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INFLUENCE OF FUEL PROPERTIES ON ENERGY TRANSFORMATION IN FUEL INJECTION SYSTEM AT DIESEL ENGINES

Abstract

Use of the alternative fuels for propulsion of motor vehicles becomes widespread in all types of transport, from public transportation, taxi vehicles up to light duty vehicles intended for use in urban areas. The greatest application of alternative fuels is achieved in case of the minor reconstruction of engine construction (especially in case of diesel engine). However, a special attention should be dedicated to the characteristics of the fuel injection system in case of use of different fuels. The injection characteristics (fuel pressure and velocity at the exit from injector orifice) at diesel engines depend on characteristics of the fuel injection systems and fuel properties. The most important characteristics of the fuel injection system are the following: volumes in the fuel injection system, lengths between locations from fuel pushing to injection, mass of moving parts in the fuel injection system, cross section of fuel flows in the fuel injection system and characteristics of reflection of pressure and velocity waves.

In order to improve the injection characteristics, the greatest attention is paid to minimize the volumes of the fuel injection system, especially in the injector. On this way, rapid increasing in pressure gradient (dp/dt), smaller generating reflected pressure waves of fuel and better characteristics were obtained, especially at low load regimes (at small amounts of injected fuel). On the other hand, reducing the volumes in the injection system has the effect of reducing the dimensions (especially the flow channels). This directly affects on the transformation of potential energy (fuel pressure) into kinetic energy (velocity of fuel flow). Any change from potential to kinetic energy in the fuel injection system results an increasing of hydraulic losses and deterioration of the fuel injection characteristics. In the context of the above mentioned facts, the paper presents a detailed analysis of the transformation from potential to kinetic energy of the fuel in the case of the usage of different types of fuel (diesel fuel, biodiesel fuel). A special attention will be dedicated to the injector, where the biggest energy transformation and energy losses in the fuel injection system are occurred.

Key words: *diesel fuel, biodiesel fuel, energy losses, diesel engine, fuel injection system*

1. Introduction

Energy efficiency of the internal combustion (IC) engine depends on the preparation of fuel-air mixture and the combustion process as well. The process of fuel-air mixture formation has an impact on [1-5]:

- the injection pressure,
- the characteristics of fuel spray,
- the start, duration and shape of injection rate,
- the equivalent fuel-air ratio,
- the intensity and form of air swirl in the combustion chamber and
- the air (pressure and temperature) in the engine cylinder during injection.

All the above listed parameters depend on the speed and engine load regimes. Looking simplified, the two key elements in the working mixture formation are:

- the energy introduced by the fuel and
- the energy introduced by the air.

The ratio of these energies depends on the type of diesel engine. For high displacement diesel engines, a dominant role in the process of working mixture forming has the energy introduced by the fuel. In this case, where a high-speed engine for commercial vehicles is used, a dominant influence has the energy introduced by the fuel, which may be expressed in the form of kinetic energy of the spray. Any increasing of the energy in the fuel injection system, especially with conventional fuel injection system, is associated with design of the system [3, 4] and physical properties of the fuel [3, 7]. The role of various physical properties of fuels is present through the use of alternative fuels, as well as a mixture with diesel fuel. An energy level of fuel at the injector orifice(s) can be defined through parameters [6]:

- fuel compressibility ($\frac{V}{E} \cdot \frac{\mathrm{d}p}{\mathrm{d}t}$),
- injection delay (l/a),
- inertia of moving parts $\left(m\ddot{x}\right)$,
- forces in elastic parts (cx),
- damping losses of certain gaps $\left(\mu A\sqrt{2\Delta p/\rho}\right)$ and
- feedback (reflection characteristics).

The listed parameters are simultaneously recognized the design characteristics of injection and physical properties of the fuel.

Researching the transformation of fuel energy in diesel fuel injection systems are based on experimental work only in the final part of the injectors or enlarged injector models [6]. In the literature, there are no presented papers that analyses the transformation of energy in the diesel fuel injection system for the whole very complex experiments, as well as the inability to simulate the fuel flows in the whole system of 3D models. For the full analysis of the transformation of the fuel energy, the only realistic way is a numerical simulation using the 0D-1D model.

In this context, the authors have developed and improved their own 0D-1D model to simulate the fuel flows in the diesel fuel injection system presented in [3- 5, 7 and 12]. On this way, the conditions for defining the energy transformation in each individual location in diesel fuel injection system were obtained. In particular, the specific solutions are made for the injector, where the most important energy transformation was done.

