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MODEL OF OPERATIONAL CHANGES IN THE COMBUSTION CHAMBER TIGHTNESS OF A DIESEL ENGINE

MODEL EKSPLOATACYJNYCH ZMIAN SZCZELNOŚCI PRZESTRZENI NADTŁOKOWEJ SILNIKA O ZAPŁONIE SAMOCZYNNYM*

The paper presents the results of tightness testing of an internal combustion engine combustion chamber during long-term operation. The tests were conducted on 5 six-cylinder diesel engines used in motor trucks. Changes in tightness for the distance range 0–500,000 km were determined based on the measurement results of the following: pressure drop measured using a cylinder leakdown tester, maximum compression pressure in the cylinders, and the blow-by flow rate at different engine operating conditions. The obtained test results were analyzed statistically. Stochastic models of changes in engine combustion chamber tightness versus distance traveled were developed. Each model describes the time history of the mean value of a selected diagnostic parameter and the limits of probable changes in this parameter. The test results have shown that both the rate and character of changes as a function of engine operation time differed depending on a parameter. The maximum compression pressure was characterized by the lowest dynamics of changes (a decrease by less than 20% for the distance range 0–500,000 km), the cylinder leakage was characterized by a moderate change dynamics, while the blow-by flow rate exhibited the highest dynamics of changes (a threefold increase at 2200 rpm). It should also be mentioned that in the case of the first two parameters, the rate of changes increased with the distance traveled, whereas in the case of the blow-by the observed changes were linear. Also, dispersion fields (i.e. changes in standard deviations) were calculated for the tested diagnostic parameters.

***Keywords**: internal combustion engine, ring pack, diagnostics, stochastic model, compression pressure, blow-by, wear.*

W artykule przedstawiono wyniki badań szczelności komory spalania silnika o zapłonie samoczynnym w czasie długotrwałej eksploatacji. Badania przeprowadzono na 5 egzemplarzach sześciocylindrowego silnika wykorzystywanego do napędu samochodów ciężarowych. Zmiany szczelności w zakresie przebiegów 0–500 tys. km określono na podstawie wyników pomiarów: spadku ciśnienia z wykorzystaniem próbnika szczelności komory spalania, maksymalnego ciśnienie sprężania w cylindrach oraz natężenia przedmuchów spalin do skrzyni korbowej w różnych warunkach pracy silnika. Wyniki badań poddano analizie statystycznej. Opracowano stochastyczne modele zmian szczelności komory spalania silnika w funkcji przebiegu samochodu. Model opisuje przebieg wartości średniej wybranego parametru diagnostycznego w czasie oraz granic obszaru prawdopodobnych zmian tego parametru.Wyniki badań wykazały, że zarówno prędkość jak i charakter zmian w funkcji czasu eksploatacji były różne dla różnych parametrów. Najmniejszą dynamiką zmian wyróżniało się maksymalne ciśnienie sprężania (spadek o mniej niż 20% w zakresie przebiegów samochodu: 0–500 tys. km), średnią dynamiką – wskaźnik szczelności, a największą – natężenie przedmuchów spalin (3-krotny wzrost przy 2200 obr/min), przy czym dla dwóch pierwszych parametrów szybkość zmian zwiększała się wraz z przebiegiem samochodu, natomiast w przypadku przedmuchów spalin zmiany miały charakter liniowy. Wyznaczono również pola rozproszeń (zmian odchyleń standardowych) dla badanych parametrów diagnostycznych.

***Słowa kluczowe**: silnik spalinowy, uszczelnienie pierścieniowe, diagnostyka, model stochastyczny,ciśnienie sprężania, przedmuchy spalin, zużycie.*

1. Introduction

Combustion chamber tightness is one of the most important features affecting the technical condition of an internal combustion engine. Due to the wear of a cylinder liner, piston rings and piston ring grooves during operation, the clearances in the piston-rings-cylinder pack increase. In effect, the combustion chamber tightness deteriorates. The decrease in tightness leads to lower engine performance, higher fuel and engine oil consumption, increased toxic substance emissions, lower cold start capacity, as well as faster engine oil degradation and piston-rings-cylinder unit wear [2, 3, 5, 12, 13, 14, 16].

The commonly used means of determining combustion chamber tightness include measuring diagnostic parameters such as compression pressure in the cylinder, sub-atmospheric pressure in the inlet duct or blow-by flow rate [12]. It is important to know operational changes in these parameters, including their rate and character of changes (linear or non-linear), as well as the scatter of measurement results, due to their importance in diagnosing the technical condition of an engine as well as predicting its durability and evaluating its reliability [1, 4, 8, 9, 10, 17]. These parameters can also be useful for the modeling of an engine ring-pack [7, 15, 18]. The relevant studies offer numerous general descriptions of various models of changes in the technical condition of objects [11]. However, there is scarce quantitative information on real changes in parameters characterizing the technical condition of the piston-rings-cylinder unit in real engine operation. [14].

