# EXPERIMENTAL STUDY ON INJECTION CHARACTERISTICS OF DIESEL AND BIODIESEL FUEL BLENDS WITH COMMON RAIL INJECTION SYSTEM

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**Abstract.** The limited fossil fuel reserves and the ecological aspects encourage the scientists to conduct the research on a new alternative renewable energy resource. In the European Union diesel – powered transport machines produce approximately 21 % of the total emissions causing the greenhouse effect and this tendency is in a constant progress. The transport and agriculture sectors are among the largest consumers of the mineral fuels contributing to the environment pollution. The EU directives promote the production and consumption of biofuels, therefore, the member-states have committed to the promotion of biofuels and other renewable fuels instead of using fossil-origin gasoline or diesel fuel. The article presents the experimental test results of the fuel injection processes of diesel and biodiesel fuel blends, when using high-pressure common rail injection system. The injection characteristics were determined using the injection rate measuring instrumentation. The aim of the study was to get insight in the changing behaviour of the injection rate, amount of the fuel injected per cycle, actual injection delay and the duration of the process over the whole variation range of both the injection pressure and the energizing time. The test results showed that the maximum injection rate of diesel – biodiesel fuel blends was lower than that of a neat diesel fuel case. It was observed that density and viscosity of the fuel have a significant effect on the form of injection characteristics. The injection process has significant influence on the combustible mixture formation inside the cylinder of a diesel engine, auto-ignition, combustion, and exhaust emissions.

**Keywords:** diesel, biodiesel, common rail,fuel injection, injection characteristics.

## Introduction

The ecological aspects, limited fossil fuel reserves, and the increased market price of mineral fuel encouraged the scientists to conduct the research on alternative renewable biofuels to adapt them for diesel engine powering. The latest achievements in the engine design and the use of biofuels in diesel-powered vehicles match well with the EU Directive 2009/28/EC, which approves a target of 20 % share of renewable biofuels in overall transport petrol and diesel consumption to be introduced in a cost-effective way by 2020. The main reason for using of biofuels in a diesel engine is to lower the greenhouse gas emissions, reduce global warming, promote rural development, and create new jobs in the global agricultural market. Until now, biofuels were mainly produced by processing edible agricultural crops with available technologies. In low percentage blends the 'first-generation biofuels' can be used with conventional fuels in most vehicles and can be distributed through the existing fuel infrastructure. Advanced energy conversion technologies are needed to produce the second-generation biofuels. The production of these biofuels will use a wider range of biomass resources-agriculture and forestry residues as well as waste materials that promises to achieve the reduction in greenhouse gas emissions and the market cost of the fuel.Biodiesel interpreted as Fatty Acid Methyl Esters (FAME), obtained from renewable resources by transesterification of fatty acids, can be used as an alternative fuel to petroleum-diesel as pure fuel or as an additive to diesel fuel. Due to its "renewable" origin and nature-friendly characteristics, such as biodegradability or lower emissions of toxic components in the exhausts, biodiesel is a highly attractive alternative to fossil-origin fuels [1]. Although it is possible to power CI engines with pure biodiesel, many researchers provide studies on operational and combustion characteristics as well as problems related with using neat biodiesel in modern engines, equipped with technologically advanced injection systems. To maintain the best performance properties of an engine, the EU standards have been adapted to control the quality of biofuel produced. These standards clearly define the requirements that biodiesel must correspond to be recognised as the fuel suitable for powering of CI engines [1]. The quality of biodiesel in the EU member-states is regulated by the EN14214 standard, which defines the main parameters of the ester content, which depends on the biofuel production technology.

Biodiesel generally is being derived from vegetable oils and alcohol in the presence of catalyst, defined as mono-alkyl esters of long chain fatty acids [2]. Until recently, rape oil was the main raw material source widely used to produce biodiesel in the EU countries [3].

