Effects of changes of injection timing on selected parameters of combustion process in a diesel engine fuelled with fuels of different properties

Z J Sroka  R Heda  and  M Romanowicz

Wroclaw University of Science and Technology, Wybrzeze Wyspianskiego 27, 50-370 Wroclaw, Poland

E-mail: zbigniew.sroka@pwr.edu.pl

Abstract. The internal combustion engine is and for many years will be the very important source of drive for many machines and vehicles. That's why research and development centres are still researching to improve the design of it. The dominant feature among these studies is the evaluation of combustion process, which can be shaped according to different rules and various parameters. Through this article, the Authors join the discussion on the assessment of changes in selected parameters of combustion process caused by changes in injection timing of different fuels. The considerations were narrowed down to self-ignition engines with their representative VW 1.9TDI PD, which was subjected to laboratory tests. When making changes in injection timing, the following parameters were evaluated: excess air ratio, pressure in combustion chamber, heat of fuel dose and the related work of a single thermodynamic cycle. The first part of the article specifies the requirements for fuels and shaping the fuel stream in order to obtain the highest efficiency. The practical part contains the results of chemical tests of two fuels with different properties and laboratory tests that allowed to carry out cycle indicators for the selected load of tested engine. By identifying factors of injection timing, it was possible to determine the most favourable values of useful work of a single cycle, in relation to heat of fuel dose expressed in the values of fuel conversion efficiency.

1. Introduction

In the functional structure of an internal combustion engine, one of the most important tasks to be carried out is to create a fuel-air mixture whose quality determines the quality of the combustion process. A well-prepared fuel-air mixture ensures obtaining satisfactory parameters such as: engine speed or brake mean effective pressure, reduces the content of harmful components of exhaust gas and reduces the noise of the engine [1, 2, 3, 4, 5]. The formation of a combustible mixture in an internal combustion engine depends on many factors, including but not limited to the geometry of the combustion chamber or structural solutions of the power system together with a work supervision system, that is, a control system that ensures proper setting of fuel injection parameters [6, 7, 8, 9, 10, 11]. Of course, the quality of the combustible mixture and the combustion process also depends on the properties of the fuel used [12, 13, 14]. Fuel injection is identified as a stream that consists of a central part called core and outer shell - the sheath. The core of the stream consists of drops with larger diameters, having greater kinetic energy and higher speed than the remaining drops in the stream. The stream envelope has direct contact with the environment, so in this area fuel and air are mixed. Differences in core speed and external coating result from different masses. The main parameters describing the fuel stream are: range, tip
angle, accuracy and uniformity of fuel atomization. The range of the fuel stream is the distance from the
injector to the face of the stream. The range of the stream increases with the injection time, which is a
parameter regulated in the engine's control system. Under the conditions prevailing in the cylinder space,
it is difficult to clearly determine the range of the stream, because the drops combine with the swirled
air. Too large range of the fuel stream causes deposition of droplets on the walls of the combustion
chamber. In turn, too small a range causes not using the mass of air contained in the cylinder space. The
next injection parameter, which is the apex angle depends on the type of injector and the pressure inside
the combustion chamber. Droplets with relatively small diameters are quickly braked and diverge from
the fuel stream thus increasing its apex angle.

In turn, the homogeneity of fuel atomization is determined by the number of droplets of the same
diameter. The requirements for the accuracy and homogeneity of the fuel stream are higher, the higher
the engine speed and the higher the load. The processes occurring in the engine are aimed at minimizing
size of droplets. Drops with small diameters affect the shorter evaporation time, the better and faster the
formation of the gas mixture. Larger diameters of droplets result in incomplete combustion, which leads
to increased smoke [4, 13].

