

## Tribological study of high-pressure fuel pump operating with ethanol-diesel fuel blends

*This paper presents comparative experimental study's results of ethanol-diesel fuel blends made effects on operational properties of a high-pressure fuel pump of a common rail injection system. The two identical fuel injection systems mounted on a test bed of the fuel injection pumps were prepared for the experimental durability tests. The lubricity properties of ethanol-diesel fuel blends E10 and E20 blends were studied using a four-ball tribometer. The test results showed that long-term (about 100 hours) using of ethanol-diesel blends produced a negative effect on the durability of the high-pressure fuel pump. Due to the wear of plunger-barrel units the decrease in the fuel delivery rate occurred of about 39% after the 100 h of continuous operation with ethanol-diesel fuel blends. The average friction coefficients of ethanol-diesel fuel blend E10 was lower than that of the normal diesel fuel. After the 100 hours of operation with ethanol-diesel fuel blend E10, the measured wear scar diameter was 10% higher than that of a fossil diesel fuel.*

Key words: diesel fuel, ethanol-diesel fuel blends, lubricity, four ball test rig, plunger-barrel units, wear scar diameter

### 1. Introduction

In the recent decades, the scientists continue to work on the rational global energy using as well as urgent ecological and environmental problems. The requirements stated by the EU parliamentarians to intensify the development of renewable energy sources, strict environmental requests associated with the reduction of greenhouse gas emissions and wastes in the municipal economy, agricultural and forestry sectors encourage the researchers to investigate alternative and renewable energy strategies including a wider use of biofuels. Up to now, the researchers have not offered new technological solutions that would completely replace internal combustion engines by other mechanical energy sources. For this reason, oil and the natural gas reserves rapidly decrease over the recent decades. Moreover, smoke and exhaust emissions produced by internal combustion engines cause serious damage to the ecological system.

Agriculture and transport sectors are among the largest fossil fuel consumers and therefore can be regarded as the biggest contributors to the environmental pollution. The mineral diesel fuel traditionally remains the most popular among the others motor fuels. Consumption of the diesel fuel has been growing steadily over the last two decades.

The physical properties of the fuel such as density, viscosity and bulk modulus of compressibility affect the delivery rate and the injection characteristics and thus the quality of the air and the fuel mixture, which in turn affects the combustion process, brake thermal efficiency and the ecological parameters of the diesel engine. Specific properties of alternative and renewable biofuels such as density, viscosity, calorific value, cetane number, freezing point, etc. differ from those of the normal diesel fuel. Mixing diesel fuel with ethanol or other alcohols reduces viscosity of the blend [1]. In case the viscosity of biofuels (ethanol) is too low, this can result in more intensive wear of plunger-barrel and the needle-valve-nozzle units. The fuel injection systems for Euro 6 and beyond will have to generate extremely high fuel injection pressures and controlled injection events to meet the strictest legislations associated with engine out

emissions [2]. A higher boiling point and aromatic, nitrogen, and sulphur contents appear to improve lubricity of the diesel fuel [3].

The three main methods can be using to measure the lubrication properties of the fuel: the High Frequency Reciprocating Rig (HFRR), Scuffing Load Ball On Cylinder Lubricity Evaluator (SLBOCLE) and the four-ball test machine method [4].

The scientists conducted the lubricity studies of ethanol and the diesel fuel by using HFRR method. They found that ethanol addition of up to 14% (v/v) to diesel fuel meets the EN 590 standard requirements and thus has minor effect on the values of the average Wear Scar Diameter (WSD) [5]. The limits of diesel lubricity standards of the wear scar are established as 460 and 520  $\mu\text{m}$ . The others authors showed that the wear scar diameter for diesel fuel is lower, while for the blend with ethanol is higher [6]. In contrast to other studies the authors reported that the addition of ethanol assisted to improve lubricity of the diesel fuel [8]. The results of these studies show that there is no consensus on the effect of ethanol on the fuel lubricity and reliability of fuel injection systems.

When the amount of ethanol in the diesel fuel is increased, the cetane number (CN) is decreased proportionally. However, the auto-ignition delay period for diesel fuel, especially synthetic biofuel, does not always directly depend on the cetane number value [7–9]. The auto-ignition delay depends on chemical composition and physical properties of the fuel as well as on gas maximum pressure and the temperature inside the combustion chamber. Significant influence on the ignition delay also provide such factors as the shape of combustion chamber, compression ratio, chemical structure of the fuel and the fuel injection characteristics that affects the quality of combustible mixture and the temperature variations prior to TDC during the compression stroke.

