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Assessment methods of the basic parameters of the combustion process in reciprocating internal combustion engines

The article presents selected methods of assessing the basic parameters of the combustion process, as well as assessing the usability and limitations of the methods used to determine the initiation and the end of the combustion process in reciprocating internal combustion engines. The methods considered are based on data contained in real, developed indicator diagrams. Basic thermodynamic assumptions and the scope of application of the combustion process evaluation method based on the actual work cycle of a combustion engine prepared in a double logarithmic scale were discussed. The article also mentions the application of the following methods: a direct pressure comparison method in the cylinder, the comparison of the first pressure derivative in the cylinder, logarithmic derivative method of pressure change in the cylinder, the method of the polytropic index, method of the first derivative of the polytropic index and the method of constant values of the polytropic index. The article presents the advantages and disadvantages of the research of our methods.

Key words: *combustion process, combustion process parameters, indicator diagram, engine operation cycles*

1. Introduction

The combustion process in a piston combustion engine is one of the basic processes of the engine's work cycle. Its assessment requires the use of appropriate research methods based on the analysis of the actual work cycle. In order to achieve the best possible effect of converting energy contained in fuel into mechanical work, it is necessary to precisely control work processes occurring in the engine cylinder [7]. An important issue in the above-mentioned area is the assessment and control of the combustion process. This topic is currently being addressed by many researchers around the world, and its complexity is related mainly to the number of independent factors directly affecting the efficiency and average theoretical pressure of the engine work cycle [1, 12]. There are many research methods to evaluate the engine cycles presented and widely described in the work of engineering researchers [7, 11, 15]. The use of new fuels, the pursuit of oil diversification and the European Union's policy of rational energy management in which transport is one of the key industries, requires increasing use of new generation fuels and assumes the widespread use of compressed natural gas CNG [16]. In Poland, supplying vehicles with CNG gas is still not common, although according to many specialists it is a promising fuel for the future [10]. This requires adapting currently operated and produced engines to supply these fuels and contributes to the need to become more familiar with the process creation of combustible mixtures and the process of their combustion. This entails the need to develop and analyse combustion process evaluation methods that can be used in the process of further engine development, mainly in terms of steering, playing a key role in achieving the required energy effect and maintaining the lowest possible concentration of harmful exhaust components. [13]. The evaluation methods of the combustion process provide information on many indicators that play an important role in the evaluation of the engine control, which can also be used to diagnose intra-cylinder processes [8, 9]. The effect of thermodynamic, thermochemical and heat exchange processes occurring in the piston cylinder of the internal combustion engine are noted on an indicator diagram. It is a quantitative and qualitative source of information about these processes. Its analysis makes it possible to determine engine indices, heat dissipation characteristics during the combustion process, the composition of the working medium as a function of the angle of rotation of the crankshaft and many others. Its course also affects the noise of the engine. The course of the curve of the indicator graph depends primarily on the quality and course of the atomisation process of the fuel having a decisive impact on the quality of the fuel-air mixture and the aerodynamic properties of the air and the way it is fed into the cylinder [4]. The developed indicator diagram of a reciprocating internal combustion engine is the basis for the application of the described methods for assessing the combustion process parameters.

Modern design solutions for motor control and regulation systems enable modelling of component work cycle processes in a wide range [3,6]. Differences in physical and chemical properties of modern fuels, including biofuels and gaseous fuels, dictate the need for a thorough assessment of the impact of feeding them on the characteristics of their operation. A slight deviation from the stoichiometric composition of the combustible mixture contributes significantly to the emission of harmful exhaust components [13]. The possibility of precise dosing of gaseous fuel and the maintenance of good atomisation determines the correct course of combustion of the fuel-air mixture [14]. The paper presents and characterises several methods of combustion process evaluation based on the developed indicator diagram. The basic parameters of this process are the beginning and end of the combustion process and the duration of the combustion process.

