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EVALUATION OF PHYSICOCHEMICAL PROPERTIES AND COMBUSTION PERFORMANCE OF LINSEED OIL-DEE MIXTURES FOR DIESEL ENGINES

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Abstract. This study focuses on the physicochemical and combustion properties of linseed oil (LO) blended with diethyl ether (DEE) and investigates its potential for application in diesel engines. While similar research exists for rapeseed oil (RO) and DEE blends, a detailed analysis of LO-DEE mixtures has been lacking. Linseed oil, a colourless to yellowish edible oil extracted from flax seeds, is notable for its high content of polyunsaturated fatty acids, especially α-linoleic acid. These properties make it suitable for multiple applications, including the chemical, biomedical, and fuel industries. However, LO's unique chemical composition presents opportunities and challenges for its use as a biofuel. Experimental results demonstrate a significant linear relationship between DEE concentration and the physicochemical properties of LO-DEE blends. For instance, density and surface tension decreased with increasing DEE content, leading to improved spray characteristics and atomization during fuel injection. The LHV of the blends was slightly reduced compared to diesel fuel (DF) but remained comparable to rapeseed oil-DEE mixtures. While LO's viscosity is lower than many vegetable oils, it remains higher than that of conventional diesel fuel, which can impact spray angle and atomization efficiency. The addition of DEE effectively reduced viscosity, enhancing the combustion process. Combustion analysis revealed that LO has a longer ignition delay compared to DF, primarily due to its high polyunsaturated fatty acid content. Blending with DEE significantly reduced the ignition delay, narrowing the gap between LO blends and DF, especially at higher engine speeds. Additionally, the high unsaturated fatty acid content contributes to increased NOx emissions and potential deposition issues on engine components. Preheating and engine modifications may help address these challenges but require further research. Statistical analysis using linear regression models confirmed the significance of the observed trends, with confidence intervals validating the reliability of the experimental data. The study emphasizes the importance of understanding the interplay between fuel properties, combustion behaviour, and engine performance to optimize the use of LO-DEE blends as a renewable alternative to diesel fuel.

Keywords: linseed oil (LO); diethyl ether (DEE); biofuel; viscosity; heat of combustion (LHV); atomization; renewable energy sources; fuel mixtures.

Introduction

There is no research on detailed analysis of the physicochemical and combustion properties of linseed oil and DEE blends, and similar research exists on the physicochemical properties of rapeseed oil and DEE mixtures. Therefore, the objective of this study was to test the effect of DEE/linseed oil fuel blends to evaluate the possibility of using such mixtures in diesel engines, as well as make a comparison of obtained results with DEE/RO blends.

The study showed that DEE reduces the density of plant oils. However, values comparable to DF are possible only for mixtures containing more than 50% of DEE. It was confirmed that necessary relationships are very well described by linear regression. The linear model also describes the impact of the DEE/LO ratio on the surface tension value. It was observed that DEE added to LO or RO reduces the surface tension of the blend. In the case of DEE/LO blend it should promote better atomization of the fuel injected into the combustion chamber. The DEE/LO mixture has a lower surface tension than DEE/RO.

At the same time, the addition of DEE to LO significantly reduces CFPP allowing to use of such blends in the winter season without the engine fuel preheating system. In this aspect, the DEE/LO blends are much more recommended compared with DEE/RO mixtures. CFPP of DEE/LO blends is also well described by a linear model. An irrational regression shown in this work better correlates with empirical data.

Research has confirmed the addition of DEE slightly reduces the LHV of tested plant oils. In this case relationship between LHV and the DEE/LO ratio is very well described by the linear mathematical model. It should be pointed out that the LHV of the tested DEE/LO or DEE/RO blend is close to 36-38 MJ/m3, i.e. about 12% less compared with DF. For this reason, the engine performance should be adequately reduced. It means that the top power and torque of an unmodified engine fuelled with an alternative fuel blend will be lower compared with DF.

Based on the engine research, it was found that the ignition delay of LO is significantly increased compared with DF. This was attributed to a considerably lower CN of plant oil. However, it was confirmed that DEE is an effective cetane improver and it allows for to reduction of ignition delay of LO. Smoke emission is also adequately reduced due to the atomization quality of a less viscous blend being better, and the consequence is lower smoke emission and slightly higher engine overall efficiency.

Analysis of modern foreign and domestic research and publications

Linseed oil, a colorless to yellowish edible oil, is a colorless to yellowish, edible oil obtained from the dried, ripened seeds of the flax plant and produced through expeller pressing and solvent extraction [1]. The average yield of linseed oil pressed from the seeds is about 35–50% of seed weight and the most frequently found fatty acids in this oil are: palmitic acid, stearic acid, oleic acid, linoleic acid, and linolenic acid. This oil contains no significant amounts of protein, carbohydrates, or fiber [2].