The changes in tightness of the combustion chamber from the moment of production to the serviceability limit of objects operated in

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(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** normal conditions is very seldom studied due to the long time and high costs of conducting such research. Such results can be obtained in a shorter time by means of curtailed studies using the layer test method [13]. The curtailed studies consist in performing tests on statistical samples of vehicles with different distances traveled. The test results are analyzed as a whole to determine a model of changes in a given parameter for the whole service life of a vehicle. A shortcoming of this method lies in the uncertainty of the assumption made, which says that there are no systematic differences between the studied layers – objects with different kilometrage values.

The aim of the tests described in the paper was to develop stochastic models of changes in diagnostic parameters that characterize the combustion chamber tightness of a high-speed diesel engine versus distance traveled based on long-term observations of the homogenous sample of objects, as opposed to the layer test method. Such models should allow for determining both mean value changing tendencies and a dispersion field of the investigated parameters versus engine operation time.

2. Test object and method

The test object was a six-cylinder compression-ignition engine with a displacement of 6.8 dm^3, maximum torque of 432 Nm in the range of 1800-2200 rpm, and a rated power of 110 kW at a speed of 2800 rpm. The engine was equipped with wet, cast iron cylinder liners with a nominal internal diameter of 110 mm. The aluminum piston was equipped with a toroidal combustion chamber and a cast-iron carrier for the top ring groove. The top ring was a keystone type, the second one was rectangular, and the twin-land oil ring was equipped with a spiral spring. The piston stroke was 120 mm. The engine had two cylinder valves powered by the camshaft mounted in the engine block and actuated by valve rods and valve arms.

The tests were performed on 5 engines mounted in trucks of a medium load capacity and gross weight of 12 tons. The tests were performed in normal operating conditions. All the vehicles were the property of one transport service provider and they were all used in similar conditions. The vehicle engines were all lubricated with CE/SF SAE 15W/40 oil. An average monthly distance traveled by the vehicles was 10,000 km.

The engines were periodically subjected to measurements, including diagnostic tests that allow for the evaluation of combustion chamber tightness. The frequency of the conducted measurements resulted from the frequencies of periodical technical inspections of the engines. By combining the measurements, the number of servicing activities and vehicle operation disturbances could be reduced to the minimum. Until the distance traveled by the vehicle was below 100,000 km, the measurements were performed approximately every 15,000 km, and when the distance traveled exceeded 100,000 km – they were taken approximately every 50,000 km. In addition to that, the tests were conducted at the same stand by the same individuals, using the same instruments, which allowed for reducing the error connected with the non-repeatability of measurement conditions.

In order to evaluate the combustion chamber tightness, the following were measured:

- cylinder leakage,
- compression pressure in the cylinder,
- blow-by flow rate.

The cylinder leakage was determined by measuring the relative pressure drop of compressed air that was led into the combustion chamber through the injector hole at the TDC piston position after the compression stroke. The measurement was conducted using a PSC-2M cylinder leak-down tester. The compression pressure, i.e. the maximum pressure in the combustion chamber at the end of a compression stroke, was measured by means of an SPCS-50 controlled compression pressure tester. The compression pressure and cylinder leakage were successively measured in the 6 cylinders of the warmed-up engine. The blow-by flow rate was measured for both idle run (approx. 600 rpm) and full load (the maximum position of the accelerator pedal) of the engine at the following speeds: 1570, 1880, 2200 and 2800 rpm.

3. Results

The diagnostic parameter values obtained in the operational tests for particular cylinders, i.e. the results of the cylinder leakage and compression pressure measurements, are shown in Figs. 1-2, while the measurement results of the blow-by flow rate for particular engines at various crankshaft speeds are illustrated in Figs. 3-7. The obtained results are characterized by a considerable scatter. What is more, the