2. Preparation of a real indicator diagram for analysis

Evaluation of the combustion process parameters based on the actual indicator diagram requires obtaining reliable values of the pressure course in the engine cylinder. The uniqueness of the work cycles obtained consecutively during the registration of the pressure course as a function of the angle of rotation of the crankshaft requires the initial processing of data consisting of averaging the experimentally recorded diagrams. According to [2] the minimum number of work cycles should not be less than 33. Current data archiving technology and computer software enable the recording of a pressure signal with a frequency of 0.1° of crankshaft rotation (°CR) and a record of a much higher number of subsequent pressure courses. Preparation for the analysis of the experimentally removed indicator graph must include an accurate and reliable determination on the indicator diagram of the position of the piston in the upper returnable position (URP) [2]. The chart obtained in this way is subjected to further processing enabling determination of the beginning and end of the combustion process on its basis and the duration of the combustion process depending on the analysis method used. The introduction of additional results determining the moment of fuel injection in the case of compression ignition engines, or the determination of the spark moment on the spark plugs in the case of forced ignition engines enables to obtain information on the duration of the self-ignition delay period and the duration of the ignition delay period. The results obtained may be subject to an error caused by high-frequency noise in the form of a hum. The use of signal filtration or smoothing methods distorts the information originally received.

3. Characteristics of methods for analysing combustion process parameters

There are many methods to assess the parameters of the combustion process in a reciprocating internal combustion engine. Basic methods of evaluation of combustion process parameters include the measurement method with the use of optical methods to determine the moment of the appearance and location of the flame, and methods based on the analysis of the actual indicator graph recorded during the experiment. In the next points of the article from 3.1 to 3.7 a description of seven selected methods for the assessment of the basic parameters of the combustion process based on the analysis of the indicator graph is presented:

a) method of analysing the combustion process on the basis of a graph prepared in a double logarithmic scale
b) a direct pressure comparison method in the cylinder
c) the method of comparing the first pressure derivative in the cylinder dP
d) logarithmic derivative method of pressure change in the cylinder dlnP
e) the method of the polytropic index k
f) method of the first derivative of the polytropic index dk
g) the method of constant values of the polytropic index kp

The method of evaluation of combustion process parameters based on direct comparison of pressure in the engine cylinder (point 3.2) and direct comparison of the first pressure derivative in the engine cylinder (point 3.3) does not allow determining the end of the combustion process, thus it is not possible to use these methods to determine the duration of the combustion process. In the method of analysing the combustion process, two cases were considered on the basis of an indicator chart prepared in a double logarithmic scale. The first describes the combustion process parameters in the event of the start of the combustion process before the upper reverse position of the piston, while the second describes a special case during operation of the engine with the initiation of the combustion process after the upper reverse position of the piston. A graphical interpretation of the described cases is shown in Figure 1a and 1b. described in 3.1. Some methods require complex calculations, and interpretation of the obtained results is difficult. The problems are particularly visible during the analysis using dk and kc methods that are very sensitive to noise. All of the above-mentioned methods are based on the analysis of the results obtained when the pressure in the engine cylinder is indicated. The calculations are carried out using a previously prepared, averaged indicator diagram.

3.1. Method of analysing the combustion process on the basis of a graph prepared in a double logarithmic scale

The evaluation of the combustion process parameters using the indicator diagram prepared in a double logarithmic scale requires the assumption that the engine cylinder is a closed thermodynamic system, i.e. there is no bleeding of the working medium through the leakage of the piston – rings – cylinder assembly and no leakage at the inlet and outlet valves. The assumption makes it possible to treat intra-cylinder processes in the form of polytropic compression transformations and expansion described by the equation [5]:

$$pV^n = B = const. \quad (1)$$

where: p – pressure, V – volume, n – polytropic index.

To the above equation, dimensionless values of pressure $\bar{p}$ and volume $\bar{V}$ were introduced by actions in order to be able to mathematically interpret the obtained values [1]:

$$\bar{p} = \frac{p}{p_o} \quad \text{and} \quad \bar{V} = \frac{V}{V_c} \quad (2)$$

where: p_o – ambient pressure, V_c – volume of the combustion chamber, p, V – instantaneous values of cylinder pressure and volume.

