

Internal combustion engine diagnostics using statistically processed Wiebe function

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Highlights

- Assessment of variability of the combustion process using the Wiebe function.
- Procedure for obtaining the lower and upper limit of the Wiebe function and utilization for diagnostics.
- More accurate determination of the angle of fuel burning beginning.
- Statistical test of relative frequencies for combustion process variability evaluation has been used.
- Procedures are usable for different computational methods of Wiebe function parameters calculation.

Abstract

The aim of the article is to present the concept of an indirect diagnostic method using the assessment of the variability of the amount of released heat (mass fraction burn) and the heat release rate. The Wiebe function for the assessment of variability has been used. The Wiebe function parameters from the course of the high-pressure indication in the cylinder of internal combustion engine using linear regression have been calculated. From a sufficiently large number of measured samples, the upper and lower limits of the Wiebe function parameters have been statistically determined. Lower and upper limits characterize variability of the heat release process not only in terms of quantity but also in terms of heat release rate. The assessment of variability is thus more complicated than using one integral indicator, typically the mean value of amount of the released heat. The procedure enabling a more accurate estimation of heat generation beginning has been shown. For the combustion process variability assessment of the engine, statistical test of relative frequencies has been used.

Keywords

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automotive engineering, engine diagnostics, Wiebe function, parameters estimation, statistics, technical condition.

1. Introduction

The internal combustion engines diagnostics has an extensive history and a lot of diagnostic methods have been applied. The condition of the technical objects, also of the internal combustion engine, for example, on the basis of tribotechnical methods of oil degradation [20, 22, 30] can be assessed or, for example, on the basis of the assessment of the acoustic emissions [16, 17, 24], or on the basis of the assessment of vibrations [27, 29], or on the basis of the assessment of the exhaust emissions [14]. For assessing of the technical condition, of course, the statistic tools are used, as mentioned in [18].

The course of the indicated pressure depending on the crank angle allows to diagnose the condition of a lot of internal combustion engine components. An example is the Covariance method (CoV) of Indicated Mean Effective Pressure (IMEP). The method evaluates the variability of the combustion process using the IMEP parameter. The variability of the combustion process is determined by the size of the standard deviation. The method is described in [34], where it is also shown that the course of the indicated pressure depends on the amount of released heat during the fuel combustion process. The procedures, referred in an article [2], describes relationship between the course of high-pressure indication and the parameters of the Wiebe function.

However, the above-mentioned approaches do not solve the specific problem of an engine diagnostics due to the variability of not only the amount of released heat (mass fraction burn), but also of the heat release rate during individual working cycles. The CoV IMEP method in principle works with the mean value of the indicated pressure, i.e. with one integral parameter, but there is no information about the distribution of the heat release rate. The presented method can thus indirectly characterize the amount of released heat, including process variability. However, the utilization of the Wiebe function also provides information about the distribution of the heat release rate. This can be advantageously utilized for the better assessment of the variability between each engine cycles, because of uses of two parameters for the burning description. This is a diagnosis of situations, such as inconsistent ignition of the mixture, or an unsuitable fuel use or local detonation combustion.

The process of fuel combustion can thus be described using the Wiebe function, as shown in [4, 31], the function is computationally very efficient, as shown in [32]. However, most methods using the Wiebe function to describe fuel combustion are focused on the best possible compliance between the theoretical model represented by the parameters of the Wiebe function and the experimentally measured values [5, 8, 11, 12, 13]. For example, „double Wiebe“ models

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are used in cases, as shown in [33], where the sophisticated „fitting“ method with weighting coefficients given in [6] is used to calculate the parameters of the Wiebe function. The calculation procedure is based on the average value of the high-pressure indication course obtained from a large number of cycles. The calculation of the parameters of the Wiebe function is then performed from this fictitious course. Obviously, this procedure does not allow to assess the variability of the combustion process. This procedure is suitable, for example, as an input to simulation calculations of internal combustion engines. In this way, it is possible to enrich the spectrum of methods already used for the diagnostics of internal combustion engines [19, 25].

Early diagnostic results allow to properly plan a preventive engine maintenance strategy and thus affect the maintenance costs. Therefore, it is an important tool of predictive diagnostics [15, 23].

