Dynamical Capillary Rise Photonic Sensor for Testing of Diesel and Biodiesel Fuel

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Abstract: There are many fuel quality standards introduced by national organizations and fuel producers. Usual techniques for measuring fuel parameters like cetane number, cetane index, fraction composition, viscosity, density, and flash point, require relatively complex and expensive laboratory equipment. On the fuel user side, fast and low cost sensing of useful state of biodiesel fuel is important. The main parameters of diesel fuel compatibility are: density, viscosity and surface tension. These three parameters define indirectly the quality of the fuel atomization process and the injected portion of energy that affect the quality of the fuel.

In the presented paper the purposefulness of fuel testing using measurements of separable parameters is discussed. On this base, a sensor which enables the examination of relation of the mentioned parameters in one arrangement is proposed, analyzed and tested. The sensor uses the dynamic capillary rise method with photonic multichannel data reading in an inclined capillary. The principle of the sensor’s operation, the construction of the sensor head, and the experimental results are presented. The capillary is a disposable element. The sensor testing was performed with freshly prepared biodiesel fuels, and fuels stored for 2 years. We conclude that the proposed construction may be in future the base of low cost commercially marketable instruments for basic fuel classification: fit for use or not. That classification includes initial fuel composition and fuel parameters change during storage. Therefore, the proposed sensor is intended to use in fuel buying/selling point rather than used as part of a diesel engine automated system. Copyright © 2015 IFSA Publishing, S. L.

Keywords: Biodiesel fuel, Diesel fuel, Fuel quality, Fuel storage, Viscosity, Density, Surface tension, Multiparametric sensor, Capillary sensor, Capillary rise.
1. Introduction

The paper consists of 5 sections. The first section is the introduction, where the diesel fuel, diesel engine properties as well as surface tension measurements and known sensors for diesel fuel testing are discussed. The second section describes the monitoring of capillary dynamical rise as an idea of multiparametric sensor for diesel fuel testing. The construction of the developed sensor is presented in section three. In section four the discussion of obtained results of diesel fuels examination using the developed sensor is presented and a method of fuels classification is proposed. The conclusion is gathered in section five.

1.1. Diesel Fuel

Classical diesel fuels are made from distillated products of crude oil with addition of improvers. Biodiesel fuel is a mixture of classical diesel fuel, biocomponents and additives, which include, for example, ignition improvers, injector cleanliness, lubricants and antioxidants. Present-day bio-components are obtained from vegetal oils, or the biomass. Important disadvantages of biodiesel fuel can be overcome by fuel processing. A new generation of biodiesel fuel can be made using bio-component isomerization or hydrogenation.

The quality of biodiesel fuel is defined in relation to four main processes: a) fuel storage stability, b) fuel transfer dynamics from tank to injection unit, c) combustion in the chamber, and d) gas emission.

Nowadays, producers define the useful state of diesel fuel by several parameters: cetane number (CN), cetane index, density, distillation parameters and kinematic viscosity. One of the most important diesel fuel quality parameters is its ignition quality. The ignition quality depends on the molecular composition of the fuel and is characterized by the ignition delay time, which is the time between the start of injection and the start of combustion. Other diesel fuel parameters, not directly related to engine performance, characterize its operability, as for example: amount of carbon residue, water and sediment, cloud point, conductivity, oxidation stability, acidity, copper corrosion, flashpoint, lubricity, appearance, and color [1].

1.2. Diesel Fuel and Engine

Diesel engine performance, fuel consumption, and emitted pollutants result from the combustion process. The environment of combustion, the injected fuel’s form and the fuel quality play primary role in the diesel combustion process [2]. Therefore, contemporary diesel engines may be equipped with the set of sensors that are aimed to monitor several parameters: engine speed, fuel temperature, fuel pressure at the injector/common rail and at the fuel supply pump, oil pressure, oil temperature, air inlet temperature, air flow/mass, coolant temperature, and oil and fuel levels as well as exhaust gas – nitrogen oxide presence. These sensors are often integrated with on board diagnostic (OBD) bus.

