The influence of the dynamic angle of fuel pumping start on selected parameters of the combustion process in diesel engine powered by mixtures of canola oil with n-hexane

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Abstract. The research conducted by the authors so far shows that powering diesel engine with the mixture of canola oil with n-hexane [C\textsubscript{6}H\textsubscript{14}] is a promising solution. It was stated that adding n-hexane to canola oil caused a positive change in physicochemical properties of canola oil. However, empirical tests proved that further works are necessary in order to adapt the fuel injection system of the engine. This article presents test results which aim at estimating the degree to which the alternation of the dynamic angle of fuel pumping start influences the parameters of the combustion process. The empirical tests were run at the stands of external exploitative characteristic. During the tests the high-frequency parameters, such as: the pressure in the cylinder, the pressure in the injection cord and the ascend of the injection needle were measured for three values the dynamic angle of pumping start, $\alpha$=14\textdegree, 17\textdegree and 20\textdegree crank angle. The received data allowed for estimating, among others, the parameters describing the combustion process: mean indicated pressure, maximum pressure of combustion, the speed of the pressure increase, the angle of the beginning of combustion and the angle of the occurrence of maximum pressure.

1. Introduction
A wide range of criteria for assessing alternative fuels significantly impedes or even eliminates the possibility of selecting the best concept for their application to diesel engines. The most important for diesel engines are plant oils [4,5,6]. They can be applied as pure oils or as a component of mixtures with diesel fuel. In many research centres – in Poland and abroad – a number of tests of engines powered with bio – fuels made from various plants are conducted [7,10,11,12,13,16,26,27]. Different physicochemical properties of those fuels directly influence the process of fuel injection and the process of combustion [8,9,10,11,12,13,15]. Powering diesel engine with fuels which have various physicochemical properties may generate incorrect combustion process. The course of this process directly influences the maximum power, useful torque and ecological parameters of the engine work [13,14,15,17,18,19]. Undoubtedly, it is crucial to analyse the influence of the alternation of the dynamic angle of fuel pumping start on the course of combustion process of fuels with various physicochemical properties. This article presents the results of tests run on an AD 3.152 engine where the variable was the dynamic angle of fuel pumping start. A typical dynamometric examination stand was used; equipped
with a system to measure high-frequency parameters of the engine work. Six different kinds of fuel were used for the tests for the engine working in typical external exploitative conditions.

2. Properties of the tested fuels
Applying pure canola oil as fuel for diesel engines is very difficult. Different (compared to diesel fuel) physicochemical properties influence directly the process of preparing the mixture and the combustion process [1,2,3,20,21,24,25]. Research shows that parameters such as viscosity, density and surface tension have the most significant influence on those processes [7,10,11,12,17]. Consequently, an attempt has been made to change the physicochemical properties of canola oil by adding n-hexane [14,22,23]. N-hexane (C6H14) is an organic chemical compound from the alkane group. N-hexane parameters are included in Table 1. The isomers of n-hexane are highly non-reactive and highly non-polar, that is why they can be applied as solvent in organic reactions. The initial composition of the fraction depends largely on the source of the oil (crude or reformed) and the constraints of the refining. The industrial product (usually around 50% by weight of the straight-chain isomer) is the fraction boiling at 65–70 °C.

| State of matter | liquid |
|-----------------|-------|
| Colour          | transparent |
| pH              | no data   |
| Melting point   | -94 [ºC] |
| Boiling point   | 68 [ºC]   |
| Autoignition temperature | 240[ºC] |
| Dynamic viscosity indicator in temp. 20 [ºC] | 0,326 [MPa·s] |
| Kinematic viscosity indicator in temp. [20ºC] | 0,55 [mm²/s] |
| Vapor pressure in temp. 20°C | 160 [mbar] |
| Density in temp. [20°C] | 0.66 [g/ml] |
| Solubility in water in temp. [20°C] | 0,00095 [g/dm²] |
| Solubility in organic solvents | liquid hydrocarbons |

The following fuels were used for tests: diesel fuel – ON; canola oil – OR; canola oil with 5% n-hexane – OR5; canola oil with 10%n-hexane – OR10; canola oil with 15% n-hexane – OR15; canola oil with 20% n-hexane – OR20. Physicochemical properties of the fuels used presented in the Table 2.