The concept of the diagnostic method described in the article is based on a statistical assessment of the variance of values of the Wiebe function parameters. From a large number of cycles for the individual crankshaft rotation angles, an interval estimation of the amount of released heat at a predetermined confidence level α has been determined. The upper and lower estimate specify the limits, between which the values of the Wiebe function parameters of the standard (etalon) engine must be found.

The number of unsatisfactory engine cycles of the diagnosed engine has been further evaluated. If the test result exceeds the confidence level α , the diagnosed engine shows greater combustion process variability, than corresponds to the expected values, thus shows the poor technical condition of the engine.

2. Mathematical model

The Wiebe function, is the default equation for description of the course of a mixture burning in the internal combustion engine cylinder, depending on the crank angle. The function is given by the equation (1), but the derivation of the equation (1) defined by the equation (2) for course description of the function often has been used:

$$F(\varphi) = \frac{Q(\varphi)}{Q_c} = 1 - e^{-A \left(\frac{\varphi - \varphi_0}{\Delta\varphi} \right)^{M+1}} \quad (1)$$

$$f(\varphi) = \frac{A \cdot (M+1)}{\Delta\varphi} \cdot \left(\frac{\varphi - \varphi_0}{\Delta\varphi} \right)^M \cdot e^{-A \left(\frac{\varphi - \varphi_0}{\Delta\varphi} \right)^{M+1}} \quad (2)$$

The equation (1) describes the ratio of the gradually released heat $Q(\varphi)$ depending on a crank angle φ , to the total amount of heat Q_c released during one cycle. The Wiebe function contains the constant A given by the used fuel type, for gasoline (RON 95) $A = 6.90$ as described in [7]. Furthermore, the Wiebe function contains the shape parameter M , which characterizes the shape of the curve of the released heat. Function also contains angle $\Delta\varphi$, which represents the time, when 95% of the heat has been released. The value of 95% is given by the fact, that the amount of released heat is very small at the beginning and the end of the cycle and thus the pressure changes in the cylinder are very small, and therefore difficult to measure [26]. The last parameter φ_0 specifies the angle of displacement of the burning beginning with respect to the top dead center (TDC).

3. Wiebe function parameters estimation

The mathematical model aims to estimate the parameters $\Delta\varphi$, φ_0 and M of the Wiebe function using a linear regression and an experimentally obtained data. The procedure requires adjustments of equation (1) to obtain a linear form (see equation (5)):

$$1 - F(\varphi) = e^{-A \left(\frac{\varphi - \varphi_0}{\Delta\varphi} \right)^{M+1}} \quad (3)$$

$$-\ln(1 - F(\varphi)) = A \cdot \left(\frac{\varphi - \varphi_0}{\Delta\varphi} \right)^{M+1} \quad (4)$$

$$\ln[-\ln(1 - F(\varphi))] - \ln(A) = \ln(\varphi - \varphi_0) \cdot (M+1) - \ln(\Delta\varphi) \cdot (M+1) \quad (5)$$

Equation (5) with the line equation has been compared, (see equation (6)) and the substitutions have been used (see equations (7) to (9)):

$$y = k \cdot x + q \quad (6)$$

$$y = \ln[-\ln(1 - F(\varphi))] - \ln(A) \quad (7)$$

$$k \cdot x = (M+1) \cdot \ln(\varphi - \varphi_0) \quad (8)$$

$$q = -\ln(\Delta\varphi) \cdot (M+1) \quad (9)$$

It is now possible to create a table of values from experimentally obtained data. Data have a structure described in Tab.1. The graph of ordered values has been created, as shown in Fig. 1. In the graph in Fig. 1 the values $\ln(\varphi - \varphi_0)$ on the x-axis have been plotted, when meanwhile $\varphi_0 = 0^\circ$ has been considered, and the values of y_i given by the substitution according to equation (7) on the y-axis have been plotted. Initial, very small values of released heat, in accordance the definition of $\Delta\varphi$, in the graph have been not considered.