It follows from the above considerations that the correct identification of fuel injection parameters
and above all the injection time, which directly determines the size of the dose may ensure the
correctness of the combustion process - depending on the load conditions. The factor that also influences
the process of creating a combustible mixture is the swirling of the air, which contributes to the
distribution of fuel throughout the combustion chamber. The turbulence can be obtained thanks to the
inlet channels and the appropriate geometry of the combustion chamber by means of a reciprocating
movement of the piston. The quality of the stream and the way of using the fuel are closely related to its
properties. In the first injection period, the fuel undergoes preparatory reactions. The result of these
reactions is the occurrence of multifocal spontaneous combustion. This period lasts from the moment
the first droplets appear on the injector until the first self-ignition fires occur. The preparation of the fuel
for ignition consists in heating the fuel droplets to complete or partial evaporation, heating the fuel
vapour to the ignition temperature, the initial oxidation reaction of the fuel, which takes place at a
relatively low speed and leads to auto-ignition of the fuel. The fuel lag period lasts about 0.0007÷0.003
seconds. The mixture is heterogeneous in the combustion chamber. There are areas in which λ factor
has values much greater than 1, but there are places where the concentration of fuel droplets is large, so
λ <1 [15, 16]. The second combustion period with a quasi-constant volume extends from the moment
the first self-ignition fires is formed until the highest combustion pressure occurs. Self-ignition sparks
form in the whole combustion chamber and at the end of this period the entire chamber is covered by a
flame. The fuel jet lights up at the tip of the injector. There is a large average factor λ because injection
has not yet been completed. This period is characterized by a rapid increase of pressure and temperature
of the load. The duration of this phase depends on the shape of the fuel stream and on the geometry of
the combustion chamber.

The third combustion period at quasi-constant pressure starts at the moment of reaching the highest
pressure and lasts until the end of combustion. Fuel after leaving the injector is subject to diffusion
combustion. Characteristic for this period is a slight pressure drop and an increase in temperature. Fuel
injection is completed in this phase, but fuel burnout is possible. During the first phase, the fuel is
gradually prepared for combustion because it constantly flows into the cylinder. The entire combustion
period depends on the duration of the ignition delay. Too long time of the first period is associated with
a large amount of fuel in the combustion chamber, which in the next phase will burn almost
simultaneously, causing a rapid increase in pressure. The reduction of the first period eliminates a rapid
pressure increase, but incomplete combustion may occur.

Once again, the importance of injection parameters is pointed and above all its time and fuel delivery
time in assessing the quality of the combustion process.

It is impossible to omit the role of the fuel itself in considering the quality of air-fuel mixture
formation and the quality of the combustion process. The most commonly used hydrocarbon fuels are
composed of carbon and hydrogen atoms that form straight, branched or annular chains [17, 18, 19].
The best self-ignition properties are characterized by hydrocarbons composed of saturated straight chains. Chain branching extends the time to self-ignition. The greater ignition delay occurs when the more carbon atoms are in the side chains. In the case of isoparaffin hydrocarbons, the ease of self-ignition depends on the location of the branching site. Aromatic hydrocarbons have the greatest ignition delay because they have a ring structure that is durable and difficult to break and thus self-ignition. Generally in fuels, self-ignition properties improve as the boiling temperature rises, however to a certain limit, because the boiling point increases the volatility. During the actual work of diesel engine, self-ignition depends on the pressure and temperature in the combustion chamber. The most widespread measure of the self-ignition properties of fuel is the Cetane Index. Fuel with lower Cetane Index can be used in engines with a high compression ratio and at the same time they can work at low rotational speeds. High-speed engines can work only on fuels characterized by high Cetane Index. Too much Cetane Index makes the combustion process worse. Fuel for diesel engines is modified by the addition of various substances that improve one or more of the fuel's operational characteristics. The following additives are distinguished: improving the rheological properties of fuel at low temperatures, preventing the formation of sediment on elements of the engine injection system, improving self-ignition properties, improving tribological properties, anti-corrosion deactivators preventing metal oxidation, anti-foaming organosilicon compounds, biocides inhibiting the growth of microorganisms, anti-aging, compounds separating water from fuel.

In order to unify the required properties for diesel, a set of parameters has to be determined. A set of such parameters and the corresponding values are given in normative acts, which are changed depending on the requirements for the operation design and technology of internal combustion engine.

