EXPERIMENTAL STUDY ON INFLUENCE OF BIOFUELS ON INJECTION CHARACTERISTICS OF DIESEL ENGINE COMMON RAIL SYSTEM

Stasys Slavinskas, Paulius Bendziunas
Vytautas Magnus University, Lithuania
stasys.slavinskas@vdu.lt, paulius.bendziunas@vdu.lt

Abstract. The presented work focuses on experimental analyses of the influence of biofuels on the injection characteristics of a common rail injection system. Mineral diesel fuel, neat biodiesel fuel made from rapeseed oil and hydrotreated vegetable oil are addressed. Attention is focused on the injection characteristics which significantly influence the engine characteristics and subsequently the exhaust emissions. The injection rate, and the cycle injection quantity are studied across a range of injection pressures and injector energising duration. The fuel injection rates were measured and analysed using an injection rate measuring system based on the Bosch method. The measurement concept is based on measuring the change in the pressure by the injection of fuel into a long measuring tube filled with fuel. This pressure change is proportional to the fuel injection rate. The tested biodiesel shows lower injection rates at the stable injection period in the volumetric injection rate curves, but the mass injection rates among all test fuels are quite close. Injection delay was longer by injection of biodiesel than by injection of other fuels tested. The injector energizing time significantly influences the shape of the injection rate curve. The actual injection duration in all cases exceeded the injector energising pulse duration. The results show that the fuel density is the main property that affects the injection process. Fuel viscosity also affects, but to a lesser extent, the injector mass flow rate since it changes the coefficient of friction.

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

Introduction

Diesel engines are extensively utilized in the transportation sector owing to their elevated thermal efficiency, longevity, and robust torque delivery [1]. Nevertheless, they possess a significant drawback: diesel engines produce higher levels of NOx and particulate matter emissions compared to gasoline engines [2]. Stringent regulations and consumption restrictions are being implemented to curb diesel fuel usage, aiming to reduce environmental pollution and mitigate climate change impacts. The substantial consumption of oil heavily pollutes the environment and contributes to global warming. The demand for biofuel is projected to grow by 38 billion litres between 2023 and 2028, representing a nearly 30% increase compared to the previous five-year span [3].

Biodiesel stands out as one of the premier alternative fuels for diesel engines. Biodiesel presents a feasible renewable and environmentally friendly substitute for conventional diesel fuel in transportation. It is derived from diverse renewable sources like vegetable oils, animal fats, and waste cooking oils via transesterification. This process involves reacting oils or fats with alcohol, typically methanol or ethanol, alongside a catalyst to produce fatty acid methyl or ethyl esters (FAME and FAEE), commonly referred to as biodiesel [4].

Hydrogenated vegetable oil (HVO) has recently become an attractive alternative to ester-type diesel fuels. It can be produced from non-edible vegetable oils, animal fats, waste oils and consists of a mixture of paraffinic hydrocarbons in diesel boiling range, is free of sulphur, oxygen and aromatics. Neat HVO has high cetane number and low density. Its bulk modulus is similar to petroleum diesel. The production is based on a catalytic reaction in which hydrocarbons are obtained by removing heteroatoms from organic raw materials using hydrogen as a reducing agent [5].

During the injection process, the energy from the fuel pressure is transformed into kinetic energy. Consequently, the injection process is influenced by the distinct physical properties of biofuels and alternative fuels. Despite having distinct physical and chemical properties compared to conventional diesel, biodiesel offers differences that encourage its increased utilization. These properties, including higher viscosity, surface tension, and density, influence the spray characteristics of biodiesel fuel [6]. Reduced viscosity is advantageous for spray properties, particularly when combined with denser fuels, but it may lead to leakage and inferior spray quality in older diesel engines with low fuel pressure. While low density is beneficial for blending with denser fuels and viscosity, it typically results in greater fuel consumption unless offset by a higher heating value, potentially causing a notable rise in volumetric fuel consumption figures [7].