For the particular case of the fuel injection systems (known design parameters of the fuel injection system) the analysis was done in order to evaluate the effects of fuel properties on:

- the level of potential and kinetic energy in the fuel injection system;
- the transformation from potential to kinetic energy, especially in the injector;
- the level of kinetic energy on injector orifice exit and
- the level of energy losses along the fuel injection system.

2. Object and method of research

The research was carried out on the so-called "conventional" fuel injection pump-pipe-injector, where: the high pressure pump manufacturer is BOSCH of PES 6A 95D 410 LS 2542 type, the regulator of number of revolution is BOSCH of RQ 250/1100 AB 1137-4 type, the high pressure pipe is of inner diameter of Φ 1.8 mm, length *L* = 1430 mm, injector bracket is BOSCH of KDAL 80S20/129 type and the injector D2L 25S834.

The study has used a self-developed computer program to simulate the parameters of the fuel injection system with the experimental verification of typical results.

2.1. A model for simulation of the fuel injection system

A physical model of the fuel injection system used in the study is shown in the Figure 1, based on the concept of combined null dimensional - one dimensional modeling, which is described in detail in [3, 5, 11 and 12]. The basic equations used in the mathematical model of the system from the Figure 1 are:

a) for pipes with the variable cross-section the used equations are:

- Equation of continuity:

$$\frac{\partial p}{\partial t}+a^2\rho\frac{\partial w}{\partial z}\pm\frac{2a^2\rho w\lambda}{d_c}=0 \qquad (1)$$

- Momentum equation:

$$\frac{\partial w}{\partial t}+w\frac{\partial w}{\partial z}+\frac{1}{\rho}\frac{\partial p}{\partial z}+\frac{\lambda w|w|}{2d_c}=0 \qquad (2)$$

while the previous equations for pipes of constant cross-section were modified and presented in the literature [7].

b) for the volumes, the equation of continuity was used in integral form of type (so called Null dimensional model):

$$\frac{V_j}{E}\frac{dp}{dt} = \sum_{m=1}^{n} \dot{V}_m \qquad (3)$$

c) for the movement of moving parts in the injection system the *Second Newton's Law* was used in the form of:

$$m\frac{d^2h}{dt^2} + k\frac{dh}{dt} + Ch = \sum F \qquad (4)$$

Equations (1) and (2) are solved by method of characteristics; and the equations (3) and (4), provided the conversion of the second order equation (4) into two equations of the first order, (which represents the linear first order differential equations), are solved with *Runge Kutta* fourth order with variable steps.

