The course of combustion process under real conditions of work of a traction diesel engine supplied by mixtures of canola oil containing n-hexane

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Abstract. Restrictions for emission of toxic substances of exhaust gases force to conduct research aimed at searching for new types of fuels for powering combustion engines. With reference to diesel engines, the main focus was on acquiring fuels not from petroleum refining, the so-called alternative fuels. While examining these issues, the authors conducted various tests on an engine dynamometer in dynamic and static conditions, in which compression ignition engine was powered by mixtures of canola oil containing n-hexane (in various V/V proportions). Although the results were promising, they did not reflect the work of an engine in real road conditions. This article presents the results of research on traction diesel engine powered by mixtures of canola oil containing n-hexane under real operating conditions, which were reflected in real traffic conditions. Mobile system for engine indicating produced by AVL - Indi Micro 602, which was built in Fiat Qubo 1,3 Multijet, was applied during research. Various thermodynamic parameters of combustion process in various dynamic states, typical for the process of real work of an engine powered by examined mixtures of canola oil containing n-hexane were analysed and compared with parameters obtained while powering research vehicle with diesel fuel.

1. Introduction
Internal combustion engine is widely used in means of transport. It is projected for the years 2020-2050 that internal combustion engine will be the basic prime mover for cars [1]. Currently, there is a heated debate concerning further possibility of using internal combustion engines powered with diesel fuel. It is mostly connected with restrictions concerning the emission of toxic substances generated by this type of engines [2,3,4,5]. In order to meet the ecological standards, a number of research projects aim at searching for new types of fuel or modifying fuel system for internal combustion engines. It particularly applies to the parameters of compression and fuel injection as these parameters are crucial for the combustion process. With reference to compression ignition engines the research also concerns the use of the so - called alternative fuels which are not obtained from petroleum refining process [Błąd! Nie można odnaleźć źródła odwołania., Błąd! Nie można odnaleźć źródła odwołania., Błąd! Nie można odnaleźć źródła odwołania.]. While examining those issues, the authors of this study conducted various tests on an engine dynamometer in dynamic and static conditions, in which diesel engine was powered by mixtures of canola oil with various additives [Błąd! Nie można odnaleźć źródła odwołania., Błąd! Nie można odnaleźć źródła odwołania., Błąd! Nie można odnaleźć źródła odwołania.]. One of the choices was the application of a mixture of canola oil containing n-hexane (in various V/V proportions) [Błąd! Nie można odnaleźć źródła odwołania., Błąd! Nie można odnaleźć źródła odwołania., Błąd! Nie można odnaleźć źródła odwołania.].
Nie można odnaleźć źródła odwołania. [Błąd! Nie można odnaleźć źródła odwołania.]. Although the results were promising, they did not reflect the work of an engine in real road conditions. The tests (static and dynamic) were run on an engine dynamometer, where the tested object was AD3.152 engine without forced induction or exhaust gas recirculation (EGR).

The following article presents the test results of a turbocharged engine with the Common Rail direct fuel injection with the EGR system which was fuelled with the mixture of canola oil with n-hexane. The engine placed in a vehicle was subjected to indication in different conditions of real traffic. The conditions of the vehicle’s movement were selected so that they represented static and dynamic conditions of the engine’s work. The aim of the research was not the mutual quantitative reference of the obtained parameters of combustion process in static and dynamic conditions, but the demonstration of the tendencies concerning changes in the course of combustion process parameters for different engine operating conditions resulting from different variants of vehicle movement and being fuelled with tested mixtures. Selected thermodynamic parameters of the combustion process in real road conditions were analysed. The engine was fuelled with the mixture of canola oil with n-hexane and - for comparison – with diesel fuel.

2. The specificity of the course of the combustion process in the diesel engine fuelled with the mixture of canola oil with n-hexane