DOI: 10.22616/ERDev.2024.23.TF067

Dong Han examined research on the injection processes on a high-pressure common rail injection system of two long-chain fatty acid esters and short–chain fatty acid ester and compared to the diesel fuel. He concluded that diesel demonstrates lower density and viscosity compared to the tested fatty acid esters, leading to a faster volumetric injection rate increase initially and higher injection rates with the needle valve fully lifted. However, despite these differences, mass injection rates remain similar due to the compensatory effect of the higher density of fatty acid esters [8]. Kegl et al. conducted an experimental and numerical investigation into the injection properties of diesel, rapeseed biodiesel, and their mixtures using a mechanical injection system. Their findings revealed that higher biodiesel content results in greater fuelling, longer injection duration, and increased injection pressure, while it reduces injection delay and advances injection timing [9-10]. Caresana determined that the utilization of biodiesel does not invariably result in a greater maximum injection pressure compared to diesel [11]. Seykens and colleagues examined the injection features, including the injection rate, pressure, and displacement of the injector control plunger, for both diesel and rapeseed methyl ester (RME) on a common rail system using a one-dimensional model. Their findings indicate that RME leads to only a slight decrease in the flow rate without any impact on injection timing [12].

Qiang Cheng and other colleagues conducted additional research into the impact of HVO diesel on spray dynamics. They concluded that there is no remarkable difference in the spray geometry between HVO and petroleum diesel. However, air density had some impact on spray dynamics based on momentum flux conservation [13].

A review of available studies showed that there is still a lack of research on the effects of HVO on injection characteristics. Most studies primarily focus on actual biodiesel fuels, which consist of various fatty acid alkyl ester blends. The purpose of the research was to investigate the effects of different properties of fatty acid esters and hydrotreated vegetable oils on the injection rate, and the quantity of fuel mass injected per cycle across various injection pressures and injector energizing duration.

Materials and methods

The analysis of injection characteristics for the test fuels was conducted using a high-pressure common rail fuel injection test setup. This setup comprises a high-pressure fuel pump, a common rail, an injector, a fuel pressure measurement system, an electronic control unit (ECU), and a data acquisition system. The diagram of the experimental arrangement is shown in Fig.1. Bosch CR 2.2 (0445110256) injector with a seven-hole nozzle was used.

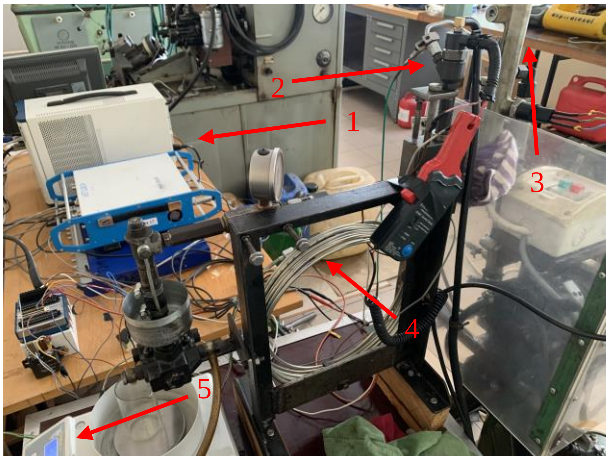

Fig. 1. **Schematic view of the fuel injection testing stand:** 1 – data acquisition system; 2 – injector; 3 – common rail; 4 – measuring tube; 5 – precision scale

The Bosch method was employed to measure the fuel injection rates [14]. Tests were conducted at different injection pressures of 60 MPa, 120 MPa, and 180 MPa and three energizing durations of 0.6 ms, 1.0 ms, and 1.4 ms. The back pressure was held at 6 MPa and the injection frequency was 8 Hz to ensure an adequate duration for the pressure fluctuations in the measuring tube to decrease before the next injection event sufficiently. The injection volume was derived from the average of 1000 consecutive injections, measured using a precision scale. The results of 300 injection cycles were recorded and averaged for the following analysis of fuel injection characteristics. A more detailed description of the equipment is presented in previous publications [15].

Table 1

Main fuel properties

Parameter	Density at 15 °C, kg·m^{-3}	Kinematic viscosity at 40 °C, mm^2·s^{-1}	Net heating value, MJ·kg^{-1}
Diesel fuel (DF)	832.7	2.13	43.0
RME	883.6	4.44	37.23
HVO	779.8	2.92	43.8

Rapeseed oil methyl ester (RME), hydrotreated vegetable oil (HVO) and mineral diesel fuel (DF) as a reference fuel were used in this study. RME diesel was manufactured by JSC “RAPSOILA” and complies with the European and Lithuanian LST EN 14214 quality standards. Diesel fuel (DF) was manufactured at the company “ORLEN Lietuva” and met the quality standards outlined in EN 590:2014. HVO fuel was manufactured at the company “NESTE” and adhered to the quality criteria specified in LST EN 15940. The table shows the main properties of the studied fuels that are relevant to this study.