The investigation on biodiesel influence on the performance of diesel engines can be divided into three major parts. The influence of the biodiesel fuel properties on the injection system characteristics, on the fuel spray formation and its effect on the diesel engine performance and emissions can be found in [7]. Variations in the fuel injection characteristics mainly occur due to changes in sophisticated hydrodynamic processes in the high-pressure pump, high-pressure pipe and in the injection nozzle itself. The fuel pressure energy is converted into kinetic energy during the injection process. Thus, different physical properties of biofuels and alternative fuels affect the history of the injection process. Biofuel density, viscosity and surface tension are similar compared to those of the diesel fuel. Nevertheless, the physical parameters have a high influence on fuel spray penetration and the combustion process [4]. The scientists have noted [5] that the fuel density, viscosity, and elasticity modulus made-effects are of great importance to the hydrodynamic fuel injection process in a high-pressure injection system especially during increasing the pressure phase [6]. Som et al. (2010) noted that the differencebetween the spray characteristics of biodiesel and diesel fuels is more pronounced for the highly evaporating sprays compared to those ofless-evaporating sprays. This is due to the higher boiling temperature and higher heat of vaporization of biodieselhaving in mind that the vaporization properties have a more significant influence on the spray behaviour rather than physical properties of the fuel such as density, viscosity, and surface tension. Gumus et al. (2010) experimentally investigated the effect of fuel injection timing on the injection, combustion, and performance characteristics of a direct-injection diesel engine fuelled with Canola oil methyl esteranddiesel fuel blends. The test results showed that the injection timings occurred earlier, when using Canola oil methyl ester and diesel fuel blends. The experimental results showed thatmaximum pressure in the cylinder, the pressure rise rate, and the heat release rate are slightly lower, while the ignition timing is higher for COME and its blends for all loads and injection timings. The brake-specific fuel consumption for COME is higher than that of diesel fuel, while the brake thermal efficiency from combustion of COME is lower than that of the normal diesel fuel.

An experimental study carried out on the effects of 10 %, 20 % and 50 % Karanja biodiesel blends on the injection rate, atomization, combustion, engine performance, and emissions characteristics of a common rail direct injection system were evaluated in a single cylinder research engine for 30, 50, 75 and 100 MPa fuel injection pressures at different injection timings and constant engine speed of 1500 rpm. The results showed that the duration of fuel injection slightly decreased with increasing the content of biodiesel in the fuel blend and significantly decreased with increasing the fuel injection pressure. The profile of injection rate and Sauter mean diameter of the fuel droplets are influenced by the injection pressure. The higher fuel injection pressure typically improves combustion and the thermal efficiency of the tested fuels and reduces emissions [8].

The experimental studies onthe impact of biodiesel bulk modulus on the injection pressure and injection timing have been carried out by Caresana (2011). The results showed that the advances in the start of injection timing are smaller, when using biodiesel rather than mineral diesel and differ from those calculated by using standard methods and may even not occur at all, depending on the design of the injection system. In addition, they demonstrated that, on the contrary to common belief, the injection pressure does not always increase, when using biodiesel.Han et al. (2014) presented an experimental investigation of injection characteristics of fatty acid esters on a diesel engine with common rail system. The results indicate that fatty acid esters show smoother rising slope intensity at the start of injection and lower injection rates within the stable injection period in the volumetric injection rate curves, but the mass injection rates of all tested fuel blends are quite similar. Fatty acid esters have longer injection delay than the diesel fuel, while the increased injection pressure decreasesthe injection delay, but extends the injection duration. The injector's energizing time has significant influenceon the shape of the injection rate and the pressure fluctuation at the inlet port of the injector.

Majority of the researchers analysed only the engine performance and exhaust emissions, therefore, in the literature there is a lack of more detailed studies on the subject to investigate the potential impact of physical parameters of the fuel on the ongoing processes in the common rail injection system. The purpose of the research was to investigate the injection characteristics of diesel – biodiesel fuel blends in a high-pressure injection system.

## Materials and test methods

The following types of the fuels were used in the experimental studies: rapeseed oil methyl ester (B100), corresponding to the requirements of LST EN 14214:2014 (produced by JSC "Rapsoila"). Diesel fuel (DF) class 1, was produced at the manufactory "Orlen Lietuva" and its quality parameters satisfied the standard EN 590:2014 + AC requirements. Properties of the tested fuels are presented in Table 1. Only the most important properties of the fuels were analysed and compared in this study.