Typical linseed oil contains a high amount of polyunsaturated fatty acids, especially essential α-linolenic acid, which is considered to have beneficial effects on human health and is one of the highest of all edible oils [3]. A level of α-linolenic acid causes the oxidative instability of linseed oil and affects the drying properties of linseed oil. The content of α-linolenic acid in seeds varies in different research from 47.7 to 62.9 % and can increase by combining increased mineral fertilization with intensive crop protection against weeds [4]. This makes it particularly suitable for the chemical industry for use as a component in numerous products such as paints [5], inks, and varnishes. Oxidative stability has been improved by altering the fatty acid profile, lowering α-linolenic, and increasing linoleic acid content, but the effects of other compounds that might be involved in oil stability are under research with the suggestion that accumulation of compounds from the phenylpropanoid pathway is required during last years [6].

Besides that linseed oil has wide application not only in the chemical industry but also in the biomedical and fuel industry. Different research shows the efficacy of linseed oil impact on health, protecting against the negative consequences of an unbalanced human diet, preventing the onset of chronic diseases like atherosclerosis, and reducing the risk of breast cancer [7], as also LO can be used as anti-hypersensitive agent based on α-linolenic acid and lignan content in oil [8].

Linseed oil, a colorless to yellowish edible oil, is one of the oils, that has an inherently high amount of mono- and polyunsaturated fatty acids resulting in one of the longest ignition delays between all vegetable oils. Detailed research of different vegetable oils has confirmed that mono- and polyunsaturated fatty acids those with two or more double bonds had mostly a greater effect on ignition delay than fatty acids with just one single double bond. The fact of usage the Fuel-Ignition-Tester for the determination of the ignition and combustion for vegetable oils confirmed at [9] and mentioned that linseed oil has the longest ignition delay of 5.93 ms instead of 4.50 ms for rapeseed oil and 2.58 ms for coconut oil. Such long ignition delay could lead to a later start of combustion and a higher local maximum of the speed of pressure rise resulting in an increase in the amount of fuel burning in the first combustion phase [10] while no differences were observed between those oils in the subsequent combustion phases. Researchers also confirmed that the ignition delay of vegetable oils is related to their fatty acid composition – the ignition delay of the vegetable oils is increasing with the rising average number of double bonds while no significant effect on ignition delay was observed from the average number of carbon atoms.

It analyzed possible consequences of linseed oil use by [11] according to which vegetable oils containing high polyunsaturated fatty acids are less viscous but contribute to higher NOx emissions. Therefore, the usage of vegetable oils with higher saturated and monounsaturated fats together with the retrofit kit or heating system was recommended. High values of linoleic/linolenic acids also could result in higher deposition rates as these acids react to heat and oxidize polymerizing on the cylinder walls and injection tips [12]. However, this statement has not won approval in all tests [13].

Possible linseed oil usage in diesel engines is strongly connected to the engine sensitivity on fuel injection and combustion, and one of the main parameters is viscosity. Viscosity which is a measure of the resistance of fluid to a flow, is the most important parameter for all vegetable oils as it leaves an impact on the quality of fuel atomization. The fuel injection system of current diesel engines accepts the use of fuels with viscosity values from 1.9 to 5.0 mm^2/s at 40 °C (1.9 to 4.1 mm^2/s at 40 °C based on standard ASTM D975, 2.0 to 4.5 mm^2/s at 40 °C from standard EN 590:2004, 3.5 to 5.0 at 40 °C from EN 14214:2009), while some sources [14] recommends 1.6 –7.0 mm^2/s values for operating at 40 °C.

Following values of viscosity is important as fuels with too low viscosity will not provide sufficient lubrication for the precision fit fuel injection pumps, resulting in leakage and increased wear, while higher viscosity means reduction of spray angle [15], higher Sauter Mean Diameter (SMD) and lower spray speed than conventional diesel fuel [16]. From a technical point of view, the viscosity of vegetable oils should reach a value close to the upper limit of the mentioned standards to avoid high viscosity problems. Regulations concerning fuels from vegetable oils are limited by DIN V 51605 for rapeseed oil, as well as further attempts for standard development for other oils [17].

Highlighting previously unresolved parts of the overall problem

Linseed oil, unlike most vegetable oils, stands out due to its low viscosity, which is closer to the characteristics of diesel fuel, particularly when added in small amounts, such as 5 % or 9 %. In spite of this linseed oil viscosity is still higher compared to diesel having higher resistance to break-up therefore increase of fuel density together with viscosity results in a decrease in the spray angle. Viscosity increase requires more energy from the fuel pump and reduces the net power output from the engine.