Using the obtained dimensionless values in equation (1), and then logarithmising and ordering them, the equation of a straight line was obtained:

$$\log\bar{p} = -n\log\bar{V} + C \quad (3)$$

The form of equation (3) indicates that the value of the polytropic transformation index is the tangent of the angle of the straight line to the axis of the abscissa of the logarithmic system. The processes of compression and expansion of the real indicator chart presented in the double logarithmic scale allow to determine the value of indexes of polytropic transformations. The beginning of the combustion process will be determined by the point of detachment of the curve of logarithms of dimensionless pressure values in the cylinder from the determined straight line for the case of initiation of the combustion process before TDC (Fig. 1), or the point of intersection of the logarithm curve with this straight line in case of ignition after the upper return position of the TDC piston (Fig. 2).

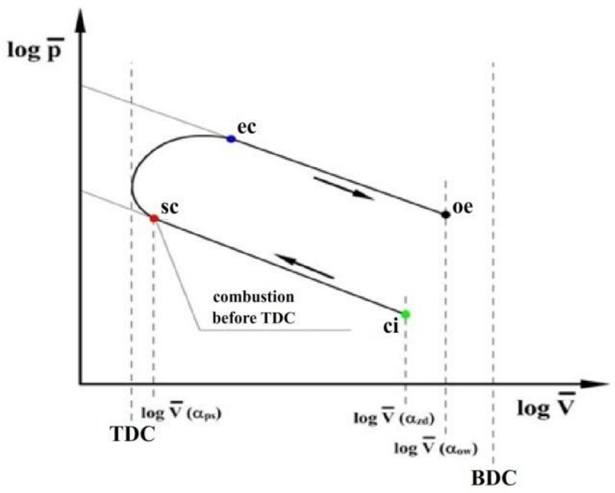

Fig. 1. Graphical representation of the combustion process evaluation method takes into account the occurrence of ignition before top dead centre: sc – the beginning of the combustion process, ec – the end of the combustion process, ci – closing the intake valve, oe – opening the exhaust valve

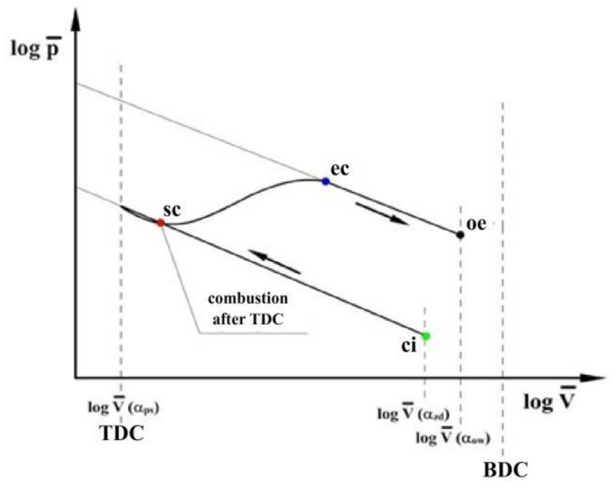

Fig. 2. Graphical representation of the combustion process evaluation method takes into account the occurrence of ignition after top dead center: sc – the beginning of the combustion process, ec – the end of the combustion process, ci – closing the intake valve, oe – opening the exhaust valve

3.2. Direct pressure comparison method in the cylinder

The direct pressure comparison method in the cylinder is one of the test methods using measurement data obtained during the engine's indication. It is used to determine the moment of initiation of the combustion process and ignition delay. However, it is not possible to determine the duration of the combustion process with this method. Determination of the initiation moment of the combustion process is defined as the point of rapid deviation of the pressure curve of the cycle with combustion from the curve of the cycle pressure without combustion. An illustration of the method is shown in Fig. 3.

