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IMPACT OF PHYSICAL PROPERTIES OF DIESEL AND BIODIESEL MIXTURE ON CHARACTERISTICS OF FUEL SPRAYING

Abstract

The use of alternative fuels in internal combustion engines is becoming increasingly attractive, both from the standpoint of energy saving as well as the reduction of emissions of regulated pollutants in the exhaust gases and the reduction of CO_2 emissions into the environment. Regarding alternative fuels in diesel engines, most of the work is based on the use of biodiesel and their blends with diesel fuel. Also, the use of a mixture of liquid and gaseous fuels (D2 and CNG) is not negligible.

The use of biodiesel and their blends with diesel fuel in the engines, due to variety of physical and chemical properties, has a significant influence on the processes in the engine, from the preparation of the air-fuel mixture to the combustion process (different combustion time, different heat release rate, etc.). For optimum engine performance, but primarily the combustion process, it is necessary to know all influential parameters, which are the result of the use of the new fuel.

This paper presents a detailed analysis of the impact of physical properties of biodiesel and their blends with diesel fuel, on the characteristics of the atomized fuel spray which has a dominant influence on the mixing of fuel and air. The results presented in this paper are combination of experimental and computational results, obtained using a self developed computer program.

Keywords: D2-biodiesel mixture, spraying of fuel, injector, diesel engine

1. Introduction

The quality of the combustion of fuel in internal combustion engines, with direct fuel injection into the engine cylinder, depends on:

- conditions of air/fuel mixing and
- environmental conditions (shape of the combustion chamber, the compression ratio, the temperature condition of the walls forming the combustion chamber, etc.).

Mixing of fuel and air depends on:

- characteristics of spray fuel (spray lenght (X_m), the spray spread angle (2θ), physical and chemical structure of the spray, spray characteristics after hitting the wall, the length of the break-up zone, etc.) and
- characteristics of air movement in the combustion chamber (speed and direction of air flow, air turbulence, air temperature, etc.).

An example of characteristics of the fuel spray (spray lenght (X_m), the spray spread angle (2θ), the angle of spray impact on the wall (β_z), the length of the break-up zone (X_b), etc.), depending on the shape and the environment in which the fuel injection is performed are shown in the Figure 1.

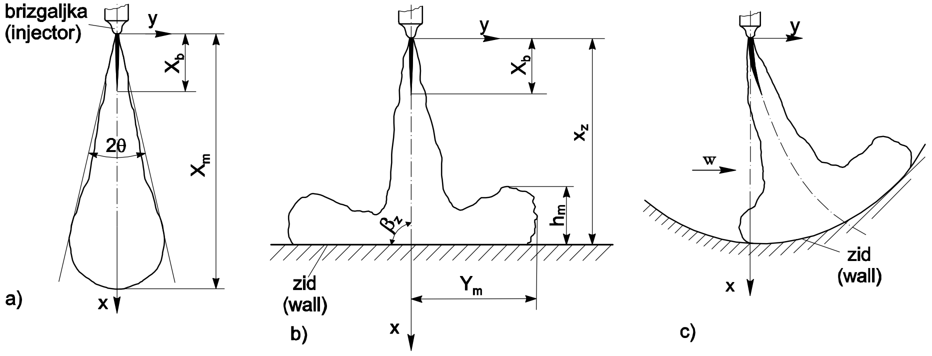

Figure 1: Typical forms of fuel sprays in different environmental conditions

In the literature [1-4, 10], there are several directions in the research of fuel spray characteristics, the most appropriate of which is the use of various semi-empirical forms. Similarly, the impact of air movement on the characteristics of fuel sprays can be studied. This paper is concerned with the characteristics of the fuel and air mixing in vehicular diesel engine with direct injection of fuel with different physical properties. Influence of air flow on the characteristics of the spray fuel in these engines is quite weak, so that main analysis will be of the characteristics of the spray fuel. Semi-empirical expressions for calculation of the fuel spray characteristics, appropriate for vehicular diesel engines with direct injection, are given in an overview of a number of authors [3, 4, 6, 10]. Most expressions treat spray characteristics length in the form of:

$$X_m = C \cdot d_b^{0,5} \left(\frac{\Delta p}{\rho_c} \right)^{0,25} t^{0,5} \tag{1}$$

where the diameter of the nozzle (d_b) and ambient density (ρ_c) are clear defined.

