]	Average fuel injection pressure
v	[mm²/s]	Kinematic viscosity of fuel
DF	-	Diesel Fuel
RO	-	Rape Oil

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Fuel Injection
Edited by Daniela Siano

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