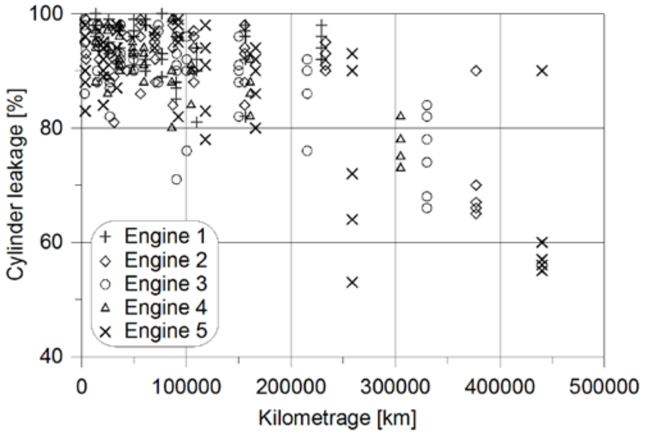

Fig. 1. Measurement results of cylinder leakage

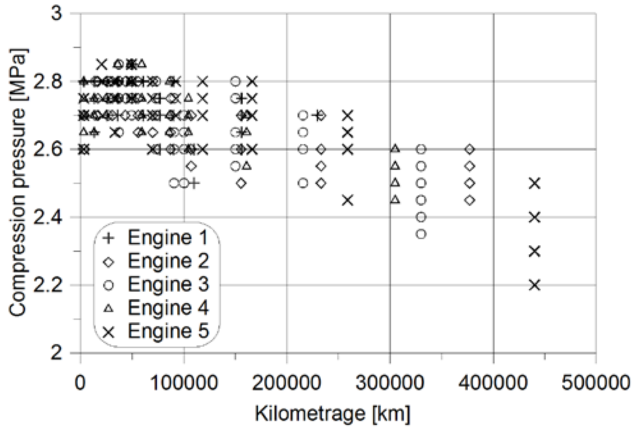

Fig. 2. Measurement results of compression pressure

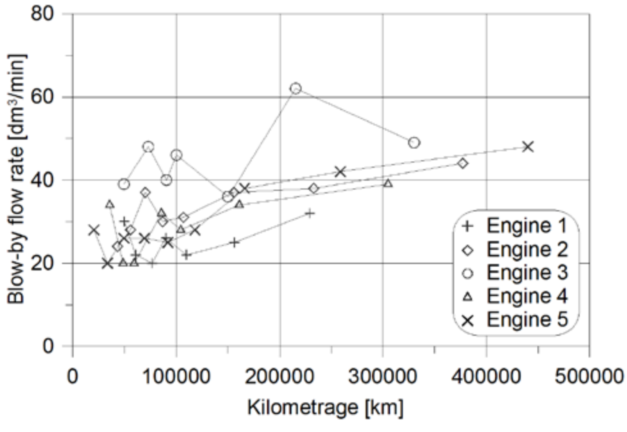

Fig. 3. Measurement results of the blow-by flow rate at idle run

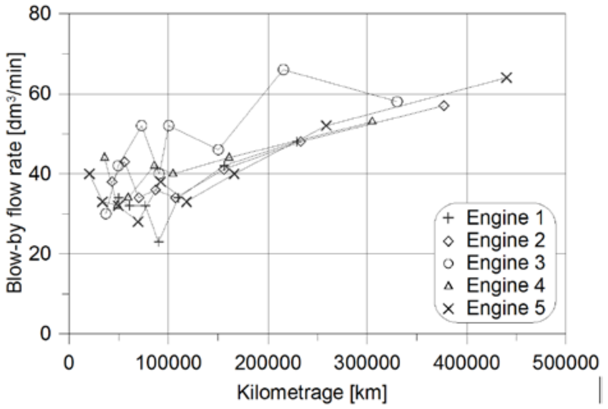

Fig. 4. *Measurement results of the blow-by flow rate at full load and a speed of 1570 rpm*

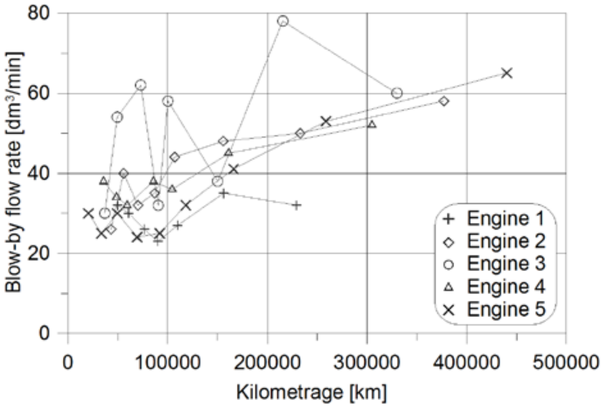

Fig. 5. *Measurement results of the blow-by flow rate at full load and a speed of 1880 rpm*

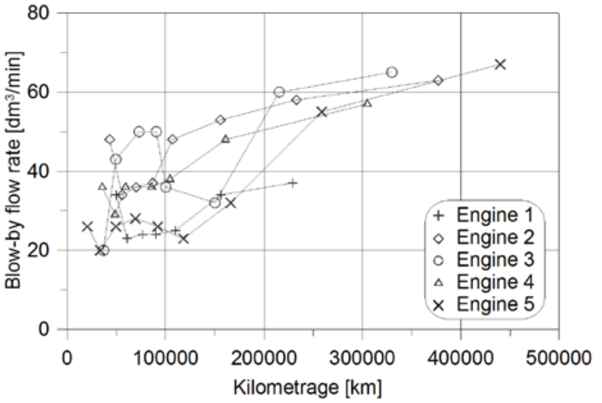

Fig. 6. *Measurement results of the blow-by flow rate at full load and a speed of 2200 rpm*