Size of the pressure drop through the fuel injector (*Δp*) is changing with time (*t*), so that various authors define this parameter differently [1, 2]. Most authors for the calculation of *Δp* use averaged pressure before the injector ($p_{II,sr}$) during the injection, and the mean pressure in the environment in which the injection is conducted (p_c), tj: $\Delta p = p_{II,sr} - p_c$. The value of the coefficient *C* in expression (1) is usually explained as a constant that includes the loss of flow in the injector and does not change significantly due to the conditions of injection and the structure of the injection system. Since the coefficient *C* appears in the literature displays dissipation of over 30%, more serious analysis of coefficient *C* is appeared in the literature [1, 2, 4]. The above mentioned literature sources generally treat the impact of geometric and hydrodynamic characteristics of fuel flows in the injector on the coefficient *C*.

Recently, one has been intensively working on the use of alternative fuels in diesel engines, whose physical characteristics are different from those associated with the D2 diesel fuel, in this paper the impact of physical properties of various fuels on the coefficient *C*, and the characteristics of the fuel spray were analyzed.

2. Physical properties of fuels

One of the alternative fuel in diesel engines is biodiesel fuel that can be used as a mixture with D2 or independently. Biodiesel fuel, which was examined, was from manufacturer PINUS, Rače, Slovenia, manufactured according to EN 14214. Basic physico-chemical properties of biodiesel and diesel fuel at a pressure of p = 1 bar and a temperature of fuel of 35 °C, which were used in the study are given in the Table 1.

Table 1: Basic physical and chemical properties of biodiesel and diesel [11]

Fuel Characteristics	Diesel	Biodiesel
Density at 35 °C (kg/m^3)	812	865
Kinematic viscosity at 35 °C (mm^2/s)	2.90	4.9
Heating value (MJ/kg)	42.6	37.3
Cetane number	46	> 49
Mass ratio		
Mass content C	0.860	0.7750
Mass content H	0.134	0.1210
Mass content S	0.003	0.0001
Mass content O	--	0.1040
Stoichiometric ratio (kg air/kg fuel)	14.5	12.4

Since in the analysis of D2 fuel, biodiesel and their mixtures are used at different conditions of pressure (the temperature is relatively constant), the impact of fuel pressure in the injection system on the most important physical properties of the fuel [5, 9] are given as follows:

Density of fuel:

$$\rho = x(0.0543p + 877) + (1 - x)(0.0611p + 826) - 13.5 \qquad \left[kg/m^3\right] \tag{2}$$

Kinematic viscosity:

$$\nu = 0.75x^2 + 1.3x + 2.9 \qquad \left[mm^2/s\right] \tag{3}$$

Velocity of sound through fuel:

$$a = \left(1302 + 0.5134p - 0.0002p^2\right)(0.995 + 0.03x) - 0.05p \cdot x \qquad [m/s] \tag{4}$$

Bulk modulus:

$$E = \rho a^2 \qquad \left[N/m^2\right] \tag{5}$$

where: x – volume fraction of biodiesel in the mixture p – pressure [bar].

Temperature of used fuel, which realistically in the injection system is in the range (34 ÷ 38) °C, was taken as a constant value of 35 °C, where for this temperature the previous expressions from (2) to (5) apply.

For the results analysis, where a key role is played by the hydrodynamic parameters in the injection system, that depend on the type of fuel used, a self-developed computer program was used for the calculation of hydrodynamic parameters, as shown in detail in [5].

