Influence of physical & chemical properties of natural and plant fuels on fuel spray process in compression ignition engine

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Abstract. Tests results of the fuel injection process and measurement in engine PERKINS 1104C-44 working per external velocity characteristic and feeding natural fuel and plant fuel were presented in this article. Analysis of the obtained results allowed to find differences in the course of the injection process and its combustion in engine fuelled with the above-mentioned fuels. Using fuels of different physical & chemical properties to compression-ignition engines requires high accuracy of selected parameters measurements in order to learn differences in processes of injection and combustion. Necessity of fulfilling more and more strict standards concerning emission of toxic components of exhaust gases forces users of diesel engines to possess quick and precision methods of their technical state assessment and particularly of a combustion process and of injection equipment technical state. Analysis of the fuel pressure in the injection pipe and injection nozzle lift allows for determining fuel outflow rate from the atomizer and fuel spray disintegration into droplets. Experimentally obtained indicator diagrams of cylinder pressure were also applied. The aim of the work is to evaluate, on the basis of a simple mathematical model, the parameters of a stream of atomized fuel, including plant fuels. In the calculations, the experimentally measured opening pressure of the sprayers and the lift of the sprayer needle were used.

1. Introduction

Proper functioning of the fuelling system in a self-ignition engine depends on physical & chemical properties of the used fuels: density, viscosity, surface tension, fractional composition, calorific value and rheological parameters in low temperature, including also their change in the temperature function, lubricity, solid pollutants and water content [1].

The fuel injection process is a complex, periodically repeatable and dynamic process in a high-pressure system (injection apparatus). Information about the course of the injection process is provided by fuel pressure progressions in the injection duct and injection nozzle lift-off. Economic, energy and ecological indicators of the engine’s performance directly depend on the indicative pressure chart in the cylinder and the course of change of the aforesaid value in the engine fuel system. Fuel intended for fast-rotation self-ignition engines should ensure [3], [4], [12], [13]:

- proper functioning of the entire fuelling system, including in particular the injection apparatus;
- proper, effective and complete combustion process;
- the least possible volume of harmful exhaust gases generated.

Fig. 1 presents physical & chemical properties of fuel, which have impact on the injection and combustion process.
During dynamometer studies of the engine three mineral fuels and four plant fuels were applied. Plant fuels were chosen due to their availability on the market and various physical & chemical properties that have considerable bearing on the course of the injection and combustion process [6], [7], [11].

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 shape of the reduced fuel spray. Greater size of the droplets and a more compact shape of the fuel jet result in an increase range. The greater viscosity and surface tension the greater is the range of the fuel jet.

Fuel viscosity has impact on the following injection parameters [8]:
- dose of the injected fuel,
- injection nozzle lift-off,
- pressure and duration of injection which has significant bearing on the process of fuel spray formation.

Fuels used during the tests: Vegetable fuels: OR (rapeseed oil - 100%), - OR, OS (soya oil - 100%), - OS, OSL (sunflower oil - 100%) – OSL, 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.

Ekodiesel Ultra fuel fulfils requirements laid down in the Ordinance of the Minister of Economy of 9 October 2015 regarding quality requirements for liquid fuels (Journal of Laws of 23 October 2015, item 1680), Ordinance of the Minister of Economy of 9 October 2015 regarding methods of assessing the quality of liquid fuels (Journal of Laws of 23 October 2015, item 1679) and requirements of the Polish Standard PN-EN 590 – Fuels for motor vehicles – Diesel oils – Requirements and methods of tests.

2. Purpose of studies

The aim of the work is to evaluate, on the basis of a simple mathematical model, the parameters of a stream of atomised fuel, including plant fuels. In the calculations, the experimentally measured opening pressure of the sprayers and the lift of the sprayer needle were used.
It was the intent of the authors to conduct and analyse simulation tests with regard to chosen problems relating to the use of plant fuels for fuelling self-ignition engines, without modernising the construction of those engines.