| Type of fuel | Density in temp. 20°C[kg/m³] | Dynamic viscosity indicator in temp. 20°C [MPa·s] | Surface tension [mN/m] |
|--------------|------------------------------|-----------------------------------------------|-----------------------|
| ON           | 840                          | 2,55                                         | 29,15                 |
| OR           | 900                          | 54,00                                        | 34,15                 |
| OR5%         | 900                          | 40,54                                        | 31,30                 |
| OR10%        | 890                          | 28,20                                        | 30,08                 |
| OR15%        | 880                          | 26,47                                        | 30,10                 |
| OR20%        | 880                          | 24,15                                        | 27,68                 |

3. The research stand
The research stand was based on a Tyree cylinder diesel engine with direct fuel injection to the cylinder, done with the injection pump CAV DPA. Table 3 presents the technical data.
Table 3. The main technical parameters of the engine AD3.152.

| Technical parameters                                    | Value       |
|---------------------------------------------------------|-------------|
| Number and type of cylinders                            | 3-vertical  |
| Cylinder diameter [mm]                                  | 91,44       |
| Piston stroke [mm]                                      | 127         |
| Total engine cubic capacity [cm³]                       | 2502        |
| Compression ratio                                       | 16,5        |
| Power rating [kW/KM]                                    | 34,6/47     |
| Rotational speed rating [rpm]                           | 2050        |
| Torque rating [Nm]                                      | 146,8       |
| Maximum torque [Nm]                                     | 165,4       |
| Rotational Speed at maximum torque [rpm]                | 1300-1400   |
| Minimum rotational speed of the neutral gear [rpm]      | 750         |
| Fuel injection system                                   | direct into the cylinder |
| Type of the injection pump                              | Lucas CAV DPA |
| Static pressure of the opening of the fuel injectors [MPa] | 17,5        |
| Moment of ineraria of the moving parts of the engine [kg·m²] | 0,76        |
| The dynamic angle of the beginning of the fuel injection| 14º before TDC |

The measuring system was equipped in three measuring lines and the decoder of the angle of the crankshaft rotation. The engine was equipped with sensors registering alternations of the pressure in the combustion chamber and in the injection cord. Piezoelectric sensors QC34D and AVL QL16D sensors (AVL company) were used. The changes of the needle of the atomizer ascend were registered by a miniature, transformer, movement sensor which cooperated with a CL104 amplifier. The signals from the pressure sensors were conducted to the inputs of the electric charge amplifier placed in the measuring case. Each electric charge amplifier was equipped with a low – pass filter with regulated cut off frequency. The processing of the registered signal through the filter is achieved in a way which allows for suppressing those parts of the spectrum which can be found beyond the selected cut off frequency. The schematic drawing of the research Figure 1.

4. The course of the tests
While preparing the programme for experimental tests, the measuring points were selected in a way that allows for testing in wide range of rotational speed of the engine, with special focus on measuring points for the maximum torque $M_{\text{omax}}$ and maximum effective power $N_{\text{emax}}$. The tests were run in the conditions of external speed characteristics in the rotational speed interval from 1000 – 2000 rpm, for three values of the dynamic angle of the fuel pumping start: nominal $\alpha_{\text{dpt}} = 14°$CA; earlier $\alpha_{\text{dpt}} = 18°$CA; later $\alpha_{\text{dpt}} = 10°$CA. During the tests the data from the sensors – pressure in the combustion chamber, pressure in the injection cord and the ascend of the injection needle - were registered for each estimated rotational speed of the engine (every 200 rpm). Before the tests, the engine was in the state of thermal equilibrium and then the settings of the transmitter of the angle of the crankshaft were checked.

The aim of the experimental tests was to estimate the influence of various physicochemical properties of the tested mixtures and the regulation parameter of the engine (which is the dynamic angle of fuel pumping start $\alpha_{\text{dpt}}$ °CA) on the parameters of the combustion process.
5. The results

Engine indicating allowed for estimating what influence on the selected parameters of the combustion process various physicochemical properties of the tested mixtures have. It also helped answer the question whether the alternation of regulation parameters of the engine may result in an improvement of those parameters, and if so – to what extent. Special attention was paid to such parameters as: auto-ignition delay angle, mean indicated pressure and the speed of the pressure increase in the combustion chamber.