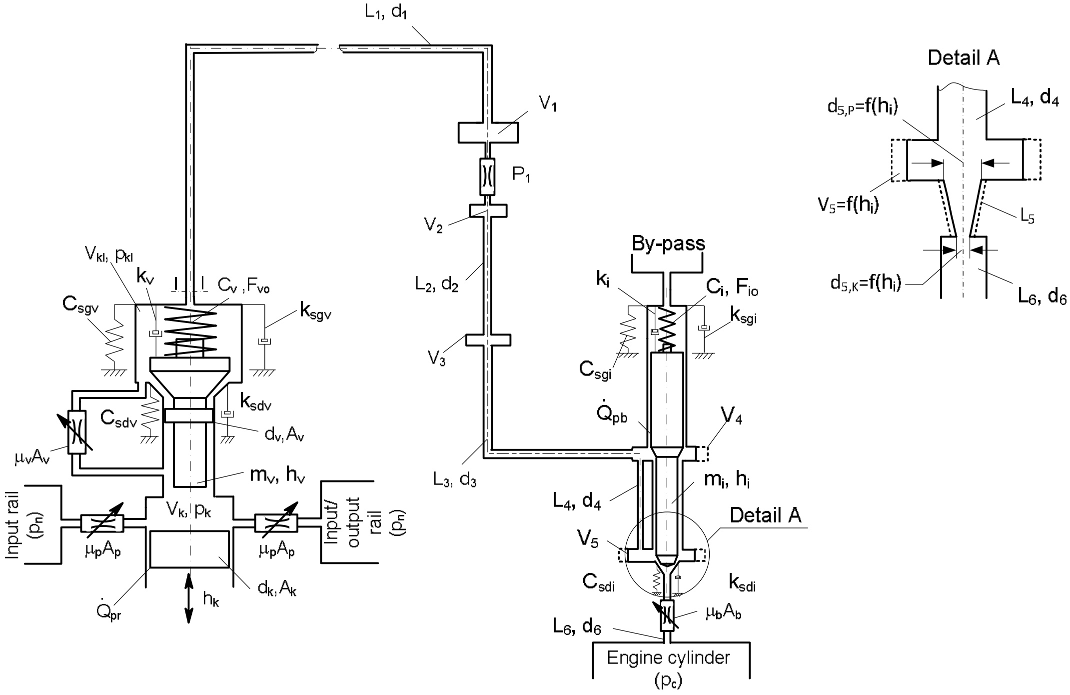

Figure 1: The physical model of the fuel injection system

The basic geometrical parameters, use in the Figure 1, are listed in the Table 1. All hydraulic losses in the fuel injection system were taken from the literature [8-10].

Table 1: The basic parameters of the diesel fuel injection system

High pressure pump	
Plunger diameter	$d_k = 9.5\ mm$
Plunger lift	$h_k = 8.0\ mm$
Initial volume in high pressure pump	$V_k = 278.0\ mm^3$
Delivery valve of high pressure pump	
Delivery valve diameter	$d_v = 6.0\ mm$
Delivery valve lift	$h_v = 4.3\ mm$
Initial volume in delivery valve	$V_k = 836.6\ mm^3$
High pressure pipe	
Diameter of high pressure pipe	$d_1 = 1.8\ mm$
Length of high pressure pipe	$L_1 = 1024.5\ mm$
Volume before the filter	$V_1 = 98.1\ mm^3$
Volume after the filter	$V_2 = 29.3\ mm^3$
Pipe in the injector body	
Pipe diameter	$d_2 = 2\ mm$
Pipe length	$L_2 = 65\ mm$
Ring volume in the injector body	$V_3 = 139\ mm^3$
Pipe in the injector body	
Pipe diameter	$d_3 = 2\ mm$
Pipe length	$L_3 = 21.63\ mm$
Ring volume around the injector needle	$V_4 = V_4\ (h_i)$
Initial volume of the ring volume	$V_{4,0} = 79.6\ mm^3$
Pipe around the injector needle	
Pipe diameter	$d_4 = 2.18\ mm$
Pipe length	$L_4 = 22\ mm$
Injector needle seat cone	
Flow cross section at the cone start	$A_{5P} = f_1(h_i) = 4.598\, h_i$
Flow cross section at the cone end	$A_{5K} = f_2(h_i) = 2.5\ h_i + 0.1226$
Cone lentgh	$L_5 = 2\ mm$
SAC volume	$V_{SAC} = f(h_i) = 1.558\, h_i^2 + 1.986\, h_i + 0.3$
Nozzle	
Nozzle diameter	$d_6 = 0.68\ mm$
Nozzle length	$L_6 = 2\ mm$
Mass of moving parts of delivery valve	$m_v = 2.6884 \cdot 10^{-3}\ kg$
Mass of moving parts of injector needle	$m_i = 14.7566 \cdot 10^{-3}\ kg$

Injector needle	
Max needle lift	$h_i^{max} = 0.3$ *mm*
Diameter of injector needle at upper seat	$d_{i1} = 6$ *mm*
Diameter of injector needle at lower seat	$d_{i3} = 4.5$ *mm*
Diameter of needle seat contact	$d_{i4} = 3.,03$ *mm*
Diameter of cone at the top of needle injector	$d_{i5} = 1.,54$ *mm*
Spring of injector needle	
Preforced injector spring	$F_{i0} = 362$ *N*
Stifness of injector spring	$C_i = 183.8$ *N/mm*
Seat of injecotr needle	
Stifness of lower needle seat	$C_{sdi} = 10^5$ *N/mm*
Stifness of upper needl seat	$C_{sgi} = 10^5$ *N/mm*
Damping coefficient on lower needle seat	$k_{sdi} = 300$ *N/(m/s)*
Damping coefficient on upper needle seat	$k_{sgi} = 300$ *N/(m/s)*

2.2. Research conditions and fuel properties

Two different fuels were used in researching:

– diesel fuel of density $\rho = 812$ *kg/m*^{3} at temperature 36 ^{o}C and
– biodiesel fuel of density $\rho = 862$ *kg/m*^{3} at temperature 36 ^{o}C.

at fuel pressure $p = 1$ *bar*.