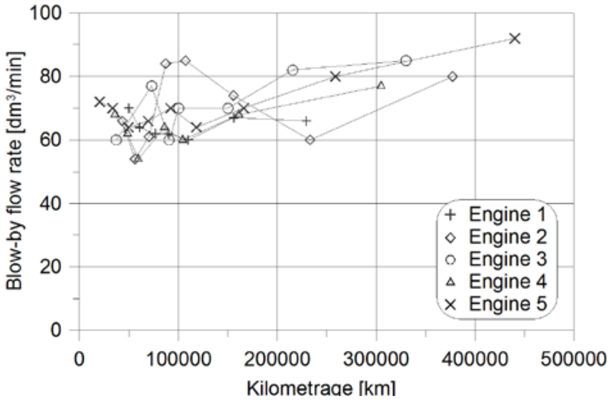

Fig. 7. *Measurement results of the blow-by flow rate at full load and a speed of 2800 rpm*

changes in a selected diagnostic parameter versus distance traveled were not always monotonic, even in the case of the same object. For that reason, the measurement results were analyzed as a whole for all the investigated cylinders and engines, using statistical methods.

4. Empirical model

The developed models should provide information on the mean value of a selected parameter in time $P(t)$ and the ranges of the parameter P with an assumed probability p. The range can be described by means of the following equations:

$$P_d(t) = P(t) - \Delta P(t)\,, \tag{1}$$

$$P_g(t) = P(t) + \Delta P(t)\,, \tag{2}$$

where: $P(t)$ is the mean value of the diagnostic parameter, $P_d(t)$ and $P_g(t)$ are the lower and upper limits of the confidence interval, respectively, $\Delta P(t)$ is a width of the confidence interval for the assumed significance level, while t is the distance traveled (Figs. 8).

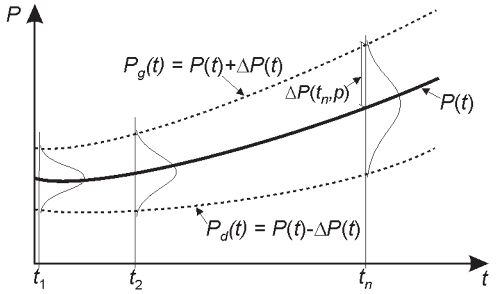

Fig. 8. *Stochastic model of changes in the diagnostic parameter P during operation*

It was assumed that mean changes in a given diagnostic parameter $P(t)$ will be best illustrated by a regression curve determined based on all measurement results. The analyzed regression curves included linear and exponential functions, as well as a second order polynomial. To describe the mean changes in a given parameter, the function with the highest coefficient of determination R^2 was selected. Table 1 lists the linear regression equations and selected curvilinear regression equations, as well as determination coefficient values.

In order to determine the scatter of the results around the mean value, standard deviations of the results obtained for different ranges of distances traveled were calculated. Determining the kilometrage ranges, the number of available measurements was taken into account – there were more measurements taken for low kilometrage. The following kilometrage ranges were adopted: 0-30,000, 30,000-70,000, 70,000-120,000, 120,000-200,000, 200,000-300,000, 300,000-400,000 and over 400,000 km, yet it should be noted that in the case of the blow-by flow rate the last two ranges were combined due to the small number of available measurement results. Figs. 9 and 10 illustrate the basic descriptive statistics for particular kilometrage ranges for cylinder leakage and compression pressure.

The standard deviation values changed with the distance traveled in an irregular manner (Figs. 9–11). In order to determine the limits of confidence intervals, it was assumed that the standard deviation would change linearly with the distance traveled. Using the least squares method, relevant regression lines were determined. Fig. 11 shows the standard deviation values for particular ranges and regression lines for compression pressure and cylinder leakage. The regression line equations of the standard deviations calculated in this way for all the investigated diagnostic parameters are listed in Table 1.