The main challenge for diesel engine designers is to adjust the combustion chamber size design according to the diesel fuel injection characteristics [3]. The diesel fuel must be introduced into the combustion chamber, vaporize, and react with oxygen at an assumed speed. The fuel properties that have the greatest effect on the injection process are viscosity, density and surface tension. If the injection is made at a constant pressure, the viscosity affects the fuel spray formation by limiting the speed of fuel flow. If the injection system is designed to meter the volume of injected fuel, the density of fuel defines the fuel injected mass that is linked with the useable portion of energy [4]. The surface tension is one of main factors that describes the fuel tendency to form drops, known also as the fuel atomization process or spray forming. Spray ignition phenomena are described by dynamic spray characterization, as for example: droplets concentrations, droplets diameters, droplets velocities [5]. In standard diesel engines, the expected injected droplet velocities are from 300 to 400 m/s, while the expected droplet diameters are in the range from 0 to 40 μm. Therefore, the costly diesel engines sometimes are equipped with fluid condition sensors that measure the density and the viscosity of fuel or oil [6]. The most costly diesel engines, for example for oceanic ships, sometimes are equipped with combustion temperature or pressure sensor as well as with spray form monitors which enables control of advanced combustion strategies [7].

1.3. Measurement of Diesel Fuel Parameters

The standardization process of measurement of diesel fuel parameters is still in progress [8]. Nowadays, the basic idea of fuel characterization is a selective and specific measurement of sequent parameters. Diesel fuel operability parameters measurements are not full standardized. The procedures and measured equipment are set to a series of parameters, for example:

- acid-number, used to describe the engine’s corrosion susceptibility by the fuel acidity level using chemical methods,
- flashpoint, used to describe the lowest temperature at which the fuel is sufficiently vaporized to form a flammable mixture with air under standard conditions, can be measured using the Pensky-Martens closed cup tester,
- lubricity of a substance is not a material property and cannot be measured directly, but a standard test method for evaluating the lubricity of diesel fuels uses a high frequency reciprocating rig and gives the value of wear trace diameter called WS 1.4 and expressed in [μm].
Measurements of ignition quality of fuel (CN) have to be carried out in the Cooperative Fuel Research Engine (CFR-5) or the Ignition Quality Tester (IQT™). The distillation parameters may be measured using the distillation unit, the basic components of which are: a distillation container, a condenser and an associated cooling bath, a heater and the temperature measuring device, as well as a receiving cylinder, or may be measured with automated distillation process analyzer [9]. The diesel fuel kinematic viscosity is a measure of the time for a fixed volume of liquid to flow by gravity through a capillary. The kinematic viscosity is calculated from calibrated device as

\[ \eta = C \cdot t, \]  

where: \( \eta \) is the viscosity, \( t \) is measured flow time, \( C \) is the calibration constant.

In a European study, it was observed that using the biodiesel fuel at low environment temperatures can lead to the degeneration of the engine [10]. Therefore, production standards for biodiesel fuel were introduced: density at 15 °C (ISO 3675) and low-temperature fluidity for the transitional seasonal periods and winter (DIN EN 116).

The basic disadvantage of such laboratory approach to fuel measurements is the high cost of the set of measurement devices and the complexity of the procedures. For the ordinary fuel user, the analysis of such collection of parameters is also too complex. Moreover, the surface tension of diesel fuel measurement is not standardized. Instead, the ASTM D971 standard is set to determine the possible contaminants of hydrocarbon fluids with water as the purity of hydrocarbon fluids is important factor of diesel fuels quality.

1.4. Surface Tension Measurement Methods

There are a few basic methods of surface tension measurements: the capillary rise method, the drop weight method, the ring or plate method, the maximum bubble pressure method, the method of analyzing the shape of the hanging liquid drop, and the dynamic methods [11].