Table 1

**Fuel properties**

| **Parameter** | **Density at 15 °C, kg·m$^{-3}$** | **Kinematic viscosity at 40 °C, mm$^2$·s$^{-1}$** |
|---|---|---|
| DF | 831.70 | 2.22 |
| B100 | 884.10 | 4.60 |

Fig.1. presents a schematic diagram of the experimental setup. It consists of two parts: the fuel injection system and the injection rate measuring system. The fuel injection system includes a high-pressure pump, a common rail, injector, and the electronic unit to control the injection pressure. A six hole injector nozzle was used, and the diameter of each hole was equal on average to 0.24 mm. The NI PXIe 1062Q system with DI Driven D000020 module was used to control the injection process. The injector was controlled by a peak current of 26.0 A and a holding current of 14.0 A.

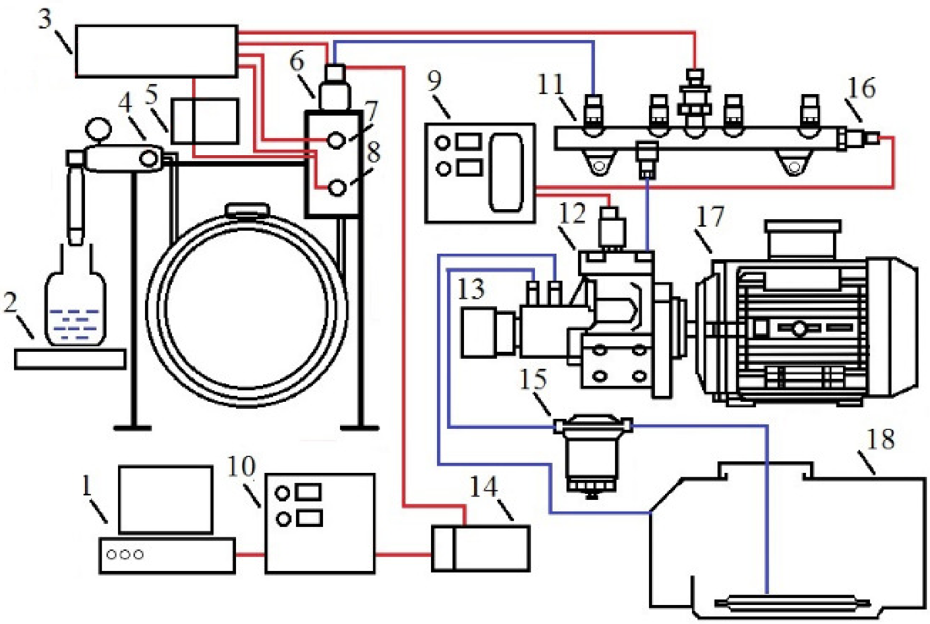


Fig. 1. **Schematic view of fuel injection testing stand:** 1 – PC; 2 – electronic scale; 3 – data acquisition module; 4 – pressure sensor; 5 – charge amplifier-module; 6 – injector; 7 – temperature sensor; 8 – pressure sensor; 9 – fuel pressure control unit; 10 – injector driver; 11 – common rail; 12 – high-pressure fuel pump; 13 – fuel pressure regulator; 14 – NI 9161 chassis; 15 – fuel filter; 16 – rail pressure sensor; 17 – electric motor; 18 – fuel tank

The fuel injection rates were measured using the Bosch method [10]. The injection rate measuring system included an adapter for mounting of the injector, measuring tube of 6 m in length, orifice, following tube and a check valve. The injection rate measuring method was based on measuring a dynamic increase in pressure produced by the fuel injection into the measuring tube filled with fuel. The orifice between the measuring tube and the following tube controls the amplitude of the variation of pressure waves at the end of the measuring tube. The increase in the dynamic pressure is proportional to the injection rate of the fuel [11].

$$\dot{m} = \frac{A_{tube}}{a} p(t), \tag{1}$$

where $\dot{m}$ – mass injection rate;
$A_{tube}$ – cross-sectional area of the measuring tube;
$a$ – sound velocity in the fuel;
$p(t)$ – pressure variation.

The pressure variation in the tube was measured with a piezoelectric pressure sensor type 6052C (Kistler) coupled to the Kistler charge amplifier-module 5064 with an accuracy of ± 0.5 % in the pressure variation range of 0-25.0 MPa. The fuel pressure at the inlet of the injector was measured with a piezoresistive high-pressure Kistler Inc. sensor 4067A2000 and an amplifier-module 4665. Both amplifier-modules were mounted on the signals conditioning platform-compact 2854A. All injector energizing, injection rate, fuel pressure and back pressure signals were recorded using an AVL IndiModul 622 data acquisition system.