Fuel temperatures in fuel injection system are in range 35÷38 ^{o}*C* and for this paper a temperature of 36 ^{o}*C* has adopted. The physical properties of fuels, necessary for simulation of the injection system, in function of the fuel pressure as follows:

- density (ρ),
- sound of speed through the fuels (a),
- bulk module (E) and
- kinematic viscosity (ν),

are defined by the correlation expressions presented in the literature [2, 3, 7, 11].

The analysis was conducted for the cases:

a) of so-called constant "geometric fuel suppression" of piston high-pressure pumps in the case of diesel fuel and biodiesel fuel injection ($h_{kg} = const.$),
b) of a constant amount of heat release in fuel per cycle and cylinder ($Q_{fc} = const.$),

at the same speed conditions of the injection system $n = 1100$ *min*$^{-1}$ (engine speed at max of engine power).

2.3. Verification of results obtained by mathematical model

The computational results obtained, according to the model outlined above, are necessary to experimentally verify by the characteristic modes of operation. Experimental testing of the fuel injection system was implemented on the test bed type 12H 100H, by manufacturer Friedmann & Maier, according to a measurement diagram in the Figure 2.

Measured values are: pressures at characteristic locations, needle lift of the injector and characteristics of injection (injection rate), fuel supply and fuel temperature. Equipment to measure these quantities and test methods is described in detail in [3 and 11].

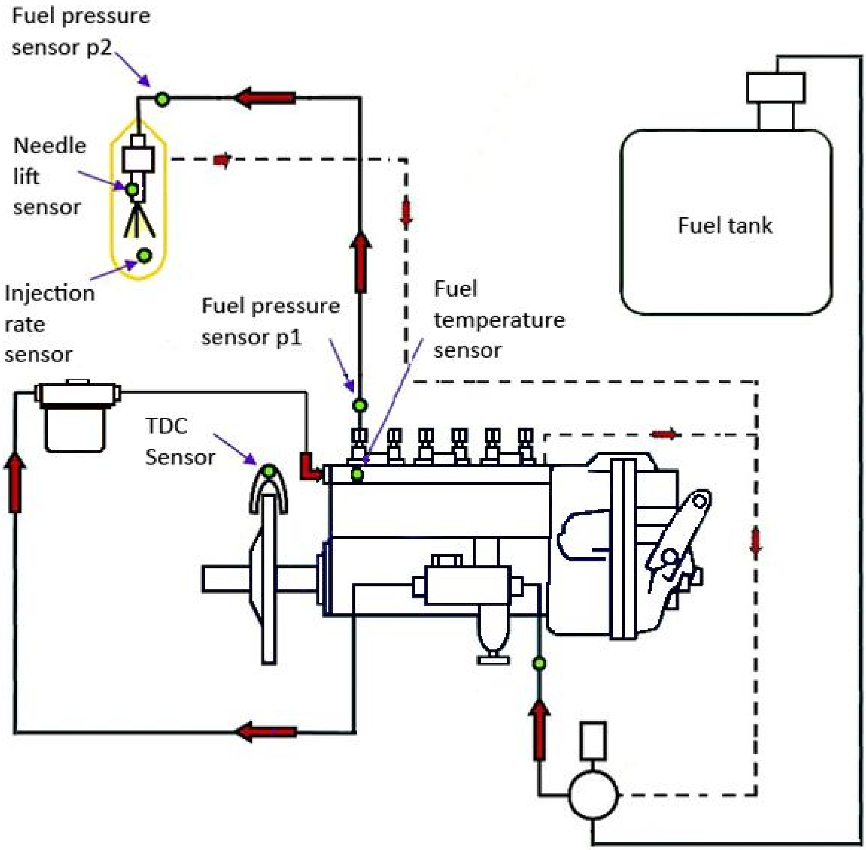

Figure 2. Scheme of measuring line for testing characteristics of the fuel injection systems

For adopted speed regime of the high pressure pump (*n* = *1100* min^{-1}), the cyclical supply of diesel fuel $q_{c,D2} = 132\ mm^3/cycl.cyl.$ was taken, while in the case of the biodiesel fuel (given in Section 2.2.) for these experiments the principle $h_{kg} = const.$ was retained. The results obtained experimentally were compared with the corresponding computational results for both fuels, as shown in the Figure 3 and in the Figure 4. The differences between the experimental and computational results, as it shown in the Figures 3 and 4, are in the domain of allowable error, which can be consider that the developed computer program for calculating the parameters of the fuel injection system provides real satisfactory results. Further research in this paper, thanks to the previous statement, were made with the computer program to simulate the injection system parameters.

