THE EFFECT OF FUEL AND AIR PROPERTIES ON THE SPRAY FORMATION GENERATED BY A DISI ENGINE FUEL INJECTOR

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ABSTRACT

The paper discusses the analysis of ethanol (E85) fuel atomization generated by piezoelectric fuel injectors operating in a high pressure DI SI Engine injection system. The methodology and tests results of the influence of the fuel (E85) injection pressure, fuel and air temperature, and combustion chamber backpressure on the changes of the fuel spray geometrical parameters have been presented in the paper. The tests were performed for 1.5 MPa of the air backpressure at the injection pressures of 5 and 20 MPa. The following comparative indexes were analyzed: linear spray penetration during the injection and velocity of the spray propagation. The investigation consisted in a visual recording of the process of ethanol E85 fuel injection realized into a high-pressure chamber.

Keywords: Direct injection, Ethanol, Fuel temperature, Spray penetration

INTRODUCTION

A continuous advancement of combustion engines forces the engineers to seek alternative fuels. One of such fuels could be ethanol. In its clean form ethanol is not used as fuel due to its low calorific value (26,855 kJ/kg – ethanol, 42,661 kJ/kg – gasoline). An alternative fuel commonly used in Europe (but not limited to) is E85 (85% ethanol and 15% gasoline). This makes the calorific value of this fuel higher than pure ethanol and at the same time the biggest advantage of ethanol is used- its high octane number.

There are many publications related to the use of ethanol (or its mixtures) as a fuel. They do not, however, assess ethanol atomization and are limited only to the analysis of the conditions of its combustion [1–4]. This paper attempts to evaluate the ethanol atomization as a fuel (min 85% ethanol) under various ambient conditions (variable fuel and air temperature). The observed conditions of atomization may have an effect on the air fuel mixture and its combustion.

Works [5, 6] discuss the issue of ethanol atomization, yet the authors analyze only the thermodynamic changes while burning different fuels. Additionally, in works [5, 13] multi whole injectors have been used, which makes a difference in comparison to the here presented investigations (here the authors use outward-opening/fixed injection angle injectors). The injection of ethanol was also realized on other types of injectors e.g. wide-cone-angle electromagnetic injectors [11] and swirl injectors [12]. The investigations on outward-opening injectors are still underway [7, 8, 9, 10] and there are no publications on their use for alternative fuels such as ethanol.

In order to select appropriate injectors for the combustion system, it is necessary to know the characteristics of the fuel injection and the relations between the basic geometrical parameters of the spray and the basic parameters of the injection nozzle as well as the basic control values of such parameters as injection pressure, back-pressure in the research chamber and the injection duration. The research served for determination of the relations for a typical penetration of operation of a high pressure gasoline injector for fuel E85.

Table 1. Physical properties of gasoline and ethanol

	Gasoline	Ethanol
Formula	C_8H_{18}	C_2H_5OH
Research octane number	91-98	108
Motor octane number	83–90	92
Cetane number	8–14	8
Density of liquid fuel [kg/dm^3]	0.746	0.783
Lower heating value [kJ/kg]	42,661	26,855
Energy compared to gasoline	100%	66%
Stoichiometric A/F ratio [-]	14.7	9
Heat of vaporization [kJ/kg]	355	842
Autoignition temperature [^{o}C]	257	423

The results of the investigations of the piezoelectrically controlled gasoline injector of type HPI applied in the SI (Spark Ignition) engines BMW have been presented in the paper. The injector was fitted with a system allowing a controlled temperature change of the nozzle (Fig. 1). This allows a simulation of the actual operating conditions of the injector in the combustion chamber. Injectors of this kind deliver cone-shaped fuel sprays that can be described by the axial and radial spray velocities and its time resolved distribution.

Fig. 1. An injector fitted with a fuel heating system

The test-stand (Fig. 2) incorporated the high-pressure gasoline injection system equipped with the high-pressure and feeding pumps. The piezoelectrically controlled gasoline injector was placed in the closed chamber (Table 1) with the controlled back-pressure in the range 0–4.5 MPa. Positioning of the injector allows recording of images of injection course from the side (for the analysis of axial fuel spray penetration) and from the bottom of the spray (for the observations of radial spray penetration).