Results and discussion

Fig. 2 provided injection rates of the tested fuel (in volume units) at different injection pressures and the injection pulse signal duration of 0.6 ms, 1.0 ms and 1.4 ms.

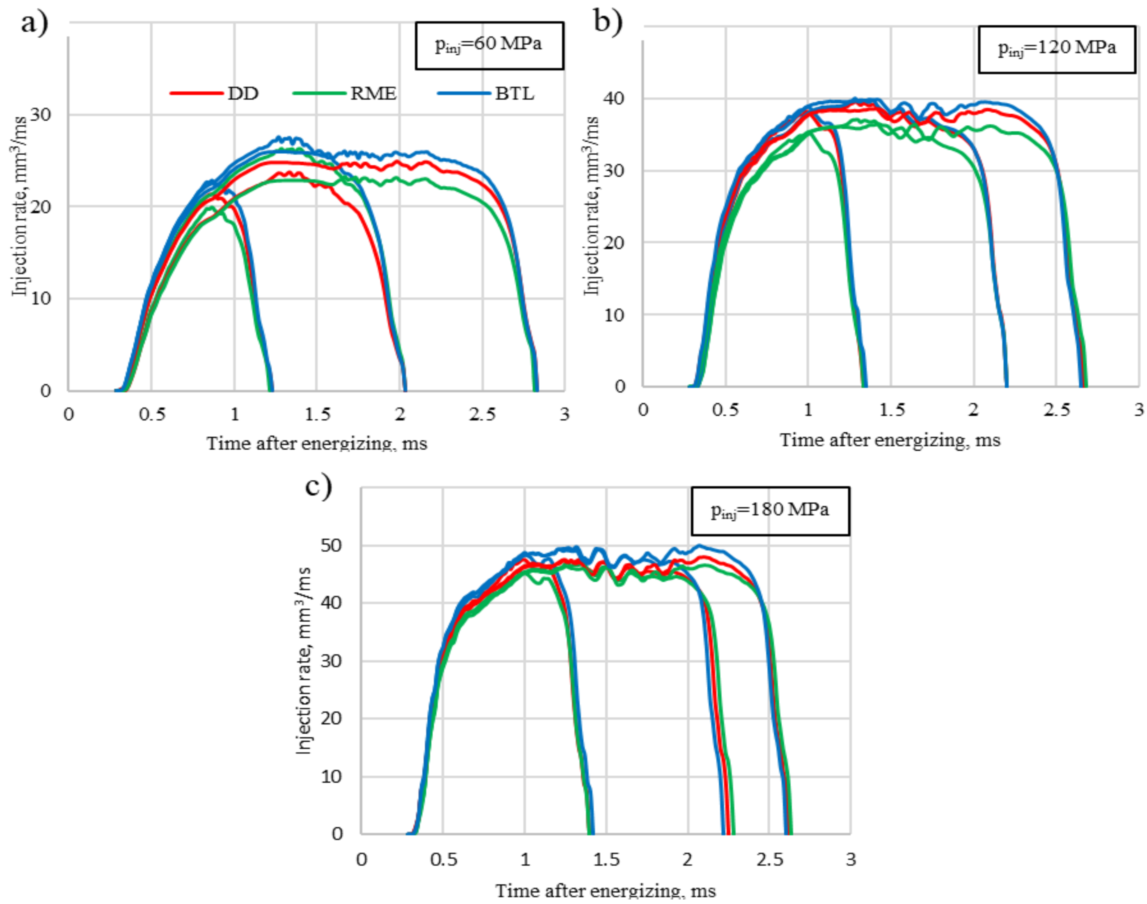

Fig. 2. **Volumetric injection rates of test fuels at 60 MPa, 120 MPa, 180 MPa injection pressures and at 0.6 ms, 1.0 ms, 1.4 ms injector energizing duration**

From the obtained data, it can be noticed that in all cases, as the injection pressure increases, the injection rate also increases. At an injection pressure of 60,0 MPa and 1.4 ms injector energizing duration, the maximum injection rate of RME was 6.43% lower compared to DF. The injection rate of HVO was 3.86% higher compared to DF. At an injection pressure of 120.0 MPa and 1.4 ms injector energizing duration, the maximum RME injection rate was 5.44% lower than that of DF. Using HVO, the injection rate was 3.02% higher compared to DF. As the injection pressure increases, the difference in the peak injection rate between fuels decreases. At an injection pressure of 180.0 MPa and 1.4 ms injector energizing duration, the injection rate of RME was 2.91% lower than DF. The peak injection rate of HVO was 2.83% higher than DF. Variations in the injection rate are caused by different densities and viscosities of the fuel. The results show that the maximum injection rate of the denser and more viscous RME fuel was lower, and the maximum injection rate of the lighter HVO fuel was higher than that of diesel fuel. Other researchers have confirmed a similar effect of fuel properties on the injection rate [12].