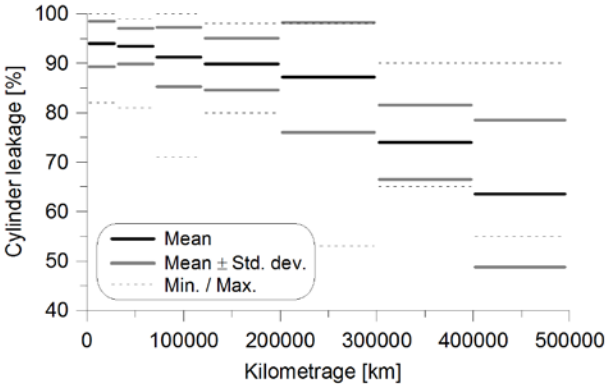

Fig. 9. Cylinder leakage versus kilometrage

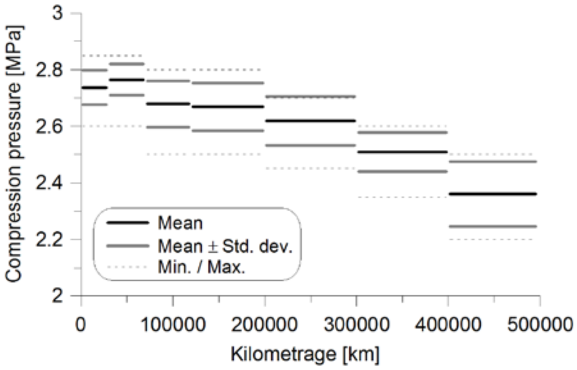

Fig. 10. Compression pressure versus kilometrage

It was assumed that the mean value of a given parameter is:

$$P(t) = y(t) \tag{3}$$

where $y(t)$ is the regression equation from column 2 in Table 1, for which the determination coefficient R^2 reached the highest value.

Based on the Kolmogorov-Smirnov tests for a confidence level of 0.99, it can be stated that the measurement results of compression pressure and cylinder leakage in particular kilometrage ranges corresponded to the normal distribution. Assuming that the measurement results have normal distributions, the confidence interval limits at a significance level of 0.05 are determined by the following functions:

Tab. 1. Results of regression analysis for particular diagnostic parameters

Diagnostic parameter	Regression equation	Coefficient of determination R^2	Regression equation for standard deviation
1	2	3	4
Cylinder leakage	$y = -1{,}58E\text{-}10t^2 - 5{,}09E\text{-}07t + 93{,}7$ $y = -5{,}75E\text{-}05t + 96{,}3$	0,516 0,463	Y = 2,16E-05t + 3,33
Compression pressure	$y = -8{,}41E\text{-}13t^2 - 4{,}60E\text{-}07t + 2{,}76$ $y = -7{,}56E\text{-}07t + 2{,}77$	0,502 0,493	Y = 9,00E-08t + 0,06
Blow-by flow rate at idle run	$y = 5{,}88E\text{-}05t + 25{,}3$ $y = 2{,}53E{+}01e^{1{,}72E\text{-}06t}$	0,372 0,366	Y = -9,12E-07t + 7,70
Blow-by flow rate at 1570 rpm	$y = 7{,}41E\text{-}05t + 31{,}8$ $y = 3{,}25E{+}01e^{1{,}65E\text{-}06t}$	0,574 0,512	Y = -2,65E-06t + 6,15
Blow-by flow rate at 1880 rpm	$y = 8{,}57E\text{-}05t + 28{,}8$ $y = 2{,}93E{+}01e^{2{,}00E\text{-}06t}$	0,421 0,409	Y = -1,50E-06t + 10,2
Blow-by flow rate at 2200 rpm	$y = 1{,}01E\text{-}04t + 26{,}0$ $y = 3{,}99E\text{-}12x^2 + 1{,}00E\text{-}04x + 26{,}0$	0,567 0,566	Y = -1,30E-05t + 11,1
Blow-by flow rate at 2800 rpm	$y = 1{,}17E\text{-}10x^2 + 7{,}49E\text{-}06x + 64{,}8$ $y = 5{,}47E\text{-}05t + 61{,}8$	0,397 0,374	Y = 4,21E-06t + 6,13

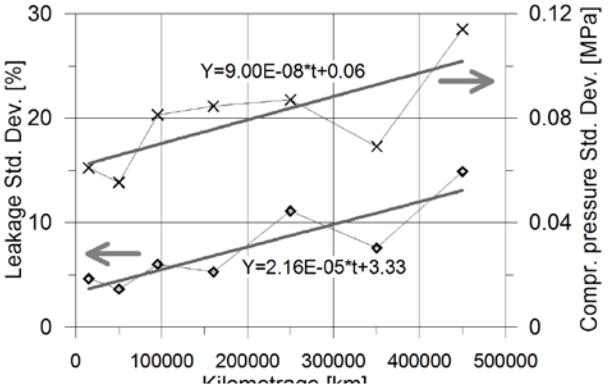

Fig. 11. Standard deviations of cylinder leakage and compression pressure

$$P_d(t) = P(t) - \Delta P(t) = y(t) - 2 \cdot Y(t)\,, \tag{4}$$

$$P_g(t) = P(t) + \Delta P(t) = y(t) + 2 \cdot Y(t)\,, \tag{5}$$

where $Y(t)$ is the regression equation of the standard deviation listed in Table 1.

The models of changes in the diagnostic parameters characterizing the combustion chamber tightness determined thereby and the marked limits of the confidence intervals at a level of 95% are shown in Figs. 12-18 (continuous lines). The thin dotted lines in Figs. 12-18 mark the rival models of changes in the diagnostic parameters versus kilometrage: the linear models for the cases when the curvilinear models were selected and the curvilinear models when the linear models were selected.