The calorific value of ethanol is lower than that of the diesel fuel. When alcohols are added to diesel fuel, net heating value of the blend decreases and the brake specific fuel consumption increases [1, 7–9]. Actually, application

oxygenated additives in the diesel fuel results in relatively higher brake specific fuel consumption, slightly higher brake thermal efficiency of an engine operating in the most common load and speed conditions. The increased brake thermal efficiency of an engine can be attributed to the fact that the fuel-bound oxygen provides an essential help in burning the fuel completely during the diffusive combustion phase. Ethanol added to diesel fuel considerably reduces flash point of the blend and increases the possibility to catch a fire. Ethanol solubility in the diesel fuel depends on the hydrocarbon composition of the fuel, temperature, content of water and wax in the blend and ambient humidity [8].

Authors of the studies [7–9] noted that using of ethanol and other oxygenated additives reduces the amount of nitrogen oxides in the exhaust gases due to lower combustion temperature of biofuel blends and higher overall relative air/fuel ratio. The amount of total unburned hydrocarbons in exhaust gases depends on engine load and has tendency to increase with increasing ethanol content of the fuel. Ethanol added to diesel fuel has the potential to reduce the production of carbon monoxide, but higher than the 4–5 wt% ethanol-oxygen content may result in higher CO emissions when running a fully loaded engine at the high speed of 2200 rpm [7].

However, the long-term impact of ethanol-diesel fuel blends with relatively lower density, viscosity and lubricity properties on the reliability of a Common Rail Direct Injection (CRDI) system remains unexplored to a greater degree of extension and thus requires specific experimental tests. The aim of the research is to investigate the effect of bio-ethanol on the durability of the main components of a high-pressure common rail fuel pump.

## 2. Materials and methods

The experimental investigation was carried out in the fuel systems testing laboratory at Power and Transport Machinery Engineering Institute, Faculty of Agricultural Engineering of Vytautas Magnus University – Agricultural Academy.

The common rail injection system has been used for the experimental tests. The principal arrangement of the test stand, equipment and apparatus are shown in Fig. 1.

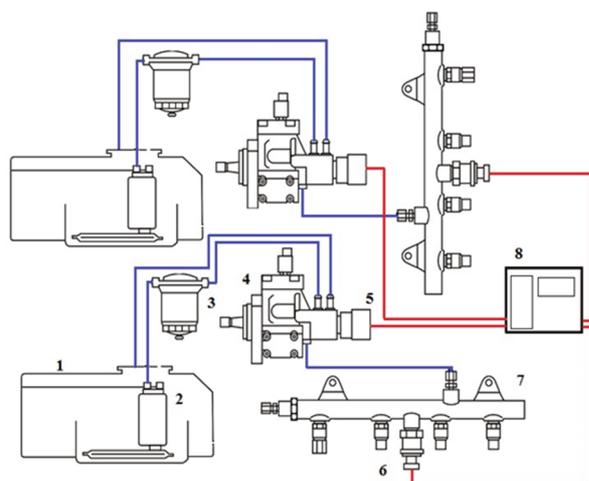


Fig. 1. Scheme of the testing stand: 1 – fuel tank; 2 – fuel supply pump; 3 – fuel filter; 4 – high-pressure pump; 5 – pressure control valve; 6 – rail-pressure sensor; 7 – fuel rail; 8 – fuel pressure control

The two Bosch-type high-pressure fuel pumps were connected by the same belt driven in the same mode at speed of 1000 rpm. The electric delivery pump (2) mounted in the fuel tank (1) supplied the fuel through the fine-porous fuel filter (3) to the high-pressure fuel pump (4). Moreover, both fuel pumps maintained the changeable pre-set pressure values depending on the on-going time of every 30 minutes. Powered by an electrical motor, the high-pressure fuel pumps operated continuously to build up the needed injection pressure, which was retained in the volume of the fuel accumulator (7). The pressure was adjusted via a pressure regulator (5) connected to the control unit (8). The sensor installed in the pressure accumulator transferred the resulting signals to the control unit to evaluate the present fuel pressure.

The fuel-flow was cooled in order to assure that the temperature does not exceed the 35°C during the reliability tests of the fuel pumps.

The changes in the fuel delivery rates determined for the various pressure values built up by both fuel pumps at the very beginning (0 hours) of the experiments are illustrated by the columns in Fig. 2.

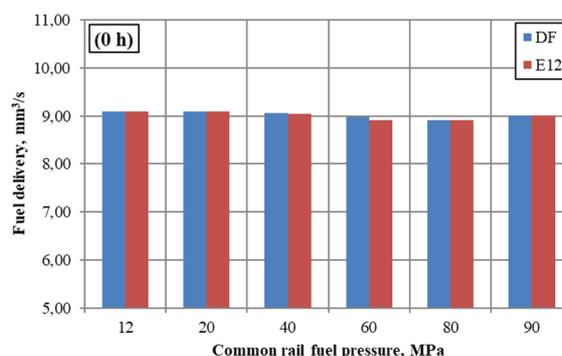


Fig. 2. Changes in a high-pressure pump's fuel delivery rate as a function of fuel pressure built up by a common rail injection system for the beginning of experiments (at zero hours of operation)

Diesel fuel (DF) and the three ethanol-diesel fuel blends E10, E12 and E20 have been used for the experimental tests. The main properties of the tested fuels are listed in Table 1.