3. Analysis of results

For analysis of spray fuel characteristics using semi-empirical expression, as well as using the more complex calculation (e.g., FMV, etc.), one of the most important elements is the knowledge of the initial and boundary conditions at the outlet of the injector (the end of the injector nozzles). This refers to the flow pressure and the velocity of fuel from the injector nozzle as a function of time. Given that these parameters are very difficult, practically impossible to obtain experimentally, computational methods are a method of choice. From computational methods, which attempt to define the hydrodynamic parameters along the injection system (pressure, velocity), there are so called 3D and 2D models and combined 1D-0D models. The first mentioned models are complicated as they require large computing time, while the latter, for practical reasons, have found their application. In this paper, the self-developed computer program will be used, combined with the 1D-0D model, used and explained in [1, 2, 5]. To summarise, the computer program is based on developed physical and mathematical model of fuel flows through the injection system, which consists of one-dimensional model of fuel flows through the pipes of constant and variable cross-section, and zero dimensional model of fuel flows through the volumes, which is also of constant and variable volume, depending on the movement of the injector moving parts.

For the calculation of characteristics of the fuel flow in volumes (V_j), the continuity equation in integral form is used of a type:

$$\frac{V_j}{E}\frac{dp}{dt} = \sum_{m=1}^{n} Q_m \tag{6}$$

Calculation of fuel flows in pipes, where the so-called one-dimensional flow is observed, the following equations were used:

- the continuity equation

$$\frac{\partial p}{\partial t} + a^2 \rho \frac{\partial v}{\partial z} = 0 \tag{7}$$

- momentum equation

$$\frac{\partial v}{\partial t} + \frac{1}{\rho}\frac{\partial p}{\partial z} + \frac{\lambda v|v|}{2\mathrm{d_c}} = 0 \tag{8}$$

which are solved by the method of characteristics.

The characteristic values of the moving elements of the injection system (distance (h), velocity ($\frac{dh}{dt}$) and acceleration ($\frac{d^2h}{dt^2}$) of the relief valve and the injector's needle are determined based on the equations of motion (Newton's second law) in the form:

$$m\frac{d^2h}{dt^2} + k\frac{dh}{dt} + ch = \sum F \tag{9}$$

In such models it is important to know precisely, the geometric forms in certain zones of the injector, as well as the friction and minor losses in all segments of the injection system. In this case, the data were used for coefficients of different losses from the literature [7, 8].

Verification of the properly adopted model was realized by comparing the calculated and experimental results on a specific type of injection system PES 6A 95d 410 LS 2542 (*Bosch*) and the injector type DLL 25S834 (*Bosch*). During the experimental study, an initial pressure and the pressure at the end of the high pressure pipe was registered, needle lift of the injector, injection rate, cycle fuel supply, the number of revolutions of the high pressure pump and fuel temperature. The calculation has enabled the knowledge of pressure and velocity of the fuel flow at each point along one-dimensional injector model. Thus, by knowing the pressure and velocity of the fuel flow at the outlet of the injector, injection rate is defined, while the calculation has determined the needle lift of the injector as well. For the verification of physical and mathematical models of the injection system, all measured characteristics are used, while the paper presents comparative computational and experimental results of the needle stroke (h_i) and the injection characteristics (q_c), as they contain as well the pressure injections indirectly. Comparison of the computational and experimental results are shown in Figure 2 and Figure 3 for diesel fuel D2 (ρ_{D2} = 812.6 kg/m^3 at p = 1 bar and t = 35 °C) and bio-diesel fuel (ρ_B = 877.1 kg/m^3 at p = 1 bar and t = 35 °C). The results are presented for the constant number of revolutions of the injection system n = 900 rev/min and the constant cycle fuel supply of 134 mm^3/cycle.

