Feasibility assessment for replacing rapeseed oil by selected vegetable oils in diesel engine

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Abstract. To study the feasibility of replacing rapeseed oil used as fuel of diesel engines by other vegetable oils, comparative studies were conducted of rapeseed oil combustion process with palm and sunflower oil. The tests have been carried out for the fuel injection pressure: 70, 100 and 135 MPa, pressure in chamber equal to 0.5, 0.7 and 0.9 MPa and the excess air factor from 1.25 to 5 (1.25; 2.50; 3.75; 5.00). The progress of the combustion process was studies for four temperature levels: 350°C, 425°C, 500°C and 575°C. The following were considered as analysed parameters of the process: self-ignition delay, burning time and pressure growth. Based on the results of the conducted research, it is recommended to use palm oil to replace rapeseed oil as a fuel in a diesel engine. In addition, it is possible to use sunflower oil for this purpose. Characteristics of the rapeseed oil combustion process is most similar to process of palm oil. Moreover, the parameters of the palm oil combustion process are similar to those characterizing diesel (at temperature equalling to 575°C and pressure of 0.7 MPa and 0.9 MPa). Sunflower oil was characterized by lower maximum combustion pressure, longer autoignition delay (after 0.1s in every case) compared to other tested vegetable oils.

1. Introduction
Constant tightening of legal regulations (among others the binding Directive 2015/1513/EC [1]) aimed at limiting the usage of fossil fuels and the consequent natural environment contamination give rise to the necessity of seeking possibilities of their substitution. In such a context it is justified to replace the oil derivative fuels used to date in transport by alternative fuels [2,20-22] (mainly transport biofuels). A solution which has been well studied and commonly used in Poland is partial substitution of diesel fuel by methyl esters of higher fatty acids, produced domestically mainly from rapeseed oil[3]. Methyl esters are a product of the transesterification process, which helps adapt vegetable oil to parameters similar as those of diesel fuel. As a result the substitution of glycerol contained in the fat (triglyceride) takes place with added aliphatic alcohol (ethanol, methanol) in the presence of base or acidic catalyster, in accordance with the reaction presented in figure 1 [4].
The application of esterified rapeseed oil in Poland is first of all limited to its blending with diesel fuel (maximum 7% by volume of biocomponent) to obtain fuel for engines with automatic ignition [3]. Available literature sources indicate that there is a possibility of its independent usage for needs related to fuels [2,5,19,23]. Nevertheless a serious problem in this respect are high costs of the generation process of ester biocomponents, with the main reason being transesterification. Consequently efforts have been undertaken to use pure rapeseed oil [6]. The available research results allow the presumption that despite differences in physical and chemical properties of diesel fuel and independent rapeseed oil (PVO), high temperature of cold filter blocking [7] and trends of sediment formation [8], the usage of crude rapeseed oil as fuel in diesel engines is possible, especially for agricultural machines [9]. This arises in the first place from basic operational parameters of their engines, which are first of all characterised by low rotational speeds, relatively low maximum power and working environment mainly in temperatures over zero. Given global change trends and development directions of the fuel sector, it seems that it would be justified to carry out an appraisal of fuel suitability of also other vegetable oils, which would help show whether in a situation of a shortage of rapeseed oil it would be possible to have it replaced by another vegetable oil without any consequences for vehicles fuelled in this way. Numerous studies are being carried out worldwide with respect to possibilities of using locally available vegetable oils as a substitute for fuels in diesel engines [10-12].

The objective of the paper was to make an appraisal of the feasibility of replacing rapeseed oil used as fuel in diesel engines by palm oil or sunflower oil. Tests were conducted during which a comparison was made of combustion processes of selected vegetable oils (including rapeseed oil – as model) and diesel fuel (point of reference).

2. Research methodology
A comparison was carried out of the course of the combustion process of diesel fuel (ONM Standard 50) and selected cold pressed vegetable oils: rapeseed, sunflower and palm oil. On the graphs that present the obtained test results diesel fuel was marked black, rapeseed oil: green, palm oil: orange, sunflower oil: yellow.

A diagram of the research stand was presented on figure 2. Its main element was a chamber having a fixed volume (1), which allows independent modification of parameters of supplied air (temperature, initial pressure, excess air) and of fuel (fuel injection pressure, fuel dose). The stand was additionally furnished with the following systems: fuel supply (Common Rail) with electronic injection control (2, 3, 4), control of fuel injection parameters (5, 6), measurement of combustion pressure in the chamber (8), air supply (9) and a computer allowing the controlling of operating parameters of the stand and recording the obtained data (7).