The above considerations indicate the need to assess the impact of injection time and advance fuel injection angle on selected parameters of the combustion process. This assessment was made by laboratory tests and theoretical analysis of operation of the diesel engine powered by fuels with different physical-chemical properties. The literature review indicates the validity of the research subject [7, 8, 9, 10, 16, 20].

2. Tests

To fulfill the aim of the study, which was the assessment of factors shaping the combustion process with fuels having various physical and chemical properties, the relationship between the controlled fuel dose and engine torque was determined by defining the useful work size and heat based on the analysis of indicator diagrams. The research was carried out at the Division of Automotive Engineering of the Wroclaw University of Science and Technology.

2.1. Methodology of the tests

Theoretical considerations have shown that the most important influence on shaping the combustion process is the process of preparation of the fuel-air mixture, in which the injection time and the injection advance angle are dominated. These parameters were subject to change during the tests of the load characteristics of the internal combustion engine and among the many measured or calculated quantities were subjected to: indicator diagrams of the combustion process, the fuel dose, air mass per work cycle, excess of the air ratio, effective cycle work and heat of dose and the conversion efficiency of the tested fuels.

The load characteristics of the internal combustion engine were rated at an engine speed of around 2000 rpm, changing the load by 50 Nm in the range from 0 to 200 Nm and max one. The tests were carried out for two different fuels and with fuel dose control, performing six repetitions of each test:
- test no. 1 - standard controller software,
- test no. 2 - extended injection time by 0.833 ms, expressed for the tested speed by an angular measurement of 5 degrees of camshaft rotation,
- test no. 3 - extended injection time by 5 degrees of camshaft rotation with simultaneous advance of fuel injection by 4 degrees of camshaft rotation (time by 0.667 ms).
2.2. Research object and test stand
A popular diesel engine 1.9 TD PD was used as a test object.

Table 1. The main technical specification of tested engine 1.9 TDI PD

| Specification            | Value                  |
|--------------------------|------------------------|
| Engine displacement (ccm³) | 1896                   |
| Bore x Stroke (mm)       | 79.5 x 95.5            |
| Engine configure         | In line 4              |
| Compression ratio        | 18.5:1                 |
| Valve train              | 8v SOHC                |
| Maximum power (kW)       | 81.0 by 4000 rpm       |
| Maximum torque (Nm)      | 235.0 by 2000 rpm      |

The engine was tested in the laboratory of the Division of Automotive Engineering equipped with the engine torque-dynamometer 240 kW AVL ALPHA and the system indicating the pressure in the combustion chamber as in figure 1.

Figure 1. View of the test stand

2.3. Tested fuels
To test, there were two different fuels chosen with properties like in tables no. 2.

Based on the conducted analyses, it was found that the tested diesel fuel samples are mediums meeting the technical requirements according to standard PN-EN 590: 2013.

Fuel no. 1 has better properties than no. 2, because it has a higher calorific value, which determines fuel consumption and more precisely the heating value of the air-fuel mixture related to the engine power, which in turn affects the amount of heat generated in the engine cylinder.
Table 2. Properties of fuels no. 1 and no. 2

| Requirements                                      | Units       | Results for Fuel 1 | Results for Fuel 2 | Standard Requirements |
|--------------------------------------------------|-------------|--------------------|--------------------|-----------------------|
| Density at 15°C                                   | g/cm³       | 0.8332             | 0.8342             | 0.8200-               |
| Density at 20°C                                   | g/cm³       | 0.8302             | 0.8312             | 0.8450               |
| Cetane index                                      |             | 53.1               | 53.1               | Min. 46              |
| Kinematic viscosity at 40°C                       | mm²/s       | 2.90               | 3.17               | 2.0 – 4.5            |
| Flash point                                      | °C          | 74                 | 66                 | Min. 56              |
| Cloud point (CP)                                  | °C          | -11                | -10                |                       |
| Cold filter filtration temperature (CFPP)         | °C          | -18                | -13                | Max. 0               |
| Water content                                     | mg/kg       | 55.6               | 75.3               | Max. 200             |
| Content of solid foreign body                     | mg/kg       | 4                  | 6                  | Max. 24              |
| Reaction                                          |             | Inert              | Inert              |                       |
| Fractional composition:                           |             |                    |                    |                       |
| Beginning of distillation, to 250°C, distils,     | °C          | 179.0              | 171.0              | Max. 65              |
| to 350°C, distils,                                | %           | 38.0               | 38.0               | Max. 85              |
| 95°C distils to temperature                       | °C          | 350                | 385.5              | Max. 360             |
| Corrosion research on copper plate (3h, 50°C)     | % (m/m)     | 0.003              | 0.005              | Max. 0.01            |
| Residue after incineration                        | MJ/kg       | 46.32              | 45.95              | Not defined          |
| Calorific value                                   | MJ/kg       | 43.11              | 42.84              | Not defined          |