Table 1. Data structure for Wiebe function parameters estimation

i	$(\varphi - \varphi_0)$ [°]	Q_i [J]	σ_i [J]	$F(\varphi) = \sum_{i=1}^n Q_i / Q_c$ [%]	$\ln(\varphi - \varphi_0)$ [-]	y_i [-]
1	-1	-0.378	0.212	-	-	-
2	0	0.012	0.281	0.001	-6.908	-13.053
3	1	0.164	0.387	0.021	0.000	-10.404
4	2	0.731	0.649	0.11	0.693	-8.763
5	3	2.030	1.056	0.35	1.099	-7.587
6	4	2.905	1.452	0.69	1.386	-6.898
7	5	5.276	2.169	1.32	1.609	-6.251

Where: i - serial number of the measurement [-]
 $(\varphi - \varphi_0)$ - crank angle [°]
 Q_i - average amount of released heat [J]
 σ_i - standard deviation of released heat [J]
 $F(\varphi)$ - Wiebe function of gradually released heat [%]
 Q_c - total amount of released heat in one cycle [J]
 y_i - value of substitution at i-th measurement according to equation (7) [-]
 n - number of engine cycles [-]

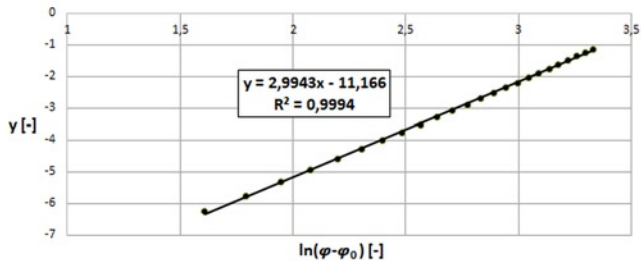


Fig. 1. Wiebe function in linear form with regression equation

The points, plotted in the graph in Fig. 1, can be intersected by a line and the equation of the line using linear regression can be obtained. From the numerical values of the equation of the line, the parameters of the Wiebe function can be calculated. The inverse transformation of equations (8) and (9) for the calculation will be used. In equation (8), the value of the direction of the line k is equal to the shape parameter $(M + 1)$ on the right side of the equation and the variable x corresponds to the term $\ln(\varphi - \varphi_0)$. The parameter M is then given by equation (10):

$$M = k - 1 \quad (10)$$

Similarly, by modification of the equation (9) the value of the parameter $\Delta\varphi$ using the equation (11) has been obtained, this corresponds to the parameter of the displacement of the beginning of the line q :

$$\Delta\varphi = e^{\left(\frac{-q}{M+1}\right)} \quad (11)$$

Furthermore, it is necessary to determinate the parameter φ_0 , which indicates the angle of displacement of the beginning of fuel burning compared to the top dead center (TDC). The amount of released heat with variation of angle φ_i (due to random fluctuations with each cycle) are changing and it is therefore a stochastic process with dispersion of values. The angle φ_0 thus can be obtained by assessing the probability of heat release for angles close to the value φ_0 . In this phase of model creation, a normal distribution of heat release Q_i has been assumed, where the mean value and standard deviation σ_i from a larger number of measured cycles have been calculated. From the measured values in Tab. 1 it can be seen that a positive value of the generated heat Q_i is firstly detected for measuring with index $i = 2$ for angle $\varphi_2 = 0^\circ$ of crank angle. Considering that the initial amount of release heat is very small and difficult to measure, the beginning of heat release will be between the values $\varphi_1 = -1^\circ$ and $\varphi_2 = 0^\circ$ of crank angle. The native resolution of the measuring equipment does not allow a more accurate determination of the angle of beginning of burning. Using the values from Tab.1, it is possible to create the course of the heat release probability density, see Fig. 2. The left area of the vertical axis represents the probability of event $N(Q)$, when the heat is negative and therefore the fuel does not burn. Vice versa, the right area of the vertical axis shows the probability of event $P(Q)$, when the released heat is positive and thus the process of burning has started.

Similarly, Fig. 3 and Fig. 4 shows the course of the heat release probability for the angle $\varphi_1 = -1^\circ$ and $\varphi_2 = 0^\circ$ of crank angle.

From Fig.3 it is clear that the probability $N_1(Q)$ for the angle $\varphi_1 = -1^\circ$ is high and therefore the probability of heat release $P_1(Q)$ will be low (approx. 4%), but on Fig. 4, the probability of heat release $P_2(Q)$ is significantly higher. Therefore, can be expected that the beginning of burning will be closer to $\varphi_2 = 0^\circ$ of crank angle.