This method requires the creation of pressure courses in the cylinder both for the combustion engine cycle and without combustion. Specialised equipment of the station is required to enable a cycle without combustion. The results obtained in this way for a cycle without combustion may not be meaningful to those obtained for the combustion cycle. The desirability of obtaining results for a cycle without combustion using the required equipment is an interference in the operation of the engine. The comparative analysis of the values of pressure waveforms from the combustion and non-combustion cycle may be biased because the results obtained from two significantly different motor states are compared. Noise can cause a scattering of pressure waveforms that make comparisons difficult. Therefore, the introduction of the criterion of differences in the values of compared pressures was adopted. The comparative criterion for the P method is in the range of 3% to 10%. According to the 3% criterion, the occurrence of ignition is considered when the value of the pressure difference of the cycle with combustion and without combustion reaches 3%.

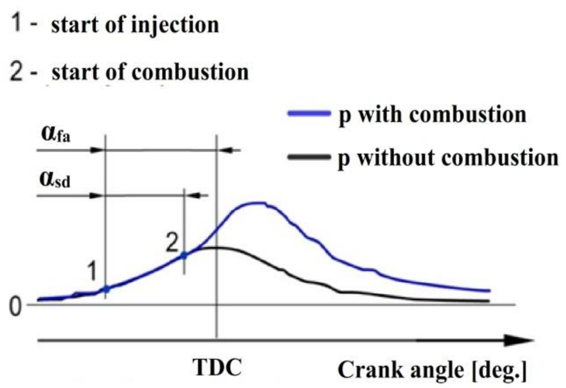

Fig. 3. Graphical representation of the direct pressure comparison method in the cylinder: α_{fa} – fuel injection advance angle, α_{sd} – self-ignition delay angle

3.3. Method of comparing the first pressure derivative in the cylinder dP

The self-ignition delay period in this method is determined based on a comparison of the first pressure derivative during the combustion cycle and the first cycle pressure derivative without combustion. The beginning of the combustion process is determined by the deviation of the first derivative of the pressure change of the cycle with combustion from the curve representing the values of the first derivative of the cycle pressure without combustion. Optionally, the second pressure derivative in the cylinder of the engine can be used for calculations. A graphic illustration of the method is shown in Fig. 4.

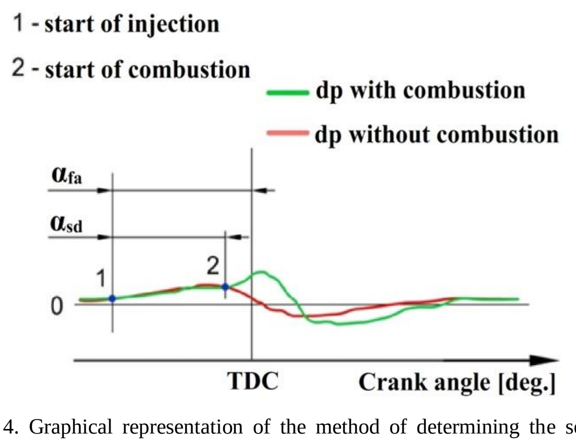

Fig. 4. Graphical representation of the method of determining the self-ignition delay based on the course of the first pressure derivative in the cylinder: α_{sd} – fuel injection advance angle, α_{fa} – self-ignition delay angle

As in the P method, also in this it is required to have a pressure course in the cycle cylinder without the combustion process. The disadvantage of the method is the inability to determine the end of the combustion process.

3.4. Logarithmic derivative method of pressure change in the cylinder dlnP

The idea of the method is based on the use of a logarithmic derivative of the course of pressure change in the cylinder of the engine. The beginning and the end of the combustion process is determined by means of two characteristic points of the logarithmic derivative of a pressure change, which are two local minimal values of the dlnP curve prepared as a function of the angle of rotation of the crankshaft. The course of the value of this curve is described by the equation:

$$\frac{d(\ln p)}{d\alpha} = \frac{\ln p_{i+1} - \ln p_i}{\alpha_{i+1} - \alpha_i} \tag{4}$$

where: p, α – dimensionless quantities.

In Figure 5 a graphic illustration of the method is presented.