The capillary rise method is the oldest method used for determination of the surface tension. To perform the surface tension measurement, a capillary is first dipped into the tested liquid. If the interaction forces of the liquid with the capillary walls are stronger than those between the liquid molecules, the liquid wets the walls and rises in the capillary to a defined level. If the cross-section area of the capillary is circular and its radius is sufficiently small, then the meniscus is semispherical. When the capillary is filled in the vertical position, the surface tension may be calculated with following equation:

\[ \gamma \cong \frac{1}{2 \cos(\theta)} \cdot r \cdot g \cdot \left( h + \frac{r}{2} \right) \cdot (\rho_l - \rho_v), \]  

where: \( \gamma \) is the surface tension, \( \theta \) is the contact angle, \( r \) is the inner radius of capillary tube, \( g \) is the gravity constant, \( h \) is the height of meniscus, \( \rho_l \) is the density of liquids, and \( \rho_v \) is the density of vapor [11]. For standard temperatures, the density of liquid is much greater than of the density of vapor, therefore the presence of the vapor phase is ignored. The contact angle may have different values in the static or dynamic situations. Such situations for a capillary being filled are presented in Fig. 1.

![Fig. 1. Static and advancing contact angle in capillary flow.](image1)

The advancing contact angle value may be measured with analysis of the shape of the sessile drop positioned on sloping surface [13]. In dynamic situations, when the liquid is moving over the surface, the velocity gradients in the fluid may be large and the viscous forces may control the shape of the fluid surface interface [14]. When the liquid is a multi-component solution, the main component surface tension is modified with the surface excess of other components related to the effective surface concentration, dependent on the nature of the solvents and solutes [15]. Many additives of diesel fuel may be considered as surfactant particles, which alter the surface properties of fuel, even when present in small quantities, Fig. 2.

![Fig. 2. Surface tension in multi-component liquid.](image2)
The diffusion of surfactants to the surface continues with a determined and limited velocity, until equilibrium is established. The time to equilibrium varies depending on surfactant concentrations and type, and may range from 0.01 s to few hours. Therefore, when the liquid flows up the capillary, the surfactants particles also flow, but not necessary maintaining the original surface concentrations, resulting in modifications of the temporary surface tension and the temporary advancing contact angle (2) [16].

The simplest technique for measuring the capillary rise is using a ruler with an optical reading, but its automation requires a camera, a mechanical device as a lift, or a liquid injector coupled with an additional light source to improve the optical reading of the meniscus position.

The readings of data in the capillary rise method to measure the surface tension may be performed for semi-transparent liquids also using the light attenuation effect. The lensing effect of the meniscus may be used for measurements of the contact angle [17]. The principle of the measuring set-up for this method is presented in Fig. 3. The lensing effect of the meniscus is registered as dimensions in the camera grid, while the capillary rise controls the amount of registered light.

The ring method and the Wilhelmy plate method are similar. In these methods an object is moved perpendicularly into or out of the liquid. The plate is moved towards the surface until the meniscus connects with it, or the submerged ring is pulled out of the liquid. The additional force acting on the plate or ring due to its wetting by liquid is measured. The ring method is unsuitable for dynamic surface tension measurements, but can be extended with captured image analysis to simultaneous measurements of surface tension and contact angle [18].

The drop weight method is one of the most common methods used for surface tension automated measurements. In this method, drops formed at the tip of the glass capillary are weighted and counted. The pendant drop at the tip starts to detach when its weight reaches the value balancing the surface tension of the liquid. The advantage of the method is the possibility to measure surface tensions between liquids and other than optically transparent materials [19]. The disadvantage of this method is the necessity to calculate the corrections for the capillary tip parameters and the volume of the drop, which are characteristic of a given device. Also evaporation of the drops may be a problem for some measurements.

The shape analyzing method of liquid drop is based on the effect of the liquid’s deformation caused by the gravitation force action. The hanging drop shape can be analyzed in set-up presented in Fig. 4.

Fig. 3. Principle of surface tension and contact angle measurement lengthwise of capillary.

Fig. 4. Pendant drop tensiometer.

When the drop lies on a plane, the surface area of a drop is proportional to its squared radius, and the gravitational deformation depends on its volume. This deformation is proportional to the third power of the drop radius and to the liquid’s surface tension as well as on the liquid – plane contact angle, or the plane’s surface energy [20].