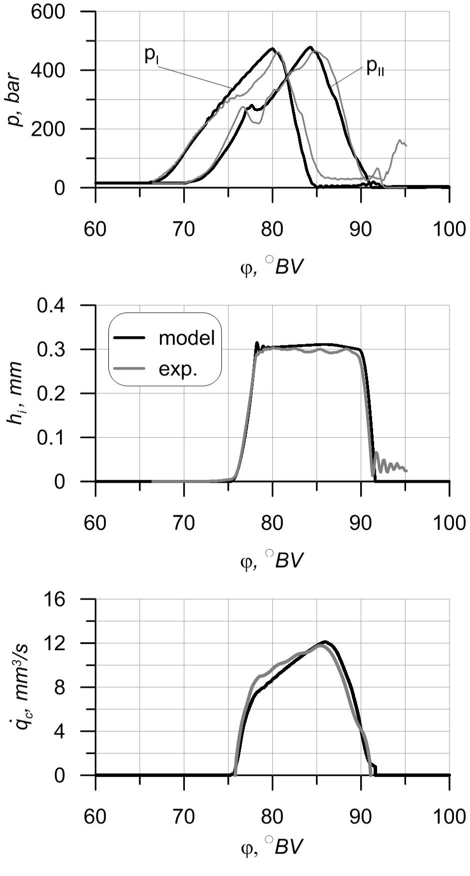

Figure 3. Comparative results of pressure, needle lift and injection rate for fuel density of ρ = 812 kg/m^3

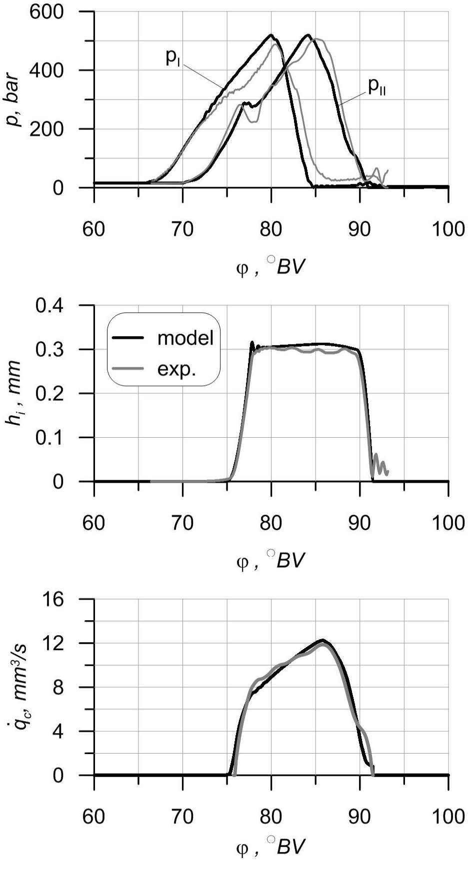

Figure 4. Comparative results of pressure, needle lift and injection rate for fuel density of ρ = 862 kg/m^3

3. Analysis of the research results

Exploring the influence of fuel properties on energy transformation in fuel injection system should be implemented for h_{kg} = *const.* and Q_{fc} = *const.* Having in mind the calorific power of diesel $Q_{d,D2}$ = 42.6 MJ/kg and biodiesel $Q_{d,D2}$ = 37.3 MJ/kg fuels, in case of Q_{fc} = *const.* a significant increase in cyclical fuel delivery (q_c) will be achieved in case of biodiesel use. Diagram of cyclical fuel delivery (q_c) as a function of fuel density in case of Q_{fc} = *const.* is given in the Fig. 5. The diagram of cyclical fuel supply in case of h_{kg} = *const*. is presented in the Figure 5 too. Having in mind the case of Q_{fc}=*const.* where the cyclical fuel supply of biodiesel fuel compared to diesel fuel is greater (about 9%), far higher than in the case h_{kg} = *const.*, all further researching will be conducted for fuels in the case of Q_{fc} = *const.* It is realistic to expect increasing resistance of fuel flow. Injection characteristics and cyclical fuel supply for this case (Q_{fc} = *const.*) is presented for diesel and biodiesel fuels in the Figure 6.