Experimental tests involved an assessment of the impact of using natural and plant fuels for fuelling Perkins 1104C-44 engine operating according to an external speed characteristic on the following: critical diameters of fuel droplets; Sauter mean diameter of droplet; range and length of fuel spray breakup into droplets; fuel spray cone angles.

3. Description of the survey 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 timing equal to \( \alpha_{\text{ww}} = 17^\circ\text{OWK} \).

During the operation of the engine according to external speed characteristics within the range of engine rotation speed \( n = 1000\text{--}2000 \text{ rpm} \), for every measured engine rotation speed (every 200 rpm) 100 further cycles of fuel pressures were registered in the injection duct and injector nozzle lift-off. The 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 - injection nozzle lift-off,

The course of injection nozzle lift-off provides many valuable information regarding the fuel injection process. It allows for – inter alia – defining the start and end of the length of the fuel injection process (fig. 2).

Period of fuel injection calculated in \(^\circ\text{OWK}\) [5]:

\[
\alpha_W = \alpha_{\alpha_1} - \alpha_{\alpha_2},^\circ\text{OWK} \tag{1}
\]

and the injection length:

\[
\tau_W = \frac{\alpha_W}{6n}, s \tag{2}
\]

The range of the fuel spray depends on the difference of pressure in the injection well and pressure in \( \Delta P \) cylinder, density of the working agent in the cylinder \( \rho_g \) and fuel density \( \rho_p \) and the diameter of the spray opening \( d \).

Calculations of the critical mean diameter of fuel droplet \( d_{kr} \) for the studied fuels were made according to the following formula [5]:

\[
d_{kr} = \frac{\sigma W_{kc}}{2}, \mu m \tag{3}
\]
where:

- \( \sigma \) - surface tension, N/m \( 10^{-2} \),
- \( \rho_g \) - density of the gaseous unit, kg/m\(^3\),
- \( \text{We}_{cr} \) - Weber number critical value, m/s.
- \( u_p \) - velocity of the fuel jet outflow from the injector, m/s.

The mean diameter of the droplets was calculated according to an empirical formula, depending on the fuel injection parameters. The Sauter mean diameter \( (d_{32}) \), i.e. diameter of a uniform collection of substitute droplets of the same volume and the same surface of all droplets as in a given collection with a particular spray spectrum, was calculated according to the formula proposed by Hiroyasu and Kadota [5].

\[
d_{32} = A (\Delta P)^{0.135} \rho_g^{0.121} V_{pj}^{0.131} \text{ [\mu m]}
\]

Where:
- \( \Delta P \) – injection overpressure (mean value), MPa
- \( V_{pj} \) – unit fuel dose, mm\(^3\)/cycle
- \( A \) - injector constant

The value of \( A \) was calculated according to the following formula [5]:

\[
A = 3 + 0.28 \left( \frac{1}{d} \right)
\]

Where for the tested WZM DSL-150 A-38 fuel nozzle in PERKINS 1104C-44 engine:
- \( l \) - length of nozzle pipe – 4 mm,
- \( d \) - diameter of nozzle opening – 0,28 mm.

Time measured from the fuel outlet to jet break-up \( t_r \), ms can be calculated based on the following formula [4]:

\[
t_r = \frac{29 \rho_p d}{(\rho_p \cdot \Delta P)^{1/2}} \text{; ms}
\]

According to Hiroyasu jet spread can be expressed with the following formulas [5]:

For \( t \leq t_{\text{break-up}} \),

\[
S_1 = 0,39 \left( \frac{2 \Delta P}{\rho_p} \right)^{1/2} t \text{; mm}
\]

For \( t > t_{\text{break-up}} \),

\[
S_2 = 2,95 \left( \frac{\Delta P}{\rho_g} \right)^{1/4} (d \cdot t)^{1/2} \text{; mm}
\]

where:
- \( \rho_p \) – fuel density, kg/m\(^3\),

The range of the fuel jet depends mainly on the density of the agent (counter-pressure) to which the fuel is injected, the diameter of the nozzle hole and the injection pressure. The viscosity of the fuel and the working agent in the cylinder and the density of fuel are of secondary importance.