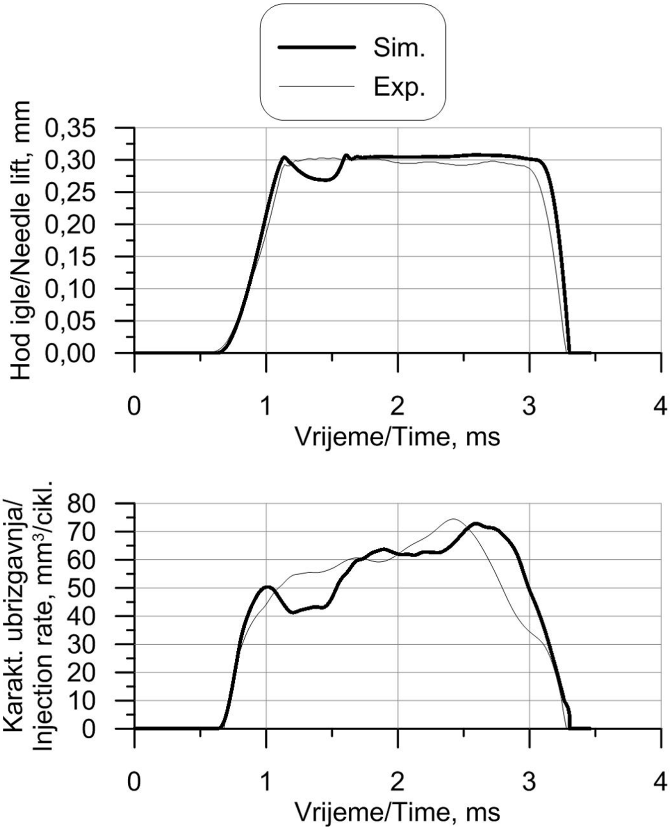

Figure 2: Comparative diagrams of needle lift (h_i) and injection rate(q_c) obtained computenationally and experimentally for the fuel with the density of 812.6 kg/m^3

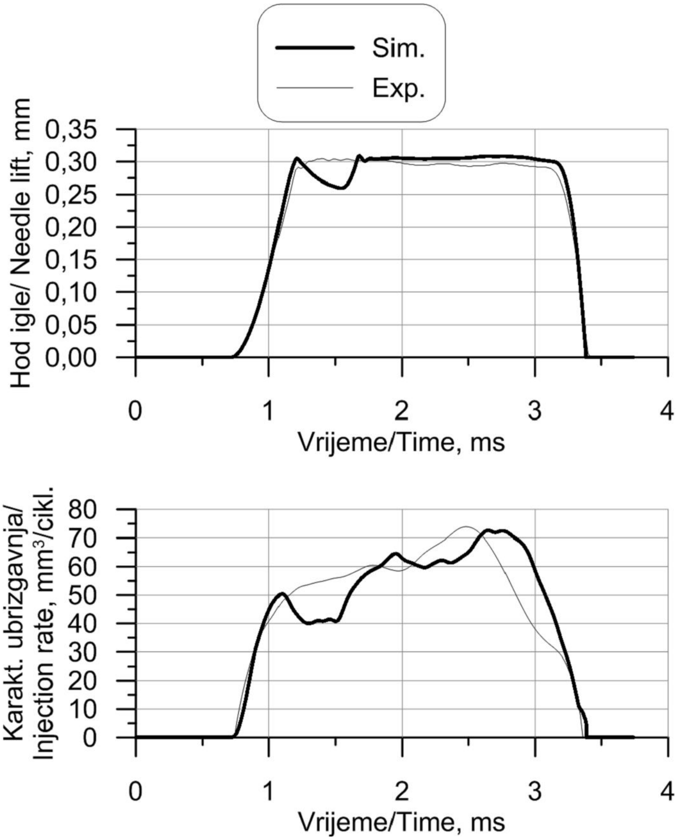

Figure 3: Comparative diagrams of needle lift (h$_i$) and injection rate (q_c) obtained computenationally and experimentally for the fuel with the density of 877.1 kg/m^3

The Figure 2 and Figure 3 show a satisfactory agreement of experimental and computational results, which confirms that the chosen injector model is adequate with corresponding numerical solutions. Additional verification confirms an integral injection rate, i.e. cycle fuel supply whereby differences are less than 2 % between the calculated and experimental values.