Density, a measure of the mass per unit volume, is a temperature-dependent parameter, that decreases linearly with increasing the temperature, and knowledge of this tendency is highly important in the provision of fuel combustion and its analysis. Viscosity dependency could be observed also in the case of the addition of other fuels, like DEE, where values of density decrease with the increase of DEE by volume. In the case of blending it could be a more simplified solution against heating have found that vegetable oils require preheating to 120 °C minimally to match the physical properties of diesel fuel concluding that temperature requirement depends on engine types and configurations. Besides the reduction of density during the heating it should be expected to increase consumption based on lower energy content per volume in systems with mechanical injection control, where the fuel is volumetrically applied in the combustion chamber. This was also observed in research, where preheating reduced the density of canola oil by 5.18 % reflecting in the increase of consumption.

Besides viscosity and density, the surface tension of fuel also leaves an impact on spray formation and especially on the formation of fuel drops. A higher surface tension coefficient increases the cohesive force, which circumvents the formation of smaller drops, which increases the evaporation rate and enhances the mixing of fuel vapor and air. The realization of such a process must be supported also by an adequate spray cone angle, which strongly depends on the nozzle size and liquid properties for a given injection pressure. Research with biodiesel-diesel confirmed that spray cone angle increases with an increase in both ambient density and injection pressure differential suggesting the use of preheating of different fuel blends to achieve values equal to those of diesel fuel. Like other parameters, surface tension also is affected by a number of unsaturated bands and the fatty acid hydrocarbon chain length, where a long fatty acid hydrocarbon chain tends to increase the surface tension. Also here preheating is not the best solution, as research on different vegetable oil types shows that vegetable oils require preheating at temperatures not lower than 120 °C to reach surface tension values corresponding to diesel fuel at 40 °C.

Cetane number is a dimensionless descriptor of the ignition quality of diesel fuel, determined by unbranched chains of fatty acids similar to those of the n-alkanes of diesel fuel. Chain length leaves an impact on cetane number, where decreasing chain length reduces cetane number. There could be determined also a relationship between cetane number and ignition delay, where the higher cetane number determines a shorter ignition delay. As previously it was mentioned – linseed oil has one of the longest ignition delays among vegetable oils and one of the smallest cetane numbers – 34.6 instead of 37.6 for rapeseed oil or 42.0 for palm oil. Therefore, the influence of increased unsaturation on the lowest cetane number is proven for linseed oil. An increase in cetane number is possible by blending oil with alcohols (like DEE), while the heating value of the blends will be practically in the same range.

The purpose and tasks of research

The objective of this research is to evaluate the feasibility of using linseed oil (LO) and diethyl ether (DEE) blends as alternative fuels for diesel engines. The purpose of the research is to investigate the physicochemical and combustion properties of linseed oil (LO) blended with diethyl ether (DEE) and explore its potential as a renewable fuel alternative in diesel engines. The study aims to address the gap in existing research on LO-DEE mixtures, focusing on their behavior in terms of fuel properties and combustion characteristics. Key tasks of the study include:

1. **Physicochemical Property Analysis**:

- the relationship between DEE concentration and the properties of LO-DEE blends, such as density, surface tension, viscosity, and lower heating value (LHV).

- comparison of these properties with conventional diesel fuel (DF) and other biofuels like rapeseed oil (RO)-DEE mixtures.

2. **Combustion Performance Evaluation**:

- assessment of the ignition delay, spray characteristics, and atomization efficiency of LO-DEE blends compared to diesel fuel.

- identification of the impact of LO's high polyunsaturated fatty acid content on combustion behavior, including its effects on emissions (e.g., NOx) and potential deposition issues in the engine.

3. **Statistical Analysis**:

- use of linear regression models to quantify relationships between fuel properties and combustion outcomes, validating the experimental data's reliability.

4. **Optimization for Biofuel Use**:

- identifying the optimal balance between fuel properties and combustion behavior to maximize the efficiency and performance of LO-DEE blends as a renewable diesel fuel alternative.

In conclusion, this research aims to enhance the understanding of LO-DEE mixtures, helping to optimize their use as an alternative biofuel in diesel engines while addressing challenges related to combustion, emissions, and engine compatibility.

Highlighting of the main research material

Operability of diesel engine in low temperature climate zones is characterized by cold filter plugging point (CFPP). Improper value of this parameter of fuel used in low temperature climate and seasonal conditions can lead to crystal formation resulting in restriction of flow through fuel lines and filters. This further can promote ignition problems. Like other analyzed parameters, also CFPP is mainly dependent on the fatty acid profile of the feedstock. The CFPP decreases with the increase of the total unsaturated fatty acid contents, which could be also confirmed in case of LO instead of RO.