The phase between the angles $\varphi_1 = -1^\circ$ and $\varphi_2 = 0^\circ$ of crank angle indirectly to the probability ratio can be divided, as shown in Fig. 5 and equation (12) can be created. Substituting of equation (13) into

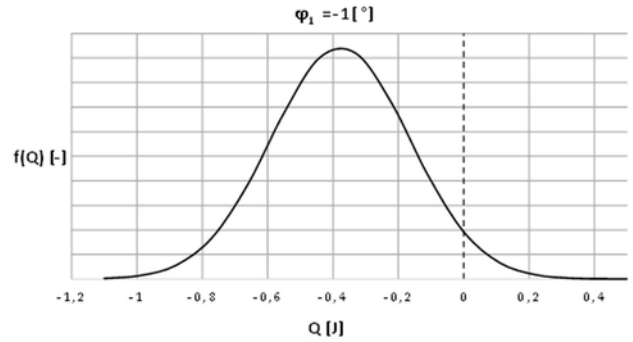


Fig. 2. Probability density of released heat

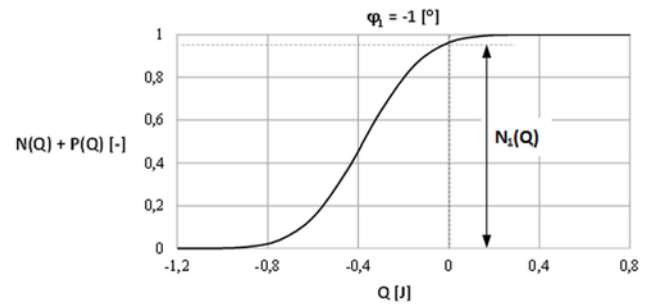


Fig. 3. Probability of heat unreleasing $N_1(Q)$ for angle $\varphi_1 = -1^\circ$

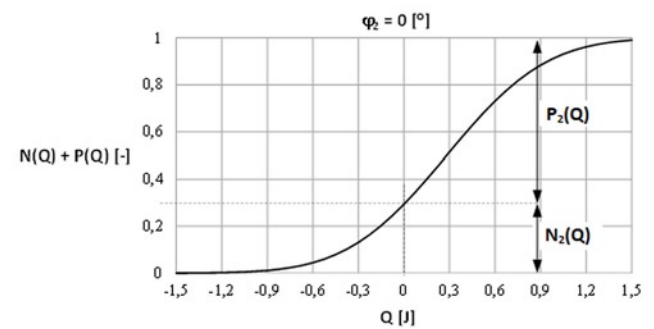


Fig. 4. Probability of heat releasing $P_2(Q)$ for angle $\varphi_2 = 0^\circ$

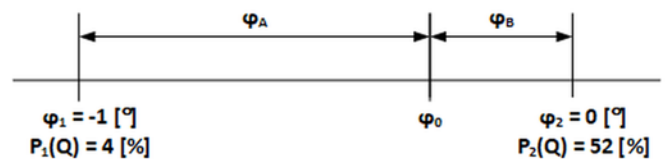


Fig. 5. Displacement of angle φ_0

equation (12) the displacement of the angle φ_0 given by equation (14) has been obtained:

$$\frac{\varphi_A}{\varphi_B} = \frac{P_2(Q)}{P_1(Q)} \quad (12)$$

$$\varphi_A + \varphi_B = 1 \quad (13)$$

$$\varphi_B = \frac{P_1(Q)}{P_1(Q) + P_2(Q)} \quad (14)$$

Substituting the probability of heat release $P_1(Q)$ and $P_2(Q)$ into equation (14), the displacement of the angle φ_B of beginning of burning before the top dead center (TDC) has been obtained:

$$\varphi_B = \frac{0.037}{0.037 + 0.517} = 0.07 [^\circ]$$

The above described procedure makes it possible to obtain the Wiebe function parameters estimation, see Fig. 6.

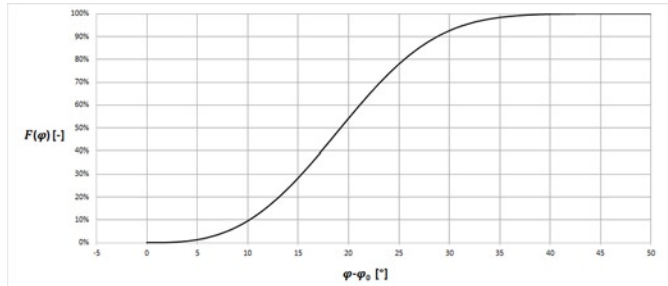


Fig. 6. Wiebe function with parameters $\Delta\varphi = 41.76^\circ$, $M = 1.99$ and $\varphi_0 = -0.07^\circ$

4. Interval estimation of Wiebe function parameters

As mentioned at the beginning of the article, the values of the parameters of the Wiebe function will correspond to one specific course of the engine cycle. On the other hand, a different cycle, due to the fluctuation of the amount of generated heat, has different course and thus the different parameters of the Wiebe function. A larger number of cycles must be statistically processed to solve this problem. The aim is to calculate a two-sided interval estimation of the amount of released heat Q_i . The interval estimation is determined from n work cycles always for one specific crank angle φ .

