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Full Length Article

Lubricity of ethanol–diesel blends – Study with the HFRR method

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HIGHLIGHTS

- Lubricity tests using the HFRR method for the ethanol–diesel blends were presented.
- Microscopic photographs of the test ball wear scars were presented and discussed.
- The results of the lubricity tests were referenced to the standard requirements.

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ABSTRACT

Due to increasing fuel consumption in various industries, especially in road transport, interest in increasing the market participation of renewable fuels is growing. One such fuel is ethanol. The raw materials for its production include sugar beets, sugar cane, potatoes and many other starch-containing plants. Ethanol can be used as a pure fuel in positive-ignition engines that have undergone relatively minor technical modifications. However, in compression-ignition engines, due to factors such as a very low cetane number and lubricity, ethanol cannot be used as a pure fuel. Therefore, increasing attention is being paid to fuel consisting of blends of diesel fuel with certain concentrations of ethanol. Diesel fuel containing up to 15% (v/v) ethanol is sometimes referred to as e-diesel or oxygenated diesel. In this paper, the lubricity of blends of conventional diesel fuel and ethanol, with ethanol content up to 14% (v/v), were tested. The HFRR (*High-Frequency Reciprocating Rig*) method was used for the research, which is a normative method of determining the lubricity of diesel fuel. For individual fuel samples, microscopic photographs of wear scar caused on test balls, along with the designation of areas that have been considered when measuring the diameters of wear scars, were presented. The obtained values of WSD (*Wear Scar Diameter*) were compared to the regulatory requirements for diesel fuels. Further measurements of kinematic viscosity, density and water content were conducted for individual fuel samples. The results showed that in the range of up to 14% (v/v), the proportion of ethanol in diesel fuel causes hardly any changes to its lubricity as determined by HFRR, and in addition, diesel fuel with up to 14% (v/v) added ethanol still meets the standard requirements in terms of lubricity.

1. Introduction

Limitations resulting from the increasingly stringent standards for exhaust emissions and the relatively high prices of fuels derived from crude oil are stimulating increased interest in alternative fuels. At the same time, an unflagging interest in the use of compression-ignition engines in industry and transport, especially road transport, can be observed. For some time, supplying engines of this type with diesel fuel containing esters of plant oils has been common, but recently, interest in the use of common alcohols in engines of this type can also be observed. Particular attention has been focused on the use of ethanol, as this alcohol can be produced from vegetable products, and thus can be considered a fully renewable fuel.

Since ethanol includes a very low cetane number, and thus a very low tendency to self-ignition [1–6], it cannot be used as a self-sustainable fuel in compression-ignition engines.

For this reason, blends of diesel fuel and ethanol, especially dehydrated ethanol that has a relatively good miscibility with diesel fuel, are considered to be a rational solution. The issue of miscibility of ethanol with diesel fuel is more widely presented in previous studies [2,7,8]. Since the higher percentages of ethanol in diesel fuel already require major modifications in order to adapt the parameters of such blends to the requirements for conven-

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Nomenclature

BOCLE	Ball-on-Cylinder Lubricity Evaluator
BOTD	Ball-on-Three Discs
BOTS	Ball-on-Three Seats
CFPP	Cold Filter Plugging Point
HFRR	High-Frequency Reciprocating Rig
MWSD	Mean Wear Scar Diameter
SLBOCLE	Scuffing Load Ball-on-Cylinder Lubricity Evaluator
WS 1.4	Wear Scar diameter corrected to a standardized water vapour pressure of 1.4 kPa
WSD	Wear Scar Diameter (WSD = (X + Y)/2)
X	Scar dimensions perpendicular to oscillation direction, expressed in micrometres (μm)
Y	Scar dimensions parallel to oscillation direction, expressed in micrometres (μm)
ν	kinematic viscosity at 60 °C (mm^2/s)
η	dynamic viscosity at 60 °C (mPa s)
ρ	density at 60 °C (g/cm^3)
γ	water content (mg/kg)
ΔWSD	uncertainty of WSD measurements (μm)
ΔWS 1.4	uncertainty of WS 1.4 measurements (μm)
Δv	uncertainty of kinematic viscosity measurements (mm^2/s)
$\Delta \upsilon$	uncertainty of dynamic viscosity measurements (mPa s)
$\Delta \eta$	uncertainty of density measurements (g/cm^3)
$\Delta \gamma$	uncertainty of water content measurements (mg/kg)

tional diesel fuels, most frequently, researchers focus on blends containing up to 15% (v/v) of ethanol [1].