It is important to note that during the experimental research and conducted calculation, the same geometric stoke of the piston of the high pressure pump is retained. This has led to the emergence of some larger cycle fuel delivery when using the higher densities of fuel. Bearing in mind that the calorific power of biodiesel is less than calorific power of diesel fuel, in order to maintain the same velocity characteristics of IC engines in terms of torque and engine power, it would be necessary to increase geometric stroke of the piston of the high pressure pump which would result in the higher cycle fuel delivery. Considering that it is common to use a mixture of diesel and biodiesel fuels (lower proportion of biodiesel fuel), without special configuration of the injection system, this paper analyses the case with the so-called constant geometric stoke of the piston of the high pressure pump.

In this paper, the analysis of the impact of physical properties of fuel will be presented over the range of fuel spray characteristics. It is already said in the introduction that the highest impact on the spray length (X_m), besides the pressure difference at the injector (Δp), and the structural dimensions of the nozzle (d_b), the highest impact has a constant C, which depends on the physical properties of fuel and the structural shape of the injector. Taking into account that in this work, analysis of the specific injection system is carried out at the same environmental conditions, as influential parameters on the spray length (expression (1)) the values of C and Δp are analyzed.

Pressure difference at the injector (Δp), as a function of fuel density, is easily defined using the self-developed computer program [5], taking the coefficients of losses on specific locations of the injection system, according to the principles of fluid mechanics law [7, 8]. Thus, for a constant mode of operation of the injection system (q_c = const., n = const.), a diagram of pressure difference (Δp) as a function of fuel density was obtained, whereas the results obtained by calculation are shown in the Figure 4 in the form of the relative pressure drop $\Delta p/\Delta p_{D2}$.

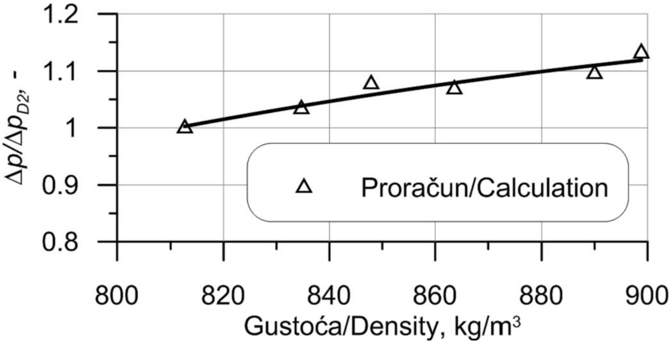

Figure 4: Diagram of the relative pressure difference in the injector as a function of fuel density

Constant C in expression (1), according to [1, 2] can be written in the form:

$$C = \frac{c_b^{0.5} \cdot c_1^{-0.5} \cdot \varphi_1^{-0.25}}{\left(1 + {}^{c_m}\!/_{2}\right)^{0.25}} \tag{10}$$

where c_b is a coefficient of losses in the injector defined in [1]. For different values of fuel density it can be presented a relative change of coefficients of losses on injector $\frac{c_b}{c_{bD2}}$ as shown in the Figure 5 for the same conditions on the injection system (n = const., q_c =const.).

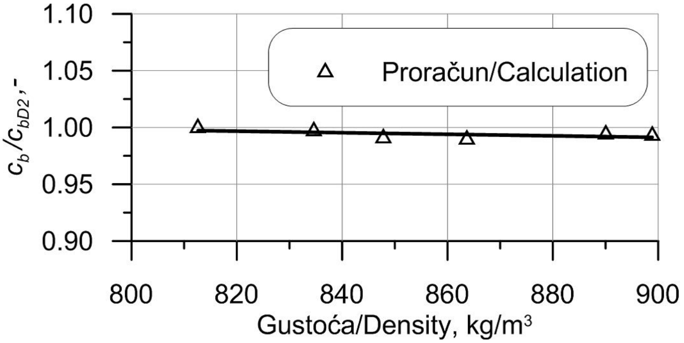

Figure 5: Change in the relative coefficient of loss as a function of fuel density

Value c_m , as a drag coefficient of droplet motion through the surrounding, practically does not depend on the fuel for realistic ranges of fuel density ρ = (800 ÷ 900) kg/m^3. A similar conclusion can be drawn for the value of φ_1 which mirrors fuel droplet velocity in the different cross sections of fuel sprays, considering that the fuel density range, referred in the previous paragraph, does not affect the droplet velocity profile in the fuel spray.