The fuels were injected with the following constant pressures of 25.0 MPa, 50.0 MPa and 100.0 MPa. The injection duration was 2.6 ms, 1.5 ms, and 1.0 ms, respectively. The back pressure in the tube was adjusted to 4.0 MPa to simulate a real value of the gas pressure in the engine combustion chamber during the injection process. The results of 100 consequential injection cycles were recorded and averaged for the analysis. The injection quantity was obtained from the mean value of 1000 continuous injections, measured by a precision scale. Temperature of the injected fuel was measured with Pt100 sensor and it remained above 30 ºC during the experiments.

## Results and discussions

In the compression ignition engine, the fuel injection process plays an important role on the in-cylinder mixture formation, auto-ignition, combustion process, engine performance parameters and ecology characteristics. Fuel injection characteristics depend on the type of the injection system and fuel properties. Among the main physical properties having the biggest influence on the injection process are viscosity, density, and the bulk modulus. Fig. 2 shows the profiles of volumetric and mass injection rates of the tested diesel and biodiesel fuel blends at various injection pressures and energizing durations.

As it can be seen in the figure (Fig. 2 a, b), the leading front of the injection-rate characteristics was steeper for the fuels possessing lower density and viscosity, when the fuel was injected at the low (25.0 MPa) and the medium (50.0 MPa) pressure. Both maximum volumetric and mass injection rates were 3.8 % and 9.1 % higher for the case of the diesel fuel injected at minimum pressure of 25.0 MPa. When the injection pressure was increased, the maximum injection rates also increased for all fuel types tested. However, the peaks of the mass and volumetric injection rates for the denser and more viscous biofuel B100 were slightly lower compared to that of diesel fuel tested under the same injection conditions. When the injection pressure increased to the maximum value of 100 MPa, the shape of volumetric injection characteristics for the tested fuels almost did not change and the maximum mass injection rate was about 7.8 % higher for the diesel fuel case. The mass-quantity of biodiesel B100 injected per cycle was 1 % lower due to its higher density and viscosity, while the mass delivery rate for the diesel fuel was about 6 % higher as shown in Fig. 4, a.

Columns in Fig. 3 show the effect made by biodiesel B100 on the injection delay time and duration measured under different injection pressures.

The injection delay is a time interval between the start of energizing of the injector and the start of fuel injection that was found by analysing the injection rate characteristics. Changes in the injection delay for different injection pressures are shown in Fig. 3, a. The injection delay time was 0.46 ms for diesel fuel and 0.40 ms for biodiesel B100 tested at the injection pressure of 25.0 MPa. The injection delay decreased to 0.40 ms for diesel fuel and to 0.36 ms for B100 fuel due to the injection pressure increase to 50.0 MPa. The injection pressure increased to maximum value of 100 MPa resulted into the injection delay time reduced to 0.36 ms for diesel fuel and to 0.33 ms for the biodiesel B100 case. The higher density and viscosity of rapeseed oil methyl ester are among the main reasons of having lower fuel B100 flow-rate, which leads to longer injection delay time than that of the diesel fuel.