In the maximum bubble pressure method, an air or gas bubble is blown at constant rate through a capillary submerged in the tested liquid. The maximum measured pressure that is required to insert the bubble of gas into the liquid may be used for surface tension determinations.

The analysis of the shape of an oscillating liquid jet method bases on optical observations of characteristic shapes of the liquid that flushes out from an elliptic orifice.

The methods that are suitable to measure the dynamic surface tension are the maximum bubble pressure and the oscillating liquid jet methods, but they require more complex experimental laboratory set-ups.
1.5. Surface Tension and Advancing Angle of Diesel Fuel

It has been proven that surface tension is one of the most important of inhomogeneous fluid properties. It reflects the range of interactions in a fluid more directly than the bulk properties do [21]. The relationship between the surface tensions of different real vegetable oils and their fatty acid composition was postulated in [22]. Predicting the surface tension of biodiesel fuels from their fatty acid composition showed that the differences in surface tension between biodiesel types are not the only cause of the reported differences in engine tests [23].

The surface tension and advancing angle are interesting case in diesel fuel characterization. On one hand the surface tension and ASTM D971 standard are proposed as useful indicator of cetane number [24] and fuel atomization process [25]. On the other hand, it was postulated that the surface tension of most liquid hydrocarbons is very similar. For example, for HydroCal 300 - a hydrotreated naphthenic medium grade lubricant oil and IFO-120, an intermediate fuel oil, the measured surface tensions at 25 °C are the same and equal 31.8 mN/m, while their viscosities differ significantly: 162mPa·s for HydroCal and 487 mPa for IFO-120 [26].

Results of investigation of surface tension values of diesel fuels and their components, with static capillary rinse method performed according (2), are presented in Table 1, where EN-590 depicted premium diesel fuel, FAME is fatty acids methyl ester - bio component, x% is concentration of bio component in fuel. For experiment VitroCom CV3040Q capillaries of inner diameter equal 300 µm were used. Since a film of oil remains on the inner surface of the capillary after the receding phase, representing complete wetting, the static contact angle in (2) was considered to be equal to 0° [27].

Obtained data shows that commercial premium diesel fuel, standard diesel fuel and 100 % biodiesel component surface tension values are considerably differ. It should be noted that contemporary diesel fuels components are not only pure hydrocarbons, it consist significant concentration of fatty acids esters. Moreover FAME requires different fuel additives than petrodiel. Therefore, such changes in fuel composition may significantly change surface tension, contact angle and other diesel fuel parameters [28].

Table 1. Surface tension values of standard fuels and their components, obtained with static capillary rinse method.

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>Surface tension, (mN/m), of fuel type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Premium, EN-590, FAME 0%</td>
</tr>
<tr>
<td>10</td>
<td>28.0</td>
</tr>
<tr>
<td>20</td>
<td>27.0</td>
</tr>
<tr>
<td>30</td>
<td>26.1</td>
</tr>
</tbody>
</table>

Advancing contact angles between a glass slide and different hydrocarbon oils differ significantly depending on the temperature, the speed of liquid creep and the type of liquid hydrocarbon. For example, measured at 25 °C and 264 µm/s the advancing angle of HydroCal 300 is 36° while of IFO-120 is 54° [26].

1.6. Sensors for Diesel Fuel Testing

Generally, diesel fuel analysis has taken place in certified laboratories. Though, there is a rising demand for on-line and real-time diesel fuel monitoring. To meet such requirements, series of different type sensors are introduced, nowadays, into market. Some sensors base on surface acoustic waves examination [29]. They are claimed as liquid/oil quality monitors, while they are used to measure acoustic impedance at monitored liquid surface:

\[ Z = \omega \cdot \rho \cdot \sqrt{\eta}, \]

where: \( \omega \) is the radian frequency, \( \rho \) is the density, \( \eta \) is the viscosity. Due to impedance dependence on density and viscosity, the postulated diesel fuel quality monitor has to consists of two sensor heads. But, the measurement tricky of proposed construction is determination of diesel fuel dynamical coupling to examined surface, which depends on surfactants properties. Therefore, mentioned sensors can be used for monitoring simpler than diesel fuel liquids as for example lubricant oil. Still the works on critical coupling surface parameters improving are in progress [30]. The density of fuel is measured with the use of resonant frequency sensors [31] that are capable of electronic integration [32].