Lower heating value (LHV) is another parameter, which increases with chain length while impact of its values is not so rapid as in case of cetane number. Like density, heating value can be calculated if weighted averaging of the property values of the original components is known. Most impact could be left by two components: hydrogen and oxygen. LHV decreases with increase of oxygen and it could increase with increase of hydrogen. Most researchers observed drop of rated brake power in case of reduced lower heating value of vegetable oils. LO presents lower heating value than diesel fuel, but almost similar to RO. The DEE was blended with LO in volumetric ratios of 10, 20 and 30%. These DEE/LO fuel blends are coded as follows: LO10, LO20 and LO30, respectively.

Measurements of physicochemical properties of DEE/LO blends were carried out at the Kazimierz Pulaski University of Technology and Humanities in Radom. Especially, the density and kinematic viscosity of the blends were tested according to requirements of EN ISO 3838 and EN ISO 3104 standards, respectively. The heat of combustion of all fuel blends was expressed by the lower heating value (LHV) measured in agreement with ASTM D240-02:2007 procedure. Temperature-dependent parameter i.e. the cold filter plugging point (CFPP) was examined according to EN 116:2015 standard. In this study, the surface tension was also performed in agreement with ISO 304:1985. All measurements were repeated three times. The average value calculated for these repetitions has been used to prepare necessary figures with empirical results of this research.

During research the engine was loaded by a hydraulic dynamometer. The in-cylinder pressure was measured by an AVL QC34D piezosensor with a sensitivity of 190 pC/bar and a measuring range of 0–25 MPa. The engine was also equipped with a CL80 needle lift sensor with a sensitivity of 0.5 V/mm and a measuring range of 0–2 mm. Needle lift sensor was made by polish company ZEPWN. Sensors' signals were sampled every 0.8 crank angle degree (°CA). Researches were carried out for nominal settings of tested engine in stationary conditions of work at 1000, 1200, 1400, 1600, 1800 and 2000 rpm of the crankshaft under load of 120 Nm. These measurement points are typical for the AD3.152 engine operated in middle and higher loads. In all such conditions 100 consecutive cycles of engine work were recorded and then processed to calculate the average value of each analyzed parameters. In this study the main analysis was focused on the fundamental combustion parameters i.e.: the ignition delay (ID) and the engine overall efficiency (EOE).

The ignition delay was determined as a °CA elapsed between the beginning of needle lift and the beginning of combustion process. The smoke opacity (SO) from tested engine was measured with the AVL 465 diGAS analyzer with accuracy 1%. In each measurement point the opacity was sampled at 15-second intervals and averaging 10 consecutive readings. The overall efficiency of the engine was calculated based on the fuel consumption measurement. In this study the amount of fuel combusted by the engine was measured volumetrically in three consecutive readings. The engine fuel supply and return pipes were connected with the cylindrical 500 mL dropping funnel with graduation marks. In each single test the time of 200 mL fuel consumption was recorded and then the average value was calculated.

According to experimental data, density *(ρ)* of DEE/LO and DEE/RO blend tested at 15 °C, surface tension *(σ)* of DEE/LO and DEE/RO blend, and lower heating value (LHV) of DEE/LO and DEE/RO blend have a direct proportional. In these cases, processing of experiment data was done using the least squares method. Since any measurement results contain random errors values y_i will be considered realizations of random variables. Here we will be interested in constructing such type of relationship between x and y as $y = a + bx$ for which errors ε_i in $y_i = a + bx_i + \varepsilon_i$ equations would be the smallest, provided that measurements were made without systematic errors.

Constructing parameter estimates a and b of linear regression are minimized by the sum of squares of errors ε_i.

Let's consider a function $f(a,b) = \sum_i^n \varepsilon^2 = \sum_{i=1}^n (y - a - xb)^2$. Where ε is errors of experiment, which should be the smallest. Since it is quadratic, it has a single extremum point that can be found from the necessary local extremum conditions $\frac{\partial f}{\partial a} = 0$, $\frac{\partial f}{\partial b} = 0$. Therefore, a system of equations (14) and (15) is defined as:

$$\begin{cases} \frac{\partial f}{\partial a} = -2\sum_{i=1}^n (y - a - xb) = 0, \\ \frac{\partial f}{\partial b} = -2\sum_{i=1}^n (y - a - xb)x = 0. \end{cases} \quad (1)$$

Formulas (1) allow to get a normal system of equations (2) necessary for calculating parameters *a, b*:

$$\begin{cases} na + \sum_{i=1}^n x_i b = \sum_{i=1}^n y_i; \\ \sum_{i=1}^n x_i a + \sum_{i=1}^n x_i^2 b = \sum_{i=1}^n y_i x_i. \end{cases} \quad (2)$$

Then, linear regression parameters a and b are expressed by formula (3) respectively:

$$a = \frac{\sum_{i=1}^n y_i \sum_{i=1}^n x_i^2 - \sum_{i=1}^n y_i x_i \sum_{i=1}^n x_i}{n\sum_{i=1}^n x_i^2 - \left(\sum_{i=1}^n x_i\right)^2},$$

$$b = \frac{\sum_{i=1}^n y_i \sum_{i=1}^n x_i - n\sum_{i=1}^n y_i x_i}{\left(\sum_{i=1}^n x_i\right)^2 - n\sum_{i=1}^n x_i^2}. \quad (3)$$

As a result of calculations linear dependences of type $y = a + bx$ were obtained for tested DEE/LO blend. Values a and b of linear regression parameters are listed in Table 1.