5. Discussion

The mean values of all the analyzed parameters were changing with the distance traveled, thus indicating the deterioration of the engine technical condition. Nevertheless, the dynamics and character of these changes differed for every parameter. In order to characterize the parameter change dynamics depending on the distance traveled, the following coefficient was employed:

$$x_d = \frac{P(t_2) - P(t_1)}{P(t_1)} \cdot 100\%\,, \tag{6}$$

where $P(t_2)$ is the value of a given diagnostic parameter calculated from the equation (3) for the distance traveled t_2 that is the section end where the parameter change dynamics is evaluated, while $P(t_1)$ is the parameter value for t_1 which is the beginning of this section.

The mean value of the compression pressure after 500,000 km decreased only by 16% compared to its value at zero kilometrage. The mean value of the cylinder leakage for the same traveled distance decreased by 42%, while the blow-by flow rates increased significantly, i.e. by 116% at idle run, whereas the increase at full load was as follows: 117% at 1570 rpm, 149% at 1880 rpm, 194% at 2200 rpm and 51% at 2800 rpm. A much lower relative increase in the blow-by flow rate at full load and a crankshaft speed of 2800 rpm

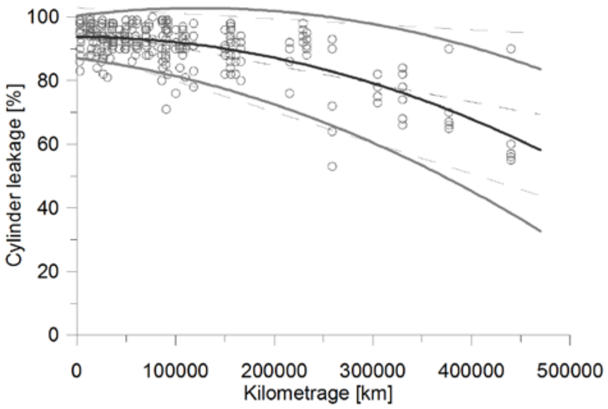

Fig. 12. Changes in cylinder leakage versus kilometrage

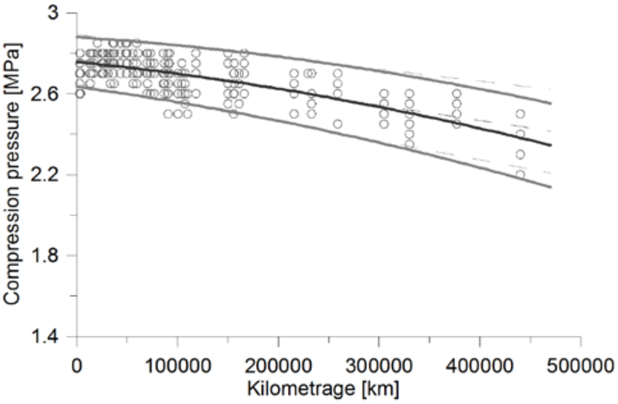

Fig. 13. Changes in compression pressure versus kilometrage

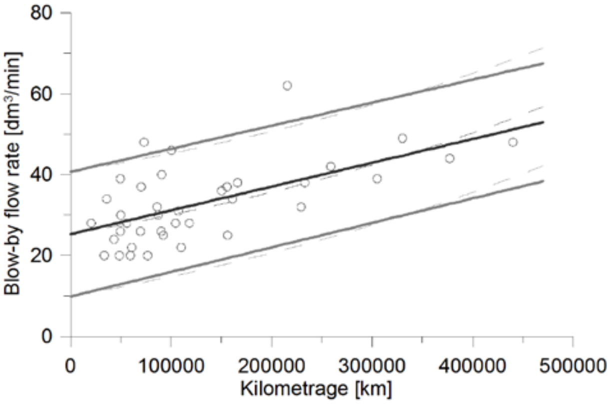

Fig. 14. Changes in the blow-by flow rate at idle run versus kilometrage

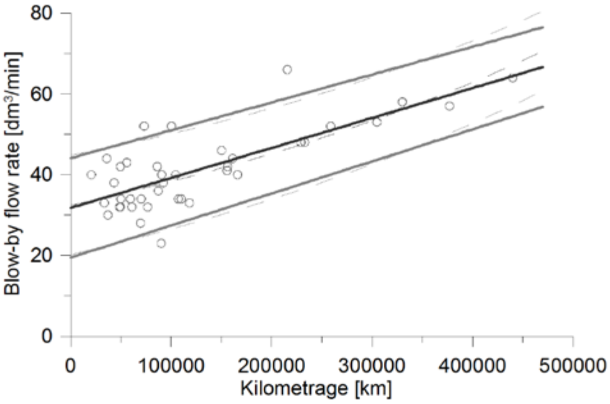

Fig. 15. Changes in the blow-by flow rate at full load and a speed of 1570 rpm versus kilometrage