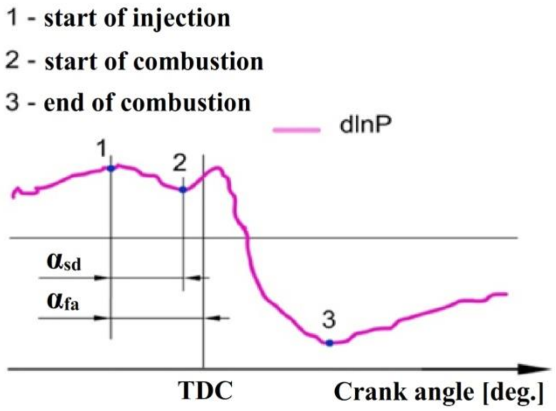

Fig. 5. Graphical interpretation of determination of combustion process parameters based on the logarithmic derivative of the pressure change in the cylinder of the engine: α_{pw} – fuel injection advance angle, α_{axis} – self-ignition delay angle

In this method, to determine combustion parameters, it is not required to have a pressure course in the cylinder from the cycle without combustion. The dlnP method allows to determine both the beginning and the end of the combustion process. The disadvantage of the method is the large spread of data. For large ignition angles, this method gives results with a large error, because the first peak of the minimum that marks the beginning of combustion disappears. The intensity of noise when measuring for large ignition angles also makes it difficult to find a characteristic local minimum, indicating the initiation point of the combustion process, also introducing errors in determining the ignition delay and duration of the combustion process.

3.5. Method of the polytropic index k

In this method, the determination of combustion parameters is based on the value of the polytropic index. The values of the polytropic index are determined by the formula:

$$k = -\frac{\frac{dp}{p}}{\frac{dV}{V}} \tag{5}$$

where: p – pressure in the engine cylinder, V – volume of the working medium in the cylinder, dp – the first pressure derivative in the cylinder, dV – the first derivative of the cylinder volume.

In order to determine the combustion parameters, the polytropic indexes are compared for the combustion engine cycle and without combustion. The beginning of the combustion process is determined by the point of propagation of the curves, while the end of the combustion process determines the point of re-joining the curves. This method is shown in Fig. 6.

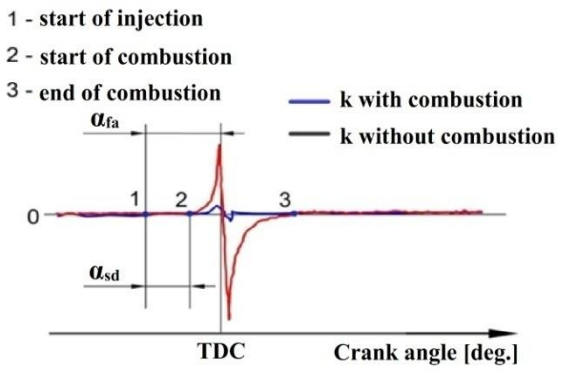

Fig. 6. Graphical interpretation of determination of combustion process parameters using the polytropic index k: α_{fa} – fuel injection advance angle, α_{sd} – self-ignition delay angle

The disadvantage of this method is the large influence of the quality of the measurement data on the final result. This is mainly because the differential function is used in the calculation algorithm. Differentiation is a mathematical action that exposes differences in input values. Therefore, the seemingly gentle course after the differential operation reveals, and to a significant degree, all kinds of minimal disturbances, e.g. noise in the input signal.

3.6. Method of the first derivative of the polytropic index dk

The method is based on data obtained as a result of the engine's indication. They are used to determine the course of the value of exponent polytropic compression k. This method uses the derivative of the compression polytropic index. The formula used to determine the value of the polytropic index has the following form:

$$k_i = \frac{\log\frac{p_{i-1}}{p_i}}{\log\frac{V_{i-1}}{V_i}} \tag{6}$$

where: p_{i-1} – the actual value of the pressure in the engine cylinder for the angle of rotation of the crankshaft α_{i-1}, p_i – the actual value of the pressure in the engine cylinder for the angle of rotation of the crankshaft α_i, V_{i-1} – the calculated cylinder volume for the crank angle rotation α_{i-1}, V_i – the calculated cylinder volume for the crank angle rotation α_i.