Table 1 – Linear regression parameters calculated for selected physicochemical properties of DEE/LO blends

property	linear regression parameters	
	a	b
density	0.931	−0.184
surface tension	32	−26.5
LHV	37.87	−4.3

Let's consider values $\hat{y}_i = \hat{a} + \hat{b}x_i$ obtained by estimated regression formula. Estimation regression parameters *x* and *y* were found from the observation of values and using the least squares method. Differences $\varepsilon_i = y_i - \hat{y}_i$ are called residuals which show how well the selective regression approximates the results of the observations (x_i; y_i). Observation errors ε_i are independent, normally distributed random variables. Therefore, if linear model is adequate, observation results are realizations of independent, normally distributed quantities.

Statistics of ratio of squared error deviation to variance $\frac{Q_e}{\sigma^2}$ has distribution χ^2 with $n-2$ degrees of freedom regardless of distribution of estimates $\hat{a}$ and $\hat{b}$.

Using this assertion, the confidence intervals for linear regression parameters and test the hypotheses about these parameters can be described. In details, the confidence interval for parameter *a* can be expressed as follows:

$$\left(\hat{a} - t_{\frac{1+\gamma}{2}}(n-2)s\sqrt{\frac{\overline{x}^2}{Q_x}};\hat{a} + t_{\frac{1+\gamma}{2}}(n-2)s\sqrt{\frac{\overline{x}^2}{Q_x}}\right), \quad (4)$$

and for parameter *b*:

$$\left(\hat{b} - t_{\frac{1+\gamma}{2}}(n-2)s\sqrt{\frac{1}{Q_x}};\hat{b} + t_{\frac{1+\gamma}{2}}(n-2)s\sqrt{\frac{1}{Q_x}}\right), \quad (5)$$

where $t_{\frac{1+\gamma}{2}}(n-2)$ denotes quantile of order $\frac{1+\gamma}{2}$ of the Student distribution with $n-2$ degrees of freedom, $Q_x = \sum_{i=1}^{n}(x_i - \overline{x})^2$. Confidence probabilities of these intervals are equal to γ.

Linear regression model will be insignificant if parameter $b=0$. If 0 is not within the confidence interval for *b*, then the model will be statistically significant and will correlate with results of observations. Confidence interval for forecast *y* can be computed from (6).

Confidence interval for variance σ^2 of observation errors is defined as (7):

$$\left(\hat{y} - t_{\frac{1+\gamma}{2}}(n-2)s\sqrt{\frac{1}{n} + \frac{(x-\overline{x})^2}{Q_x}};\ \hat{y} + t_{\frac{1+\gamma}{2}}(n-2)s\sqrt{\frac{1}{n} + \frac{(x-\overline{x})^2}{Q_x}}\right). \quad (6)$$

$$\left(\frac{(n-2)s^2}{\chi^2_{\frac{1+\gamma}{2}}(n-2)};\ \frac{(n-2)s^2}{\chi^2_{\frac{1-\gamma}{2}}(n-2)}\right), \quad (7)$$

where $\chi^2_{\frac{1+\gamma}{2}}(n-2)$ and $\chi^2_{\frac{1-\gamma}{2}}(n-2)$ denotes quantiles of orders $\frac{1+\gamma}{2}$ and $\frac{1-\gamma}{2}$ according to the Pearson distribution χ^2 with $n-2$ degrees of freedom.

The next step is to find the residual variance $s^2 = \frac{\sum_{i=1}^{n} e_i^2}{n-2} = 0{,}00003829$ and debugging $Q_x = \sum_{i=1}^{n}(x_i - \overline{x})^2 = 0{,}05$.

Let us choose the confidence probability $\gamma = 0{,}95$ and find from the tables quantile of order $\frac{1+\gamma}{2}$ of Student distribution with $(n-2)$ degrees of freedom $t_{\frac{1+\gamma}{2}}(n-2) = 4{,}3$. Therefore, the confidence intervals for linear regression parameters for *a* and *b* will be expressed by formula 8 and 9 respectively.

