The impact of physical & chemical properties of natural and plant fuels on indexes of non-repeatability of the fuel pressure and combustion processes in the combustion engine

S Kruczyński¹  P Orliński²  and  W Gis¹

¹Motor Transport Institute, 80 Jagiellonska Street, 03-301 Warsaw
²Combustion Engines Department, Institute of Vehicles, Warsaw University of Technology

Corresponding author: wojciech.gis@its.waw.pl

Abstract. The article presents results of tests regarding the injection and fuel combustion process in PERKINS 11004C-44 engine working in line with external speed characteristics and fuelled with natural and plant fuels and the impact on the indexes of non-repeatability of fuel pressure and combustion processes. The analysis of the test results allowed for identifying the differences in the injection and combustion processes in the engine fuelled with the different fuels. The use of fuels with different physical & chemical properties in diesel engines requires high precision measurements of the diagnostic in order to establish the existing differences in the processes of injection and combustion engines running on these fuels. The comparative analysis points indicate similarity in character of changes as regards the non-repeatability indexes of the fast-changing magnitudes for engine powered mineral fuels and plant. Compliance with more and more stringent standards regarding toxic contents in exhaust gases forces modern users of diesel, self-ignition engines to have quick and accurate methods for assessing the technical condition of the engine, in particular the combustion process and the technical condition of the injection unit based on indexes of non-repeatability of maximum fuel and combustion pressures.

1. Introduction

Indication is a reliable and repeatable testing procedure that provides accurate information about real processes occurring in the engine. It allows for recording transient values of parameters in processes that take place in the cylinder and helps analyse the impact of various factors on those processes [3].

Experimental methods of testing processes in the combustion chamber of a diesel engine include the following [7], [8], [9], [12]:

- Engine indication – measuring the course of pressure changes in the cylinder, supplemented with the following measurements: course of pressure changes in the fuel injection, injector nozzle lift-off and valve lift-off, in the function of the crankshaft rotation angle or the location of the piston in the cylinder;
- Optical tests comprising visualisation of processes in the engine’s working space.

Information obtained by way of cylinder indication provides basis for diagnosing and optimising the combustion process and allows for a qualitative assessment of its performance. With the development of computer systems and measurement sensors, the measurement of dynamic values of the engine, in particular pressure in the cylinder, meets the requirements in terms of accuracy. With such accuracy it is possible to achieve critical and reliable values assessing the performance of the tested engines.
Pressure indication in the cylinder has become a standard testing method applied in diesel piston engines [6].

Plant fuels have different physical & chemical properties compared to mineral fuels, thus there are differences between them in the pressing, spraying and combustion process. Viscosity and density have impact on the quality of fuel spray formation, which in turn determines the course of combustion and as a result the emission of toxic substances with exhaust gases. Viscosity and surface tension also have impact on the mean diameter of droplets and the spread of the fuel jet. Greater size of the droplets and a more compact shape of the fuel jet result in an increased spread. The greater viscosity and surface tension, the greater is the range of the fuel jet [1], [6], [14].

Moreover, the demand for alternative fuels has increased considerably due to need to warrant own (and possible the largest) fuel base in the country, which could be used for fuelling diesel engines in farming vehicles. One of the ways to solve the problem is to use plant fuels. This solution allows for developing new fuel production technologies, more jobs and positive environmental effects. Plant fuels have different physical & chemical properties compared to hydrocarbon fuels, hence there are differences in the piston-system process, fuel spray and combustion in the cylinder of the self-ignition engine [1].

The application of more and more stringent standards regarding toxic emissions in exhaust gases forces a modern user of diesel, self-ignition engines to have quick and accurate methods for assessing the technical condition of the engine, in particular the technical condition of the injection unit. One of the major causes of uniqueness of subsequent cycles of the engine’s operation is the uniqueness of injection in self-ignition engines, different mass of the fuel dose in successive cycles and the scholastic nature of the spray process and fuel mixing with air in the engine’s cylinder. This problem is the topic of numerous studies [7], [13].