The values of the polytropic index, obtained on the basis of formula (6), are then subjected to differentiation operations:

$$dk(\alpha) = \frac{dk_i}{d\alpha} \quad (7)$$

The result of equation (7) is the course of the compression polytrope as a function of the angle of rotation of the engine crankshaft. On the basis of the course obtained, it is possible to determine the period of self-ignition delay. The method is used to determine the boundaries of the combustion process in the engine. As the points of beginning and end of the combustion process, we assume moments for which the dk/dα curve takes the value of zero. This method does not require to have a polytropic index on the compression cycle for the cycle without combustion, i.e. no pressure cycles of the compression process are necessary. A graphic illustration depicting the described method is shown in Fig. 7.

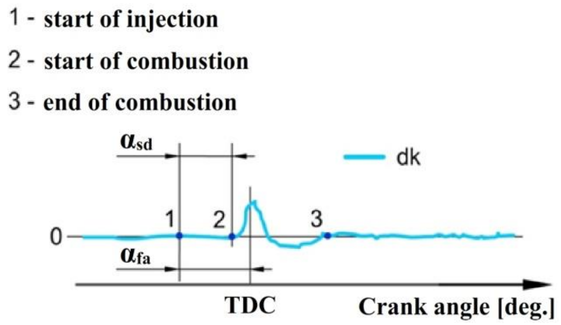

Fig. 7. Illustration of the method for evaluation of combustion process parameters using the first derivative of the polytropic index: α_{fa} – fuel injection advance angle, α_{sd} – self-ignition delay angle.

3.7. Method of constant values of the polytropic index kp

The determinant of the beginning and end of the combustion process are the breakaway points of the curve, respectively $\frac{dk}{d\alpha}$ from a constant value (initiation of the combustion process) and its re-adoption of a constant value (end of the combustion process). As in the previously discussed methods, also in this we use the results obtained in the process of indication of the engine (the actual value of the pressure in the cylinder and the corresponding angle of rotation of the crankshaft). In the Fig. 8 the method described graphically is presented.

For different values of the ignition advance angle, the collected data is characterised by quite a large spread. This creates difficulties in determining the detachment points and the return to the horizontal straight line, which takes a constant value, which are next to the beginning and the end of the combustion process.

Conclusions

The evaluation of the combustion process in a piston combustion engine is a very complex problem and is still a field of interest for engineers' researchers and is the subject of numerous scientific and research works. Constant efforts to reduce the harmful impact of engines on the environment dictated by the restrictions of exhaust emission standards and rationalisation of intra-cylinder processesaimed at achieving the greatest possible conversion of chemical energy contained in fuel requires adjusting tools to assess the basic parameters of processes in the engine cylinder. These are the methods of evaluation of one of the most important components of the work cycle, i.e. the combustion process, which primarily influences the formation of harmful exhaust components in the cylinder and plays a key role in the efficiency of the engine. Among the methods described, we can distinguish those that require engine cycles with combustion and without combustion, we include the method of direct comparison of cylinder pressure and the method of comparing the first pressure derivative in the cylinder. These simple methods allow to determine only the moment of initiation of the combustion process and determination of the ignition delay period of the combustible mixture. The methods of the polytropic index, the constant value of the polytropic index, and the first derivative of the polytropic index, are sensitive to the level of noise. The limitation in the application of the logarithmic derivative method of pressure change in the cylinder of the dlnP engine is engine operation at high ignition angles and combustion of poor mixtures. The methods of assessment of the basic combustion process parameters presented in the article show advantages and disadvantages, therefore their use must be accompanied by the researcher's intuition and reliable evaluation and verification of the results obtained by means of several available research methods.