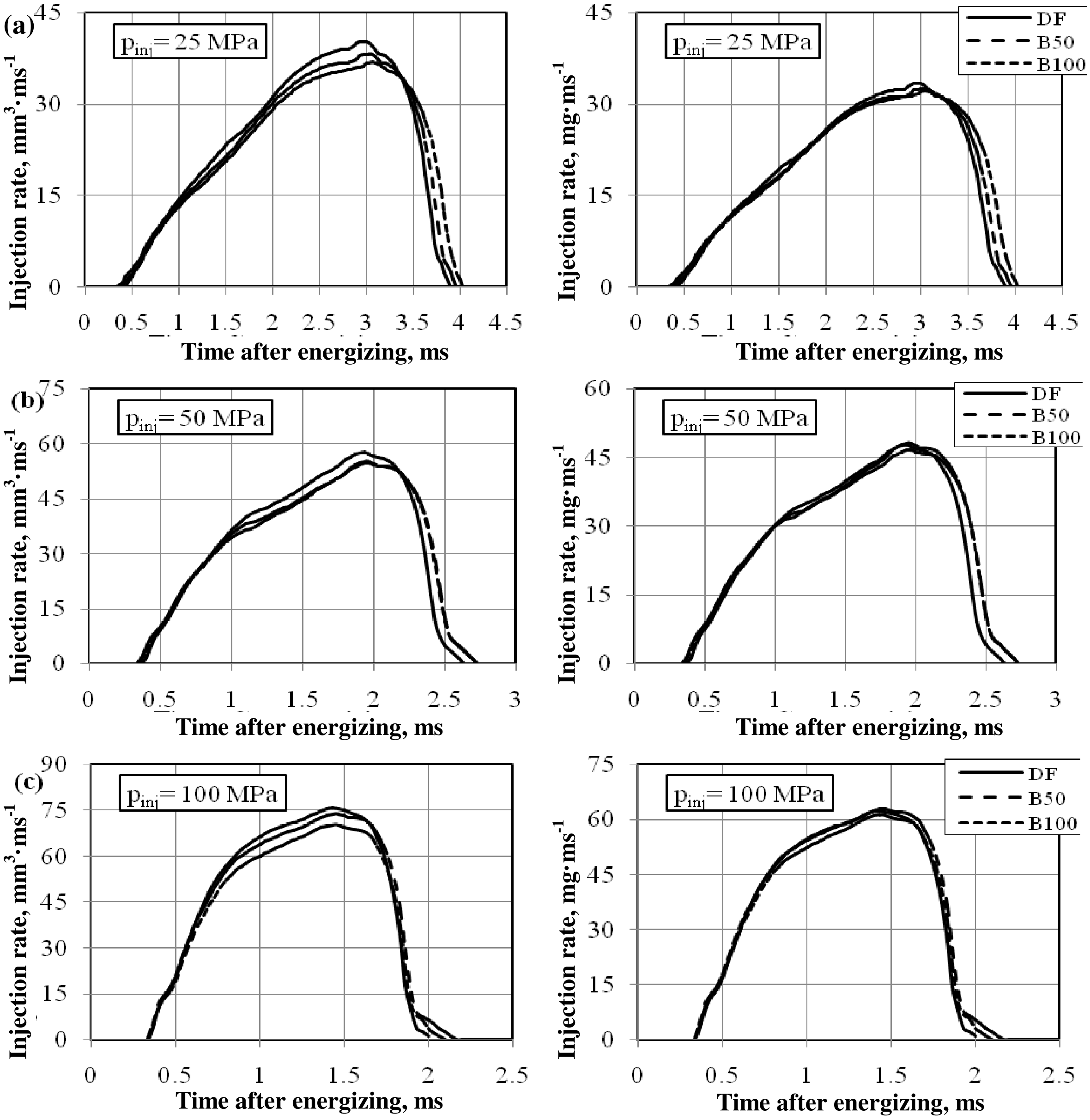


Fig. 2. **Effect of injection pressure on injection rate for various fuel types: back pressure 4.0 MPa; a – $t_{en}$ = 2.6 ms; b – $t_{en}$ = 1.5 ms; c – $t_{en}$ = 1.0 ms**

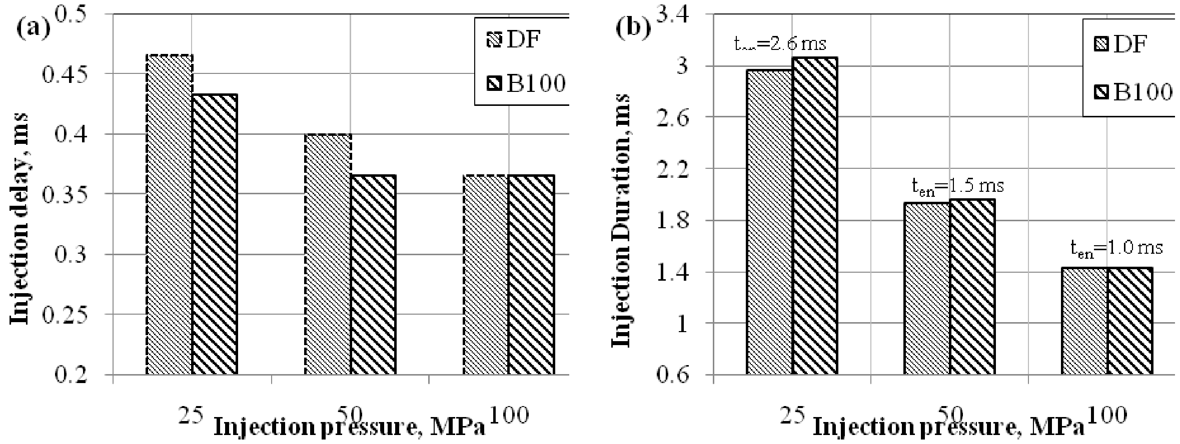


Fig. 3. **Effect of fuel injection pressure on injection delay time and injection duration**