Because zero does not fall within the confidence interval for parameter *b* of linear regression, then at a significance level of 0.05 the linear model is significant. Confidence interval for predicting the value of value of density (ρ) of DEE/LO and DEE/RO blend tested at 15 ° (see formula 10).

$$\left(0.929 - 4.3 \cdot 0.006188\sqrt{\frac{0.035}{0.05}};\ 0.929 + 4.3 \cdot 0.006188\sqrt{\frac{0.035}{0.05}}\right) = (0.907;\ 0.951); \quad (8)$$

$$\left(-0.17 - 4.3 \cdot 0.006188\sqrt{\frac{1}{0.05}};\ -0.17 + 4.3 \cdot 0.006188\sqrt{\frac{1}{0.05}}\right) = (-0.289;\ -0.051); \quad (9)$$

$$\left(\hat{y} - t_{\frac{1+\gamma}{2}}(n-2)s\sqrt{\frac{1}{n} + \frac{(x-\overline{x})^2}{Q_x}};\hat{y} + t_{\frac{1+\gamma}{2}}(n-2)s\sqrt{\frac{1}{n} + \frac{(x-\overline{x})^2}{Q_x}}\right) = (0{,}855;0{,}951). \quad (10)$$

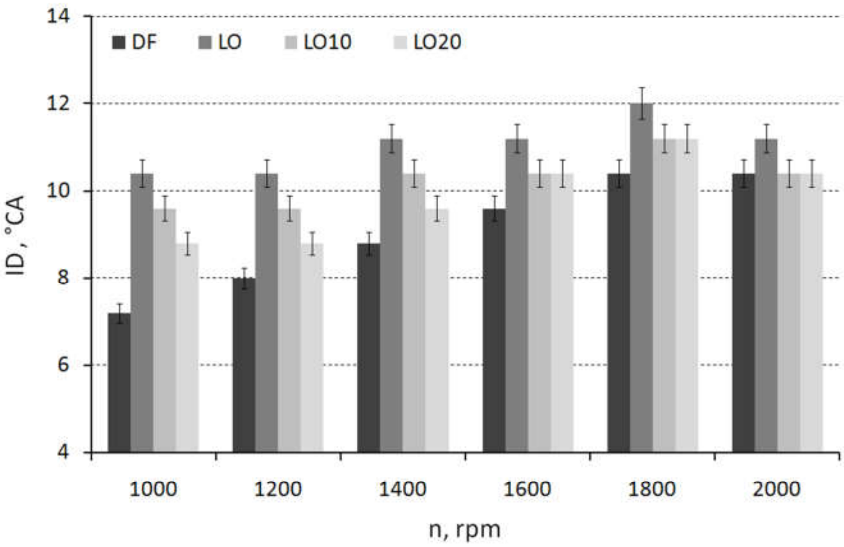

Figure 1 – Variation of ignition delay (ID) for AD3.152 engine operated at 120 Nm

Confidence interval for variance of observation errors σ^2 looks like (at the level of reliability $\gamma = 0,95$, $\chi^2_{\frac{1+\gamma}{2}}(n-2)$ and $\chi^2_{\frac{1-\gamma}{2}}(n-2)$ quantiles of orders $\frac{1+\gamma}{2} = 0,975$ and $\frac{1-\gamma}{2} = 0,025$ according to Pearson distribution χ^2 with $(n-2)$ degrees of freedom $\chi^2_{0,975}(n-2) = 7,38$ and $\chi^2_{0,025}(n-2) = 0,051$.

$$\left(\frac{(n-2)s^2}{\chi^2_{\frac{1+\gamma}{2}}(n-2)}; \frac{(n-2)s^2}{\chi^2_{\frac{1-\gamma}{2}}(n-2)} \right) = (0,00001038; 0,001502). \quad (11)$$

Thus, calculation of confidence intervals of linear regression parameters confirms importance of mathematical model chosen.

For surface tension (σ) of DEE/LO and DEE/RO blend and lower heating value (LHV) of DEE/LO and DEE/RO blend similar calculations of confidence intervals of linear regression parameters were performed, which confirmed significance of the linear mathematical model.

In this work the selected parameters of combustion process were also investigated. Research confirmed that ignition delay (ID) of LO is bigger (0.8 – 2 °CA) than in case for DF, but it was observed directly at lower speeds, while in other conditions the gap slightly narrow down (see Fig. 1). As it was mentioned previously, there is possible to observe impact of polyunsaturated fatty acids in LO allowing to reach such difference between LO and DF. Here it is seen an impact of physical delay influenced by fuel properties and composition. Addition of DEE reduces value of LO ignition delay together with viscosity resulting in wider spray pattern. As it can be seen from Fig. 1, ID of DF at larger engine speeds (2000 rpm) is similar to DEE/LO blends. Here it is possible to observe impact of cylinder temperature and pressure on chemical part of delay period, which is more pronounced at higher speeds.

Results suggest (Fig. 2) that the engine overall efficiency powered with LO is slightly lower than for DF. It can be explained by weak combustion characteristics stimulated by higher viscosity and low volatility. DEE addition increases overall efficiency, especially according to high level blends like LO20. It can be associated with lower self-ignition temperature and surface tension of DEE resulting in complete combustion of tested blends.