Fuel 1 contains less water, which can affect the intensification of corrosion processes. Fuel 1 has a higher flash point, which affects safety during storage, transport, distribution and use of diesel fuel, but it delays the moment of ignition.

3. Results and interpretation

The starting point for the assessment of the assumed problem were indicative diagrams describing the pressure changes in the combustion chamber depending on the tested injection parameters of two different fuels. Examples of graphs at the speed of around 2000 rpm and for a torque of 200 Nm are shown in fig. 2-4. The record of about 2000 rpm results from the fact that during tests there were oscillations of rotational engine speeds resulting inter alia from the power supply conditions, i.e. fuel injection parameters. On the basis of obtained diagrams of pressure changes and direct tests of engine operation parameters such as: engine speed, torque and power, fuel consumption, engine temperature etc. for various values of injection timing including advance, the parameters describing injection and combustion processes such as air-fuel equivalence ratio (λ), dose of fuel, heat of dose, operation of a single thermodynamic cycle, useful efficiency are determined - tables 3-5.

Some average values were also identified, such as maximum values of pressure in the combustion chamber or absolute work of the thermodynamic cycle and the efficiency of fuel conversion depending on the injection parameters - fig. 5 and table 6.
**Figure 2.** Diagram of pressure in combustion chamber vs. the angle of rotation of engine crankshaft for the operating parameters: \( n=2016 \text{ rpm} \) and \( M_o=200 \text{ Nm} \) with the standard engine control for fuel no 1

**Figure 3.** Diagram of pressure in combustion chamber vs. the angle of rotation of engine crankshaft for the operating parameters: \( n=2016 \text{ rpm} \) and \( M_o=200 \text{ Nm} \) with extended injection time by 5 degree for fuel no 1

**Figure 4.** Diagram of pressure in combustion chamber vs. the angle of rotation of engine crankshaft for the operating parameters: \( n=2016 \text{ rpm} \) and \( M_o=200 \text{ Nm} \) with extended injection time by 5 degrees and advance of the injection angle by 4 degrees for fuel no 1
### Table 3. Selected engine operating parameters for 1.9TDI PD with different fuels and with standard control of the injection system - test no. 1

| Engine revolution (rpm) | Engine torque (Nm) | Fuel dose (mg/cycle) | Air mass (mg/cycle) | Heat of fuel dose (J) | lambda in the cycle |
|-------------------------|--------------------|----------------------|---------------------|-----------------------|---------------------|
| fuel 1                  | fuel 2             | fuel 1               | fuel 2              | fuel 1                | fuel 2              |
| 1995                    | 2037               | 0                    | 0                   | 8.5                   | 8.5                 | 299                 | 270                 | 366                 | 364                 | 2.39               | 2.16               |
| 1995                    | 2058               | 50                   | 50                  | 14.0                  | 13.7                | 412                 | 392                 | 604                 | 587                 | 2.00               | 1.95               |
| 2016                    | 2037               | 100                  | 100                 | 22.8                  | 22.0                | 549                 | 573                 | 983                 | 942                 | 1.64               | 1.77               |
| 2079                    | 2038               | 150                  | 150                 | 30.5                  | 30.7                | 828                 | 735                 | 1315                | 1315                | 1.85               | 1.63               |
| 2016                    | 2037               | 200                  | 200                 | 38.2                  | 38.2                | 985                 | 980                 | 1647                | 1636                | 1.75               | 1.75               |
| 2016                    | 2016               | 215                  | 215                 | 42.5                  | 41.2                | 1029                | 1029                | 1832                | 1765                | 1.65               | 1.70               |