Lubricating properties of the fuels were determined by using the four-ball test machine shown in Fig. 3 [4, 5].

Table 1. Properties of the tested fuels

Parameter	Diesel	E12	Ethanol
Density at 40°C (kg/m <sup>3</sup> )	812.6	804.9	788
Kinematic viscosity at 40 °C, mm <sup>2</sup> /s	2.06	1.8	1.2
Lower heating value (MJ/kg)	42.88	40.56	26.95
Cetane number	51.5	44.4	8.0
Flash point, °C	55	13	13
Carbon (% w/w)	87	81.8	52.2
Hydrogen (% w/w)	12.6	12.7	13.0
Oxygen (% w/w)	0.4	5.6	34.8
Sulphur (ppm w/w)	4.1	3.6	–
Molecular weight (g/mol)	200	179.91	46

The load of 150 N was used during the experiments. The tests continued over 1 hour. Before each experimental test,

the all appropriate parts of the machine, i.e. bottom and upper ball holders, fuel vessel and test balls were cleaned up in an ultrasonic bath, and then all parts were dried completely.

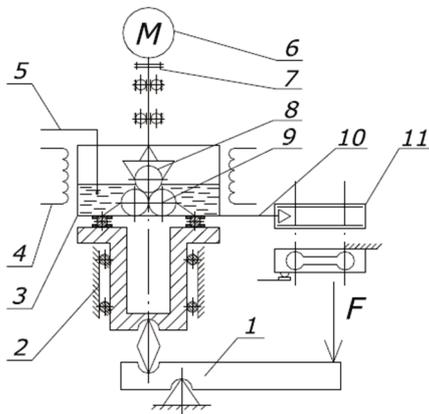


Fig. 3. The scheme of the four-ball tribotester: 1 – load transfer lever; 2 – vertical centre bearing; 3 – oil sample compartment; 4 – oil heater; 5 – thermocouple; 6 – electrical motor; 7 – clutch; 8 – upper rotary ball; 9 – lower stationary balls; 10 – torque transfer lever; 11 – force transducer

The temperature of the fuel was maintained to be of a constant value of about 30° C during the lubricity tests.

The intensity of the balls’ surface wear images was evaluated by using Nikon Elipse MA100 optical microscope.

### 3. Analysis if the results and discussions

The primary purpose of the fuel-injection system is to supply the fuel to the cylinder of a diesel engine. The fuel-injection pump builds up the fuel pressure needed for injection and then at the required rate delivers the fuel to the engine’s cylinders [11].

The columns in Fig. 4 illustrate the changing trends in fuel delivery rate determined for various pressure values built up by the both fuel pumps at the end (after 100 h) of the experimental tests.

Analysis of the obtained results shows that the resulting decrease in the fuel delivery rate was about 16% higher with ethanol-diesel fuel blend E12 at the injection pressure of 60 MPa, while the relative decrease was equal to 39% at a higher pressure of 90 MPa. From the observation of the test results, it can be assumed that the wear intensity of the plunger-barrel units was significantly greater when using ethanol-diesel fuel E12 blend that is especially a case at the injection pressure of 90 MPa. Most likely, that the delivery rate of ethanol-diesel fuel E12 blend was reasonably lower due the resulting wear and thus the leakage of the fuel. The revealed decrease in fuel delivery rate shows that the pump has lost the ability to operate with fuel blend E12, so further experimentations were suspended. The obtained test results actually differ from those effects noted by Armas et al. (2012) illustrating that using of fuel blend with a lower ethanol content (7.7% vol.) does not significantly affect the durability of the common rail fuel pump [12].

The plunger-barrel unit is one of the most overloaded components of the fuel system [11]. It can be assumed that this element is one of the most friction-sensitive units operating in the heaviest friction conditions in the diesel engine and therefore it can be chosen to evaluate the effects done by the rela-

tively worse lubricating properties of ethanol-diesel fuel blends. Columns in Fig. 5 show how the average wear scar of the test ball changed when using the normal diesel fuel and ethanol-diesel fuel blends E10 and E20.

