IMPACT OF PHYSICAL PROPERTIES OF MIXTURE OF DIESEL AND BIODIESEL FUELS ON HYDRODYNAMIC CHARACTERISTICS OF FUEL INJECTION SYSTEM

by

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One of the alternative fuels, originating from renewable sources, is biodiesel fuel, which is introduced in diesel engines without major construction modifications on the engine. Biodiesel fuel, by its physical and chemical properties, is different from diesel fuel. Therefore, it is expected that by the application of a biodiesel fuel, the characteristic parameters of the injection system will change. These parameters have a direct impact on the process of fuel dispersion into the engine cylinder, and mixing with the air, which results in an impact on the quality of the combustion process. Method of preparation of the air-fuel mixture and the quality of the combustion process directly affect the efficiency of the engine and the level of pollutant emissions in the exhaust gas, which today is the most important criterion for assessing the quality of the engine.

The paper presents a detailed analysis of the influence of physical properties of a mixture of diesel and biodiesel fuels on the output characteristics of the fuel injection system. The following parameters are shown: injection pressure, injection rate, the beginning and duration of injection, transformation of potential into kinetic energy of fuel, and increase of energy losses in fuel injection system of various mixtures of diesel and biodiesel fuels. For the analysis of the results a self-developed computer program was used to simulate the injection process in the system. Computational results are verified using the experiment, for a few mixtures of diesel and biodiesel fuels. This paper presents the verification results for diesel fuel and biodiesel fuel in particular.

Keywords: *injection system, physical characteristics, diesel, biodiesel, hydrodynamic characteristic*

Introduction

In the seventies of the last century, the use of alternative fuels in internal combustion (IC) engines has started to seriously emerge with the first crisis in the supply of crude-oil products. Even then the main objectives were set, to enable the replacement of conventional fuels from crude-oil with alternative fuels, with the increased presence of alternative fuels from renewable energy sources. Even in the eighties of the last century, there was an awakening of consciousness on surrounding environment, where vehicles are one of the biggest polluters. In the first place the emission limits of pollutants CO, NO_x, C_xH_y, smoke particles, and recently of CO_2 emissions were set. Alternative fuels, in addition to the replacement of conventional fuels have a

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significant impact on the emission of pollutants, which have become a very important factor in the development of new engines for the vehicles.

In diesel engines, which are massively used today on all types of vehicles, because of its efficiency, one of the realistically perspective alternative fuels is bio fuel, derived from renewable sources (biodiesel). In general, biodiesel fuel is introduced into the IC engine in the form of a mixture with diesel fuel or it can completely replace diesel fuel. Certainly due to the different heat capacity of biodiesel and various physical properties (density, viscosity, speed of sound propagation through the fuel tank, and modulus of elasticity) compared to conventional diesel fuel, it will change the parameters that create the process of air fuel mixture formation, including the process of combustion. Because of that it is important to know:

- the impact of the type of fuel with its physical characteristics on the parameters which are obtained on the outlet of the fuel supply system and
- the impact of the outlet parameters from fuel supply system and the chemical characteristics of the fuel combustion process.

As a part of this study, the influence of physical characteristics of alternative fuels will be evaluated (from mixtures of diesel and biodiesel fuels to pure biodiesel fuel) on the parameters of the injection system. In doing so, the following will be analysed:

- injection pressure by different fuels,
- cyclical fuel supply in the context of the fuel heat input into the engine per cylinder and per cycle,
- the angle of fuel injection delay and the angle of injection duration, and
- energy transformation in the fuel injection system with special attention to energy losses in the injector.

The process of dispersion of these fuels, which presents a separate entity analysed in [1-3], are not going to be treated separately in this study.

Physical properties of fuels

The whole analysis is based on different mixtures of diesel and biodiesel fuels, whose the most important physical and chemical properties are given in tab. 1, for atmospheric pressure of 1 bar and temperature of 36 °C. Temperature of the fuel injection system is changing very little during the operation of the system, and will be adopted as a constant value (average temperature is 36 °C).