Canola oil applied as fuel has certain qualities more useful than diesel oil, the amount of oxygen in the fuel is particularly beneficial. Canola oil contains about 10% of oxygen and it has less carbon and hydrogen than mineral diesel fuel, that is why its calorific value is lower. It also has very good lubricating properties. For diesel engine obtaining required operational parameters such as mean effective pressure, rotation speed, overall efficiency and limiting fumes toxicity and engine noise, depends mainly on proper making of combustible mixture. The mixture needs to be characterised by specific homogeneity and fragmentation of fuel into drops of the smallest possible diameter. In the process of creating the proper combustible mixture, the most important factors are the fuel injection parameters which directly influence the fuel combustion. The combustion process may be divided into four stages such as: the first period of combustion, known as the ignition delay period; the second combustion period which covers the time from creating the first spontaneous combustion moment until the occurrence of the highest combustion pressure; the third period of combustion which commences the moment the pressure in the cylinder reaches its peak value and lasts until the combustion ends; and the fourth period of combustion also called after combustion meaning combustion lasting till expansion stroke. The characteristic feature of combustion in diesel engine is spontaneous fuel ignition preceded by the period of ignition delay, which has direct influence on the further combustion process [Błąd! Nie można odnaleźć źródła odwołania.] The main focus is on the first stage of ignition delay on which basic parameters which refer to circulation efficiency and ecological parameters – such as the speed of heat development, the speed of pressure and temperature increase – depend mostly. The fuel injection process, which depends on control parameters of the injection system and certain physicochemical qualities of fuels, has a huge influence on ignition delay stage.

Physical properties essential from the point of view of the work of diesel engine are: density, viscosity and surface tension. These parameters greatly influence the diameter of the drops, the reach of the stream of sprayed fuel therefore, they affect the spontaneous ignition delay [21]. The chemical fuel parameters, however, depend on the structural composition of hydrocarbons, among which the most numerous group for diesel oil are paraffin hydrocarbons C_nH_{2n+2} [Błąd! Nie można odnaleźć źródła odwołania.].

While applying plant fuel for powering compression ignition engine it is essential to take into consideration the fact that these engines were constructed for fuels of physicochemical properties characteristic for diesel fuel. It is crucial to aim at changing the physicochemical characteristics of plant fuels so that they are similar to the physicochemical properties of diesel fuels. This effect can obtained
by adding n-hexane as a solvent to plant fuels. As a result of data analysis and running preliminary tests, the optimal volume composition of the mixture of canola oil and n-hexane was estimated. Consequently, the following fuels were subjected to further analysis:
- diesel fuel - Df
- canola oil - Co
- canola oil with 10% n-hexane - 10%Hex90%Co.

The physicochemical parameters of canola oil with n-hexane were described – table 1 [21]. Mixtures of n-hexane and canola oil start to distil in the temperature of about 60°C and cease to distil in around 100-110°C. In the temperature above 250 °C decomposition of canola oil is visible (the amount of the distillate was adjusted to the amount of hexane added to the mixture). N-hexane additive greatly influenced the combustion temperature of the mixture mainly due to its volatility and low ignition temperature (-22°C)[Błąd! Nie można odnaleźć źródeł odwołania]. Slight drop in density of the created mixtures in comparison to Co was observed. Physicochemical qualities and the research methods for the diesel fuel used for testing were in accordance with the Polish norm: PN EN 590:2013 [Błąd! Nie można odnaleźć źródeł odwołania].

| Type of fuel          | Density in 20°C [kg/m³] | Kinematic viscosity indicator 40°C [mm²/s] | Surface tension [mN/m] | Ignition temperature [°C] |
|-----------------------|--------------------------|-----------------------------------------------|-------------------------|---------------------------|
| Co                    | 920.7                    | 34.89                                         | 34.15                   | 199                       |
| 10%Hex90%Co           | 900.1                    | 19.64                                         | 30.08                   | <40                       |
| Df                    | 840                      | 2.7                                           | 29.15                   | 72                        |

As mentioned before, in preliminary tests on the engine dynamometer a series of works was done [Błąd! Nie można odnaleźć źródeł odwołania.Błąd! Nie można odnaleźć źródeł odwołania.Błąd! Nie można odnaleźć źródeł odwołania.Błąd! Nie można odnaleźć źródeł odwołania.], during which the parameters of the engine work in dynamic conditions and static conditions (imitated with the use of the external exploitative characteristic) were compared. The object of the study was a diesel engine AD3.152 with direct injection characterised with one constant fuel injection per cycle. On the basis of the tests it was stated that:

- for the mixtures of canola oil with n-hexane there was decrease in the values of mean indicated pressure, while together with the increase of n-hexane in the mixture with Co, those values were reaching those of diesel fuel.
- With respect to rotational speed up to about 1600 rotation per minute the angle of spontaneous ignition delay was bigger while powering the engine with mixtures of canola oil with n-hexane in comparison with diesel fuel. From rotational speed of about 1600 rotations per minute the tendency was reversed.
- for the mixtures of canola oil with n-hexane the maximum speed of pressure increase escalated.