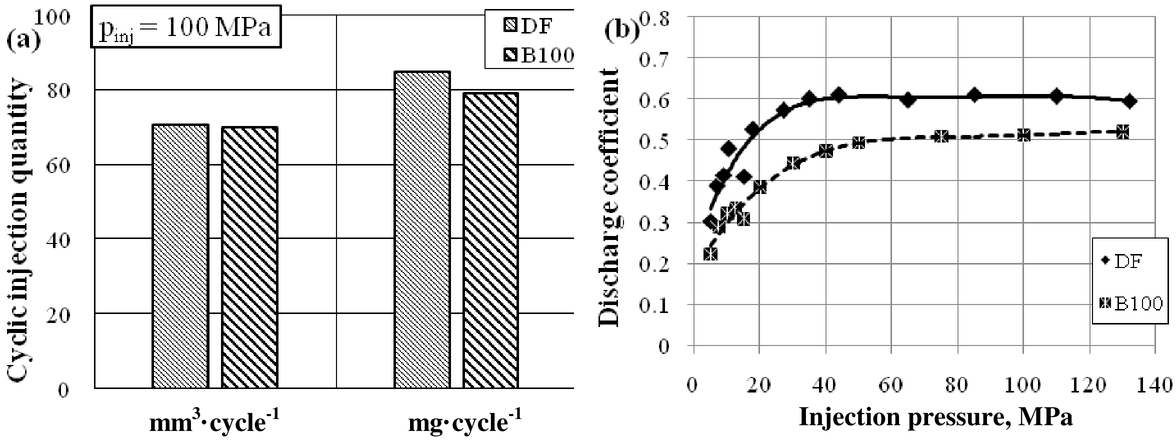


Fig. 4. **Dependencies of cyclic injection quantity on fuel used (a) and discharge coefficient on injection pressure of tested fuels (b)**

Changes in the injection duration for different injection pressures of the tested fuels are shown in Fig. 3, b. As it can be seen, the injection duration of biodiesel B100 was always somewhat longer than that of the diesel fuel especially under the influence of the injection pressure reduced to 25.0 MPa. In all cases, the actual injection duration was always longer for all fuels tested than the energizing-pulse duration of the injector itself. The injection duration for diesel fuel was 11 %, 26 %, and 40.0 % longer than the duration time of the energizing-pulse for the respective injection pressures of 25.0, 50.0, and 100 MPa. Actual fuel injection duration represents the time interval between the start and the end of injection and it was found by analysing the measured injection rate characteristics.

Fig. 4b shows the dependency of the discharge coefficient on the injection pressure of the tested fuels. The discharge coefficient of diesel fuel is considerably higher than that of biodiesel B100 within a wide variation range of the injection pressure. The discharge coefficient increased up to certain extent for diesel fuel and biodiesel to sustain at almost stable level with further increase of the injection pressure of the fuels. It should be toted that the discharge coefficient for biodiesel B100 was about 18 % lower than that for the normal diesel fuel, when the injection pressure reached the maximum value of 100.0 MPa.

## Conclusions

The peak injection rate (by volume and mass) for biodiesel B100 was lower than that of diesel fuel under similar test conditions. The injection rate of diesel fuel differs as having the highest front-rising slope after the start of injection compared to that produced by the injection of neat biodiesel B100.

The actual injection duration time was always longer than the duration of the energizing-pulse of the injector itself. This occurred because the response time of the injector solenoid to the in-coming control signal was quicker than that needed to actuate the fuel injector.

The discharge coefficients for biodiesel B100 were always lower than of diesel fuel, because the density and viscosity of RME were about 6 % and 2 times higher than the respective values of the normal diesel fuel.

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