### Table 4. Selected engine operating parameters for 1.9TDI PD when feeding with different fuels and when changing the operation of the injection system – test no. 2

| Engine revolution (rpm) | Engine torque (Nm) | Fuel dose (mg/cycle) | Air mass (mg/cycle) | Heat of fuel dose (J) | lambda in the cycle |
|-------------------------|--------------------|----------------------|---------------------|-----------------------|---------------------|
| fuel 1                  | fuel 2             | fuel 1               | fuel 2              | fuel 1                | fuel 2              |
| 1995                    | 2037               | 0                    | 0                   | 8.7                   | 7.3                 | 225                 | 240                 | 377                 | 313                 | 1.75               | 2.24               |
| 1974                    | 1953               | 50                   | 50                  | 16.2                  | 16.4                | 240                 | 265                 | 698                 | 703                 | 1.01               | 1.10               |
| 2016                    | 1974               | 100                  | 100                 | 25.7                  | 24.0                | 603                 | 363                 | 1107                | 1029                | 1.60               | 1.03               |
| 2058                    | 2058               | 150                  | 150                 | 37.5                  | 37.6                | 671                 | 657                 | 1616                | 1610                | 1.22               | 1.19               |
| 2016                    | 2100               | 200                  | 200                 | 48.7                  | 48.8                | 995                 | 1029                | 2101                | 2091                | 1.39               | 1.43               |
| 2079                    | 1995               | 230                  | 220                 | 51.8                  | 50.4                | 990                 | 1039                | 2235                | 2158                | 1.30               | 1.40               |

### Table 5. Selected engine operating parameters for 1.9TDI PD when feeding with different fuels and changing the control of the injection system operation – test no. 3

| Engine revolution (rpm) | Engine torque (Nm) | Fuel dose (mg/cycle) | Air mass (mg/cycle) | Heat of fuel dose (J) | lambda in the cycle |
|-------------------------|--------------------|----------------------|---------------------|-----------------------|---------------------|
| fuel 1                  | fuel 2             | fuel 1               | fuel 2              | fuel 1                | fuel 2              |
| 2037                    | 2037               | 0                    | 0                   | 7.2                   | 7.3                 | 250                 | 245                 | 310                 | 313                 | 2.36               | 2.28               |
| 2016                    | 1974               | 50                   | 50                  | 15.3                  | 13.9                | 230                 | 265                 | 660                 | 593                 | 1.02               | 1.30               |
| 1974                    | 1932               | 100                  | 100                 | 25.2                  | 25.9                | 387                 | 392                 | 1088                | 1110                | 1.04               | 1.03               |
| 1995                    | 1653               | 150                  | 150                 | 35.9                  | 32.9                | 642                 | 642                 | 1549                | 1409                | 1.22               | 1.33               |
| 2016                    | 2079               | 200                  | 200                 | 48.7                  | 48.8                | 1000                | 956                 | 2101                | 2091                | 1.40               | 1.33               |
| 2016                    | 2016               | 216                  | 215                 | 51.8                  | 51.9                | 941                 | 980                 | 2235                | 2225                | 1.23               | 1.28               |
Figure 5. Maximum pressure values in the combustion chamber for various tests (test descriptions in the methodology chapter)

Table 6. Specific fuel consumption and fuel conversion efficiency describing changes in combustion process of tested engine supplied with different fuels, in accordance with the tests carried out at load of 200 Nm / 2000 rpm

| Tests     | Specific fuel consumption (g/kWh) | Fuel conversion efficiency |
|-----------|----------------------------------|-----------------------------|
|           | fuel 1   | fuel 2   | fuel 1   | fuel 2   |
| Test no. 1| 217.1    | 214.9    | 38.5     | 38.9     |
| Test no. 2| 276.9    | 266.4    | 30.2     | 31.3     |
| Test no. 3| 276.9    | 265.6    | 30.2     | 31.0     |