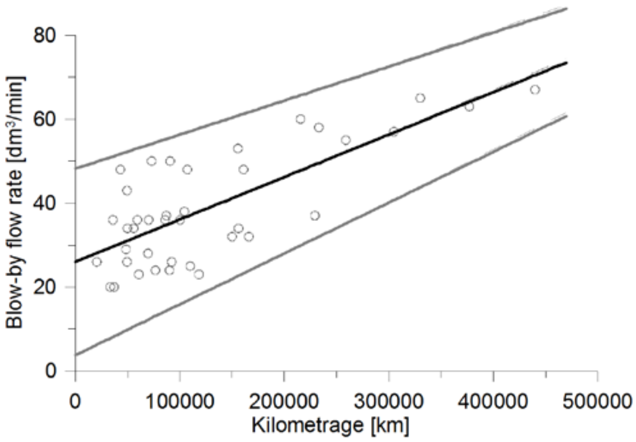

Fig. 16. Changes in the blow-by rate at full load and a speed of 1880 rpm versus kilometrage

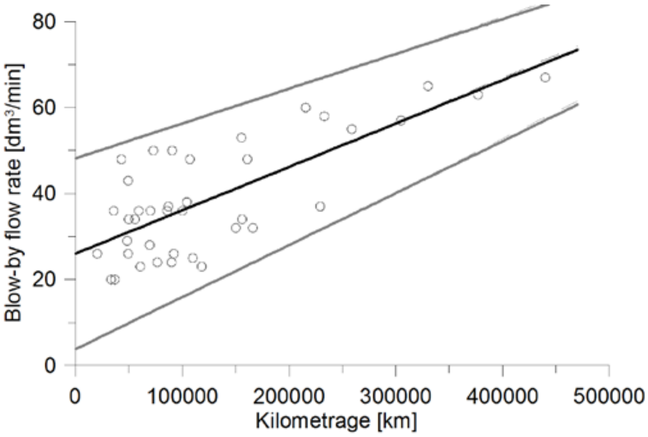

Fig. 17. Changes in the blow-by flow rate at full load and a speed of 2200 rpm versus kilometrage

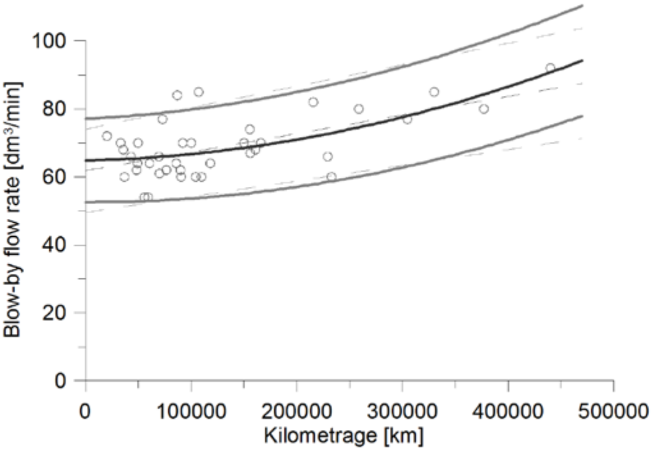

Fig. 18. Changes in the blow-by flow rate at full load and a speed of 2800 rpm versus kilometrage

resulted from approximately two-times higher absolute values of the blow-by in these engine operating conditions, compared to the blow-by flow rate in other measurement conditions.

In four cases, the obtained models are linear, while in three cases – they are non-linear. However, it is only in the case of the cylinder leakage and blow-by flow rate at a speed of 1570 rpm that the differences between the determination coefficients for the linear and curvilinear regression are significant, which proves that the selected regression curve was much better fitted. In other cases, the differences are smaller, which does not allow for a definite selection of

Table 2. Values of dynamics coefficient and coefficient of variation

	x_d calculated based on mean values from the first and last kilometrage range, [%]	x_d calculated based on curvilinear regression equation, [%] **	x_d calculated based on linear regression equation, [%] **	Coefficient of variation V, [%] (calculated for 250000 km)
Cylinder leakage	−32,3	−32,9	−25,6	10,4
Compression pressure	−14,6	−13,0	−11,6	3,18
Blow-by at idle run	71,3 *	73,4	66,6	18,7
Blow-by at 1570 rpm	64,9 *	69,6	66,8	10,9
Blow-by at 1880 rpm	78,5 *	89,6	82,9	19,6
Blow-by at 2200 rpm	100,5 *	104,9	104,1	15,3
Blow-by at 2800 rpm	31,6 *	27,7	27,1	9,71