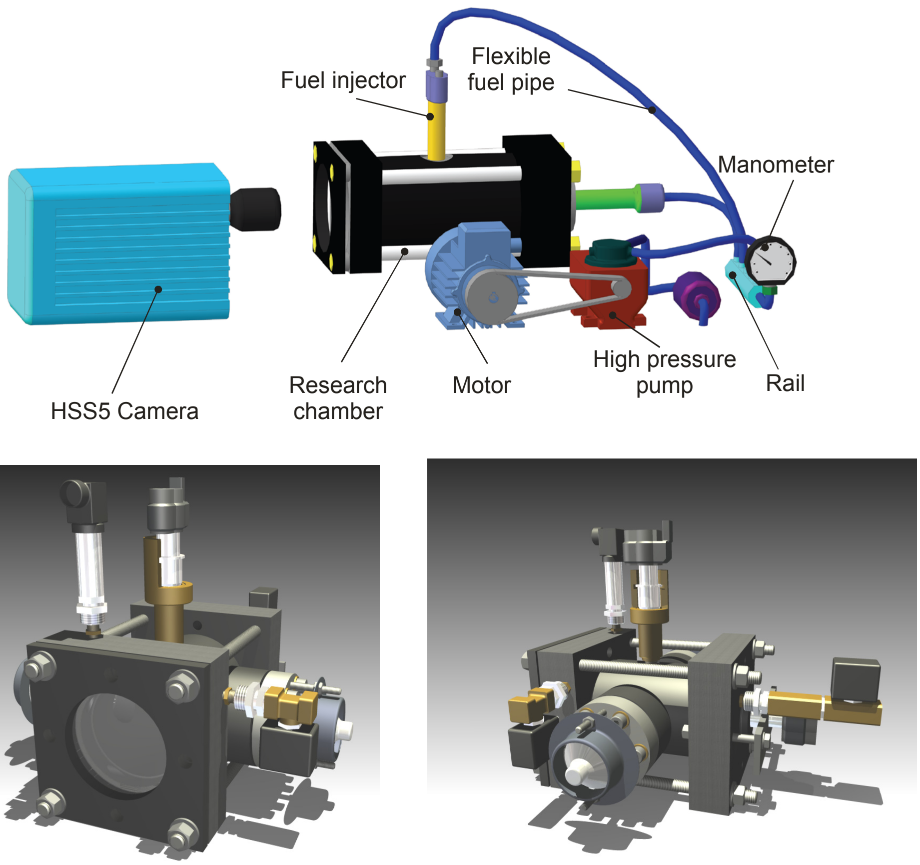


Fig. 2. Schematics of the stand measuring the geometrical parameters of the fuel spray

Table 1. Technical data of the test chamber

Chamber	Outer cell	Material ($\phi \times H$)	Steel (110 mm × 400 mm)
	Inner core	Material ($\phi \times H$)	Steel (90 mm × 350 mm)
		Volume	2200 cm^3
	Accessible pressure		0–4.5 MPa
Heater	Air	External heating	20–100^oC
	Fuel	Heating injector	20–200^oC
Windows	Material Thickness		Quartz Glass 30 mm
Injector	Injection	Pressure	5–30 MPa
		Duration	0.2–5 ms
	Injector type	HPI BMW	Outward-opening, 90^o
Light	Type	2 × Halogen Lamp	24 V; 250 W, angle 30^o

In the research a high-speed camera, namely High Speed Star 5 manufactured by LaVision [3] and equipped with a CMOS monochromatic image converter has been used. The recording speed was limited to 10000 frames per second (FPS, time resolution 100 μs) in order to obtain maximum image resolution of 512×512 pixels (pixel size of 17×17 μm). The camera operated in the spectral wave length of λ = 380-800 nm.

A so-called *sequencer* – a computer device generating particular control signals to the actuators (electromagnetic valves) – was used for the system operation control. It facilitated control of operation of several elements of the research system such as opening of supply and exhaust of control air (under the piston), opening of the gas supply valve, release of electrical impulse in the spark plug and completion of the recording process.

The research was conducted for two different values of injection pressure 5 and 20 MPa (Table 3). These values have been chosen as boundary ones typical for injection systems used today. The measurements were carried out in the research closed chamber with the back pressure in the 1.5 MPa, in all cases for the injection duration 500 μs. The camera was positioned perpendicularly to the injector axis – it allowed the analysis of the axial fuel spray penetration (Fig. 3).