Table 1. Basic physical properties of diesel and biodiesel [1]

Fuel characteristics	Diesel	Biodiesel
Density, [kgm^{-3}]	812	862
Kinematic viscosity, [mm^{2}s^{-1}]	3.1	5.1
Calorific power, [MJkg^{-1}]	42.6	37.3
Stoichiometric ratio, [kg airkg^{-1}fuel]	14.5	12.4

The physical properties of different fuels presented in tab.1, based on the literature [4, 5] and [6], can be defined in correlation forms. Thus, the density of the fuel, for different mixtures of diesel and biodiesel fuels at different pressures, can be determined on the basis of correlation:

$$\rho(x, \rho) = 811.94 + 0.06p + x(50 - 0.0068p) \quad (1)$$

where ρ is the density of the fuel expressed in kg/m^3, p – the fuel pressure expressed in bar, and x – the volume fraction of biodiesel in the mixture ($0 < x < 1$).

Similarly, the kinematic viscosity of mixtures of diesel and biodiesel fuels is determined, given in correlation expression:

$$\nu(\rho) = 0.289 \cdot 10^{-3}\rho^2 - 0.445\rho + 173.94 \tag{2}$$

where ν is the kinematic viscosity expressed in mm²/s and ρ – the density expressed in kg/m³.

Propagation of speed of sound through a mixture of diesel and biodiesel fuels according to the research [1, 4, 5] can be represented in the form:

$$a(\rho,p) = 0.585\rho + 0.34p + 833 \tag{3}$$

where a is the propagation of speed of sound expressed in m/s, ρ – the fuel density expressed in kg/m³, and p – the fuel pressure expressed in bar.

Assuming that the process with sufficient accuracy can be considered as an adiabatic process, the volume modulus of elasticity of fuel is defined as:

$$E = \rho a^2 \tag{4}$$

Object and method of research

The research was carried out on the so-called conventional fuel injection pump-pipe-injector. The high pressure pump manufacturer is BOSCH of PES 6A 95D 410 LS 2542 type, theregulator of number of revolution is BOSCH of RQ 250/1100 AB 1137-4 type, the high pressure pipe is of inner diameter of ϕ 2 mm, length L = 1410 mm, injector holder is BOSCH of KDAL 80S20/129 type and the injector D2L 25S834. The mentioned fuel injection system has been using in middle speed diesel engines for busses and trucks and still present in modern vehicle exploitation.

In order to research the impacts of physical properties of different fuels on the parameters of fuel injection system and compare to the same parameters in case of diesel fuel use, the computation approach is much appropriate due to less research time and possibilities to determinate soma parameters that could not be measured. The relative parameters of the fuel injection systems are obtained more accurate by the calculation. 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. Having in mind the problem of energy transformation, a special attention is dedicated to the conical part between needle and needle seat that is modeled by the pipe with variable diameter in function of conical length and time (detail A, fig. 1.)

A model for simulation of a fuel injection system

The physical model of the fuel injection system used in the study is shown in fig. 1, based on the concept of combined null dimensional – one dimensional modelling, which is described in detail in [1, 6] and improved with detail A (fig. 1).

The basic equations used in the mathematical model of the system, presented in fig. 1, are:

– the equation of continuity and the momentum equation for pipes with the constant cross-section,
– the equation of continuity in integral form for the volumes, and
– the second Newton's law for the movement of moving parts in the injection system.

Having in mind the conical part between needle and needle seat (detail A, fig. 1), for conical pipe the following equations were used:

– equation of continuity

$$\frac{\partial p}{\partial t} + a^2 \rho \frac{\partial v}{\partial z} \pm \frac{2a^2 \rho v \lambda}{d_c} = 0 \tag{5}$$