By assessing pressure diagrams, one can notice some relationships between pressure spikes before or after top dead centre (TDC) with time and the angle of advance of fuel injection:
- in the case of standard controller settings at low torque values i.e. 0÷100 Nm, the pressure drop occurs behind TDC. The reason for this may be too low temperature in the combustion chamber so that the entire dose of fuel could not evaporate. The majority of the fuel dose, however, ignited spontaneously before TDC, which is why this part of the graph is evaluated as correct - consistent with the theory. The lower load means less the pressure jump. At higher loads, the engine worked longer, reached operating temperature, so the higher temperature was in the combustion chamber,
- after extending the injection time by 5° of crankshaft rotation, the situation is identical to that described for the standard injection settings, but the maximum pressure values in the load range 0-150 Nm increase and above 150 Nm decrease. This is accompanied by higher fuel consumption compared to standard controller parameters,
- in the situation of extending injection time and the advanced injection angle, the pressure jump behind TDC occurs only for zero load. Changed parameters caused that the engine did not run smoothly at idle.
This made measurement difficult. From a load of 50 Nm, pressure spikes occurred before the TDC piston reached. Confirmation of mentioned above evaluation of the combustion process expressed in the graphs of pressure changes in the combustion chamber are the parameters of injection and the determined engine operation indicators:

- for standard injection parameters (table 3) it can be observed that as the load increases, the amount of air sucked in and the value of controlled fuel dose increase. Differences in the value of fuel and air doses result not only from different properties of tested fuels, but also from the oscillation of the rotational speed around the tested value - shaping the excess air ratio. Lambda factors for unloaded operation and low torque values indicate a poor mixture, which results from design of the engine, in which there is no air dampers to limit the amount of air. This phenomenon can be also explained by the EGR valve, which along with the change in injection parameters has attempted to match and multiplied the degree of opening of the valve (increasing EGR rate) – corresponding to [10, 21].

- when the injection time is increased (table 4), the increase in load is accompanied by an increase in fuel doses and consequently, an increase in the heat of dose. At the same time, the excess air ratio decreases. The variability of this ratio results from the load map, in which the dominant is the rotational speed. This is best seen with 50 and 100 Nm load range, when the measured speed during subsequent measurements was significantly lower than assumed in the 2000 rpm. This results in the volatility of the lambda factor around unity which is unusual for diesel engines. The result is an increase in the specific fuel consumption, which was also observed in the pressure diagrams. Generally, this change in injection parameters has contributed to deterioration of the combustion process expressed in the lower useful efficiency of the engine 6-12% compared to the standard controlled injection.

- change of injection parameters by extending the injection time by 5 deg and increasing the injection advance angle by 4 deg (table 5) results in improved engine performance parameters compared to the variant only with the change of injection time, but they are lower than the standard version. The change of injection parameters has significantly influenced the change in the lambda factor, indicating a richer versus the standard mixture, which results in a comparable useful engine power with a higher specific fuel consumption by 5 to 20% compared to the standard injection control.

4. Summary
This article assesses the impact of changes in fuel injection parameters on engine performance expressed through changes in combustion process indicators. The changes in the absolute work of a single thermodynamic cycle, in relation to the heat of the fuel dose in individual tests, confirmed the possibility of shaping the combustion process expressed by specific values of the fuel conversion efficiency. For the test conditions adopted, the most effective combustion process is obtained with a simultaneous change of injection time and injection advance angle. Due to changes in the injection parameters, a slight relationship with fuel properties has been demonstrated as long as these meet the requirements of the standards. It has been shown that the change in injection time significantly changes the amount of fuel dose, which results in an increase in the heat of the dose, a decrease in cycle work and a decrease in the lambda factor. The simultaneous change of the injection time and the increase of the injection advance angle cause the cycle work to increase, but the fuel conversion efficiency is reduced, expressed in increasing the specific fuel consumption. The change values are closely related to the torque and engine speed values. Further work on shaping the combustion process will be carried out in terms of the application of artificial intelligence in the supervision and independent learning of the control system of the operation of injection units.