Table 3. Indexes of the research on gasoline injection into chamber with back-pressure

No. -	Injection pressure P_{inj} [MPa]	Back-pressure of air P_{air} [MPa]	Air temperature t_{air} [^oC]	Fuel temperature t_{fuel} [^oC]	Test-code P_{inj}- P_{air}- t_{air}- t_{fuel}
1	50	1.5	20	20	HPI-E-50-15-20-20
2	50	1.5	45	20	HPI-E-50-15-45-20
3	50	1.5	20	120	HPI-E-50-15-20-120
4	200	1.5	20	20	HPI-E-200-15-20-20
5	200	1.5	45	20	HPI-E-200-15-45-20
6	200	1.5	20	120	HPI-E-200-15-20-120

The analysis of the spray penetration, spray area velocities of its changes were processed in the computer with the use of DaVis program implemented by own programmes worked out on the basis of *Command Language CL* [3]. The fuel spray penetration was determined according to the algorithm (Fig. 3):

1) the initial position for fuel outflow from the injector was determined from X and Y coordinates;

2) the fuel spray penetration values were determined for a single picture as a result of analysis of the entire width of spray of injected fuel and on the basis of its luminance;

3) velocity of medium penetration of dose of injected fuel was determined;

4) by taking into account time intervals between subsequent pictures, velocities of propagation of injected fuel spray front were determined.

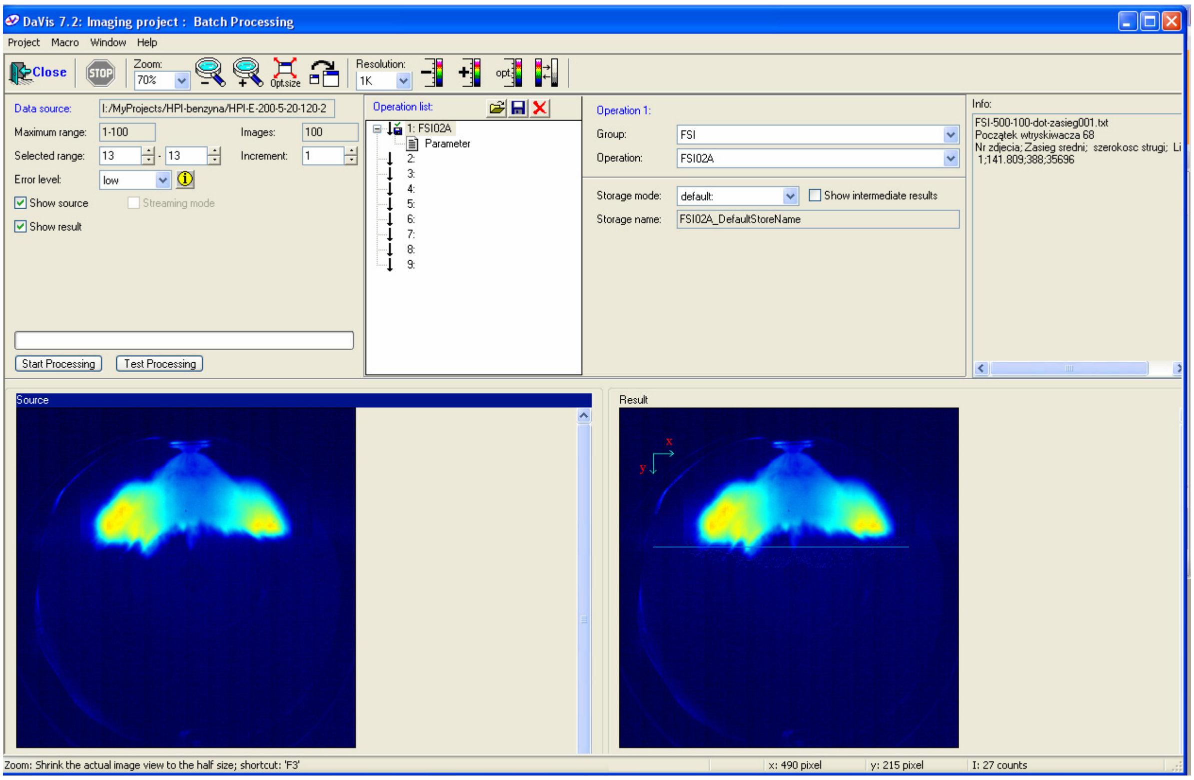


Fig. 3. Evaluation of fuel spray axial penetration in the DaVis numerical program

INFLUENCE OF the FUEL TEMPERATURE ON THE FUEL SPRAY PENETRATION

The authors analyzed the images that form the projection of the spray cone on the plane perpendicular to the spray axis (Fig. 4). The changes in the fuel atomization depending on the temperature of fuel and air for two injection pressures (P_{inj} = 5, 20 MPa) have been shown in the form of a table.