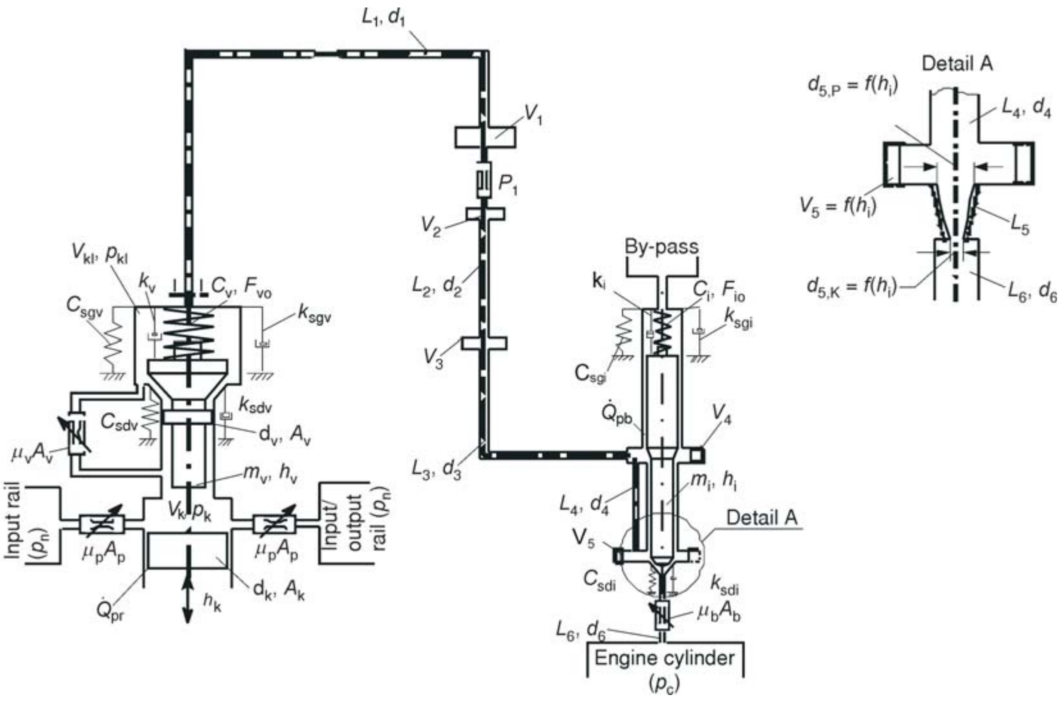

Figure 1. The physical model of the fuel injection system

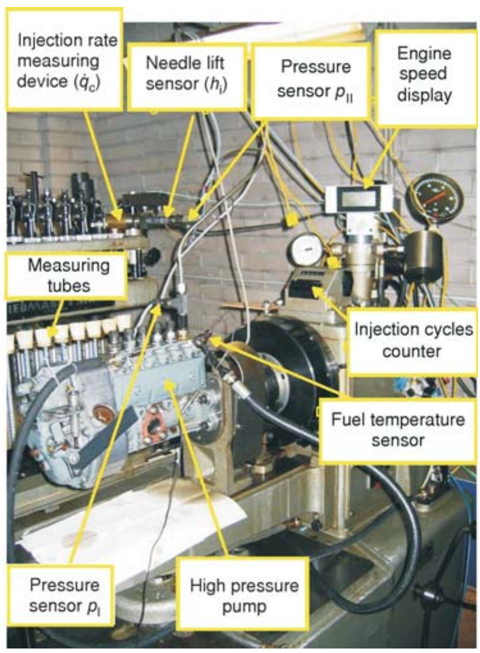

Figure 2. Scheme of measuring lines for testing fuel injection systems [1]

– momentum equation

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial z} + \frac{1}{\rho}\frac{\partial p}{\partial z} + \frac{\lambda v|v|}{2d_c} = 0 \qquad (6)$$

Equations (5) and (6) are solved by the method of characteristics. All hydraulic losses of local and line character were calculated from the literature [7].

Model verification

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 injection system was implemented on the test bed type 12 H 100 H, by manufacturer Friedmann & Maier, Austria, according to a measurement diagram in fig. 2.

Measured values are: pressures at characteristic locations, needle stroke of the injector, and characteristics of injection. Equipment to measure these quantities and test methods are described in detail in [1]. As a representative of speed regimes adopted in this study is a number of revolutions of the high pressure pump n = 1100 rpm, with cyclic displacement of q_c = 132 mm^3/cycle. cyl. for diesel fuel. Comparison was made between computational and experimental results for the case:

(a) diesel fuel of density ρ = 812 kg/m^3 at temperature of 36 °C,
(b) biodiesel fuel of density ρ = 862 kg/m^3 at temperature of 36 °C,

provided that the geometric stroke of fuel pressure into the high-pressure pump is the same. Comparative results, due to the limitations, are presented for the case of (a) and (b) in figs. 3 and 4.

From the obtained results, the characteristic values of pressures (p_I and p_{II}), injector's needle stroke (h_i) and injection characteristics (q_c) are shown. The difference between the experimental and computational results is in the domain of allowable error, which can be considered that developed computer program for the calculation of the parameters for the fuel injection system provides reasonably satisfactory results, so that further research in this paper will be done with the help of computational simulation of the injection system parameters.