Optical sensors are also popular in diesel fuel examination. Infrared sensors are used for two proposes, to measure the blend concentration in blended fuel and to measure predict fuel quality [33]. Some smart ultraviolet sensors enable the examination of a set of fuel parameters, but the possibility of easy measurement comes with a high price of the devices [34]. On the other hand, some proposed multiparametric sensors may be low cost, but using them requires trained operating personnel. The possibility of diesel fuel quality testing using an optoelectronic set-up implementing a multiparametric method was shown in [35] and [36]. The components for such sensors are under technological optimization [37] [38] [39].


Diesel fuel users require the simplest possible answer to a question: is that fuel useful for my engine?
This answer may be deducted from capillary rinse sensor depicted in [40].

The idea of the sensor was inspired by the need to come up with a measurement method of a set of diesel fuel parameters in one system that would require the minimum of automated mechanical elements. The aimed at set of diesel fuel parameters includes: density, viscosity, surface tension and wetting represented by the advancing contact angle between fuel and glass. To obtain the dynamical data of advancing contact angle one needs to measure the capillary rise speed. An increase of the speed of the liquid’s movement and its distance in the capillary in order to improve the precision of the measurement is possible by inclination of the capillary. When the capillary’s axis is inclined at the $\alpha$ angle to the horizontal, a liquid is drawn in by capillary forces according to equation (4).

$$\frac{dl}{dt} = \frac{2\gamma \cos(\theta)}{r} \frac{g \cdot l \cdot \rho_l \cdot \sin(\alpha)}{8 \cdot \eta \cdot t} \cdot r^2 ,$$  

(4)

where $\gamma$ is the surface tension, $\theta$ is the advancing contact angle, $r$ is the inner radius of the capillary tube, $g$ is the gravity constant, $l$ is the length coordinate of meniscus at capillary axis, $t$ is the time of measurement, $\alpha$ is the angle of inclination, $\rho_l$ is the density of liquid, and $\eta$ is its viscosity. In the general case depicted by equation (4) the advancing contact angle $\theta$ is a function of the liquid’s speed. This results in an involved dependence for dynamical calculation of liquid parameters. Assuming that the advancing contact angle is characterized by semi constant values, equation (4) may be solved for the dynamical diesel fuel analysis in two ways.

The first solution of equation (4) is for local speed measurement at a set length coordinate of meniscus with the difference equation:

$$\frac{\Delta l}{\Delta t_s} = \frac{2\gamma \cos(\theta_s)}{r} \frac{g \cdot l_s \cdot \rho_l \cdot \sin(\alpha)}{8 \cdot \eta \cdot t_s} \cdot r^2 ,$$  

(5)

where: $\theta_s$ is the semi constant value of advancing contact angle at coordinate $l_s$, while $l_s$ and $\Delta l_s$ are presented in Fig 5.

The second solution of equation (4) is for average speed measurement at a set distance and is based on integration:

$$\frac{t_2 - t_1}{l_2 - l_1} = \frac{8 \cdot \eta \cdot t_1}{2 \gamma \cos(\theta_2)} \int_{l_1}^{l_2} \frac{dl}{\frac{g \cdot l \cdot \rho_l \cdot \sin(\alpha)}{r} \cdot r^2} ,$$  

(6)

where: $\theta_2$ is the average and semi constant value of advancing contact angle between coordinate $l_1$ and $l_2$ presented in Fig 6. For the sensor application, equation (6) may be solved numerically by inputting in the measured time of rise $t_2$-$t_1$ at corresponding coordinates of meniscus.

3. Sensor Construction

The sensor construction used in dynamical capillary rise application analysis was firstly presented at the SENSORDEVICES 2015 Conference [40].