When investigating the fuel injection rate characteristics, the injection delay and injection duration were calculated. Injection delay is the time between the start of the injector energizing and the start of injection. Fig. 3 shows the effect of the injection pressure on the injection delay for the studied fuels.

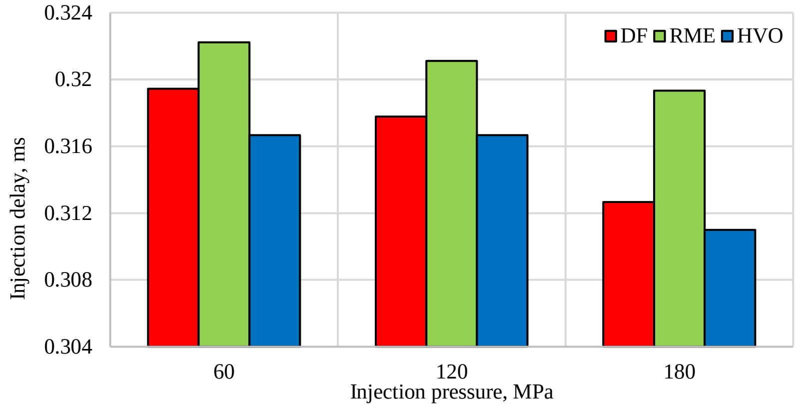

Fig. 3. **Injection delay versus injection pressure for different test fuels**

At an injection pressure of 60 MPa and 120 MPa, the maximum injection delay of RME was approximately 1% greater compared to that of DF. The shortest injection delay was obtained for HVO, which was approximately 1% and 0.6% less than that of DF at 60 MPa and 120 MPa injection pressures respectively. Increasing the injection pressure to 180 MPa, the injection delay of RME was even 2.24% greater than for DF, while for HVO, it was 0.32% less. As shown, lower density and lower viscosity fuels reduce injection delay, although overall the differences are very small.

The injection delay decreases with increasing the injection pressure. Higher fuel injection pressure results in greater force, which quicker lifts the injector needle. Additionally, the viscosity and density values of the fuel also influence the start of injection, as they are related to fluid inertia and flow resistance. Fuels with high viscosity or density slow down the flow processes when fuel flows out of the injector control chamber and nozzle.

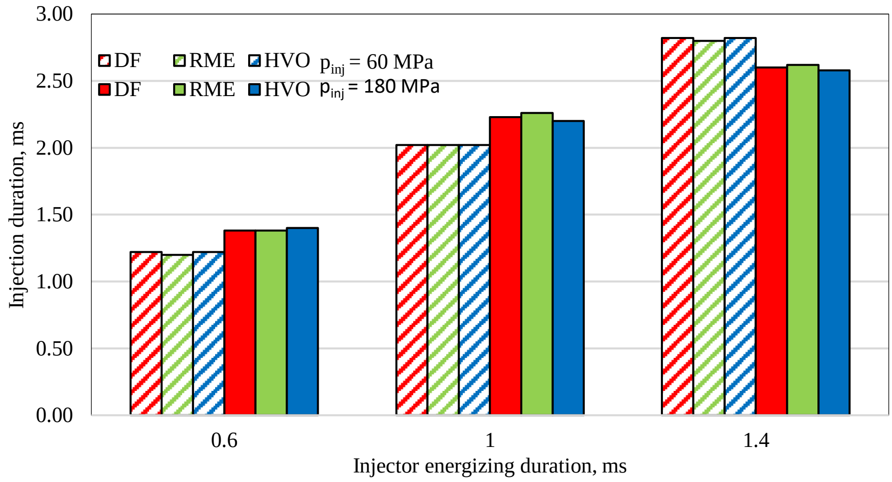

Fig. 4. **Injection duration versus injector energizing duration for different test fuels**

Injection duration is the time interval between the start and the end of the injection. Fig. 4 illustrates the influence of the injection pressure on injection duration for injector control pulse durations of 0.6 ms, 1.0 ms, and 1.4 ms. From the graphs provided, it can be inferred that there is little difference in injection duration. In all cases, the injection duration exceeded the duration of the injector control pulse by 1.9-2.3 times.