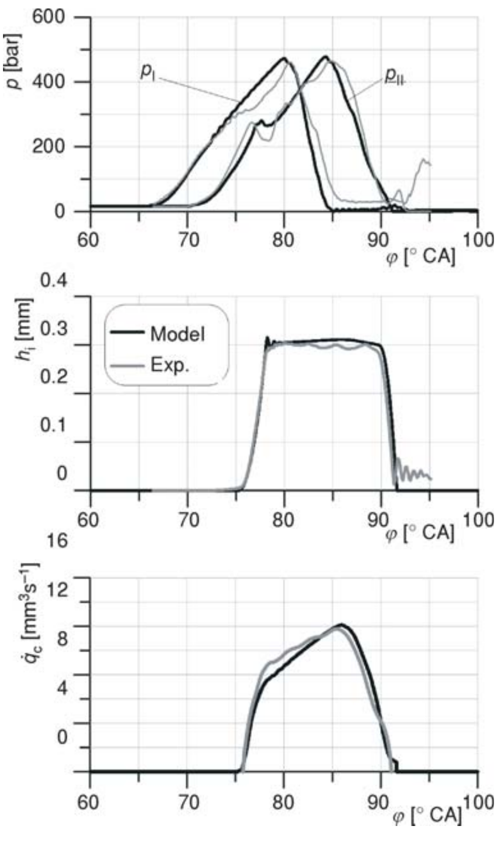

Figure 3. Comparative results of pressure, needle lift and injection rate for diesel fuel (ρ = 812 kgm^{-3})

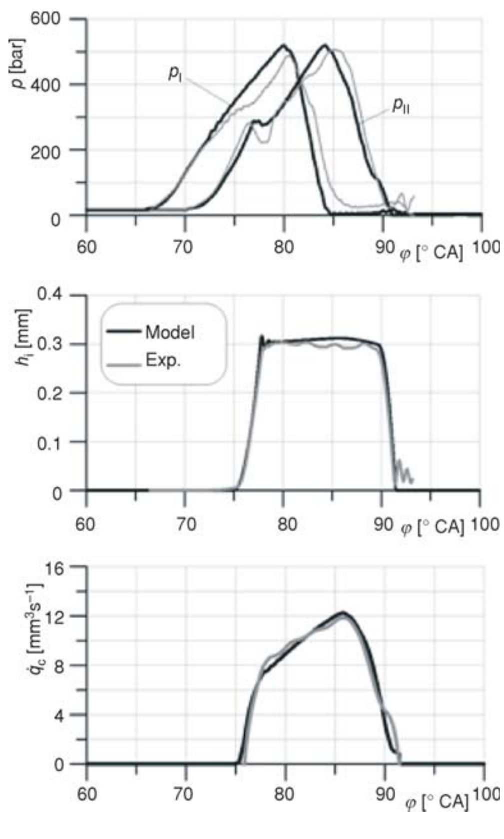

Figure 4. Comparative results of pressure, needle lift and injection rate for biodiesel fuel (ρ = 862 kgm^{-3})

Analysis of the hydrodynamic characteristics of the fuel injection system

Complete analysis of the impact of various physical properties of a mixture of biodiesel and diesel fuel injection systems of hydrodynamic characteristics was conducted for the cases:

(a) of so-called constant "geometric fuel suppression" of piston high-pressure pumps. This is a condition when there is no cyclical adjustment of fuel supply with the fuel type change, but it uses the same geometric stoke suppression (h_{kg} = const.) as in the case of diesel fuel injection,

(b) of a constant amount of input heat in fuel per cycle and cylinder constant heat release,

at the same speed conditions of the injection system (n = 1100 min^{-1}). With regards to the lower calorific value of biodiesel (Q_{dB}) and diesel (Q_{dD2}) fuels, cyclical supply (q_{CM}) of a fuel mixture, in the case (b), can be defined as a function of volumetric content of biodiesel (x) as:

$$q_{CM} = \frac{q_{CD2}}{(1-x) + x\dfrac{\rho_B}{\rho_{D2}}\dfrac{Q_{dB}}{Q_{dD2}}} \tag{7}$$

where q_{CD2} is the cyclical fuel supply during the diesel fuel injection, while other values are given in the tab. 1. Given the satisfactory agreement of experimental and computational results of all hydrodynamic characteristics in the injection system for the mixtures of fuels for various fuels (figs. 3 and 4), a more detailed analysis of the research results will be conducted using the simulation process. The analysis of these results will present only those parameters that directly affect the characteristics of the fuel dispersion and the combustion process itself. Apart from the cyclical fuel supply, this refers to:

– pressure in the injector,
– delay and duration of the injection process, and
– energy transformation from potential into kinetic energy as well as energy losses along fuel injection system.