3.1. Sensor Head

The sensor’s head consists of two functional blocks: the base and the disposable capillary optrode, shown on Fig. 7.

The base is used to integrate the removable vessel for the examined liquid, the three optical paths of the source and the receiver, as well as for positioning the disposable capillary optrode at one of the three possible inclination angles. The ramp geometry used in presented experiments is shown in Fig. 8. The capillary optrode is dipped for 3 mm into the liquid.
The disposable optrode is made from 15 cm sections cut from the TSP 700-850 capillary from Polymicro Inc. In the optical paths, large core optical fibers BFH 37-800 from Thorlabs were used. They are characterized by the core radius of 800 µm and the hard clad outer diameter of 830 µm, which is similar to the capillary’s outer diameter. The tips of the fibers are positioned at the distance of 1 mm, where in the middle of the distance between the tips is positioned the capillary (Fig. 9).

![Fig. 8. Ramp geometry used in experiments.](image)

![Fig. 9. Optical path.](image)

The geometry of the optical path defines the value of $\Delta l_3$, required in equation (3). The approximate value of $\Delta l_3$ may be interpreted as, visible by fiber, section of capillary at its axis. Therefore it may be calculated using numerical aperture of fiber and its core diameter. As the optical paths are the same $\Delta l_1 = \Delta l_2 = \Delta l_3 = 1.2$ mm.

### 3.2. Optoelectronic Signal Processing

As light source, three fiber coupled LEDs with three different emission wavelengths were used. The lowest-power LEDs were selected from Thorlabs list of high power devices: M490F2, blue with the 490 nm wavelength; M565F1, green/yellow - 565 nm wavelength; and M625F1, red - 625 nm wavelength. The diodes were connected to DC2100 controllers operating in the light modulation mode. The receiving fibers were inserted into the optoelectronic detection unit of our own design, presented previously in [41]. The optoelectronic unit was connected to a PC by an analog input of IOtech Personal DAQ 3000 data acquisition system. That system was also used to monitor the ambient temperature with two LM35DT circuits and control it with a radiant heater at 25 °C.

To operate the system, at the 0.1 s sampling rate, a script in DasyLab 10 was designed. The script algorithm is based on the signal filtration and signal derivative analysis [42].

The raw data collected for acetone are presented in Fig. 10. The initial values of signals for different paths are off-set on Fig. 10 for clarity. Moreover, the differences of the initial signal values do not matter, as the sensor operation is based on the differences of the measured time values. The measured time differences for acetone increase with capillary length coordinate: $\Delta t_1 < \Delta t_2 < \Delta t_3$ and $\left[ (t_2-t_1) = 0.9 \text{ s} \right] < \left[ (t_3-t_2) = 2.6 \text{ s} \right]$. Therefore obtained results are in agreement with theoretical model represented with equations (5) and (6).

![Fig. 10. Acetone characteristics.](image)

The results of measurement of fresh PD presented in Fig. 11 show that, contrary to acetone, the $\Delta t_i$ are measurable in each optical patch $\Delta t_1 = 0.2$ s, $\Delta t_2 = 0.3$ s, $\Delta t_3 = 0.7$ s, and that the time intervals $(t_2-t_1) = 6.5$ s and $(t_3-t_2) = 13$ s are greater than for acetone, as fuel viscosity is much greater than that of acetone.

![Fig. 11. Measurement signals of fresh premium quality petrodiesel PD.](image)

In the presented set-up, the $t_1$ measurement value is uncertain, as the filling of the vessel may not be repeatable when a hand held pipetor is used.
4. Experimental Results

In this section are presented the diesel and biodiesel fuels parameters examination as well as experimental classification procedure results.

4.1. Diesel and Biodiesel Fuels Used for Examination

The operation of the sensor was examined with fuels that are mixtures prepared from components according to the European Union standards. The fuels were fresh, or stored in room condition for two years.