The spray angle according to Abramowicz [1] is [5]:

\[
tg \frac{\theta}{2} = 0,13 \left[ 1 + \left( \frac{\rho_g}{\rho_p \cdot \Delta P} \right) \right]
\]
The tests were conducted on a typical dynamometer stand constructed in line with BN-74/1340-12 and PN-88/S-02005 standards, with self-ignition engine PERKINS 1104C-44 with direct injection, equipped with a system for dynamic pressure measurements and a sensor for measuring the shift in injection nozzle lift-off.

The flowchart of the test stand is presented in fig. 3. Table no. 1 presents chosen physical & chemical properties of fuel, i.e. hydrocarbon fuel EKODIESEL PLUS-50B and plant fuel FAME-100B.

![Flowchart of the test stand](image)

**Figure 3.** Flowchart of the test stand [2]:
1- computer with inbuilt computing board KPCI 3110 by Keithley, 2 – rotary – impulse converter Introl, 3 – electronic fuel consumption weigh CT15B with a timer, 4 – PERKINS 1104C-44 engine, 5 – AUTOMEX brakes with electronic gauging modules, 6 – electronic board for brake control and engine operation control with PARM-1.3 software, 7 – timing generator, 8 – crankshaft rotational speed measuring module, 9 – signal amplifier.

| 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    |

5. Analysis of test results
The comparison of test results is presented in fig. 4–8. Fig. 4 presents a comparison of mean diameters of droplets forming in the fuel flow from spray hole with a regular cross-section dk, µm determined in
line with Sauter within crankshaft rotational speed range of n= 1000–2000 rpm for 7 fuels and with fuel injection advance angle $\alpha_{ww} = 17^\circ$ OWK. Fig. 5 shows a comparison of mean diameters according to Sauter ($d_{32}$) in a collection of substitute droplets with the same summarized volume and the same summarized surface of all droplets as in the given collection with a specific spray spectrum within the crankshaft rotational speed range of n= 1000–2000 rpm for 7 fuels and with fuel injection advance angle $\alpha_{ww} = 17^\circ$ OWK. Fig. 6 shows a comparison of the length of spray break-up into fuel droplets $t_{\text{break-up}}$, $\mu$s, with fuel injection advance angle $\alpha_{ww} = 17^\circ$ OWK for all tested fuels within the speed range of n= 1000–2000 rpm. Fig. 7 shows a comparison of transient fuel spray penetration $S_1$, mm for $t \leq t_{\text{break-up}}$, with fuel injection advance angle $\alpha_{ww} = 17^\circ$ OWK for all tested fuels within the speed range of n= 1000–2000 rpm. Fig. 8 shows a comparison of secondary fuel spray penetration $S_2$, mm for $t > t_{\text{break-up}}$ with fuel injection advance angle $\alpha_{ww} = 17^\circ$ OWK for all tested fuels within the speed range of n= 1000–2000 rpm.

**Figure 4.** Comparison of mean critical diameters of droplets $d_{kr}$, $\mu$m within the crankshaft rotation speed range n= 1000–2000 rpm for 7 fuels and with fuel injection advance angle $\alpha_{ww} = 17^\circ$ OWK.