2. The methodology of describing the uniqueness of the combustion and injection parameters in defined operating conditions of the engine

The diagnostic tests of the injection and combustion processes may use indicators of uniqueness of dynamic pressures. According to Heywood the index of non-repeatability of fast-changing magnitudes, i.e. combustion pressures, fuel pressures in the injector duct are defined as the relation of standard variance and the mean value [4]:

\[ x_i = \frac{\sigma_{si}}{x} \]

\[ \sigma_{si} = \sqrt{\frac{1}{k} \sum_{i=1}^{k} (x_i - x)^2} \]

where:

- \( x_i \) - index of non-repeatability
- \( \sigma_{si} \) - standard variance
- \( x \) - mean value
- \( i = 1 \div k \) - number of the subsequent fuel injection cycle

Non-repeatability of the fuel injection process
The indicators of uniqueness of the maximum fuel pressure in the injection duct $X_{pw,max}$ are calculated according to the following formula [4]:

$$X_{pw,max} = \frac{\sigma_{(pw,max)i}}{p_{w,max}}$$  \hspace{1cm} (2)

$$X_{pw,max} = \frac{\sigma_{(pw,max)}}{p_w} = \frac{\sqrt{\frac{1}{k} \sum_{i=1}^{k} \left(\overline{p_{w,max}} - \overline{p_{w,cmax}}\right)^2}}{\overline{p_{w,max}}}$$  \hspace{1cm} (3)

where:

- $p_{w,max}$ - maximum fuel pressure in the injection duct MPa,
- $i = 1 \div k$ - number of the subsequent fuel injection cycle,
- $\overline{p_{w,cmax}}$ - averaged maximum fuel pressure in i-cycles, MPa.

Fig. 1 presents an example of an averaged fuel pressure process in the injector for ULTRA-B fuel with crankshaft rotational speed $n = 2000$ rpm and angle $\alpha_{ww}$ $17^\circ$ crank angle.

![Figure 1](image1.png)

**Figure 1.** Example of an averaged – based on 100 cycles – fuel pressure process in the injector for ULTRA-B fuel with crankshaft rotational speed $n = 2000$ rpm and angle $\alpha_{ww}$ $17^\circ$ crank angle [2]

Fig. 2. Maximum fuel pressures in the injection duct $P_{w,max}$ based on 100-cycles with the angle $\alpha_{ww}$ $17^\circ$ CRANK ANGLE and $n = 2000$ rpm [2]

**Index of non-repeatability of the maximum combustion pressure**

The index of non-repeatability of the maximum combustion pressure $X_{pc,max}$ is calculated based on the following formula [4]:

$$X_{pc,max} = \frac{\sigma_{(pc,max)}}{\overline{p_{c,max}}} = \frac{\sqrt{\frac{1}{k} \sum_{i=1}^{k} \left(\overline{p_{c,max}} - \overline{p_{c,max}}\right)^2}}{\overline{p_{c,max}}}$$  \hspace{1cm} (4)

where:

- $p_{c,max}$ - maximum combustion pressure MPa,
$p_{c \text{ max}}$ - averaged maximum fuel pressure in i-cycles, MPa,
i = 1 \div k$ - number of the subsequent fuel injection cycle

Fig. 2 shows a comparison of maximum combustion pressures $p_{c \text{ max}}$ recorded for 100 cycles in the tested fuels with angle $\alpha_{ww}$ $17^\circ$ crank angle and rotational speed of $n = 2000$ rpm.

Figure 2. Example of an averaged combustion pressure process for ULTRA-B fuel with crankshaft rotational speed of $n = 2000$ rpm and angle $\alpha_{ww}$ $17^\circ$ crank angle [2]

3. Purpose of research
The purpose of research was to assess the impact of fuelling the PERKINS 1104c-44 engine with seven fuels of different physical & chemical properties on the indicators of uniqueness of maximum pressures in injection and combustion processes for the said fuels according to external speed characteristics.

4. Description of research method
Prior to the start of engine measurements, a thermal balance was achieved and then measurement paths were scaled, and operating pressure of injector holes adjusted according to the producer’s recommendations (18.5 MPa). Adjusted was the nominal fuel injection advance angle equal to $\alpha_{ww} = 17^\circ$ crank angle.