Figure 3 shows the test site. Three groups of systems can be distinguished on the test bench. The first is a system for supplying fuel and electricity to drive a high-pressure pump and to supply the control systems (supply pump supplying fuel at a pressure of 0.3 MPa; fuel filter with a pore size of approximately 4-5 μm; high-pressure pump allowing fuel to be pumped at a pressure of up to 170 MPa;
fuel pressure sensor; storage tank; pressure regulator). The second group consists of electronic control systems made on their own and necessary to control the operation of the injection system (electric motor controller for high-pressure pump drive in the range of 10-100% of the nominal engine speed; pressure regulator controller with adjustable width in the range of 1-95% at the repetition frequency of about 200 Hz; injector controller allowing for the implementation of the cycle in the range of time changes from 0 to 3000 µs; temperature control system controller, which enables the temperature change of fuel in the injection system and the injector casing). The third group is Daimler-Chrysler's proprietary Common Rail diesel injection system OM611.

The research chamber allows the visualisation of the injection process and combustion, as well as heating up of the agent to a temperature of 700°C.

![Figure 2. Scheme of test stand; clarifications of symbols contained in text.](image1)

![Figure 3. General view of the test site.](image2)

To allow the appraisal of existing possibilities of having rapeseed oil replaced by another vegetable oil, combustion tests were carried out of selected oils in a chamber with a constant volume, at variable physical parameters of the process. The studies comprised the impact of air pressure in the chamber, of
the excess air factor, fuel injection pressure and impact of air temperature on the combustion process at different temperature.

Air pressure in the combustion chamber affects the process of fuel spray, the creation of a fuel and air mixture and the course of chemical reactions. They may be referred to the pressure of compression end in the engine combustion chamber.

An increase in air pressure in the chamber is related with the increase of gas density, which in turn is transposed on an increase in aerodynamic resistance affecting the fuel being injected and as an effect a decrease in the range of the stream front. Concurrently the lower pressure of gas that forms the injection environment hinders the secondary decomposition of drops, and causes the increase in the share of larger drops, which are characterised by better penetration properties [13]. The excess air factor defines the relation of actual air amount at which fuel is combusted to its stoichiometric amount (theoretical air amount calculated in a mathematical way, indispensable for complete combustion of supplied fuel) [14]. Given the lack of possibility of achieving in reality a perfect mixing of fuel with air (as for liquid fuels – vaporisation and mixing), to achieve complete combustion it is as a rule necessary to provide a bigger amount of air than results from stoichiometric equations[15]. As vegetable oil has a much higher viscosity than diesel fuel [16], the vegetable oil stream injected to the composition chamber is sprayed in a much lesser extent than a stream of oil derivative fuel. Drops of dispersed vegetable oil are larger, and the fuel stream much denser, which increases its range. As an effect the formation process of the fuel and air mixture proceeds worse and much slower [17]. Air temperature in the chamber if a parameter of critical importance for burning of vegetable oils. The higher is air temperature in the chamber, the easier and quicker proceeds the evaporation process of the injected fuel dose and the formation of the fuel and air mixture [18].

The tests have been carried out for the fuel injection pressure (p) 70 MPa, 100 MPa and 135 MPa, pressure in chamber (P) equal to 0.5 MPa, 0.7 MPa and 0.9 MPa and the excess air factor (λ) od 1.25 from 5 (1.25; 2.50; 3.75; 5.00). The progress of the combustion process was studies for four temperature levels (T) - 350°C, 425°C, 500°C and 575°C. The following were considered as analysed parameters of the process: self-ignition delay (τ₀), burning time (τₛ) a nd pressure growth (Δp).

3. Analysis of results

In tests concerning the impact of air pressure inside the research chamber on the combustion process carried out at various temperatures, the pressure level was determined at three levels, i.e. 0.5 MPa, 0.7 MPa and 0.9 MPa. The measurements have been carried out for air temperatures inside the chamber, i.e. 350°C, 425°C, 500°C and 575°C. The pressure value of fuel injection and the value of the excess air factor remained unchanged and they have been determined at the level of 135 MPa and 1.25 respectively.