5.1. The period of fuel auto-ignition

Certain amount of time is necessary to initiate the process of fuel auto-ignition from the moment of the beginning of injection. The time is needed for chemical and physical preparation of the combustible mixture and it depends on a number of factors; the crucial ones are: pressure and temperature inside the combustion chamber at the moment of injection, physicochemical properties of the fuel, the crankshaft rotational speed, air-fuel ratio and the parameters of the occurring combustible mixture – Figure 2.
Figure 2. The course of the angle of ignition delay in the function of the dynamic angle of pumping start achieved in the conditions of the external characteristics AD3.152 for various rotational speeds of the engine: a=1000, b=1200, c=1400, d=1600[rpm]

5.2. Mean indicated pressure

The values of the maximum combustion pressure of diesel fuel for three values of the dynamic angle of pumping start depending on the angle of crankshaft rotation presented on an open indicatory chart – Figure 3.

Figure 3. Open indicatory chart in the function of the crankshaft location for three values of the dynamic angle of fuel pumping start, registered in the conditions of external characteristics, rotational speed 1000 rpm; A – the beginning of injection, B – the beginning of combustion, C – maximum pressure in the combustion chamber

It was stated that the highest values of the mean indicated pressure occurred for the dynamic angle of fuel pumping start 18°CA before TDC - figure 4. Maximum variations of the mean indicated pressure were about 0,12 MPa. The results obtained for two selected types of fuel - OR10% and OR20% are presented in Figure 5.
Figure 4. The values of the mean indicated pressure of the tested mixtures depending on rotational speed of the engine for two values of the dynamic angle of fuel pumping start.

Figure 5. The course of the mean indicated pressure in the function of rotational speed of the engine powered with 10% and 20% mixtures of canola oil with n-hexane for three different values of the dynamic angle of fuel pumping start.

5.3. The speed of pressure increase - \( dp/da \) [MPa/°CA]

Obviously, the change of the dynamic angle of pumping start influenced the change of the speed of pressure increase. The increase of the maximum speed of the pressure increase for high values of the dynamic angle of fuel pumping start is visible. In cases of bigger angles of auto-ignition delay more fuel was injected into the combustion chamber in a pre – flame period. The results are presented in figure 6.
Figure 6. The course of the speed of pressure increase in the function of rotational speed and the dynamic angle of pumping start in conditions of the external characteristics of the engine AD3.152 for the tested fuels: a-ON, b-OR, c-OR5%, d-OR10%, e-OR15%, f-OR20%.

It was also noted that for the value a larger amount of n-hexane in the mixture causes a decrease of the speed of pressure increase $\frac{dp}{d\alpha}$ [MPa/°CA] shows Figure 7.
Figure 7. The course of the speed of pressure increase in the function of the dynamic angle of pumping start in conditions of the external characteristics of the engine AD3.152 for different rotational speeds of the engine $a=1000$, $b=1400$, $c=1800$, $d=2000\,[rpm]$

6. Conclusions
The conducted tests and the analysis of their results confirm theoretical speculations. Applying pure canola oil for powering diesel engines is difficult and significantly limited due to its different physicochemical properties [13,15]. Adding n-hexane resulted in a positive change of those parameters – making such parameters of canola oil as viscosity and surface tension similar to the parameters of diesel fuel. The research showed [14,22,23] that adding a non-reactive solvent influences – in a number of ways – the process of fuel pumping, injection and the process of combustion. However, it was noted that adding the solvent to canola oil is not sufficient. The empirical tests showed the necessity to adjust the engine’s injection system. The main goal of the authors of this work was to estimate the degree to which the change of the dynamic angle of fuel pumping start influences the parameters of combustion for the engine powered with mixtures of canola oil with n-hexane. The tests showed that together with the increase of the value of the dynamic angle of fuel pumping start there is a significant increase of the values of: the angle of the ignition delay, mean indicated pressure, maximum combustion pressure and the speed of pressure increase. In diesel engine the lengthening period of ignition delay results in the increase of the speed of combustion. The increase of the moment of the beginning of injection makes the injection happen at the moment when the pressure and temperature in the combustion chamber are lower. These conditions affect the lengthening of the chemical and physical period of the fuel ignition. Too high combustion speeds and too high pressure can be damaging for the engine. On the basis of the tests it was stated that the amount of n–hexane in canola oil did not have a significant influence on the change of the angle of the ignition delay. However, detailed analysis of data and the charts of the combustion parameters shows that for the dynamic angle of pumping start $\alpha_{dpt}=18\,[^\circ\text{CA}]$ together with the increase of the amount of n-hexane there is a visible increase in the values of mean indicated pressure. Moreover, it also results in the decrease of the speed of pressure increase (max. about 30%) in comparison to diesel fuel and canola oil. From the perspective of the engine’s functioning and the load of its construction knots it is a highly unfavourable phenomenon.

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