Independent changes in the temperature of the injected fuel and air temperature inside the test chamber at a steady backpressure value have been shown as well.

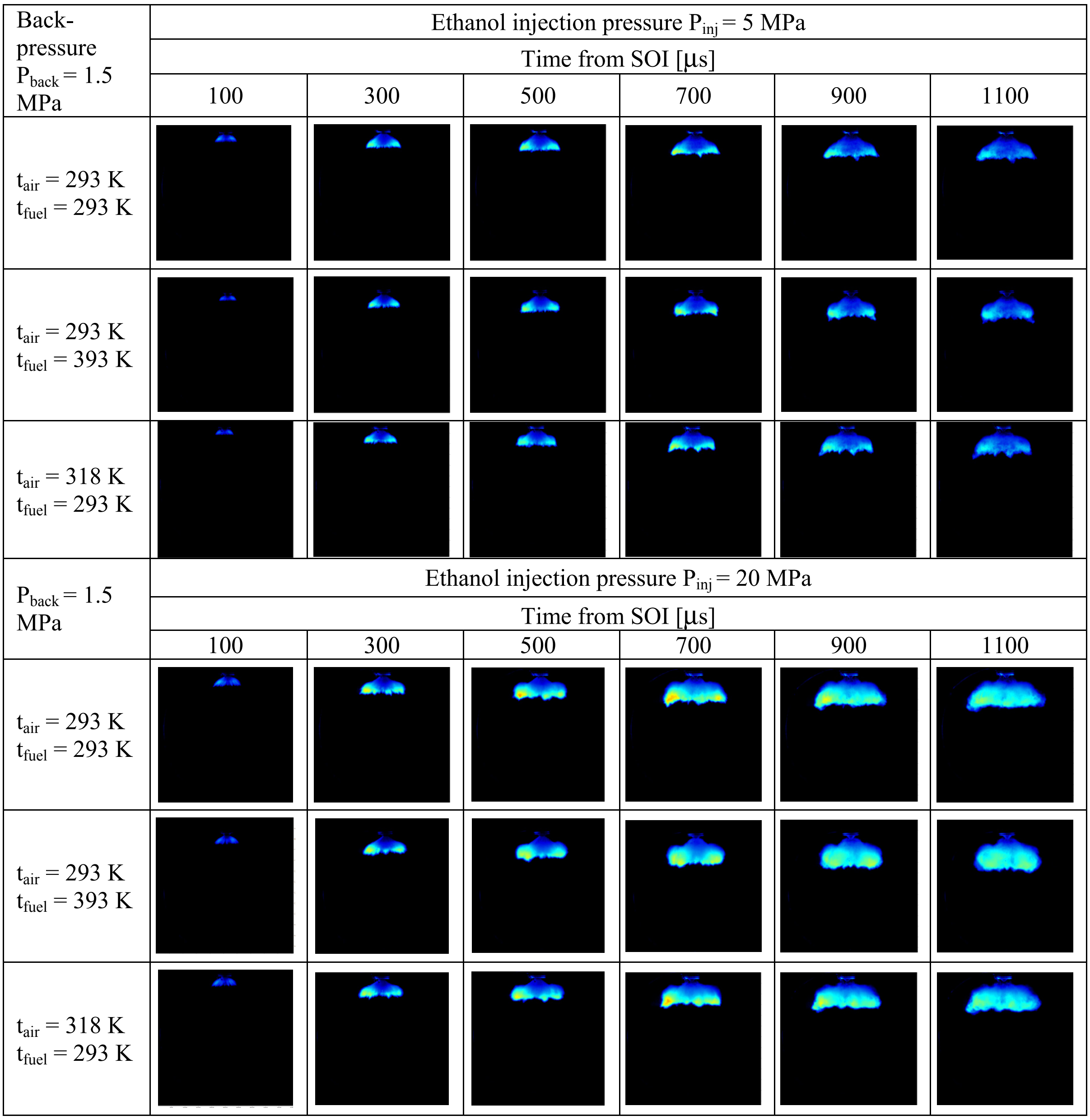
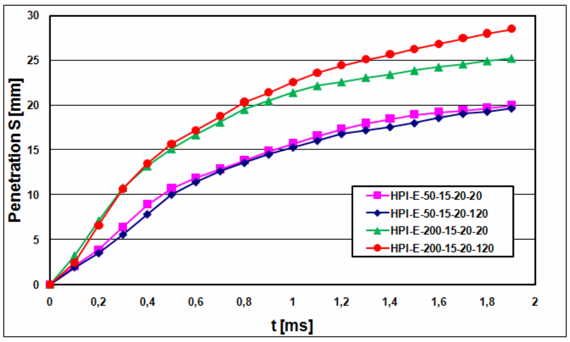
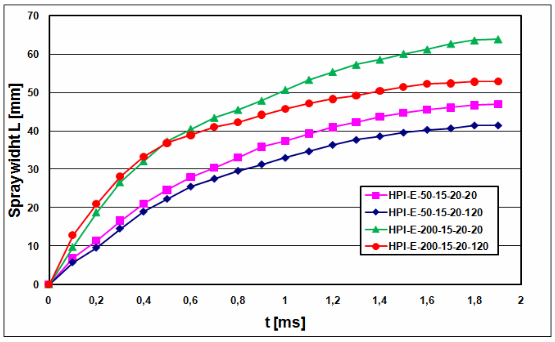