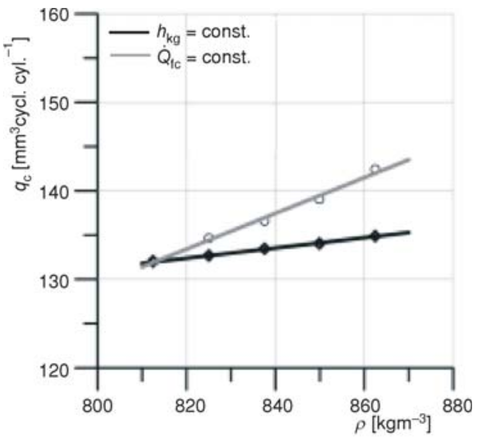

Figure 5. Diagram of fuel supply for different fuel density in case of h_{kg} = const. and $\dot{Q}_{fc}$ = const.

Figure 5 shows the cyclical changes in fuel delivery (q_C) depending on the density of a mixture of diesel and biodiesel fuels for the case of h_{kg} = = const. and constant heat release for both fuels.

For the case of h_{kg} = const, a cyclical supply is in the range of q_C = 132-136 mm^3/cycl. cyl., while in the case of constant heat release, a cyclical supply varies from 132-143 mm^3/cycl. cyl., with changing density of the mixture. The first case is practically with negligible change of cyclical supply, while in the second case the change of cyclical supply ranges to up to 8-9% when compared with the conventional diesel fuel. This of course, in addition to conditions of constant heat input related to fuel, it significantly affects the process of injection duration (t_{ub}) and the state of injector pressure.

Figure 6 shows the duration of the fuel injection as a function of the same value as with the conventional diesel fuel, as a function of density.

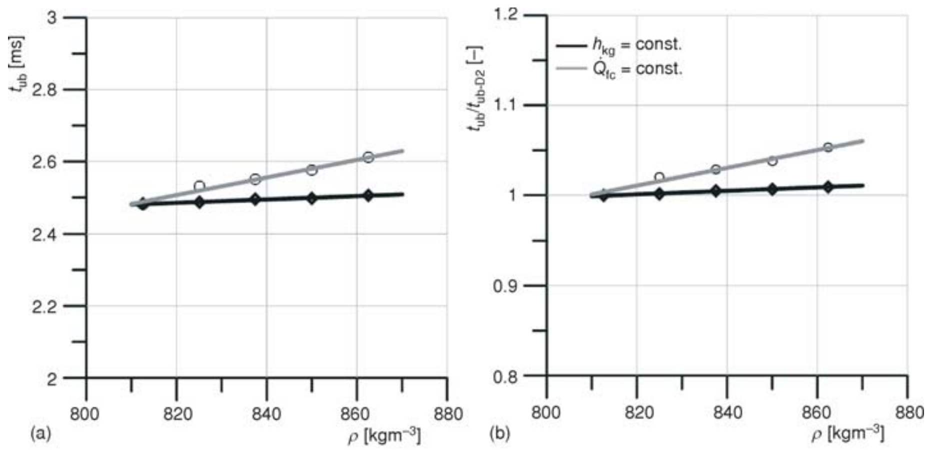

Figure 6. Diagram of injection duration (a) and relative injection duration (b) as a function of fuel density in case of h_{kg} = const. and $\dot{Q}_{fc}$=const.

The results in fig. 6 show the following behaviors:

– for the case of h_{kg} = const. the duration of injection has a negligible change with the density of fuel of (up to 1%), from which follows the fact that with changing the density in this case the duration of injection does not affect the process of air-fuel mixture formation, and

– in the case of constant heat release the injection duration varies in the range of up to 5% with increasing of the density mixture of diesel and biodiesel fuels; this increase in the injection duration has also minimal effects on process of air-fuel mixture formation and the combustion process in the engine; if you take into account that the spray range characteristics in these circumstances increase 6-8% with increasing density of fuel [8], one cannot speak about the deterioration of the process of air-fuel mixture formation of a larger scale.