At air temperature in testing chamber at the level of 350°C, pressure changes are of no major importance for the course of combustion process of analyses fuels. At this temperature the tested vegetable oil burns very slowly, and the pressure increase inside the chamber is minimal. The most prominent impact of pressure value in the chamber was recorded for temperatures equaling to 425°C and 500°C. As the pressure grows, the time of delay of self-ignition is considerably shortened and the maximum height of burning pressure increases. The combustion progress of the tested vegetable oils is quite similar within the temperature range 350°C - 500°C. At air temperature level in the chamber equalling to 575°C and pressure of 0.7 MPa (figure 4) and 0.9 MPa (figure 5), palm oil differs from among the tested vegetable oils, because it reaches combustion parameters that characterise diesel fuel.
In tests oriented at analysing the impact of the excess air factor on the combustion process at different temperatures the value of the factor was determined at four levels, i.e. 1.25, 2.50, 3.75 and 5.0. The measurements were carried out for four air temperatures inside the chamber, i.e. 350°C, 425°C, 500°C and 575°C. The value of pressure inside the chamber and of the fuel injection pressure remained unchanged and have been determined at the levels of 0.9 MPa and 135 MPa respectively.

Similarly as in the case of tests of pressure value inside the chamber, at a temperature at the level 350°C, the excess air factor does not have a significant impact on the course of combustion process of tested fuels. At the factor of 1.25, only for rapeseed oil a noticeable increase of pressure inside the
chamber takes place. The biggest impact of the excess air factor on the combustion process of the oils being subject of our analysis is visible at the temperature inside the chamber of 425°C and 500°C. In such an event along with an increase in the value of the factor observed was a clear elongation of the self-ignition delay period, limiting the pressure growth and extension of the combustion process. Combustion of vegetable oils at a value of the excess air factor at the level of 3.75 and 5.00 does not cause significant changes of pressure inside the chamber. Only at a temperature amounting to 575°C the combustion process inside the chamber proceeds regardless of the value of the factor, yet as regards values higher than 3.75 the pressure growth is relatively insignificant. Concurrently the course of pressure changes during the combustion of vegetable oils in such conditions indicates that their combustion process proceeds better than in the case of diesel fuel. Vegetable oils ignite and burn more quickly as compared to diesel fuel. In this respect palm oil appears to become distinguished from the others, because its combustion parameters are the best from among the analysed fuels (figure 6).

In tests of the impact exerted by fuel injection pressure on the combustion process at various temperatures, its height was determined at three levels, i.e. 65 MPa, 100 MPa and 135 MPa. The measurements were carried out for four air temperature inside the chamber, i.e. 350°C, 425°C, 500°C and 575°C. The value of pressure inside the chamber and the excess air factor remained unchanged and they have been determined at a level of 0.9 MPa and 1.25 respectively.

Within the scope of analysed temperatures, the impact of injection pressure on the progress of combustion of vegetable oils proved to be insignificant. At the temperature of 350°C the combustion of analysed fuels did not lead to a pressure growth inside the chamber. The only exception is rapeseed oil, for which at the maximum tested value of fuel injection pressure (135 MPa), the pressure growth is noticeable. The elevation of air temperature up to 425°C does not cause an increase in the dependence of the combustion process on fuel injection pressure. However, at the highest of the studied levels (135 MPa) a certain shortening of the delay in self ignition was recorded and an increase in the maximum combustion pressure. At the temperature of 500°C differences in parameters of the combustion process between particular vegetable oils begin to be clearly noticeable. Differences in combustion time and maximum combustion pressure become particularly visible for the lowest (65 MPa) (figure 7) and the highest (135 MPa) injection pressure (figure 8). At the pressure of 65 MPa rapeseed oil is distinguishable among all oils, but at the level of 135 MPa the best parameters of the

![Figure 6](image)

**Figure 6.** Increase in combustion pressure in the chamber; T=575°C, P=0.9 MPa, p=135 MPa, λ=3.75; clarifications of symbols contained in text.
Combustion process were recorded for palm oil, slightly exceeding rapeseed oil, first of all from the viewpoint of maximum combustion pressure. At the temperature of 575°C the best characteristics of the combustion process at each of the three levels of fuel injection pressure, have been recorded for palm oil. In such circumstances it equals to diesel fuel with respect to the self-ignition delay period, combustion time and pressure growth inside the chamber (as an example figure 5).

![Figure 7. Increase in combustion pressure in the chamber; T=500°C, P=0,9 MPa, p=65 MPa, λ=1,25; clarifications of symbols contained in text.](image)

![Figure 8. Increase in combustion pressure in the chamber; T=500°C, P=0,9 MPa, p=135 MPa, λ=1,25; clarifications of symbols contained in text.](image)

In tests of impact of air temperature in the research chamber on the combustion process, fuels were injected to the chamber heated up to the temperature of 350°C, 425°C, 500°C and 575°C. The
remaining parameters of the process, such as pressure inside the chamber (0.9 MPa), injection pressure (135 MPa) and the excess air factor (1.25) remained constant.