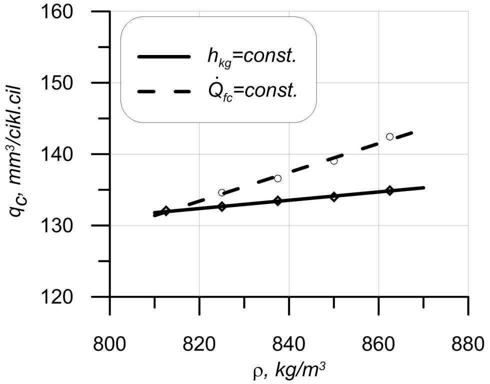

Figure 5. Diagram of fuel supply for different fuel density in case of h_{kg} = const. and Q_{fc} = const.

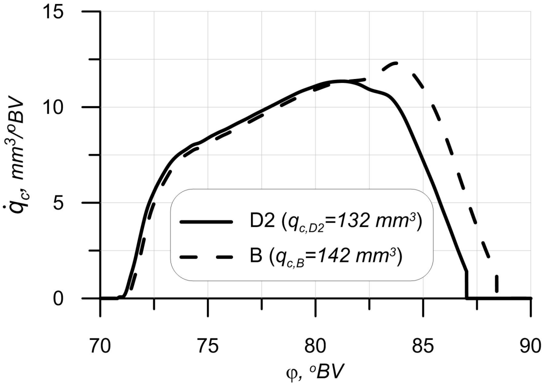

Figure 6. Injection rates for diesel and biodiesel fuel in case of Q_{fc} = const.

One of the most important parameter in the process of energy transformation and creating energy losses in the fuel injection system is the fuel flow rate through the system. Definition of fuel velocity along the fuel injection system is very sensitive, due to the dynamic processes that occur in the system, where velocity, next to location of observation, must be viewed with the changing times. In any case, in order to better understand the character of velocity change along the fuel injection system, it is the most appropriate to consider fuel velocity at the outlet of the high pressure pump and relief valve (section I-I, Figure 1) and track its changes along the fuel injection system whose signal has a propagation by the speed of sound (*a*) of the fuel. One such example of changes in fuel velocity along the fuel injection system is shown in the Figure 7, in case of two different types of fuel (Q_{fc}=*const.*).

The presented results show certain, but very little increase in velocity of biodiesel compared to diesel fuel. More interesting is the velocity along the injection system where the velocity of 20 ÷ 30 *m/s* in the pipe and most of the injector rises to a value of more than 200 *m/s* in the final part of the injector (injector orifice). This suggests, essentially, the biggest transformation of potential energy into kinetic energy of the fuel takes place in the final part of the injector, where it generates the largest losses.

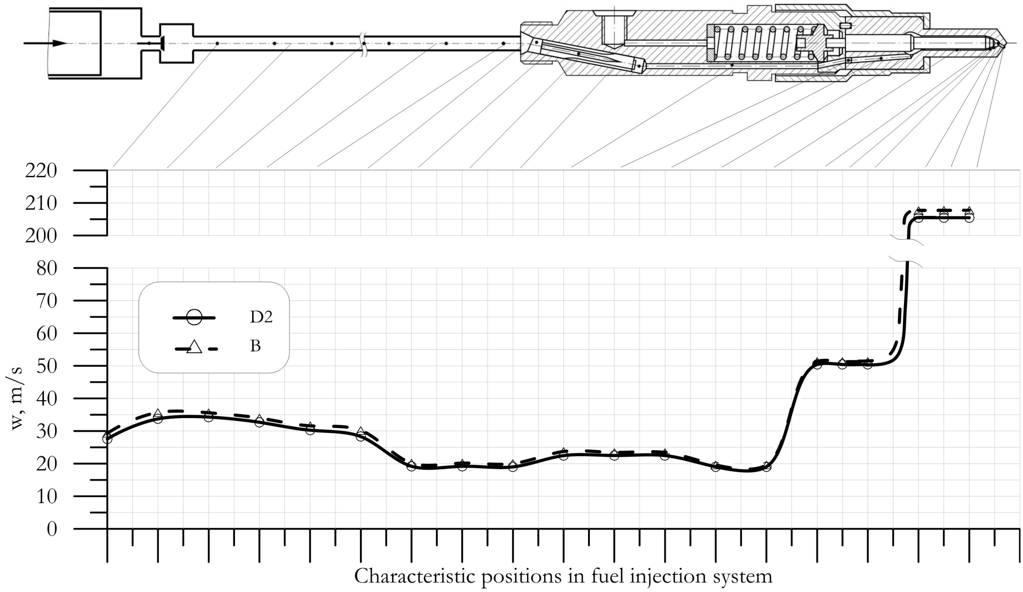

Figure 7: Diagram of fuel velocities along the fuel injection system in case of diesel and biodiesel fuel use (Q_{fc} = const.)