**Figure 5.** Sauter mean diameter $d_{32}$, $\mu$m in the collection of substitute droplets within the crankshaft rotation speed range n= 1000–2000 rpm for 7 fuels and with fuel injection advance angle $\alpha_{ww} = 17^\circ$ OWK.
**Figure 6.** Comparison of the length of spray break-up into fuel droplets $t_{\text{break-up}}$, ms, with fuel injection advance angle $\alpha_{\text{ww}}$– 17° OWK for all tested fuels within the speed range of $n$= 1000–2000 rpm

**Figure 7.** Comparison of transient fuel spray penetration $S_1$, mm for $t \leq t_{\text{break-up}}$, with fuel injection advance angle $\alpha_{\text{ww}}$– 17° OWK for all tested fuels within the speed range of $n$= 1000–2000 rpm

**Figure 8.** Comparison of secondary fuel spray penetration $S_2$, mm for $t > t_{\text{break-up}}$ with fuel injection advance angle $\alpha_{\text{ww}}$– 17° OWK for all tested fuels within the speed range of $n$= 1000–2000 rpm
Table 2. Fuel spray cone angles $\tan \Theta/2$ according to external speed characteristics within crankshaft rotational speed range of $n=1000$-2000 rpm for 7 fuels and with fuel injection advance angle $\alpha_{ww}$=17° OWK

| Fuel type | ULTRA-B | ULTRA-D | ULTRA-F | FAME | OR | OS | OSŁ |
|-----------|---------|---------|---------|------|----|----|-----|
|           | 8° 10’  | 8° 10’  | 8° 10’  | 7° 50’ | 7° 45’ | 7° 45’ | 7° 45’ |

By comparing simulation tests results presented above it is possible to formulate an important conclusion for diagnosing the fuel jet process (in an engine working according to external speed characteristics). There is an evident impact of the properties of tested fuels, i.e. density, viscosity and surface tension, upon mean diameters $d_{kr}$, $\mu$m of droplets forming upon fuel flow from the injector nozzle with a constant slot-thru profile (fig. 4), Sauter mean diameter $d_{32}$, $\mu$m in the collection of substitute droplets (fig. 5), length of spray break-up into fuel droplets $t_{\text{break-up}}$, $\mu$s (fig. 6), transient fuel spray penetration $S_1$, $\text{mm}$ for $t \leq t_{\text{break-up}}$ (fig. 7), secondary fuel spray penetration $S_2$, $\text{mm}$ for $t > t_{\text{break-up}}$ (fig. 8) and fuel spray cone angles $\tan \Theta/2$ (table no. 2).

6. Summary

This article discusses tests and an analysis of changes in the specified engine operating conditions. While high viscosity increases pressure and the injection angle, it hinders the process of fuel break-up into droplets. Droplets in a compact-shaped jet have bigger sizes and thus increase the jet spread.

Based on the test results, in fuelling the engine with natural fuels and plant fuels the following conclusions can be drawn:

- A comparison of mean droplet diameters $d_{kr}$, $\mu$m forming upon fuel jet break-up in the combustion chamber proved smaller diameters in natural fuels as compared to plant fuels. Absolute percentage differences between the used fuels range from 5.7% to 8.5%.
- The Sauter mean diameter of droplets $d_{32}$, $\mu$m in the collection of substitute droplets is greater for plant fuels than for mineral fuels from 5.3% to 6.3%.
- The fuel jet spread $S_1$, $\text{mm}$ for $t \leq t_{\text{break-up}}$ for all tested fuels is greater for mineral fuels as compared to plant fuels by 5% to 11%.
- The fuel jet spread $S_2$, $\text{mm}$ for $t > t_{\text{break-up}}$ for all tested fuels is lesser for mineral fuels than as compared to plant fuels by approx. 20%.
- The length of jet break-up into droplets $t_s$, $\mu$s for all tested fuels within crankshaft rotational speed range of 1000 – 2000 rpm is greater for mineral fuels compared to plant fuels by c.a. 10–22%.
- The fuel jet cone angles $\tan \Theta/2$ for all tested fuels are greater for mineral fuels than for plant fuels by approx. 1.2–2.5%.
- Further simulations studies on the fuel injection processes in an engine fuelled with mineral fuels and plant fuels with different physical & chemical properties will be empirically verified.

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