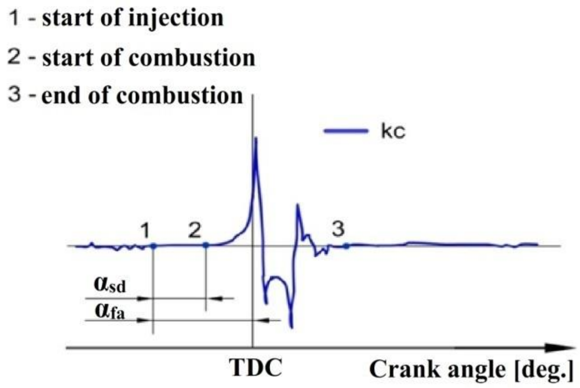

Fig. 8. Graphical representation of the method for determining the beginning and ending of the combustion process based on fixed values of the polytropic index, allowing the determination of the self-ignition delay: α_{fa} – fuel injection advance angle, α_{sd} – self-ignition delay angle

Bibliography

[1] AMBROZIK, A. Analiza cykli pracy czterosuwowych silników spalinowych. *Wydawnictwo Politechniki Świętokrzyskiej*. Kielce 2010.

[2] AMBROZIK, A. Wybrane zagadnienia procesów cieplnych w tłokowych silnikach spalinowych. *Wydawnictwo Politechniki Świętokrzyskiej*. Kielce 2003.

[3] AMBROZIK, A., KURCZYŃSKI, D., ŁAGOWSKI, P., WARIANEK, M. External speed – torque characteristics of Fiat 0.9 TwinAir petrol and CNG fuelled engine. *Combustion Engines*. 2017, **171**(4).

[4] AMBROZIK, A., AMBROZIK, T., KURCZYŃSKI, D., ŁAGOWSKI, P. Interpolacja rzeczywistego wykresu indy-

katorowego silnika o zapłonie samoczynnym za pomocą funkcji sklejanych. *Autobusy*. 2012, **4**.
[5] AMBROZIK, T., KOSNO, M. Wpływ kąta wyprzedzenia wtrysku na okres opóźnienia samozapłonu w silniku o zapłonie samoczynnym. *Logistyka*. 2014, **6**.
[6] CHEN, D., SUN, R., WU, Y., WANG, B. A research on compressed natural gas engine fuel supply system for prototyping based on AMEsim. *Applied Energy Technology*. 2013, 724-725.
[7] CONEY, M.W., LINNEMANN, C., ABDALLAH, H.S. A thermodynamic analysis of a novel high efficiency reciprocating internal combustion engine – the isoengine. *Energy*. 2004, **29**(12).
[8] GAJEK, A., JUDA, Z. Czujniki. *WKiŁ*. Warszawa 2015.
[9] KNEBA, Z., MAKOWSKI, S. Zasilanie i sterowanie silników. *WKiŁ*. Warszawa 2004.
[10] KUCZYŃSKI, S., LISZKA, K., ŁACIAK, M. et al. Wpływ zastosowania paliw alternatywnych w transporcie, ze szczególnym uwzględnieniem CNG, na ograniczenie emisji zanieczyszczeń powietrza. *Energy – Policy Journal*. 2016, **19**, 91-104.
[11] OPPENHEIM, A.K. Combustion in piston engines, technology, evolution, diagnosis and control. *Springer-Verlag*. Berlin Heidelberg 2004.
[12] PADEN, B.A., SNYDER, S., PADEN, B.E. Modeling and control of an electromagnetic variable valve actuation system. *Ieee-Asme Trans Mechatronics*. 2015, **20**(6).
[13] PRZYBYŁA, G. Studium stosowania biopaliw gazowych do zasilania silników spalinowych. *Wydawnictwo Politechniki Śląskiej*. Gliwice 2015.
[14] ROMANISZYN, K. Alternatywne zasilanie samochodów benzyną oraz gazami LPG i CNG. *WNT*. Warszawa 2007.
[15] ZERVAS, E. Comparative study of some experimental methods to characterize the combustion process in a SI engine. *Energy*. 2005, **30**, 1803-1816.
[16] http://eur-lex.europa.eu: Dyrektywa Parlamentu Europejskiego i Rady 2014/94/UE z dnia 22 października 2014 r. w sprawie rozwoju infrastruktury paliw alternatywnych.

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