* *for the blow-by flow rate the first range is 30000-70000 km*

** *for the tightness ratio and compression pressure, x_d was calculated for t_1 = 15000 and t_2 = 440000, while the blow-by for t_1 = 50000 and t_2 = 370000*

the parameter change character as a function of kilometrage. Owing to this, increases in the mean parameter values for successive kilometrage ranges were additionally evaluated. The changes in the cylinder leakage and compression pressure in the first period of engine operation were smaller than in the second one – exceeding 300,000 km (Figs. 9 and 10). Moreover, in the case of the compression pressure, an improvement in the initial period of operation could be observed. Also, the values of the coefficient (6) that were calculated based on the mean values of the first and last kilometrage ranges and the values of this coefficient calculated based on the linear and curvilinear regression equations were compared (Table 2).

Based on the results of the above analysis, it can be stated that the changes in the cylinder leakage and compression pressure with the distance traveled were non-linear – their rate was increasing with the kilometrage. In the case of the blow-by at the speeds of 1570 rpm and 1880 rpm, the changes were however linear. In the remaining cases, the models selected due to the determination coefficients should be adopted; yet the rival models also seem acceptable.

The scatter of the results of particular diagnostic parameters differed both in terms of their values and character of changes versus kilometrage.

The standard deviation of the cylinder leakage in the range of 0-500,000 km increased by more than three times, while in the case of the compression pressure – by 75%. The changes were smaller in the case of the blow-by, yet it should be mentioned that an increase with the distance traveled (by 34%) was observed only at a speed of 2800 rpm, whereas in the other engine operation conditions a decrease was observed, ranging from 6% to 58%. It should however be remembered that the standard deviations of the blow-by were calculated based on six times smaller number of measurements than in the case of the cylinder leakage and compression pressure, and the last two kilometrage ranges contained only four measurement results each. Taking the above into consideration, it should be stated that based on the available results it cannot be unanimously claimed whether and to what extent the scatter of the results changes with the distance traveled in the case of the blow-by flow rate. The obtained results do not undermine the hypothesis that the standard deviations of the blow-by flow rates are constant and do not depend on the distance traveled.

In order to perform the quantitative evaluation of the scatter of the results of particular diagnostic parameters, the coefficient of variation was applied:

$$V = \frac{S}{P} \cdot 100\% , \qquad (7)$$

where S is the standard deviation and P is the mean value.

The values of coefficient of variation significantly changed with the distance traveled only in the case of the cylinder leakage: from 3.6% at zero kilometrage to 26% at 500,000 km – which is a sevenfold increase (a significant increase in S and a decrease in P, simultaneously). As for the remaining parameters these changes were much smaller, the mean values of V – calculated for the traveled distance of 250,000 km – can be used to evaluate the scatter of the results. Comparing the coefficient of variation of particular diagnostic parameters at 250,000 km, it should be observed that compression pressure results varied the least – by approx. 3%, while the blow-by flow rates were characterized by the highest variations – by 10-20% depending on the engine speed (Table 2).

The rates and character of changes of the analyzed diagnostic parameters as a function of distance traveled were different, despite the fact that they all characterized the combustion chamber tightness. The variations resulted from different conditions in which the engine was operating when the measurements were taken: the cylinder leakage was measured when the engine was at a standstill, the compression pressure was measured when the engine was being rotated by the starter, whereas the blow-by flow rate was measured when the engine was operating.

6. Conclusion

Based on the tests conducted on 5 trucks, the changes in combustion chamber tightness of a diesel engine during long-term operation were analyzed. The stochastic models of changes in the diagnostic parameters versus the distance traveled were determined. The mean values and standard deviations – two parameters of the instantaneous distribution of the measurement results, were calculated based on the regression analysis.

It was found that the cylinder leakage and compression pressure changed in a non-linear manner, i.e. their change rates increased with the distance traveled. The rate of change of the cylinder leakage was three times higher than that of the compression pressure – they decreased by 42% and 16% for the distance range 0–500,000 km, respectively. The standard deviation values for these diagnostic parameters also increased as a function of distance traveled – but in the case of the cylinder leakage the increase was 4 times higher than in the case of the compression pressure.

The blow-by flow rate exhibited a considerably higher dynamics of changes – it increased by three times for the distance range 0–500,000 km (at an engine speed of 2200 rpm). The changes in the blow-by flow rate as a function of the distance traveled were linear (with the exception of the blow-by flow rate at 2800 rpm). The dispersion of the results for the blow-by flow rate was higher than in the case of the cylinder leakage and compression pressure; yet it did not increase with the distance traveled.

The determined models of changes in the diagnostic parameters characterizing the combustion chamber tightness, correlated with the data on engine wear [6], will be used as the point of reference to verify the results of the blow-by flow rate simulations based on the analytical model of the ring pack.

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