Pressure in the injector with a change of the fuel density for different mixtures of diesel and biodiesel fuels is shown in the fig. 7. As it can be seen in fig. 7, the change of the maximum

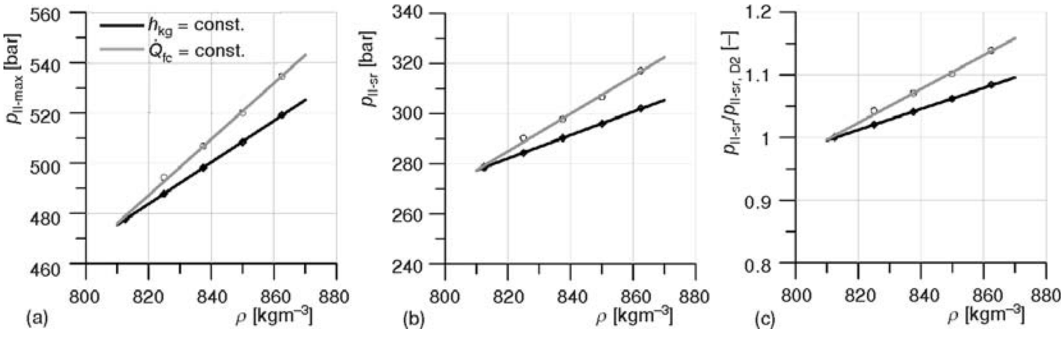

Figure 7. Diagram of change of max ($p_{II\text{-}max}$) (a), average ($p_{II,sr}$) (b), and relative average ($p_{II\text{-}sr}/p_{II\text{-}sr,D2}$) (c) pressure as a function of fuel density in case of h_{kg} = const. and $\dot{Q}_{fc}$ = const.

pressure in front of the injector ranges to up to 10% for the case of h_{kg} = const., or up to 15% for the case of constant heat release, while the mean values of pressure are increasing to up to 9% and 14% for these cases. This certainly has an impact on the characteristics of the fuel spray (spray length, quality of dispersion) having in mind the assumption of same energy transformation inside the injector.

In this analysis, it cannot be by-passed a delay angle of injection. Specifically, the dynamic angle of injection timing of fuel in the engine cylinder depends on time, *i.e*. an angle, travelling of pressure pulses from the pump to the injection (through the high pressure pipe, *L*), which are generally defined as:

$$\varphi_{z,u} = 6n\frac{L}{a} \tag{8}$$

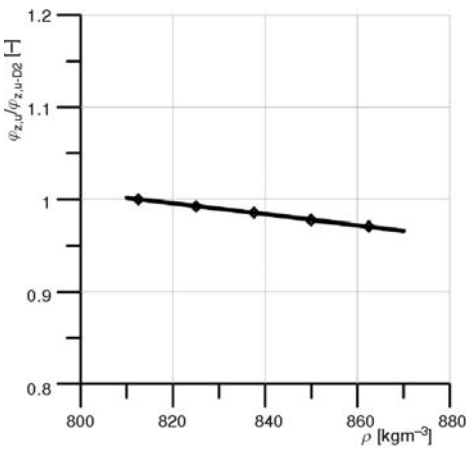

Figure 8. Diagram of relative injection delay in case of mixture diesel and biodiesel fuels use as a function of fuel density

In this injection system, the angle of the injection delay is shown relative to the same size in diesel fuel, as shown in fig. 8. The relative reduction of the angle is up to 4% as compared to the diesel fuel, as indicated in the fig. 8.

In addition to previously mentioned, the important characteristics of the fuel injection system are the characteristics of the energy transformation changes from potential to kinetic energy, and the level of energy losses. These characteristics are processed and presented in the case of constant heat release as unfavorable.

Diagram of change of kinetic energy is expressed in terms of changes in the speed of the fuel through the system. This is especially interesting in the final part of the injector where the biggest transformation of potential into kinetic energy is occurred. The diagram of changes in the speed of the fuel (in a case of the maximum fuel pressure in the fuel injection system during one injection cycle) in the final part of the injector is shown in fig. 9. From fig. 9 one can see a very small difference between the speeds of diesel and biodiesel fuels at the exit from injector orifice. The same conclusion is valid for the whole injection system.