Research did not confirm smoke reduction for LO (Fig. 3), while it showed smoke reduction for blends with DEE due to its oxygen content. Usage of vegetable oils can lead to higher smoke opacity due to poor atomization and insufficient time for oxidation, but sometimes there could be observed also reduction of smoke based on loads and diffusion combustion intensity. Research confirmed that advance of injection timing, more pronounced for LO and LO10, results to oxidation of the soot particles due to a longer duration and higher temperatures during expansion stroke allowing to conclude that increase in ignition delay leads to poor combustion. Besides of that combustion quality decreases also with unsaturation of LO. DEE addition could resolve smoke opacity problem, at least at higher speeds.

In overall, DEE leaves better impact on smoke reduction than LO, where apart from

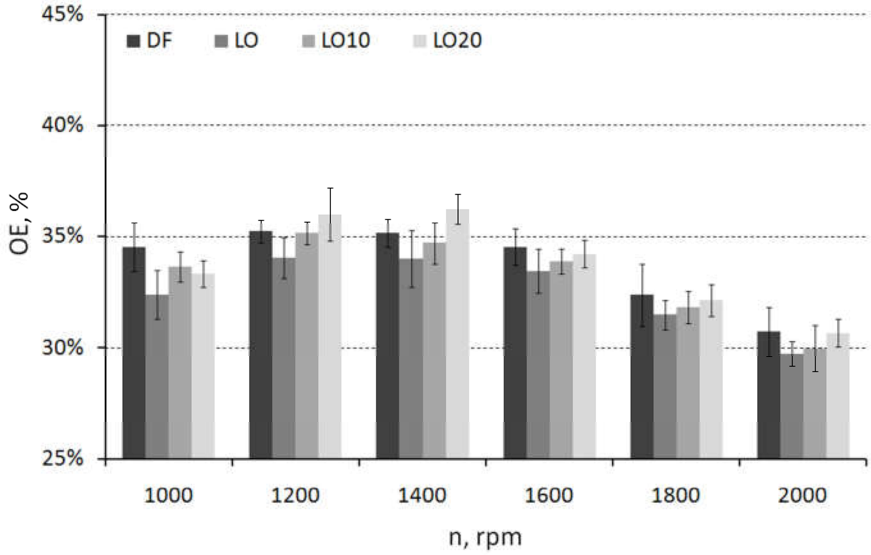

Figure 2 – The overall efficiency (OE) calculated for AD3.152 engine operated at 120 Nm

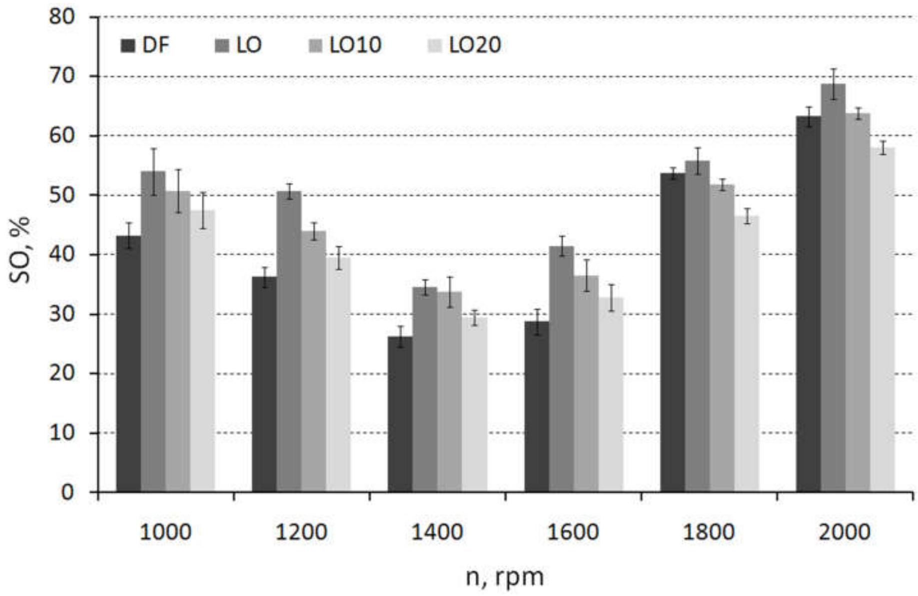

Figure 3 – Variation of smoke opacity (SO) for AD3.152 engine operated at 120 Nm

dominating factor – molecular structure of DEE, could be observed also positive impact of lower viscosity causing a better atomization.