The statistical model of the amount of released heat Q_i assumes a normal distribution of a random variable. To obtain a two-sided estimation, it is necessary to determine the limits of the interval, i.e. to determine the confidence level α , the confidence level $\alpha = 5\%$ has been chosen. The estimation in Fig. 7 has been shown.

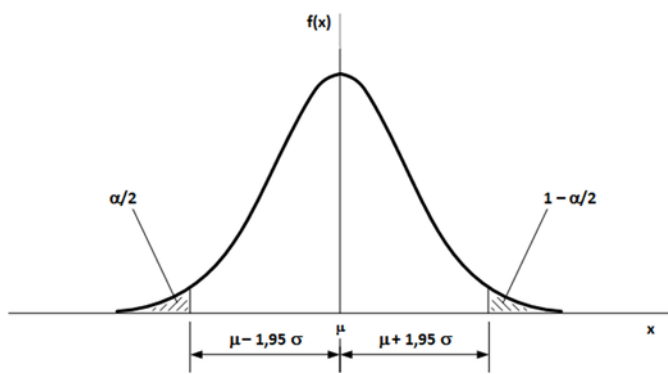


Fig. 7. Two-side interval estimation on confidence level $\alpha = 5\%$

Fig. 7 shows the probability density of a normal distribution and the interval limits using the σ rule, where σ represents the standard deviation of the considered set and μ is the mean value. Details of the application of the σ rule in [3] have been published.

5. Experimental part

The experimental part is based on measurements performed by the engine manufacturer, the used data from the source [2] have been obtained. The gasoline car engine with mixture preparation outside the engine cylinder with multi-point injection and with a displacement of 1400 cm^3 has been measured on the test bed. The tested engine was in

good technical condition and the measurement of the indicated pressures was performed in an engine steady state, i.e. at constant speed 3500 min^{-1} and constant power 50 kW .

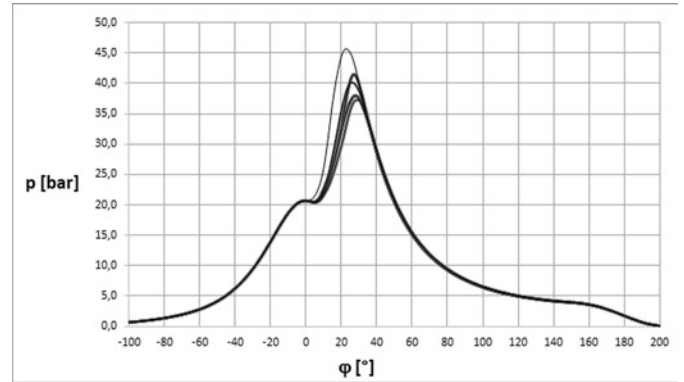


Fig. 8. Variability of an indicated pressure

Data of 100 working cycles was stored in the memory unit of the measuring equipment, the pressure measurement was performed for 1° of crank angle. The variability of the course of the indicated pressure for five randomly selected working cycles is shown in Fig. 8 and the amount of released heat is in Fig. 9.