At an injection pressure of 60 MPa and an injector control pulse duration of 0.6 ms, the injection duration for HVO and RME was about 4.5% shorter than that for DF. At higher injection pressure and longer injector control pulse, the injection duration was slightly longer for RME and shorter for HVO injection. These differences result from the later end of RME injection and the earlier end of HVO injection. The less dense and viscous HVO likely fills the injector control chamber more quickly. As a result, the pressure in it increases faster and the plunger closes the nozzle earlier. In addition, due to the lower viscosity of the fuel, the resistance to movement of the nozzle needle is lower.

Fig. 5 shows the fuel cycle injection quantities versus the injection pressure for different test fuels and 1.0 ms energizing duration. As shown, the volumetric cycle injection quantities are higher by injection of lower density and viscosity fuels. At 60 MPa and 120 MPa injection pressure, the volumetric cycle injection quantities of RME compared to DF were approximately 6.5% less. At 180 MPa injection pressure, the difference in the volumetric cycle injection quantity decreases to 1.3% compared to DF. The volumetric cycle injection quantity of HVO at 60 MPa injection pressure was 5.5% higher compared to DF, while at 120 MPa and 180 MPa injection pressure, the difference decreased to approximately 2%.

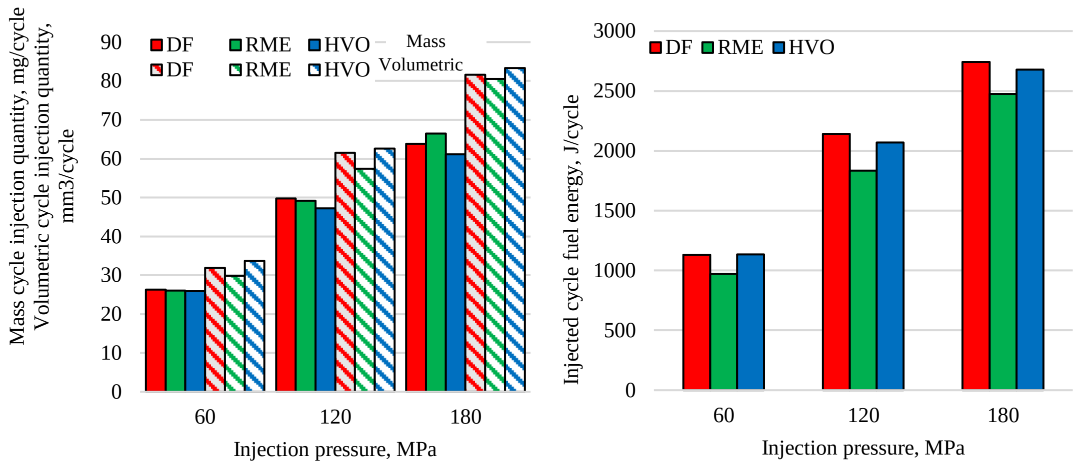

Fig. 5. **Volumetric and mass cycle injection quantity of different test fuels at different injection pressures and 1.0 ms energizing duration**

However, the lower density of fuels reduces its mass cycle injection quantities. At 60 MPa and 120 MPa the injection pressure mass cycle injection quantities of RME were nearly 1% less than those of DF. As the injection pressure gets higher to 180 MPa, the difference in the mass cycle injection quantity reaches 4.2% between RME and DF. Mass cycle injection quantities of HVO were 1.7%, 5.2%, and 4.2% lower compared to DF at 60 MPa, 120 MPa, and 180 MPa injection pressure respectively.

The injected cycle fuel energies of RME fluctuated around 14.4% less than DF at lower 60 MPa and 120 MPa injection pressures. At 180 MPa injection pressure, the injected cycle fuel energy of RME difference decreases to 9.7% compared to DF. The injected cycle fuel energies of HVO were 0.2%, 3.4%, and 2.4% lower compared to DF at 60 MPa, 120 MPa, and 180 MPa injection pressure respectively.

Conclusions

1. The peak volumetric injection rate of RME was obtained 6.43, 5.44 and 2.91% lower and the peak volumetric injection rate of HVO was obtained 3.86, 3.02 and 2.83% higher compared to that of mineral diesel fuel at an injection pressure 60, 120 and 180 MPa correspondently.
2. The tested biofuels did not significantly affect the injection delay and injection duration.