A number of researchers [1,2,4,9,10] simultaneously indicate different physico-chemical properties of such blends with respect to diesel fuel. Tores-Jimenez et al. [9] have conducted extensive research on physico-chemical properties of diesel fuel and diesel blends comprising ethanol volumes of 5%, 10% and 15%. In their research, they have shown, *inter alia*, that increasing the volume of ethanol decreases the density of the blend (determined at 15 °C), kinematic viscosity (determined at 40 °C) and pour point, while the cloud point and water content increase. For all blends, they obtained the same value of the flash point (25 °C for blends and 66 °C for diesel fuel). For the tested blends, virtually no impact of the ethanol volume on the cold filter plugging point (CFPP) or changes in corrosion influence on the copper plates were observed.

An important parameter in terms of the sustainability of precision pairs of compression-ignition-engine power supplies is the viscosity and lubricity of the fuel [11,12]. To prevent the seizing of friction connections in the supply system, the friction surfaces must be separated by a durable layer of lubricant. In the vast majority of the currently used structural solutions for systems of injection in compression-ignition engines, the only lubricant is fuel. Due to the relatively low viscosity of the fuel, the conditions generally present in the friction connections of injection systems allow the occurrence of boundary lubrication, rather than hydrodynamic lubrication [13]. Durability of boundary layers in the friction connections limiting the wear processes is determined by fuel lubricity. Fuels with better lubricating properties have greater ability to create permanent boundary layers. In turn, this ability depends, *inter alia*, on adsorptive properties of the fuel – i.e., the presence of fuel substances of polar nature. Such substances include, among others, sulphur and its compounds.

Several methods are used to assess the lubricity of fuels. The most frequently used is the HFRR method in which a loaded steel ball is the operating member. The ball, being under an appropriate load, is pressed against a fixed steel plate immersed in the tested fuel, and it moves along in a reciprocating manner, at an established stroke, and with a specified frequency. The lubricity measure of fuel in this method is the diameter of the wear scar resulting on the ball. The results of the research on fuel lubricity determined by the HFRR method can be found, for example, in Refs. [9,14–20].

Some works, including [21–23], point out that the HFRR method is characterized by the low sensitivity of lubricity results in cases of low concentrations of some fuel additives. This may be due to the nature of the wear mechanism that occurs in the test friction node of this method. Hsieh and Bruno [24] reported that the predominant wear in the HFRR method is plasticity-dominated – i.e., adhesive wear and delamination wear. Under such conditions, some polar compounds, due to their low concentrations, may not produce a sufficiently stable lubrication film that can subsequently degrade within the tribological node [25]. Fox [26] proposed a relation between HFRR wear scar diameter and lubricity additive concentration as an inverse sigmoidal curve. From this relation, three characteristic ranges can be observed. For the first range (specified low additive concentrations), there is no reduction in wear scar with an increase in additive concentration. For the second range (determined, effective additive concentrations), a clear reduction in wear scar is observed when increasing the concentration of the additive. The third range (defined higher concentration of additives) indicates that increasing the level of additives beyond a specified concentration does not reduce the wear scar. It should also be noted that some lubricant additives under the HFRR test conditions may have a different efficiency for mineral and synthetic diesel fuels [27].

Although the HFRR method may not be sensitive to the presence of fuel additives at low concentrations, in accordance with the standard requirements, the lubricity of diesel fuel should be determined by this method. According to the EN 590 standard [28] to evaluate the lubricity of diesel fuel, the ISO 12156-1 standard [29] must be applied, while according to the ASTM D975 standard [30], ASTM D6079 [31] or ASTM D7688 [32] should be applied for this purpose, with the prevailing application of ASTM D6079 [31]. For aviation kerosene, the recommended and standard method of lubricity evaluation is the BOCLE (*Ball-on-Cylinder Lubricity Evaluator*) method, where the loaded ball cooperates with a rotating ring partially submerged in the tested fuel, and the diameter of the wear scar formed on the ball is used as a measure of the lubricity of the fuel. Other, less frequently used methods for assessing fuel lubricity include BOTS (*Ball-on-Three Seats*), its modified version BOTD (*Ball-on-Three Discs*) and SLBOCLE (*Scuffing Load Ball-on-Cylinder Lubricity Evaluator*) [13].

In general, although many publications indicate the physico-chemical properties of blends of diesel fuel and ethanol, including lubricity, there are relatively few studies that include the test results of the lubricating properties of such blends determined using the normative HFRR method. For example, in Refs. [1,2,4], the authors demonstrate very poor lubricity and low viscosity of ethanol, with the result that an increase in the volume of ethanol in the diesel fuel aggravates the conditions of the cooperation of the engine supply system parts, which may lead to their premature wear. In the study [1], it was stated that for a blend of diesel fuel containing 15% (v/v) of ethanol, the wear scar as determined by HFRR was 226 μm. No further details regarding the research were