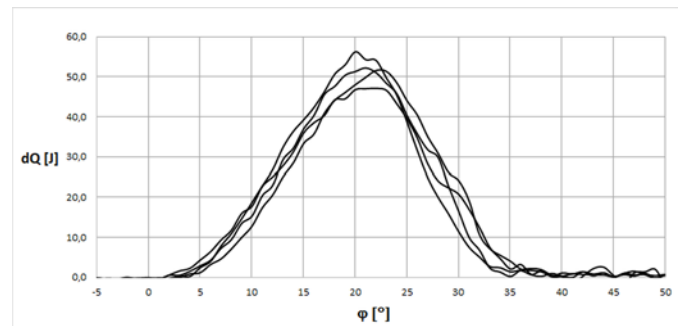


Fig. 9. Variability of a course of heat rate release dQ

5.1. Determination of two-way estimation of Wiebe function parameters

Statistical processing of the amount of released heat Q_i for the crank angle φ is performed on a sample of $n = 100$ engine operating cycles. For each crank angle φ , the average amount of released heat Q_{AVG} has been calculated according to equation (15) and the standard deviation σ according to equation (16) have been calculated. Compliance testing of the experimental data with the expected normal distribution using the Chi-square goodness of fit test has been performed, in all cases fit has not been rejected:

$$Q_{AVG} = \frac{1}{n} \cdot \sum_{i=1}^n Q_i \quad (15)$$

$$\sigma = \sqrt{\frac{\sum (Q_i - Q_{AVG})^2}{n}} \quad (16)$$

Where: Q_i - amount of released heat of individual cycle [J]
 Q_{AVG} - average amount of released heat [J]
 n - number of engine cycles [-]

The data with the structure according Tab. 2 tabularly has been processed. In the table, the lower estimate of the amount of released heat Q_{LE} according to equation (17) and the upper estimate of the

amount of released heat Q_{UE} according to equation (18) from n cycles have been determined:

$$Q_{LE} = Q_{AVG} - 1.95\sigma \quad (17)$$

$$Q_{UE} = Q_{AVG} + 1.95\sigma \quad (18)$$

Table 2. Data structure for interval limits calculation

$(\varphi - \varphi_0)$ [°]	Q_{AVG} [J]	σ [J]	Q_{LE} [J]	Q_{UE} [J]
-4	-0.539	0.253	-1.032	-0.046
-3	-0.285	0.271	-0.814	0.244
-2	-0.388	0.242	-0.859	0.083
-1	-0.378	0.212	-0.790	0.035
0	0.012	0.281	-0.535	0.560
1	0.164	0.387	-0.592	0.919
2	0.731	0.649	-0.534	1.996
3	2.030	1.056	-0.030	4.090
4	2.905	1.452	0.074	5.736
5	5.276	2.169	1.046	9.506

The data with structure according Tab. 2 will be further processed using the procedure described in chapter 2. The mean value, and the lower and upper estimate of the parameters of the Wiebe function at the confidence level α have been obtained. The lower and upper estimate represent the limit values, between which the values of the Wiebe function must be found, if the tested engine is in a fault-free state. Numerical values for estimation in Tab. 3 are described, the functions are sketched in Fig. 10.

Table 3. Limit values estimation of Wiebe function

Parameter	$F_{AVG}(\varphi)$	$F_{LE}(\varphi)$	$F_{UE}(\varphi)$
M (-)	1.98	3.04	1.66
$\Delta\varphi$ [°]	41.76	36.69	44.21
φ_0 [°]	-0.07	3.18	-3.98

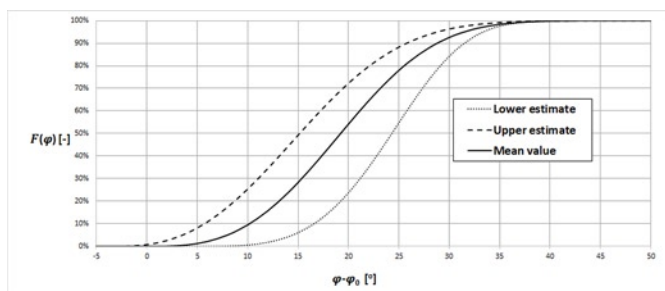


Fig. 10. Limit values of Wiebe function on confidence level $\alpha = 0.05$

5.2. Engine technical condition assessment

For an assessment of the technical condition of the tested engine, it is necessary to determine the number of cycles outside the limits of the Wiebe function, described in previous chapter. It can be expected that an increased number of cycles outside the limit values will signify increased variability of burning. Furthermore, if the number of cycles outside the limits is significantly increased, a significant shift of the Wiebe function towards the limit values can be expected. This may reflect disturbances of tightness of engine cylinder [9, 10].