During the operation of the engine according to external speed characteristics within the range of engine rotation speed $n = 1000–2000$ rpm, for every measured engine rotation speed (every 200 rpm) 100 further cycles of fuel pressures were recorded in the injection duct and pressures in the combustion chamber. Indicator charts were made using a piezo quartz sensor, adjusted statistically and dynamically in conditions similar to real conditions.

Perkins 1104C-44 engine tests resulted in the following:

- averaged - based on 100-cycles - course of fuel pressure in the injection duct
- averaged – based on 100 cycles – course of pressure in the combustion chamber.

The course of fast-changing magnitudes has been visualised in Fig. 3.
Figure 3. Example of the process regarding [2]: 1 – pressure in the combustion chamber, 2 – fuel pressure in the injection duct, 3 – injector nozzle lift

Fuels used during the tests:
- Plant fuels: OR (rapeseed oil - 100%), - OR, OS (soya oil - 100%), - OS, OSŁ (sunflower oil - 100%).
- OSŁ, Rapeseed methyl ester FAME-100B conforming to PN-EN 14214.
- Mineral fuels: Diesel oil Ekodiesel Ultra type B with CFPP no more than 0°C, Diesel oil Ekodiesel Ultra type D with CFPP no more than -10°C, Diesel oil Ekodiesel Ultra type F with CFPP no more than -20°C.

Based on the recorded courses of fast-changing magnitudes for 100 cycles of the engine operation, the following was calculated:
- index of non-repeatability of maximum fuel pressure in the injection duct $X_{pw,max}$,
- index of non-repeatability of maximum combustion pressure $X_{pc.spl}$.

5. The test stand and physical & chemical properties of fuels. The test stand

The tests were conducted on a typical dynamometer test stand constructed according to PN-88/S-02005 standard, with a self-ignition, direct injection engine PERKINS 1104C-44, equipped with a system for measuring dynamic pressures and a sensor for measuring the shift in injection nozzle lift-off, with the use of Schenck and AVL measuring equipment. Perkins 1104C-44 engine is used mainly in farming tractors and fulfils the standards regarding toxic exhaust emissions EU Stage II (for Nonroad Diesel Engines) in G version, which applies to engines with effective output (i.e. net performance) within the range of $37 \leq N_e < 75$ kW [2].

The flowchart of the test stand is presented in Fig. 4. Table 1 presents chosen physical & chemical properties of seven tested fuels. The measurement path for recording fast-changing pressures is presented in Fig. 5.
Figure 4. Flowchart of the test stand [2]:
1 – PERKINS 1104-C44 engine; 2 – air inlet; 3 – exhaust outlet; 4 – current brake SCHENCK II; 5 – dynamic values system AVL IndiSmart; 6 – exhaust gases analyser AVL CEB 2; 7 – heated path; 8 – set of model gases; 9 – control – notebook

Figure 5. Measurement path for fuel pressure in the injection duct [7]  
P – pressure, Q – electric charge, U – electric potential difference

Table 1. Chosen physical & chemical properties of the used fuels [10, 11]

| Property                        | Hydrocarbon fuels | Plant fuels |
|--------------------------------|-------------------|-------------|
|                                | ULTRA-B | ULTRA-D | ULTRA-F | FAME-100B | OR 100% | OS 100% | OSL 100% |
| Density [kg/m³]                 | 845     | 836     | 820     | 882      | 914      | 916      | 917      |
| Kinematic viscosity ~40°C [mm²/s] | 4.2     | 3.59    | 2.83    | 4.75     | 34.56    | 31.98    | 31.54    |
| Cetane number                   | 51.8    | 51.2    | 51.7    | 51.3     | 49       | 50       | 50       |
| Calorific value [MJ/kg]         | 43      | 43.83   | 43.2    | 38.7     | 37.2     | 37.8     | 37.7     |
| Surface tension 10⁻² [N/m]      | 3.47    | 3.71    | 3.64    | 3.52     | 3.38     | 3.28     | 3.22     |

6. Graphical comparison of test results
The figures below show graphical comparisons of maximum fuel and combustion pressures – chosen in the testing process – determined based on the system for measuring dynamic values for the standard fuel
injection advance angle and seven selected fuels. A comparison of the averaged process of fuel pressure in the injection duct $P_w$ for engine rotational speed $n = 1000–2000$ rpm fuelled with ULTRA-B is shown in Fig. 6.