With respect to the process of pressing and injection, the acceleration of the angle of the beginning of injection and slight increase of the maximum injection pressure was stated while applying the mixture of canola oil with n-hexane in comparison to applying diesel fuel. These phenomena were caused mainly by residual pressure increase in the high pressure conductors. The tested engine had a traditional rotational fuel injection pump. Due to the development of diesel engines, traditional injection systems (e.g. rotation pump) are replaced with direct fuel injection systems in which the injection strategy (several fuel injections per one work cycle) is immediately corrected by a controller. In the following article the authors intended to estimate the tendency in the changes of the parameters describing the combustion process in dynamic conditions – in comparison to static conditions – during the real vehicle movement in traffic conditions while powering the engine with the fuels tested. The conditions of the
engine’s work reflected typical conditions of the vehicle functioning. The engine was equipped with Common Rail direct fuel injection. The research showed the influence of the conditions of the engine’s work and the type of fuel used on (among others): mean indicated pressure, the maximum Speer of pressure increase, the amount of heat produced and the process of heat production. With respect to the injection process, the injection strategy monitored by the engine controller was described.

3. Empirical research

3.1. The research stand, the researched object

The research was conducted in the Laboratory of the Department of Car Vehicles at the University of Technology in Lublin. The object of tests was Fiat Qubo with a diesel engine fulfilling all emission standards specified by Euro 5 and a five speed gearbox. In the tested vehicle an additional fuel supply system, with an exchangeable fuel tank was installed. The main technical parameters of the tested car engine are shown in table 2.

| Number of cylinders | 4 |
|---------------------|---|
| Cylinder diameter (mm) | 69.6 |
| Piston stroke(mm) | 82 |
| Total engine cubic capacity (cm3) | 1248 |
| Maximum power (kW CEE) | 55 |
| Maximum power (KM CEE) | 75 |
| Functioning at maximum power (rpm) | 4000 |
| Maximum torque (Nm) | 190 |
| Maximum torque (Nm) (kgm CEE) | 19.4 |
| Rotational Speed at maximum torque (rpm) | 1500 |
| Revolutions at neutral gear (rpm) | 850 ± 20 |
| Compression ratio | 16.8 : 1 |

The system for indicating the engine Indi Micro 602 made by AVL with a built-in signal amplifier, cooperating with four analogue input channels and two digital inputs was used in tests. The signals recorded by the AVL Indimicro system are the following:

- the course of pressure inside the cylinder – it was recorded by means of a piezoelectric sensor AVL GH13P installed in the glow plug seating of the first cylinder;
- the signal of engine crankshaft position;
- injection parameters were analysed on the basis of the analogue signal of controlling the electromagnetic injector after converting it into the digital signal.

Figure 1 presents the test stand used during the research.
The diesel engine installed in the vehicle was subjected to induction in selected movement conditions reflecting static and dynamic conditions. The tests were run in the vehicle moving in real road traffic. The vehicle was subjected to motion resistance forces mainly rolling resistance force and air resistance force. During the tests, the high-frequency parameters of the engine’s work were registered (those parameters were registered for 1000 consecutive cycles of the engine’s work) for the following cases of the vehicle movement:

- Case 1 - stop – engine neutral gear, conditions of static engine work with rotational speed from 800 to 4000 rpm.
- Case 2 - driving in the fourth gear on even, smooth surface of a straight, asphalt expressway (direct gear)– conditions of static engine work, constant load from rolling resistance forces;
- Case 3 - starting the vehicle – on neutral gear, conditions of dynamic engine work;

4. Analysis of the obtained results

In the figures from 2 to 8, the obtained results of tests and calculations are shown. The course of producing heat and the amount of produced heat were analysed for the selected engine work cycles and the course of the rotational speed and mean indicated pressure in consecutive cycles of the engine work. Mean, minimum and maximum values and standard deviations of mean indicated pressure, engine rotational speed, maximum combustion pressure and maximum speed of pressure growth were calculated from all the cycles of engine work. The conducted research refers to static conditions of the engine work (Cases 1 and 2) and dynamic conditions (Cases 3). The analysis of the test results conducted in static conditions of the engine work (case 1 and 2) showed that:

- In the conditions of driving in the fourth gear (case 2, picture 2B) the mean indicated pressure obtained with powering the engine with plant fuels (for all the registered cycles) was Lower than while powering the engine with diesel oil.
In the conditions of driving in the neutral gear (case 1, picture 2A) the tendency was reversed.