Value c_1, according to the research of many authors who have analyzed the spread of a spray fuel angle [3, 6, 10], is defined by the tangens angle of the fuel spray spread $b = c_1 \cdot X_m$, where:

$$c_1 = tg\theta = K^* \left(\frac{\rho_0}{\rho} \right)^{0.5} \propto \rho^{-0.5} \tag{11}$$

Value $c_1 = f(\rho)$ according to the expression (11) can be presented relative to the value of c_{1D2} for diesel fuel, as shown in the Figure 6.

The comparative analysis of the expression (10) for different fuel densities may lead to the conclusion that the coefficient C for the specific injection system and the same experimental conditions, changes at the same dependencies as the product of ($C^* = c_b^{0.5} c_1^{-0.5}$). Based on this, the changes of the above product can be made relative to the same parameters with the conventional fuel injection D2 as:

$$C^* = \left(\frac{c_b}{c_{b,D2}}\right)^{0.5} \left(\frac{c_1}{c_{1,D2}}\right)^{-0.5} \tag{12}$$

Coeffient C^* according to the expression (12) can be presented in the Figure 7 as a function of fuel density.

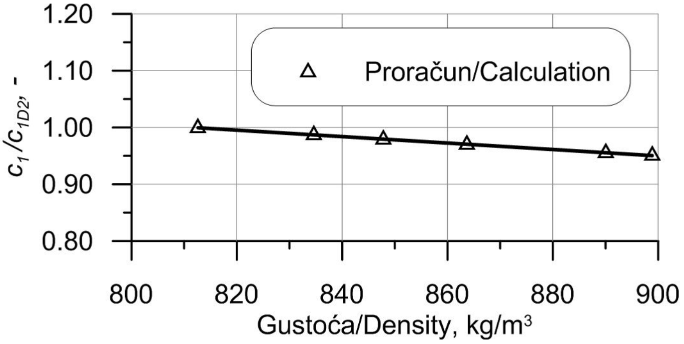

Figure 6: Constant c_1 changes in comparison with the same value of D2 as a function of fuel density

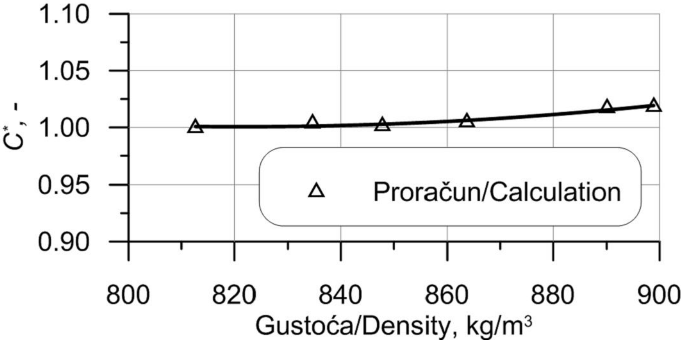

Figure 7: Change of relative constant C^* for different fuel density

By combining the results from the diagram in the Figure 7 and the results in the Figure 4, it can be defined the relative change in the spray length as:

$$\frac{X_m}{X_{m,D2}} = C^* \cdot \left(\frac{\Delta p}{\Delta p_{D2}}\right)^{0.25} \tag{13}$$

which represents a real impact on the physical properties of the fuel spray penetration. These results are shown in the Figure 8. Indeed, the size of Δp and C^* are taken into account, as well as other physical properties of the fuel, primarily viscosity of the fuel. The diagram in the Figure 8 shows that with increasing fuel density range $\rho = 800 \div 900$ kg/m^3 there is an increased spray range of atomized fuel up to 5%. This change is negligible in terms of impact of adding biodiesel in diesel fuel, from the viewpoint of the characteristics of the fuel and air mixing, which is critical for the combustion process in the engine, providing that there is a constant geometric stoke of the piston of the high pressure pump.