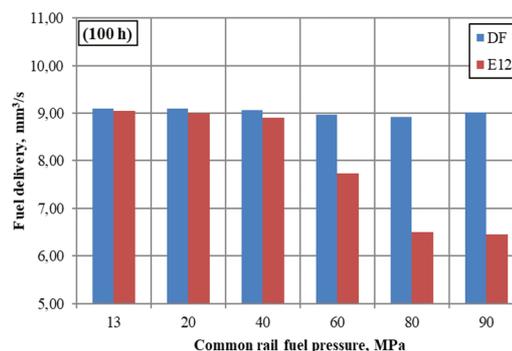


Fig. 4. Changes in a high-pressure pump’s fuel delivery rate as a function of fuel pressure built up by a common rail injection system for the end of experiments (after 100 hours of operation)

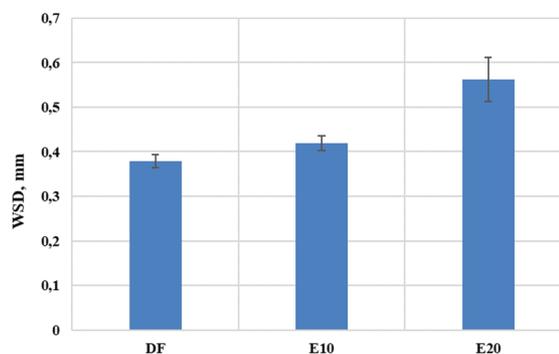


Fig. 5. The dependency of the average wear scar caused by the diesel fuel and ethanol-diesel fuel E10 and E20 blends

The test results demonstrate that the average wear scar with maximum decrease in the diameter of 0.56 mm was obtained when using diesel-ethanol fuel E20 blend. While the minimum wear scar with the diameter of 0.38 mm was recorded with the normal diesel fuel. At the same time, the wear scar diameter was equal to 0.42 mm when running with ethanol-diesel fuel blend E10.

The changing trends in variation of the friction coefficients are illustrated by the diagrams presented in Fig. 6. As can be seen in the diagrams, the friction coefficient was relatively lower and its variation was more stable when using the lowest ethanol-diesel fuel blend E10.

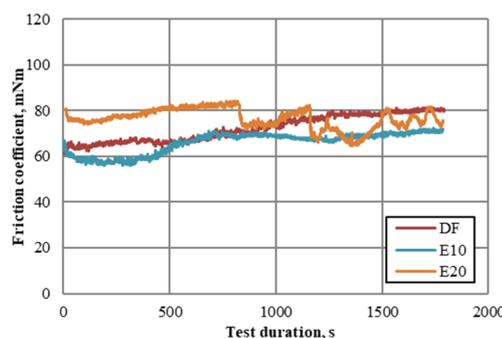


Fig. 6. Variations of friction coefficient for diesel fuel and ethanol-diesel fuel blends E10 and E20 as a function of time

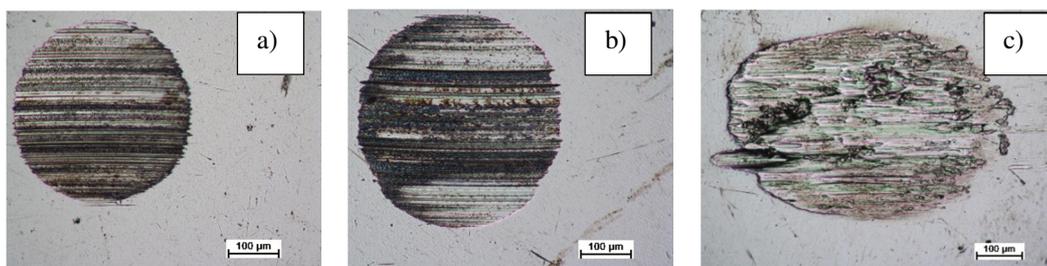


Fig. 7. Images of the worn surfaces areas obtained when lubricating with: a) DF; b) E10; c) E20

Figure 7 shows the images of the worn steel ball surface. The obvious difference in the worn surface area can be seen by comparing the friction pairs lubricated with the different fuels. The images show that using of the diesel fuel resulted in a relatively lower the worn surface area if compared to that caused by ethanol-diesel fuel blends.

### Conclusions

1. The capacity (fuel delivery rate) of a high-pressure fuel injection pump decreased by 39% after the 100 hours' of operation with ethanol-diesel fuel blend E12 under close to real operating conditions.

2. Maximum mean diameter of the wear scar was equal to 0.56 mm when using ethanol-diesel fuel blend E20 and the minimum value of the wear scar was measured when running with the normal diesel fuel.
3. Maximum averaged frictional coefficient was measured when using ethanol-diesel fuel blend E20.
4. Analysis of the experimental data shows that the resulting area of a ball surface wear scar was relatively lower when using diesel fuel due to its better lubricating properties.

### Nomenclature

E ethanol  
E10 10 vol% ethanol/90 vol% diesel fuel  
E12 12 vol% ethanol/88 vol% diesel fuel

E20 20 vol% ethanol/80 vol% diesel fuel  
WSD wear scar diameter

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