Conclusions

Key parameters analyzed include density, kinematic viscosity, surface tension, lower heating value (LHV), and cold filter plugging point (CFPP). These parameters were measured according to international standards (e.g., EN ISO 3838, EN ISO 3104, ASTM D240-02:2007, EN 116:2015, and ISO 304:1985). The study also evaluates combustion characteristics, including ignition delay (ID) and engine overall efficiency (EOE), using a Perkins AD3.152 diesel engine equipped with advanced instrumentation for in-cylinder pressure and needle lift measurements.

Experimental results demonstrate a significant linear relationship between DEE concentration and the physicochemical properties of LO-DEE blends. For instance, density and surface tension decreased with increasing DEE content, leading to improved spray characteristics and atomization during fuel injection. The LHV of the blends was slightly reduced compared to diesel fuel (DF) but remained comparable to rapeseed oil-DEE mixtures.

The study also found that DEE addition improved the engine's overall efficiency, particularly for blends with higher DEE content (e.g., LO20). This improvement is attributed to the lower self-ignition temperature and reduced surface tension of DEE, which facilitate more complete combustion. Despite these improvements, the study identifies several challenges associated with using LO-DEE blends. The oxidative instability of LO, influenced by its high α-linolenic acid content, affects its long-term storage and performance.

The study emphasizes the importance of understanding the interplay between fuel properties, combustion behavior, and engine performance to optimize the use of LO-DEE blends as a renewable alternative to diesel fuel. In conclusion, this research provides valuable insights into the physicochemical and combustion characteristics of LO-DEE blends, offering a foundation for their potential application in diesel engines. While LO-DEE blends show promise as a renewable biofuel, further studies are needed to address challenges related to oxidative stability, emissions, and engine operability in diverse conditions.

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Conflict of interest
None.

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ОЦІНКА ФІЗИКО-ХІМІЧНИХ ВЛАСТИВОСТЕЙ ТА ЕФЕКТИВНОСТІ ЗГОРЯННЯ СУМІШЕЙ ЛЛЯНОЇ ОЛІЇ ТА ДІЕТИЛОВОГО ЕФІРУ ДЛЯ ДИЗЕЛЬНИХ ДВИГУНІВ

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Анотація. Це дослідження зосереджене на фізико-хімічних та характеристиках згоряння лляної олії (LO), змішаної з діетиловим ефіром (DEE), та досліджує її потенціал для використання у дизельних двигунах. Хоча існують аналогічні дослідження для ріпакової олії (RO) та сумішей із DEE, детальний аналіз сумішей LO-DEE досі був відсутній. Лляна олія – прозора або жовтувата їстівна олія, яку отримують із насіння льону, відзначається високим вмістом поліненасичених жирних кислот, зокрема α-ліноленової кислоти. Ці властивості роблять її придатною для застосування у різних галузях промисловості, включаючи хімічну, біомедичну та паливну. Водночас унікальний хімічний склад LO створює як можливості, так і виклики для її використання як біопалива. Експериментальні результати показали суттєву лінійну залежність між концентрацією DEE та фізико-хімічними властивостями сумішей LO-DEE. Наприклад, густина та поверхневий натяг знижувалися зі збільшенням вмісту DEE, що призводило до покращення характеристик розпилення та атомізації під час впорскування палива. Нижча теплота згоряння (LHV) сумішей була дещо зниженою порівняно з дизельним паливом (DF), але залишалася подібною до сумішей ріпакової олії з DEE. Хоча в’язкість LO є нижчою порівняно з багатьма іншими рослинними оліями, вона все ж вища, ніж у традиційного дизельного палива, що може впливати на кут розпилення та ефективність атомізації. Додавання DEE ефективно зменшувало в’язкість, покращуючи процес згоряння. Аналіз згоряння показав, що LO має довший час затримки запалювання порівняно з DF, головним чином через високий вміст поліненасичених жирних кислот. Проте змішування з DEE суттєво скорочувало затримку запалювання, зменшуючи розрив між сумішами LO та DF, особливо за високих швидкостей двигуна. Крім того, високий вміст ненасичених жирних кислот у LO сприяє підвищенню викидів NOx і може створювати проблеми з відкладеннями на компонентах двигуна. Попереднє нагрівання палива та модифікація двигуна можуть допомогти вирішити ці проблеми, але потребують подальших досліджень. Статистичний аналіз із використанням лінійних регресійних моделей підтвердив значущість спостережуваних тенденцій, а довірчі інтервали засвідчили надійність експериментальних даних. Дослідження наголошує на важливості розуміння взаємозв’язку між властивостями палива, поведінкою при згорянні та характеристиками роботи двигуна для оптимізації використання сумішей LO-DEE як відновлювального аналога дизельного палива.

Ключові слова: лляна олія (LO); діетиловий ефір (DEE); біопаливо; в’язкість; теплота згоряння (LHV); атомізація; відновлювальні джерела енергії; суміші палива.