Base oil (BO) was prepared from crude oil distillation products. The petrodiesel (PD) was prepared with additives according to the EN-590 norm. Biodiesel fuels (BDx – x is the volume ratio of the biocomponent) were prepared from PD with addition of fatty acids methyl esters (FAME) and other additives according to the EU standard. The lubricants were added in different volumes, but in the standard range, to different fuel mixtures. This enables testing the lubricant effects on CI and the fuel classification.

The results of laboratory examination of prepared fuels are presented in Table 2. The accuracy of the density measurement was ±2.0 kg/m³ while the resolution was ±0.1 kg/m³. Kinematic viscosity, lubricity (ISO 12156) and oxidation stability (EN 16091) measurement accuracy was ±1 %. Kinematic viscosity was measured at 40 °C, while the density at 15 °C.

The density and kinematic viscosity increase monotonic with FAME fuel component concentration (Fig. 12), while cetane index decreases monotonically. The fuels BO, BD30 BD50, BD70 and BD100 do not meet the standards of density, viscosity and FAME ratio, but meet the quality test of CN. In our opinion (tests on CFR-5), fuels from PD up to BD30 can be used without problems. The characteristics of lubricity and oxidation stability of examined fuels are not monotonic versus FAME fuel component concentration, as depicted in Fig. 13.

The calculated values of surface tension of fuels, basing on equation (6), as well as on the assumption that average advancing contact angle is 0 and using data collected in Table 2, are presented in Fig. 14. The obtained results show that the assumption for the advancing angle is not correct when absolute values are under consideration. But experiment show, that when fuel speed decreases, the calculated surface tension increases and tends to the static measured values presented in Table 1.

<table>
<thead>
<tr>
<th>Fuel acronym</th>
<th>FAME [%]</th>
<th>Density [kg/m³]</th>
<th>Kinematic viscosity [mm²/s]</th>
<th>Lubricity WS 1.4 [μm]</th>
<th>Oxidation stability [min]</th>
<th>CN</th>
</tr>
</thead>
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<tr>
<td>BO</td>
<td>0</td>
<td>805.0</td>
<td>1.581</td>
<td>734</td>
<td>55.02</td>
<td>49.8</td>
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<tr>
<td>PD</td>
<td>0</td>
<td>832.6</td>
<td>3.367</td>
<td>321</td>
<td>37.56</td>
<td>59.6</td>
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<tr>
<td>BD02</td>
<td>2</td>
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<td>3.3825</td>
<td>209</td>
<td>41.36</td>
<td>58.4</td>
</tr>
<tr>
<td>BD04</td>
<td>4</td>
<td>834.5</td>
<td>3.394</td>
<td>202</td>
<td>50.28</td>
<td>58.3</td>
</tr>
<tr>
<td>BD06</td>
<td>5.8</td>
<td>835.4</td>
<td>3.401</td>
<td>215</td>
<td>50.19</td>
<td>58.6</td>
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<tr>
<td>BD08</td>
<td>7.8</td>
<td>836.4</td>
<td>3.413</td>
<td>207</td>
<td>50.18</td>
<td>57.3</td>
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<tr>
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<td>48.9</td>
<td>857.4</td>
<td>3.813</td>
<td>216</td>
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<td>BD70</td>
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<td>867.3</td>
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<td>BD100</td>
<td>100</td>
<td>883.2</td>
<td>4.509</td>
<td>196</td>
<td>19.02</td>
<td>51.2</td>
</tr>
</tbody>
</table>

Fig. 12. Density and kinematic viscosity of examined fuels vs. FAME component concentration.

Fig. 13. Lubricity and oxidation stability of examined fuels vs. FAME component concentration.

Table 2. The parameters of investigated fuels.
The non-monotonic character of surface tension versus FAME concentration is visible, but should not disturb further considerations as the lubricity of examined fuels also does not depend monotonically. These results show also that the values of surface tensions are probable and that the advancing contact angles differ significantly for the analyzed fuels as differs the lubricity.

![Fig. 14. Surface tensions of fresh fuels calculated from equation (6).](image)

The comparison of surface tension calculated with above mentioned assumption for methods based on local (5) and average measurement (6) is presented in Fig. 15. Obtained results confirm previous conclusion of the speed influence on calculated surface tensions. It is thus evident that standardization of dynamic surface tension measurements of diesel fuel is not a trivial task.