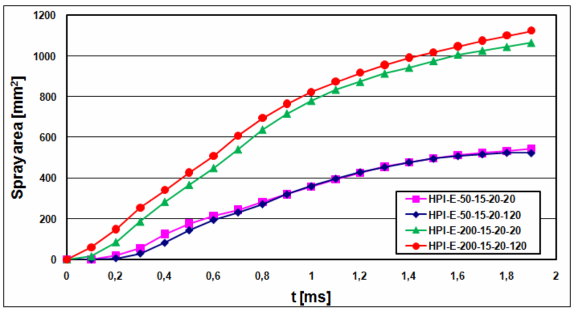
Fig. 4. Pictures of the axial fuel spray penetration for high-pressure gasoline injection into chamber with back-pressure (P_{back} = 1.5 MPa, t_{inj} = 500 µs)

The change of the spray penetration as a result of the fuel temperature change is visible at high injection pressures (P_{inj} = 20 MPa). The maximum changes of the penetration reach approximately 3.5 mm (which is approximately 11%) 1.9 ms after the onset of the injection (Fig. 5a). For the pressure of

P_{inj} = 5 MPa we can see no differences in the fuel penetration (ethanol). From the above it results that low pressures of the injected ethanol do not change the structure of the fuel spray. The size of the fuel droplets does not change when heated. This could mean that the evaporation rate is lower than 2 ms at such pressures under such thermodynamic conditions (P_{inj} = 5 MPa, P_{back} = 1.5 MPa, t_{fuel} = 120°C, t_{air} = 20°C). The application of such thermodynamic parameters allows a conclusion that low pressures do not change the fuel spray penetration when the spray is heated.

a) 

b) 

c) 

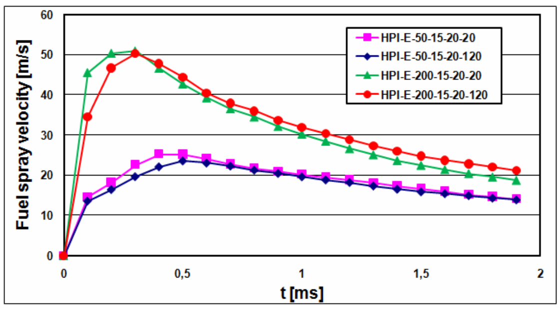
d) 

Fig. 5. The influence of the fuel temperature on the fuel spray indexes: a) spray penetration; b) spray cone tip diameter; c) area occupied by the spray; d) spray front velocity (P_{inj} = 50; 20 MPa; t_{inj} = 500 μs; back-pressure: P_{air} = 1.5 MPa)