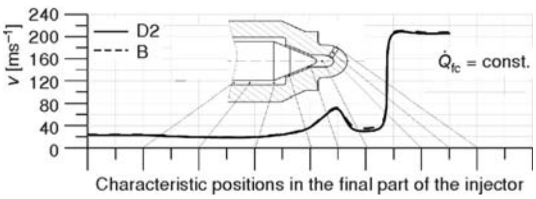

Figure 9. Diagram of changes in the speed of diesel and biodiesel fuel in the final part of the injector

The impact of the physical properties on the level of change of potential energy in the injector is expressed in terms of pressure and shown in fig. 10(a), in case of a constant amount of heat release in the engine. By use of biodiesel fuel, the potential energy inside the injector increased by 10-12% compared to diesel fuel. The same trend is present in the whole system of injection. The minimum difference between in the speed of diesel and biodiesel fuel in the injection system can be interpreted through a significant increase in energy losses in the fuel injection system in case of biodiesel fuel use. The comparative changes in energy losses in the fuel injection system, expressed in terms of pressure for diesel and biodiesel fuel, is shown in fig. 10(b).

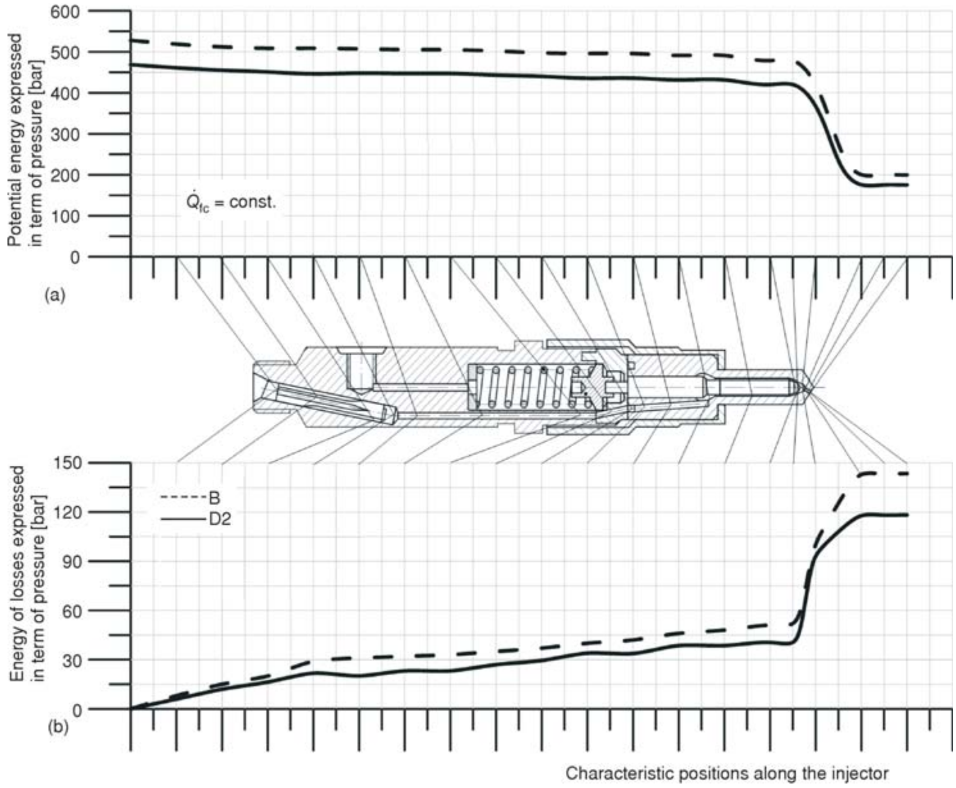

Figure 10. Diagram of changes in potential energy (a) and energy of losses (b) along the injector in case of diesel and biodiesel fuel use

Figure 10(b) shows that the source of the greatest losses in the fuel injection system is the final part of the injector. Therefore, it is very important to find the optimum balance between dispersal characteristics (dimensions orifices on the injector) and energy losses.