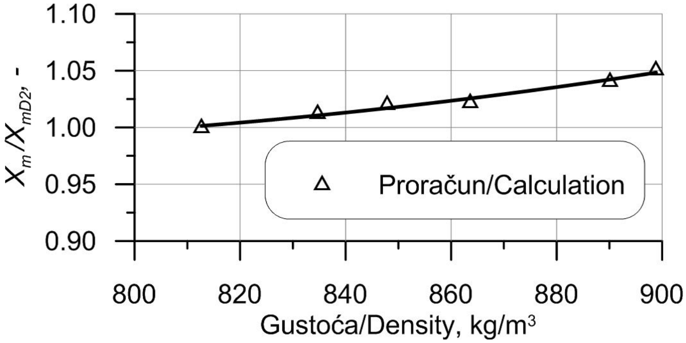

Figure 8: Diagram of impact of the fuel density on the fuel spray range

Change of results of spray length, shown in the Figure 8, with changing density of fuel i.e. changing the mixture of diesel and biodiesel fuels, is consistent with the experimental studies of spray length for D2 diesel fuel and biodiesel, given in [12].

4. Conclusion

This paper analyses the effect of the physical properties of a mixture of biodiesel and diesel fuel on the characteristics of the injected fuel spray. For a realistic range of physical properties of these fuels (at pressure of 1 bar and temperature of 35 °C of fuel):

- density $\rho = 800 \div 900$ kg/m^3,
- kinematic viscosity $\upsilon = 2.9 \div 4.9$ mm^2/s,
- velocity of sound propagation through fuel $a = 1300 \div 1340$ m/s,
- bulk modulus $E = (1.35 \div 1.616) \cdot 10^9$ N/m^2,

while maintaining a constant geometric stroke of the piston of the high pressure pump, spray characteristics (length and its expansion) scattered in the range of up to 5 %. This practically has no significant impact on the character of air and fuel mixing. Chemical composition of fuel has a significant role in the combustion process.

Assuming the change in geometric stoke of the piston of the high pressure pump, in order to maintain the same amount of heat introduced into combustion engines for different fuels, there will be no significant change in the spray fuel length. Increase of the length of sprays of different fuels within reasonable limits, keeping in mind its behavior after hitting the combustion chamber wall [3, 4], provides improved mixing characteristics of the fuel and air. This confirms that the use of different ratios (percentages) of biodiesel fuel in the mixture with diesel fuel provides some improvement in the preparation of the fuel-air mixture for combustion.

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Nomenclature:

a [m/s]	Velocity of sound propagation through fuel
C [-]	Coefficient
C [-]*	Constant

c_b [-]	Coefficient of losses in the injector
c_m [-]	Coefficient of drag of droplets
c_1 [-]	Parameter of spray spreading
d [m]	Pipe diameter
d_b [m]	Nozzle diameter
E [N/m^2]	Bulk module
F [N]	Force
h [m]	Distance
h_i [m]	Needle lift
K [-]	Constant
m [kg]	Mass
n [1/min]	Number of revolutions
p [bar]	Pressure
$p_{II,sr}$ [bar]	Mean fuel pressure before an injector
p_c [bar]	Pressure in injection environmental
Q [m^3/s]	Flow
q_c [mm^3/s]	Injection rate
t [s]	Time
V [m^3]	Volume
v [m/s]	Speed of fuel flow
x [-]	Volume fraction of biodiesel in the mixture
X_b [m]	Break-up zone length
X_m [m]	Spray length
z [m]	Coordinate along the pipe
	Greek letters
β_z [°]	Angle of spray impact to wall
Δp [bar]	Pressure difference through an injector
φ_l[-]	Parameter related to the droplets speed profile
λ[-]	Friction coefficient
v [mm^3/s]	Kinematic viscosity
ρ[kg/m^3]	Density
ρ_c [kg/m^3]	Density of the injection environment
2θ [°]	Spray spreading angle
	Index
D2	Diesel fuel
BIO	Biodiesel

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