The fuel temperature has a significant effect on the width of the ethanol spray. At the injection pressure P_{inj} = 5 MPa a reduction of the width while heating amounts to 5 mm (12% change) (Fig. 5b) 1.9 ms after the onset of the injection. The increase in the fuel pressure results in a decrease in the width of the spray by approximately 11 mm (18%) 1.9 ms after the injection onset. It is characteristic that the reduction of the spray width at low pressures (P_{inj} = 5 MPa) continues as the time passes from the onset of the injection. For higher pressures (P_{inj} = 20 MPa) the change (abrupt reduction) of the spray width begins after approximately 0.6 ms from the onset of the injection. It results from the fact that the fuel evaporation under such conditions initiates after approximately 0.6 ms. The reduction of the spray penetration also initiates after 0.6 ms from the onset of the injection, which affects the spray width and confirms that it is the duration (time), the elapse of which changes the fuel properties. A better evaporation causes the diameter of the fuel droplets to change. A reduction of the diameter of the fuel droplets results in a decrease of the velocity of the smaller droplets (as a result of this process the reduction of the fuel spray penetration takes place).

The observation of the fuel spray area depending on the fuel temperature indicates a growth of the fuel spray area only at higher injection pressures (Fig. 5c and 7a). The increase in the temperature at low pressures does not trigger any change in the fuel spray area. The heating of the fuel at higher injection pressures cause the fuel spray area to grow by approximately 6% irrespective of the time elapsed from the injection onset. The typical shape of the spray cone fades away. This indicates that it is possible to trigger changes in the ethanol atomization when it is heated only in the range of high injection pressures (20 MPa).

INFLUENCE OF AIR TEMPERATURE ON THE FUEL SPRAY PENETRATION

The temperature of air has a much lower impact on the fuel atomization than the temperature of fuel. The change on the fuel penetration as a result of the change in the temperature of fuel occurs after a time t = 1.2 ms from the onset of the injection for both pressure values. Yet, these changes are miniscule. For the injection pressure P_{inj} = 5 MPa the change (higher penetration) amounts to 4% (growth by 0.9 mm). At the pressure P_{inj} = 20 MPa the growth is smaller and amounts to 2.5% (which is 0.7 mm). The growth of the penetration is caused by a reduction in the density of the environment to which the injection is realized.

The width of the injected fuel spray (Fig. 6b) is reduced (similarly to the fuel heating phase) as the temperature grows. At higher injection pressures (P_{inj} = 20 MPa) the reduction of the width is significant and amounts to approximately 6% (which is 3.6 mm). A lower injection pressure results in a uniform reduction of the fuel spray width irrespective of the time elapsed form the onset of the injection (change by approximately 3%, which corresponds to 1.4 mm). The fuel spray area does not change (Fig. 6c) for either low and high injection pressures (Fig. 7b). Small changes occur for low injection pressures in the final phase of the fuel atomization (for the times of 1.4 to 2 ms after the onset of the injection). The growth of the fuel spray area as a result of air heating amounts to 7–8%.

The velocities of the fuel spray change more than in the case of fuel heating. The changes were mainly observed in the initial phase of the fuel injection. For the time t = 0.3 ms elapsed from the onset of the injection the growth of the velocity amounts to approximately 12% (which is 5 m/s) at high injection pressures. Yet, in the final phase of the injection and after the injection the velocities are identical. Under low injection pressures the heating of air results in a constant difference in the velocities. This may result from a slight time shift (inertia of the injection system) in the onset of the injection of both fuel doses (when the air is heated and when it is not heated).