Fig. 7–10 show averaged fuel pressures in the injection duct $P_w$ based on 100 cycles for chosen natural and plant fuels, with defined engine rotational speeds when making external speed characteristics.

**Figure 6.** Comparison of averaged fuel pressure process in the injection duct $P_w$ for engine rotational speed $n= 1000-2000$ rpm, fuelled with ULTRA-B and with fuel injection advance angle $\alpha_{ww} = 17^\circ$ crank angle

**Figure 7.** Comparison of specified maximum fuel pressures in the injection duct $P_{w,max}$ with fuel injection advance angle $\alpha_{ww} = 17^\circ$ crank angle, for all tested fuels, within engine rotational speed range of 1000–2000 rpm

The analysis of the combustion process was conducted based on angles and combustion pressures determined with the use of open indicator charts recorded by the measurement system for fast-changing
magnitudes in 100 cycles of the engine’s operation with 3 fuel injection advance angles $\alpha_{ww}=17^\circ$ crank angle and with the engine fuelled with seven tested natural and plant fuels (Fig. 8).

![Figure 8. Charts of pressure in the combustion chamber in an engine fuelled with ON-ULTRA-B for different crankshaft rotational speeds $n$ and with angle $\alpha_{ww}=17^\circ$ crank angle](image)

Fig. 9 shows a comparison of maximum combustion pressures $P_{c,max}$, MPa, with fuel injection advance angle $\alpha_{ww}=17^\circ$ crank angle.

![Figure 9. Comparison of maximum combustion pressures $P_{c,max}$, MPa, with fuel injection advance angle $\alpha_{ww}=17^\circ$ crank angle for all tested fuels, within engine rotational speed range of 1000–2000 rpm](image)

The analysis of the non-repeatability of the injection and combustion processes was performed and calculated on the basis of specified angles and pressures of the injection and combustion processes recorded by the system for measuring fast-changing magnitudes in 100 cycles of the engine’s operation, with fuel injection advance angle $\alpha_{ww}=17^\circ$ CRANK ANGLE and with the engine fuelled with seven tested natural and plant fuels.

The analysis of non-repeatability of the fast-charging magnitudes helps understand the phenomenon with regard to non-repeatability the angles values and pressures in the injection duct and the cylinder.

Fig. 10 presents an exemplary graphic comparison resulting from tests of the impact of the change in the fuel injection advance angle $\alpha_{ww}$ on the indicator of maximum pressures in the injection duct $X_{pw,max}$. 
6. Summary
Since the injection and combustion processes are the least explored processes and among all processes in the engine’s working cycle, this article discusses the surveys and delivers an analysis of the impact of the type and properties of fuel in a self-ignition engine operating according to external speed characteristics on the features of the injection and combustion process.

Considering only the technical aspect, diesel oil should be substituted by plant fuels that:
- demonstrate higher calorific value and complete combustion,
- have lesser density,
- ensure higher general performance of the engine,
- support the durability and unfailing operation of the engines,
- are easily available and in large volumes,
- originate from inexhaustible sources or are renewable,
- are easier to store, transport and distribute,
- are less harmful for the environment,
- produce unharmful - or harmful to a minimal degree - combustion products in a self-ignition engine.

Based on the tests results and following their analysis conducted in line with the developed methodology the following empirical conclusions can be formulated:

1. Plant fuels contain a glyceride group in their chemical composition, whereby they are less compressible than mineral fuels and at the same have a greater viscosity. For this reason, they tend to decrease the leakage in piston system and the jet system, which contributes to the increased fuel dose in the engine working cycle by approx. 8–12% and higher fuel pressure in the injection duct by 12.9–18.6% compared to mineral fuels, with crankshaft rotational speed ranging from 1000 to 2000 rpm. The maximum pressures in the injection system increase together with the increase of the engine’s rotational speed.