Figure 2. A. Case 1 – engine in neutral gear, the course of mean indicated pressure (IMEP1) for all the cycles of the engine work (1000 cycles). B. Case 2 – engine in fourth gear, the course of mean indicated pressure (IMEP1) for all the cycles of the engine work (1000 cycles). Black colour – diesel fuel, Green colour – canola oil, purple colour – canola oil with n-hexane 10%Hex90%Co.

Figure 2 shows the values of mean indicated pressure calculated from 1000 cycles of the engine work. During testing in road traffic conditions there was certain inconsistency concerning the regulation of the rotational speed. Despite the fact that all the tests were run on the same part of the road, there is a possibility of slight changes in the vehicle load and its engine with the movement resistance forces. Consequently, in order to analyse the results of the tests shown in picture 2B the cycles of the engine work with the most similar rotational speed were selected and further analysis was conducted on those cases. Those cycles were chosen on the basis of picture 3. Therefore, individual cycles of the engine work such as 214 and 267 with the rotational speed of about 3000 rotations per minute were analysed. For those cycles it was stated that the addition of n-hexane to canola oil had a positive effect on the values of the mean indicated pressure causing its increase: 0.786 MPa for cycle 214 and 0.673 MPa for cycle 267. Respective values for diesel oil were 0.532 MPa and 704 MPa and for canola oil: 0.564 MPa and 495MPa. Plant fuels were characterised by the fact that the beginning of the initial and main injection occurred earlier than for diesel fuel, which is shown in Figure 4. For the fuel with n-hexan 10%Hex90%Co the beginning of the initial injection occurred at 36.5°CA before TDC and was about 3.8° CA earlier than for diesel fuel. For canola oil the beginning of initial injection occurred 1.4°CA earlier than for diesel fuel. A similar relation was observed during the main injection where the beginning of injection for 10%Hex90% Co-occurred 9.9° CA before TDC, 0.7° CA earlier than for diesel fuel. For canola oil the beginning of the main injection occurred 0.34°CA earlier than for diesel fuel. It was estimated that for the selected work cycle the main injection for the fuels with n-hexane lasted 2.88°CA longer and it ended after the piston reached TDC point. For canola oil the time of the main injection duration was similar to diesel fuel. For all the fuels the duration of the initial injection was similar. For Case 1, with the rotational speed of about 3000 rpm there were three injections (two initial ones and one main one) for one cycle of the engine work. For all the fuels the time of the beginning of the injection occurred about 46°CA before TDC, while the main injection was 1.4°CA shorter for diesel than for the fuel with n-hexane and 1.6°CA shorter than for pure canola oil.
Case 2 – driving in real road traffic conditions, rotational speed 3000 rpm, the course of mean indicated pressure (IMEP1) and the engine’s rotational speed (SPEED) for 1000 cycles and the values for the selected 214 and 267 cycles of the engine work. Black colour – diesel fuel, DI, green colour – canola oil Co, purple colour – canola oil with n-hexane 10%Hex90%Co. The table presents the number of the cycle and the values for mean indicated pressure (IMEP1) and the rotational speed (SPEED).

In Case 2 (figure 5) the average values of the maximum speed of pressure increase were higher for powering the engine with diesel fuel when compared with plant fuels. For the engine powered with fuel with n-hexane with the rotational speed of about 3000 rpm the maximum speed of the pressure increase was 0.547 MPa/CA and was 0.053 MPa/CA slower in comparison with diesel fuel. In Case 1 the tendency was reversed – figure 6.

Figure 3. Case 2 – driving in real road traffic conditions, rotational speed 3000 rpm, the course of mean indicated pressure (IMEP1) and the engine’s rotational speed (SPEED) for 1000 cycles and the values for the selected 214 and 267 cycles of the engine work. Black colour – diesel fuel DI, green colour – canola oil Co, purple colour – canola oil with n-hexane 10%Hex90%Co. The table presents the number of the cycle and the values for mean indicated pressure (IMEP1) and the rotational speed (SPEED).