3. At the same injection pressure and injector control pulse duration, the volumetric cycle injection quantities of RME are lower, and of HVO are higher compared to that of DF.
4. Replacing mineral diesel with HVO reduces the amount of cyclic energy supplied to the cylinders less than replacing it with RME.

Author contributions

Conceptualization, S.S., methodology, S.S. and P.B., formal analysis, S.S. and P.B., investigation, S.S. and P.B., data curation, S.S., and P.B., writing – original draft preparation, P.B., writing – review and editing, S.S. and P.B., visualization, P.B. All authors have read and agreed to the published version of the manuscript.

References

[1] Wei J., He C., Lv G., Zhuang Y., Qian Y., Pan S. The combustion, performance and emissions investigation of a dual fuel diesel engine using silicon dioxide nanoparticle additives to methanol. Energy 2021, Vol. 230, DOI: 10.1016/j.energy.2021.120734
[2] Li X., Gao H., Zhao L., Zhang Z., He X., LiuF. Combustion and emission performance of a split injection diesel engine in a double swirl combustion system, Energy, Vol. 114, 2016, pp. 1135-1146, DOI: 10.1016/j.energy.2016.08.092
[3] IEA (2024), Renewables 2023, IEA, Paris, Licence: CC BY 4.0 [online] [11.02.2024] Available at: https://www.iea.org/reports/renewables-2023
[4] Emmanouilidou E., Lazaridou A., Mitkidou S., Kokkinos N. C. A comparative study on biodiesel production from edible and non-edible biomasses, Journal of Molecular Structure, Vol. 1306, 2024, DOI: 10.1016/j.molstruc.2024.137870
[5] Szeto W., Leung D. Y. C. Is hydrotreated vegetable oil a superior substitute for fossil diesel? A comprehensive review on physicochemical properties, engine performance and emissions. Fuel, Vol. 327, 2022, pp. 1-23. DOI: 10.1016/j.fuel.2022.125065
[6] Al-Dawody M. F., Al-Farhany K. A., Hamza N. H., Hamzah D. A. Numerical study for the spray characteristics of diesel engine powered by biodiesel fuels under different injection pressures. Journal of Engineering Research (2307-1877), 10(1B), 2022, pp. 264-289.
[7] Smigins R., Sondors K., Pirs V., Dukulis I., Birzietis G. Studies of engine performance and emissions at full-load mode Using HVO, diesel fuel, and HVO5. Energies, 16, 2023, 4785. DOI: 10.3390/en16124785
[8] Han D., Duan Y., Wang C., Lin H., Huang Z. Experimental study on injection characteristics of fatty acid esters on a diesel engine common rail system. Fuel. Vol. 123, 2014, pp. 19-25, DOI: 10.1016/j.fuel.2014.01.048.
[9] Kegl B., Hribernik A. Experimental analysis of injection characteristics using biodiesel fuel. Energy Fuels 2006:20(5), pp. 2239-2248.
[10] Kegl B. Numerical analysis of injection characteristics using biodiesel fuel. Fuel. 2006:85(17-18), pp. 2377-2387.
[11] Caresana F. Impact of biodiesel bulk modulus on injection pressure and injection timing. The effect of residual pressure. Fuel, Vol. 90, 2011, pp. 477-485, DOI: 10.1016/j.fuel.2010.10.005
[12] Seykens X.L.J, Somers L.M.T, Baert R.S.G. Modelling of common rail fuel injection system and influence of fluid properties on injection process. In: Proceedings of VAFSEP Conference, Dublin, 2004.
[13] Cheng Q., Tuomo H., Kaario O.T., Martti L. Spray dynamics of HVO and EN590 diesel fuels. Fuel, Vol. 245, 2019, pp. 198-211, DOI: 10.1016/j.fuel.2019.01.123
[14] Bosch W. The Fuel Rate Indicator: A New Measuring Instrument For Display of the Characteristics of Individual Injection. SAE Transactions, 75, 1967, pp. 641-662. [online] [11.02.2024] Available at: http://www.jstor.org/stable/44553433
[15] Slavinskas S., Labeckas G., Mickevičius T. Experimental study on injection characteristics of diesel and biodiesel fuel blends with common rail injection system. In: Proceedings of 17th International Scientific Conference "Engineering for Rural Development", Faculty of Engineering, Jelgava, LLU, 2018, pp. 2134-2140. DOI: 10.22616/ERDev2018.17.N504