Bearing in mind the comprehensive analysis of the hydrodynamic characteristics in the injection system, the results of the research presented in this paper, and the research published in [8, 9], it can be concluded that the significant increase in fuel density, *i. e.* the increase the proportion of biodiesel in the mixture, could not have significant influence on spray formation. In the same time, in case of the IC engines with "sensitive" pre-injection angle, the optimal combustion conditions can be disarranged.

Conclusions

By the comprehensive analysis of the injection characteristics using a mixture of diesel and biodiesel fuels in diesel engines can be concluded as follow.

- The proportion of biodiesel fuel in the mixture below 20% did not need any special adjustment of the fuel injection system, and it can be used the same geometric stroke of piston on the high-pressure pump (h_{kg} = const.) as when using diesel fuel.
- The use of larger share of biodiesel fuel in the mixture above 20% requires adjustment of so called geometric stoke of piston on the high pressure pump with the aim of establishing an adequate intake of energy chemically bound in the fuel.

- Increased share of biodiesel in the fuel mixture requires besides adjusting the fuel injection system, optimization of the angle of pre-injection, with the aim of getting the proper engine efficiency and pollutant emissions in the exhaust gases. This is especially important in IC engines with the greater "sensitivity" on the angle of fuel pre-injection.
- Use of larger percentage of biodiesel in the mixture, especially with the condition of constant heat release, causing a significant increase of energy losses in the fuel injection system, which has a minimal effect on the change of the engine efficiency.

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Nomenclature

A – area, [m^2]
a – propagation of speed of sound through the fuel, [ms^{-1}]
C – rigidity, [–]
d – diameter, [m]
d_c – inner diameters of high pressure pipes or channel, [m]
d_{5p}, d_{5k} – diameter at the start and at the end of conical pipe, [m]
$d_{1,2,3,4,6}$ – inner diameters of pipes in a model – system of fuel injection, [m]
E – modulus of elasticity, [Nm^{-2}]
F – force, [N]
F_{io} – pre-compression force of the injector spring, [N]
F_{vo} – pre-compression force of the relief valve spring, [N]
h – stoke of moving parts of the injection system, [m]
h_i – injector's needle lift, [m]
h_{kg} – geometric stoke of suppression, [m]
k – damping coefficient for moving parts in fuel injection system, [–]
L, $L_{1,2,3,4,6}$ – length of pipe in the fuel injection system model, [m]
L_5 – length of conical pipe in the fuel injection system, [m]
m – mass, [kg]
n – number of revolutions, [1min^{-1}]
p – pressure, [bar]
p_c – pressure in the engine cylinder, [bar]
p_n – pressure in low pressure rail, [bar]
p_I – high pressure pump outlet pressure, [bar]
p_{II} – upstream injector pressure, [bar]
$p_{II,max}$ – maximal pressure upstream of injector, [bar]
$p_{II,sr}$ – average pressure upstream of injector, [bar]
Q_d – calorific power, [MJkg^{-1}]
Q_{fc} – heat release, [MJcycl. cyl.$^{-1}$]
$\dot{Q}_{pb}$ – leaking of fuel next to the needle injector, [mm^{3}s^{-1}]
$\dot{q}_c$ – injection rate, [mm^{3}s^{-1}]
q_C – cyclical supply of fuel, [mm^{3}cycl. cyl.$^{-1}$]
q_{CM} – cyclical supply of fuel mixture, [mm^{3}cycl. cyl.$^{-1}$]
q_{cD2} – cyclical supply of diesel fuel, [mm^{3}cycl. cyl.$^{-1}$]
t – time, [s]
t_{ub} – duration of injection, [s]
$t_{ub,D2}$ – duration of diesel fuel injection, [s]
V, V_j – volume in section j (j = 1, 2, ..., 5), [m^3]
v – velocity of fuel flow, [ms^{-1}]
x – volumetric fraction of biodiesel in mixture, [–]
z – longitudinal co-ordinate along the high pressure pipe, [m]

Greek symbols

λ – coefficient of linear losses, [–]
μ – flow losses coefficient, [–]
ν – kinematic viscosity, [mm^{3}s^{-1}]
ρ – density of fuel, [kgm^{-3}]
φ – cam shaft, [º CA]

Indexes

B – biodiesel
b – injector
D2 – diesel fuel
i – injector needle
k – high pressure pump piston
kl – relief valve
M – mixture
p – inlet overflow openings
sd – min. position of moving part in the injection system
sg – max. position of moving part in the injection system
v – valve

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