Figure 4. A. Case 1 – neutral gear, rotational speed about 3000 rpm, the course of the digital injection signal for the selected 699 cycle of the engine work. B. Case 2 – driving in real road traffic conditions the rotational speed about 3000 rpm, the course of the digital injection signal for the 214 engine work cycle. Black colour – diesel fuel Df, green colour – canola oil Co, purple colour – canola oil with n-hexane 10%Hex90%Co.
Figure 5. Case 2 – driving in real road traffic conditions, rotational speed 3000rpm. A. the course of the combustion pressure of the tested fuels for 214 engine work cycle. B. the rotational speed (SPEED), mean indicated pressure (IMEP1), maximum combustion pressure (PMAX1) maximum speed of the pressure increase (RMAX1) for 214 cycle of the engine work C. Minimum, maximum and mean values, average and standard deviation for mean indicated pressure (IMEP1), maximum combustion pressure (PMAX1), maximum speed of pressure growth (RMAX1) and rotational speed of the engine (SPEED) for 1000 cycles of the engine work.

Figure 6. Case 1 – neutral gear, rotational speed 3000rpm. A. the course of the combustion pressure for 699 cycle of the engine work. B. Rotational speed (SPEED), mean indicated pressure (IMEP1), maximum combustion pressure (PMAX1) and maximum speed of the pressure (RMAX1) for 699 cycle
of the engine work. C. Minimum, maximum and mean values, average and standard deviation for mean indicated pressure (IMEP1), maximum combustion pressure (PMAX1), maximum speed of pressure growth (RMAX1) and rotational speed of the engine (SPEED) for 1000 cycles of the engine work.

A. B.

Figure 7. A. Case 1 – neutral gear, rotational speed about 3000 rpm, the course of the heat production for the selected 699 cycle of the engine work. B. Case 2 – driving in real road traffic conditions the rotational speed about 3000 rpm, the course of the heat production for the selected 214 cycle of the engine work. Additionally, the table shows minimum, maximum and mean values, average and standard deviation for heat production (Q1) for 1000 cycles of the engine work. Black colour – diesel fuel Df, green colour – canola oil Co, purple colour – canola oil with n-hexane 10%Hx90%Co.

The above cycles of the engine work were selected for analysis. The engine was powered with the tested fuels and for those cycles the course of heat production was described Q1. In both cases, the average values of heat production were higher for plant fuels in comparison with diesel fuel. The chart (Figure 7), presents the courses of heat production for the analysed cycles of the engine work. For the engine in neutral gear (case 1, picture 7A), for diesel fuel the average value of heat production was 3.36 kJ/m\(^3\)deg, for canola oil 3.83 kJ/m\(^3\)deg and for 10%Hx90%Co 3.85 kJ/m\(^3\)deg. For the engine while driving (case 2, picture 7B), for diesel fuel the average value of heat production was 8.30 kJ/m\(^3\)deg, for canola oil 9.35 kJ/m\(^3\)deg and for 10%Hx90%Co 13.05 kJ/m\(^3\)deg. In case of maximum values of heat production it was noticed that in Case 1 the relations are similar to those for average values. In Case 2 maximum values of heat production for plant fuels were lower than for diesel fuel (Figure 7B). For plant fuels (especially for 10%Hx90%Co) high values of the course of heat production were more in the range of the angle of the crankshaft, which can be attributed to a longer injection time.
Figure 8. Case 3 – starting the engine in neutral gear. The chart presents the course of the mean indicated pressure (IMEP1), the engine’s rotational speed (SPEED). The table shows minimum, maximum and mean values, average and standard deviation for mean indicated pressure (IMEP1), maximum combustion pressure (PMAX1), maximum speed of the pressure growth (RMAX1) and rotational speed (SPEED) for 1000 cycles of the engine work. Black colour – diesel fuel Df; green colour – canola oil Co, purple colour – canola oil with n-hexane 10%Hex90%Co.

5. Conclusions
Applying pure canola oil for powering compression ignition engines is difficult due to its physiochemical properties, especially its viscosity, particularly in low temperatures. Adding a non-reactive solvent – n-hexane – causes a positive change of the physiochemical qualities of the mixture, especially with respect to density and viscosity. The observation of the courses of parameters of the injection process and combustion parameters shows that:

- For pure canola oil (Co) and for the oil with n- (10%Hex90%Co) fuel injection is earlier than for diesel fuel (Df)
- Adding 10% n-hexane to canola oil improved the physiochemical properties of the fuel in comparison with diesel, which may be observed on the example of the course of the parameters of combustion process, particularly in dynamic conditions; the values of the mean indicated pressure (IMEP) were similar to those of diesel fuel but the values of the heat of combustion were bigger (Q1). At the same time, the values of maximum speed of the pressure growth were lower.

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