Diagram of energy transformation along the fuel injection system is given in relative values in percentage compared to the total energy, as shown in Figure 8a).

Total energy is taken at the beginning of high pressure pipe (section I-I, Figure 1) and it is expressed as 100 % of the energy in the form of total pressure p_{I-I} and there are no losses. Signal propagation of fuel velocity (*w*) and pressure (*p*) along the fuel injection system by the speed of sound (*a*) allows in any position on the injection system (*k*) to make definition the values of the kinetic and potential energy and energy losses expressed in terms of appropriate pressures, in the form:

$$p_{I-I} = p_{pe} + p_{ke} + p_{eg} = p_{pe,k} + \frac{\rho_f w_k^2}{2} + \sum_i^k \xi_i \frac{\rho_f w_k^2}{2} + \sum_j^k \lambda_j \frac{L_j}{d_j} \frac{\rho_f w_j^2}{2} \qquad (5)$$

Dividing equation (5) with $p_{I\text{-}I}$ and multiplying by 100 the following relation is obtained:

$$100\% = e_{pe} + e_{ke} + e_{eg} \qquad (6)$$

where e represents relative value of potential energy (e_{pe}), the kinetic energy (e_{ke}) and the energy losses (e_{eg}) expressed in percentage.

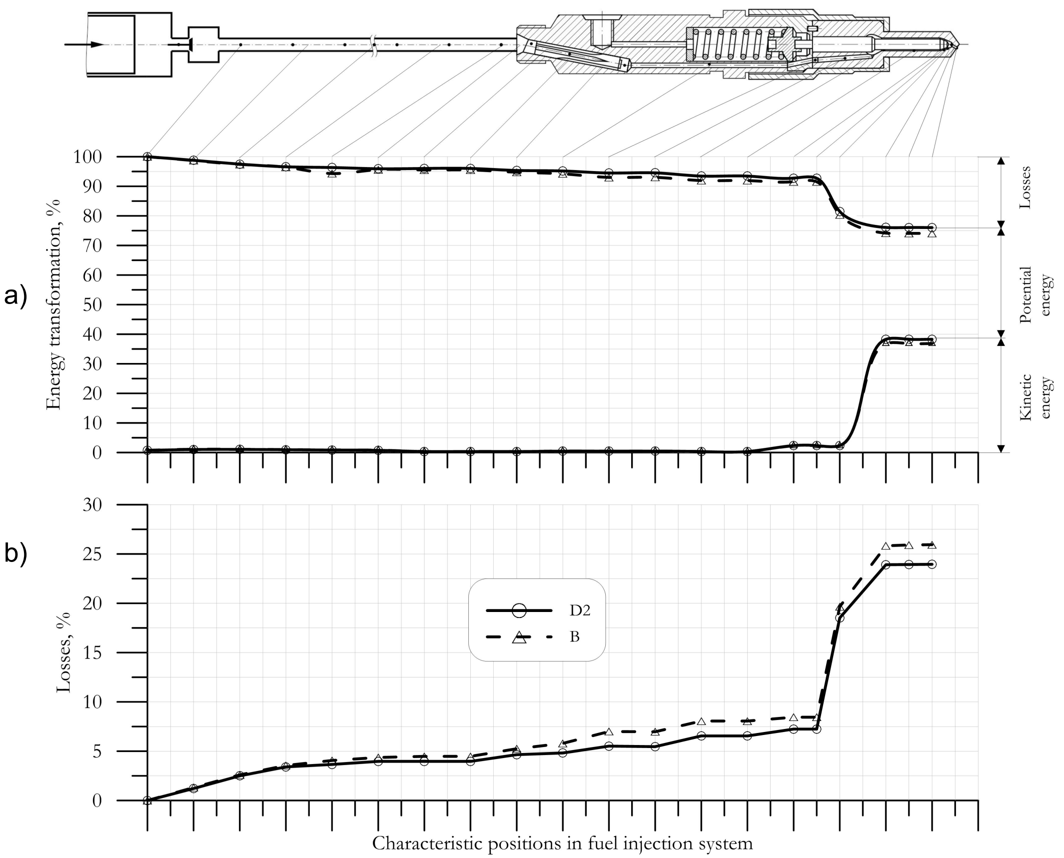

Figure 8. Diagram of energy transformation along the fuel injection system
a) and diagram of energy losses
b) along the fuel injection system in case of diesel and biodiesel fuel use