![Fig. 15. Surface tensions of fresh fuels calculated from equations (5) and (6).](image)

4.2. Procedure of Diesel Fuel Classification

On the base of previous results, it is clear that the direct calculation of physical values of fuel parameters including dynamical values of surface tension is methodologically difficult. But, methods represented by equations (5) and (6) in $t_{x-t_{x-1}}$ and $\Delta t_3$ contain information on surface tension dynamics, density and viscosity. The difference in $(t_3-t_2)$ or $(t_2-t_1)$ times varies much more from one fuel to another than the fuels densities or viscosities.

For the purpose of diesel fuel classification with the use of dynamical capillary rise measurement, freshly prepared fuels from PD to BD30 meet quality requirements. On the base of oxidation stability investigation, all fuels stored for two years in closed dark tanks do not meet quality requirements. The volumes of stored fuels seemed to be constant, no presence of resins was observed, but the fuels were more transparent, which indicated that chemical reactions occurred in the fuels under storage.

Data of time intervals obtained for fresh fuels are presented in Fig. 16. The amplitude difference of $(t_1-t_2)$ is greater than $(t_2-t_1)$. Therefore, the allowed range of $(t_3-t_2)$ is set. It should be pointed that this determination of fuel quality is not always accurate, as BD50 biodiesel fuel looks here acceptable.

![Fig. 16. Measurement data of fresh diesel fuels related for method described by (6) – time intervals.](image)

The time interval values of fuels stored for two years are presented in Fig. 17.

![Fig. 17. Measurement data of stored diesel fuels related for method described by (6) – time intervals.](image)
The results presented in Fig. 17 in comparison to the results seen in Fig. 16 indicate that the measured times intervals increase for stored fuels, but not monotonically. The proposed time difference range discrimination is again not conclusive, as spoiled BD02 is classified as fulfilling the quality requirements.

The results of examination of time differences $\Delta t_3$ for fresh and stored fuels are presented in Fig. 18. The set range of allowed range of time difference to meet proper quality fuel is again not conclusive as according to it the stored base oil meets requirements.

Conclusive examination can be obtained with simultaneous examination of time difference and time interval data as presented in Table 3.

Therefore, on the base of data collected in the experiments, the set of parameters determining the useful state of biodiesel fuel should include the limits of the time intervals $t_3-t_2$, the limits of time differences $\Delta t_3$, and the results of logical operator $[(t_3-t_2) \text{ and } \Delta t_3]$.

![Fig. 18. Measurement data of fresh and stored diesel fuels related for method described by (5) – time differences.](image)

<table>
<thead>
<tr>
<th>Table 3. Comparison of fuels classification results.</th>
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<td><strong>Fuel acronym</strong></td>
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N – Wrong classification result; Y – Proper classification result.

5. Conclusions

We proposed a sensor working on the principle of optical examination of diesel fuel under dynamical capillary rise conditions. The presented device has been tested with fuels of different compositions and storage age, and it shows great promise for practical implementation.

The experiment data indicate that stored fuels may flow significantly slower than fresh ones, and their flow speeds can be determined by measurements of time intervals. The change in flow speed modifies the conditions of fuel injection and spray formation. The
The analysis of the measured signals of diesel and biodiesel fuels showed the relationship of the times of fuel flow in the capillary with the useful state of diesel fuels. Especially, the summarized results of the experiments led us to the conclusion that Δt time measurement data differences and t₁-t₂ time intervals relate more clearly to the acceptable quality fuels than independent set of surface tension, viscosity and density data.

We showed that the information on useful state of diesel fuel could be presented in the form of recommended ranges of times of the fuel crossing sections of an inclined capillary during the capillary fill. Specific results can be obtained applying logical and operator to the capillary fill analysis using two methods: time difference and time interval. This approach is not yet as accurate as other laboratory methods, but its intrinsic advantages of simplicity of design and low instrumentation costs could make the technology viable in the near future.

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References