References
[1] Heywood J B 1988 Internal Combustion Engine Fundamentals Ed. McGraw-Hill Inc. (Singapore) pp. 491-558
[2] Kulażynski M, Sroka Z J 2011 Developing Engine Technology (Ed. Printpap Łódź) p. 93
[3] Luft S 2011 Podstawy budowy silników: Silniki spalinowe (Ed. WKŁ Warszawa) p. 368
[4] Rychter T J, Teodorczyk A 2006 Teoria silników tłokowych (Ed.WKŁ Warszawa) p. 272
[5] Stone R 1992 Introduction to Internal Combustion Engines (Macmillan Press Ltd. Hong Kong) p. 569
[6] Murari M R 2009 Effect of Fuel Injection Timing and Injection Pressure on Combustion and Odorous Emissions in DI Diesel Engines J. Energy Resour. Technol 131(3), 032201 doi:10.1115/1.3185346
[7] Zhihao M, et al 2007 Effects of Fuel Injection Timing on Combustion and Emission Characteristics of a Diesel Engine Fueled with Diesel–Propane Blends Energy Fuels 21 (3), pp 1504–1510
[8] Ritchie D et al 2012 Effects of Combustion Phasing, Injection Timing, Relative AirFuel Ratio and Variable Valve Timing on SI Engine Performance and Emissions using 2,5-Dimethylfuran SAE International doi:10.4271/2012-01-1285
[9] Mingrui W et al 2017 Effects of injection timing on combustion and emissions in a diesel engine fueled with 2,5-dimethylfuran-diesel blends Fuel Volume 192 pp.208-217
[10] Xinling L et al 2014 Effect of injection timing on particle size distribution from a diesel engine Fuel 134 (134) pp. 189-195
[11] Fanga T, Lee C F 2009 Bio-diesel effects on combustion processes in an HSDI diesel engine using advanced injection strategies Proc Combust Inst 32 pp. 2785-2792
[12] Ambrozik A, et al 2004 Wpływ zasilania silnika AD3.152 różnymi paliwami na parametry i wskaźniki cyklu pracy Proc. Int. Scien. Cong. on Powertrain and Transport Means European KONES 2004 (Kraków-Zakopane) pp. 7-16
[13] Brzeżański M et al 2017 Analysis of creation and combustion process of hydrogen-air mixtures by optical method in isochoric chamber, J.Combustion Engines 170(3) (Poznań) pp.121-125
[14] Reksa M, Sroka Z J 2013 The impact of fuel properties on shape of injected fuel spray J. Combustion Engines 52(3) pp. 806-81
[15] Postrzednik A, Żmudka Z 2007 Termodynamiczne oraz ekologiczne uwarunkowania eksploatacji tłokowych silników spalinowych (Ed. Politechnika Śląska Gliwice) p. 387
[16] Lejda K, Woś P 2012 Fuel injection in Automotive Engineering – simulation of combustion process in direct injection diesel engine based on fuel injection characteristics (Ed. InTech London) p. 144
[17] Baczewski K, Kaldoński T 2008 Paliwa do silników o zapłonie samoczynnym (Ed. WKŁ Warszawa) p. 220
[18] Kułażyński M, Sroka Z J 2007 Problem jakości paliw a parametry pracy silnika spalinowego. Proc. Conf. Innowacje w motoryzacji a ochrona środowiska (Słupsk) pp. 573-578
[19] Sitnik L 2004 Ekopaliwa Silnikowe (Ed. Politechnika Wrocławska Wrocław) p. 336
[20] Ambrozik A, et al 2003 Simulation of on indicato diagram of a diesel engine Proc. Comission of Motorization and Energetics in Agriculture Polish Academy of Sciences vol. III (Lublin) pp.12-17
[21] Xiao-cao Yu et al. (2011), Effects of EGR rate and excess air ratio on the combustion characteristics of compressed natural gas engine, Proc. International Conference on Transportation, Mechanical, and Electrical Engineering (TMEE) December 16-18, Changchun, China, pp.1177-1180