Two types of problem solving can be used to determine the number of a substandard cycles. Firstly, it is necessary to test the condition in

the analytical solution, if there exist an intersection of the course of the tested cycle with the limit values of the Wiebe function. If so, the test cycle is a substandard, but this condition is not sufficient. There may be situations where the course of the whole function lies outside the limit values, so the intersection does not exist, but logically it is also a substandard cycle. The second possibility is the utilization of an algorithm, where the condition (with a small increment of angle φ) has been gradually tested, whether the value of the function $F(\varphi)$ of the tested engine lies in the range of limit values or not. If the condition is not met, it is a substandard cycle.

Quantitative assessment of the tested engine condition is based on hypothesis testing of concordance of relative frequencies. The number of unsatisfactory engine cycles in a fault-free state of engine (etalon) against the tested engine has been tested. The advantage of the test is that the number of measured duty cycles of both engines does not have to be the same. E.g. for the standard (etalon) engine, 100 working cycles are measured and for the tested engine 50 cycles. The null and alternative hypothesis has the form:

$H_0: \pi_1 = \pi_2$ - relative number of unsatisfactory cycles for both engines is the same, tested engine is in good technical condition, similarly as standard engine

$H_1: \pi_1 < \pi_2$ - relative number of unsatisfactory cycles is for tested engine higher, tested engine is not in good technical condition

This test is generally known in statistics, therefore the equations used for the calculation of relative frequencies is taken from published source [21], with specification of its interpretation published in source [28], and also example of the application in [1] have been published:

$$T(X) = \frac{p_1 - p_2}{\sqrt{p \cdot (1-p) \cdot \left(\frac{1}{n_1} + \frac{1}{n_2}\right)}} \rightarrow N(0;1) \quad (19)$$

$$p = \frac{x_1 + x_2}{n_1 + n_2} \quad (20)$$

$$p_1 = \frac{x_1}{n_1} \quad (21)$$

$$p_2 = \frac{x_2}{n_2} \quad (22)$$

For a standard (etalon) engine, the manufacturer shall have a maximum of $x_1 = 5$ unsatisfactory cycles of a total number of $n_1 = 100$ cycles. The number of cycles x_1 is given by the fact, that Wiebe function limit values the confidence level $\alpha = 5\%$ has been chosen. The tested engine shows x_2 unsatisfactory cycles out of a total number of $n_2 = 50$ measured cycles. The test results, in dependence on unsatisfactory cycles x_2 , in Tab. 4 have been described.

Table 4. Relative frequencies test results

Number of cycles x_2	p - value	Rejection of H_0 ($\alpha = 5\%$)
3	0.398	no
4	0.232	no
5	0.123	no
6	0.060	no
7	0.027	yes

The test result shows that with increasing number of substandard cycles x_2 of the diagnosed engine, the p-value criterion changes. For $x_2 = 6$ cycles, the p-value is already close to the confidence level $\alpha = 5\%$, and at $x_2 = 7$ cycles, the null hypothesis must be rejected. The test result shows that the poor technical condition of the tested engine will be identified in $x_2 = 7$ substandard cycles of total number of 50 measured cycles.

This means that the diagnosed engine shows increased combustion process variability with a probability greater than 95%, and thus shows poor engine technical condition. Whereas the article shows the concept of the diagnostic method, the given example is focused only on an example of the calculation procedure.

6. Conclusions

The aim of the article was to show the advantages of the Wiebe function utilization for statistical processing of data characterizing the nonuniformity of the combustion process between individual cycles. The Wiebe function contains information about the amount of released heat, including process variability, and also provides information about the distribution of the heat release rate. It allows better evaluation of the combustion nonuniformity than the IMEP methods.

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However, this advantage means that the mathematical apparatus is more complicated.

The Wiebe function parameters from the course of the high-pressure indication in the cylinder of the internal combustion engine using linear regression have been calculated. From a sufficiently large number of measured samples, the upper and lower limits of the Wiebe function parameters have been statistically determined. The upper and lower estimate specify the limits, between which a certain number of cycles must be located with a given probability.

The evaluation of the statistical test of relative frequencies using the p-value criterion makes it possible to decide whether the diagnosed engine shows a statistically significant deviation from the standard engine. If the statistical test of relative frequencies has been rejected, it thus shows the poor technical condition of the engine, and it is necessary to locate a specific failure, which caused the problems.

The described procedures for different computational methods of the Wiebe function parameters calculation also can be used e.g. when using the "fitting" method, including process for more accurate determination of the angle of fuel burning beginning. This is another advantage of the described diagnostic method concept.

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