A very similar relative energy transformation in the fuel injection system for both fuels is shown in the Figure 8a). By analyzing the detail of energy losses expressed as a percentage of the total energy at the beginning of the injection system (section I-I, Figure 1), which is shown in Figure 8b), it can be concluded that the losses are greater in the fuel injection system for 2÷3 % relative when used biodiesel compared to losses in case of diesel fuel use. This increase in losses, in case of biodiesel fuel use, compared to diesel fuel has no special significance.

For this research it is more important to mention the diagram of energy transformation in the final part of the injector nozzle, where it is most intense and creating the largest losses. In the design process of the injector nozzle, where the biggest transformation of potential energy into kinetic energy happened, the main goal to injector constructor is to bring all the energy in the form of potential energy at the final part (the outlet nozzle) and transform into kinetic energy which leads to two key objectives:

- reduction of energy losses in the fuel injection system and
- improving conditions for better fuel spraying.

4. Conclusion

Thanks to the self-developed physical model and the corresponding computer program to simulate the fuel flows along the fuel injection system for diesel engines is possible to define the energy potential of the fuel in the form of kinetic and potential energy at each location in diesel fuel injection system. Based on the results of the research the following can be concluded:

- Hydrodynamic characteristics of the fuel injection systems for diesel and biodiesel differ very little, in the case of h_{kg} = *const.*, as well as in the case of Q_{fc} = *const.*
- The most significant increasing of fuel velocity in the fuel injection system is in the final part of the injector for diesel and biodiesel fuel use.
- Losses in the fuel injection system are slightly higher when using biodiesel fuel compared to losses in case of the diesel fuel use. Change these losses, with the change of fuels, has no significance to energy transformation in the fuel injection system.
- For diesel and biodiesel fuel, the biggest transformation of potential energy into kinetic energy is in the final part of the injector nozzle, where the largest losses are generated and which can adversely affect on the characteristics of the fuel spraying.

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Nomenclature:

A [m^2]	*Cross-section area*
a [m/s]	*Speed of sound*
C [N/m]	*Rigidity*
d [m]	*Pipe diameter*
E [N/m^2]	*Bulk module*
e [%]	*Relative energy*
F [N]	*Force*
h [m]	*Stroke of moving parts of the fuel injection system*
K [-]	*Constant*
k [Ns/m]	*Damping coefficient for moving parts in fuel injection system*
L [m]	*Pipe length*
m [kg]	*Mass*
n [min^{-1}]	*Number of revolutions*
p [bar]	*Pressure*
Q_{fc} [MJ/cycl.cyl.]	*Heat release*
$\dot{q}_c$ [mm^3/s]	*Injection rate*

q_c [mm^3]	*Fuel supply (delivery)*
t [s]	*Time*
V [m^3]	*Volume*
$\dot{V}$ [m^3/s]	*Flow*
x [-]	*Longitudinal coordinate along trajectory of moving parts*
w [m/s]	*Fuel velocity*
z [m]	*Longitudinal coordinate along high pressure pipe*
	Greek alphabet
Δp [bar]	*Decreasing of fuel pressure*
φ [□BV]	*Cam angle*
λ [-]	*Coefficient of minor losses*
μ [-]	*Flow coefficient*
ν [mm^3/s]	*Kinematic viscosity*
ρ [kg/m^3]	*Density*
ξ [-]	*Coefficient of losses*
	Indexes
D2	*Diesel fuel*
B	*Biodiesel*
b	*Injector*
eg	*Energy of losses*
i	*Injector needle*
k	*Piston*
ke	*Kinetic energy*
kv	*Relief valve*
p	*By-pass orifice*
pe	*Potential energy*
sd	*Min. position of moving parts in the fuel injection system*
sg	*Max. position of moving part in the fuel injection system*
sui	*Internal combustion*
v	*Valve*

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