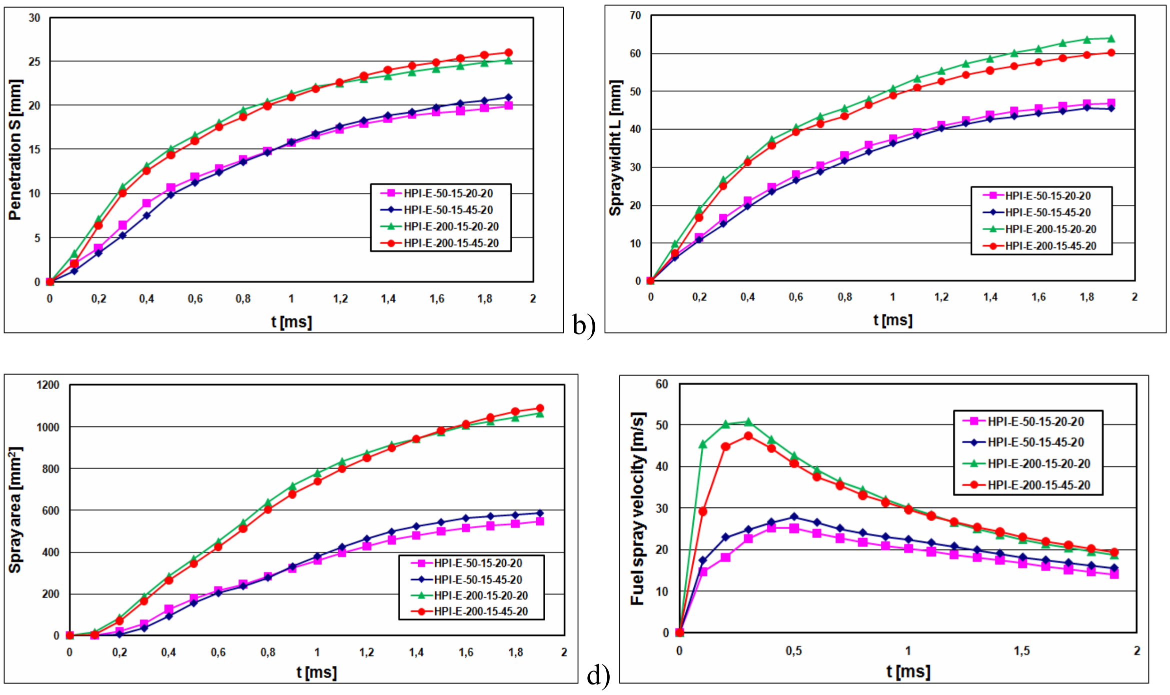


Fig. 6. The influence of the air temperature on the fuel spray indexes: a) spray penetration; b) spray cone tip diameter; c) area occupied by the spray; d) spray front velocity (P_{inj} = 50; 20 MPa; t_{inj} = 500 us; back-pressure: P_{air} = 1.5 MPa)

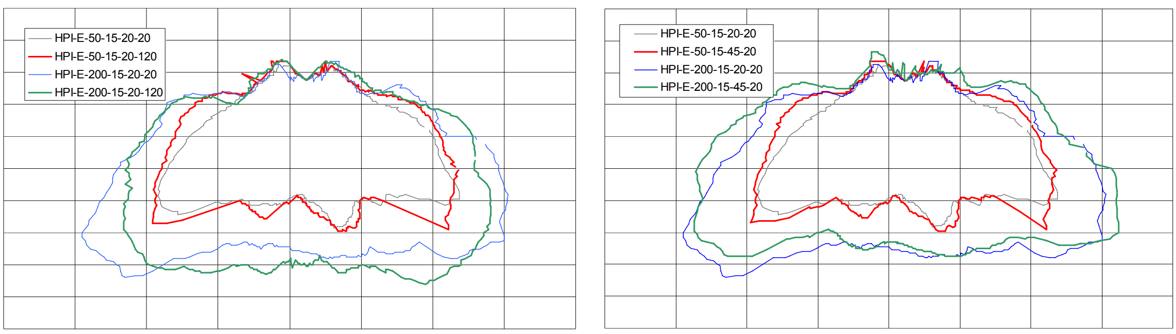


Fig. 7. The comparison of the influence of the fuel temperature (a) and air temperature (b) on the fuel spray areas (P_{inj} = 50; 20 MPa; t_{inj} = 500 μs; t = 1.1 ms), back-pressure: P_{air} = 1.5 MPa)

CONCLUSIONS

Based on the performed investigations on the ethanol injection with a cone-shaped spray configuration the authors concluded that:

The change in the fuel temperature causes more significant changes in the fuel atomization than the change in the air temperature. The increase in the fuel temperature causes more significant changes in the fuel atomization at pressures of the order of 20 MPa. The changes at the pressure of 5 MPa are miniscule or negligible. The change in the fuel penetration triggered by the change of the temperature amounts to approximately 11% (at P_{inj} = 20MPa).

The growth in the fuel temperature results in a decrease in the fuel spray width: at the pressure P_{inj} = 5 MPa by approximately 3%, at pressure P_{inj} = 20 MPa by approximately 6%. The increase in the fuel spray area amounts to 6% at P_{inj} = 20 MPa. The shape of the fuel spray is also changed – the typical cone shape of the fuel spray fades away.

The temperature of air (environment to which the fuel is injected) only slightly influences the ethanol spray penetration. The width of the fuel spray is reduced by 6% at higher pressures of the injected fuel (for P_{inj} = 20 MPa).

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