At a temperature of 350°C the process of ignition and combustion of vegetable fuels progresses slowly and does not cause significant pressure growth. Only for rapeseed oil the self-ignition moment appears to be clearer and it is possible to delimit the maximum combustion pressure. At the temperatures of 425°C (figure 9) and 500°C (figure 8) all the tested oils ignite and burn in the same way. At a lower temperature (425°C) noticeably higher maximum combustion pressure characterises rapeseed oil, yet this difference vanishes following an increase in temperature (500°C). In such circumstances similar combustion parameters are recorded for palm oil. In both temperatures the combustion process of sunflower oil proceeds less advantageously than rapeseed oil. At a lower temperature the self-ignition temperature is similar, yet the burning time is noticeably longer. However, at an elevated temperature the combustion time is similar, but a considerable extension takes place of the self-ignition delay period. In this context of interest are combustion courses of palm oil, which at the temperature of 435°C ignites in the same period as rapeseed oil and sunflower oil, yet it burns for the longest period and causes the smallest pressure increase. But at the temperature of 500°C it acquires optimum combustion parameters, which is continued at the highest temperature: 575°C.

![Figure 9. Increase in combustion pressure in the chamber; T=425°C, P=0,9 MPa, p=135 MPa, λ=1.25; clarifications of symbols contained in text.](image)

The temperature increase inside the research chamber causes the approximation of combustion process parameters of vegetable oils with parameters that characterise diesel fuel. Yet even at the level of 500°C oil derivative fuel ignites more quickly, burns for a shorter time and causes a pressure increase inside the chamber twice higher than vegetable oil. An increase of temperature up to 575°C causes that parameters of the combustion process of all tested vegetable oils and diesel fuel become similar (figure 4). Despite the fact that as regards the highest combustion pressure diesel fuel is better than the studied vegetable oils, the delay of self-ignition is very similar, with an indication on vegetable oils, first of all palm oil. Rapeseed oil and sunflower oil have inferior characteristics, yet from the viewpoint of maximum combustion pressure it is similar to the third of the studied vegetable oils. Attention should be drawn to the fact that the analysed highest parameters of the combustion process of analysed oils are most similar to the conditions prevalent in diesel engines during regular operation from among the analysed variants.
4. Conclusions
On the basis of executed research it may be presumed that the biggest impact on the progress of combustion of analysed vegetable oils is exerted by air temperature inside the chamber. As it grows, until the time of achieving the maximum analysed value, the time of self-ignition delay is shortened, the combustion pressure increases are quicker, and its maximum values are higher. At the highest analysed temperature, with maintained optimum values of the remaining parameters, the progress of the combustion process of the analysed vegetable oils is similar to the one that characterised diesel fuel. Particularly insignificant differences may be recorded for palm oil. The value of temperature in the research chamber affects to a much bigger extent the progress of combustion of vegetable oil than diesel fuel, which arises from viscosity differences between the analysed fuels, which grow with the growth of temperature.

A factor that affects to a much bigger extent the progress of combustion of the tested vegetable oils more than diesel fuel is also air pressure in the combustion chamber. This parameter is clearly correlated with the level of temperature inside the chamber. At lower values, the impact is practically unnoticeable, yet as temperature grows, pressure in the chamber causes the shortening of the self-ignition delay time, increase in the pressure growth rate and the increase in maximum combustion pressure.

Fuel injection pressure at a temperature up to 425°C has the biggest impact on the combustion of rapeseed oil, while above 500°C it affects positively the combustion of palm oil. The excess air factor, with an increase of its value, extends the time of the combustion process of all the tested fuels, and once the maximum value has been achieved – limits their capacity for self-ignition.

An analysis of obtained results in the aspect of feasibility of obtaining vegetable oils for power needs, other than rapeseed oil, allows the presumption that it is possible to have it replaced by palm oil and by sunflower oil. However, it should also be borne in mind that operating parameters of an engine in which it is used as propulsion may become impaired. The characteristics of the combustion process of rapeseed oil appears to be most similar to the characteristics of palm oil, in the case of which the selected parameters prove to be more advantageous. In addition, in specific conditions parameters of palm oil combustion are identical to parameters that characterise diesel fuel. In research conditions the sunflower oil was characterised by a lower value of maximum combustion process and longer self-ignition delay period, in relation to other tested vegetable oils.

The combustion process of vegetable oils may be streamlined by increasing the temperature and pressure in the combustion chamber, which in relation to engine operation may indicate the needs of changing the injection angle and an increase in the compression degree. The temperature may also be increased by increasing the operating temperature of the agent that cools the engine.

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