2. As regards all tested fuels the maximum pressure in the cylinder when the engine was fuelled with plant fuels was 15÷25% higher than as compared to the engine fuelled with mineral fuels.

3. Based on the calculations and graphical comparison of the indexes of non-repeatability with \( \alpha_{ww} = 17 \)° crank angle and crankshaft rotational speed within range of 1000–2000 rpm it has been found that the values of non-repeatability index of maximum averaged fuel pressure in the injection system \( X_{pw,max} \) are lower for mineral fuels as compared to plant fuels by 5.5–20.2%. The comparison proves similarities in the character of changes in the indexes of non-repeatability fast-
changing magnitudes with regard to engine fuelled with mineral and plant fuels. The fuel density has impact on the indexes of non-repeatability of fast-changing magnitudes regarding pressures.

4. The research showed the impact of the angle \( \alpha_{\text{ww}} \) on non-repeatability in subsequent courses of fuel pressure in the injection line. The values of non-repeatability index calculated for the maximum averaged fuel pressure in the injection line \( X_{\text{pw, max}} \) with \( \alpha_{\text{ww}} = 12, 17 \) and \( 22^\circ \) crank angle for the tested fuels with crankshaft rotational speed within the range of 1000-2000 rpm are lower for \( \alpha_{\text{ww}} = 22^\circ \) crank angle as compared to \( \alpha_{\text{ww}} = 12^\circ \) crank angle for mineral fuels than for plant fuels by 10–12%.

References

[1] Baczewski K, Kałdoński T, Paliwa do silników o zapłonie samoczynnym. WKL, Warszawa 2004.
[2] Dokumentacja techniczna stanowiska badawczego. Wydział Samochodów i Maszyn Roboczych. Politechnika Warszawska, Warszawa 2010.
[3] Kruczyński S, Orliński P, Combustion of methyl esters of various origins in the agricultural engine. Indian Journal of Engineering & Materials Sciences, p. 483-491, New Deli 2013.
[4] Heywood J B, Internal Combustion Engines Fundamentals, Mc Graw Hill Co. N. Y., 1988.
[5] Kruczyński S, Orliński P, Orliński S, Wpływ kąta wyprzedzenia wtrysku oraz właściwości paliw naturalnych i roślinnych na proces wtrysku silnika o zapłonie samoczynnym, Autobusy, X, 2007.
[6] Kowalewicz A, Wybrane zagadnienia samochodowych silników spalinowych, Wydawnictwo WSI Radom, Radom 1996.
[7] Orliński P, Wybrane zagadnienia procesu spalania paliw pochodzenia roślinnego w silnikach o zapłonie samoczynnym, Instytut Naukowo Wydawniczy SPATIUM, Radom 2013.
[8] Orliński S, Orlińska M, Wpływ obciążenia silnika rolniczego Perkins zasilanego etanolom na operacyjne wskaźniki jego pracy. XI Konferencja Naukowo - Techniczna „LogiTrans 2015” Logistyka Nr 3/2014. S 4866-4877.
[9] Orliński S, Wpływ zasilania silnika rolniczego Perkins 1104C-44 paliwami estrowo-etanolowymi na wybrane parametry procesu wtrysku i spalania w aspekcie ekologicznym, LOGISTYKA 3/12, s. 1761-1768.
[10] Świadectwo, jakości badanych paliw roślinnych, Zakład Produkty Naftowych, WMTiW, UTH, Radom 2014.
[11] Polski Koncern Naftowy ORLEN S.A, Świadectwo jakości, Płock 2015.
[12] Fuc P, Lijewski P, Kurczewski P, Ziolkowski A, Dobrzyński M, 2017 The analysis of fuel consumption and exhaust emissions from forklifts fueled by diesel fuel and liquefied petroleum gas (LPG) obtained under real driving conditions ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE) 6.
[13] Merkisz J, Pielecha J, 2015 Nanoparticle Emissions from Combustion Engines. Springer Tracts on Transportation and Traffic 8.
[14] Pielecha J, Jasinski R, Magdziak A, 2017 MATEC Web of Conferences 118 00021