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DIAGNOSTIC ANALYSIS OF EXHAUST GAS WITH A QUICK-CHANGING TEMPERATURE FROM A MARINE DIESEL ENGINE PART II / TWO FACTOR ANALYSIS

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ABSTRACT

The article presents a continuation of research carried out to determine the effect of input parameters (changes in engine structure parameters) on selected output parameters (diagnostic measures), based on quickly changing exhaust gas temperature. A method of determining the simultaneous influence of two input factors (the structure parameter and the engine load) on one output factor was presented, as well as an evaluation of which of the analysed input factors has a stronger influence on the output parameter. The article presents the stages of the experimental research conducted and statistical inference based on the results. Three changing parameters for the structure were reviewed: the active cross-sectional area of the inlet air channel, the injector opening pressure and the compression ratio. Based on the quickly changing temperatures of the exhaust gases, three diagnostic measures were defined and subjected to statistical tests. The following data were averaged over one cycle for a 4-stroke engine operation: the intensity of changes, the specific enthalpy and the peak-to-peak value of the exhaust gas temperature. The results of the two-factor analysis are presented. Conclusions on the analysis are given and a criterion for the selection of a diagnostic measure, depending on the analysed parameter of the structural design of the diesel engine, is proposed.

The previous part of the article presented the results of the first stage of the elimination study: the one-factor statistical analysis (randomised complete plan). This paper presents the results of the second stage of the studies: two-factor analysis (block randomised plan), where the significance of the effect of changing the values of the structural parameters on the diagnostic measures were analysed in the background of a variable engine load. The next (third) part will present the results of the calculations and analysis of the interaction coefficient of significance.

Keywords: marine diesel engine, exhaust gas temperature, diagnostic information, F-statistic of Fisher-Snedecor distribution

INTRODUCTION

The first part of this series of articles presented the results of a single-factor statistical analysis [15], which made it possible to evaluate the influence of a single input factor (load or structural parameter) on diagnostic measures determined from the course of quickly varying exhaust gas temperature. These were: the intensity of changes $(\Delta T/\Delta \tau \uparrow)_{śr}$, the specific enthalpy $h_{spśr}$ and the peak-to-peak value $\Delta T_{spśr}$ of the quick-changing exhaust gas temperature. All diagnostic measures were for a single cycle of compression-ignition engine operation. One-factor analysis was performed to eliminate output factors deemed not to be statistically significant. It was then concluded that the reduced injector opening pressure p_{wtr} did not significantly affect the specific enthalpy of the exhaust gas $h_{spśr}$ of the test engine. In the next step (in this article), the results of a two-factor analysis are presented to determine the effect of the structural parameters in the background of the variable engine load on the mentioned diagnostic measures. The second goal was to determine which of the two input factors analysed has a greater influence on the output parameter. The research, the statistical analysis results of which are presented in this article, was carried out on a test bench of a small-scale model of a marine engine [15].

The utilitarian goal of the research was to formulate a methodology for diagnostic testing of a ship's engine under operating conditions, based on measurements of the rapidly changing exhaust gas temperature. The novelty of the proposed method is that the quickly changing exhaust gas temperature is not monitored in the standard measurement system of control parameters of a marine engine. However, there is an average temperature measurement point required by classification societies, so that it can be used for fast variable measurements. Analysis of the rapidly changing signal gives more diagnostic information about the condition of the structural components of the compression ignition engine and injection system under consideration.

QUICK-CHANGING EXHAUST GAS TEMPERATURE AS A DIAGNOSTIC PARAMETER

Diagnostics of marine diesel engines is a current and important issue. Piston engines, which are the main propulsion systems of ships, as well as their power plants, generate operating costs that account for more than 70% of the cost of maintaining the entire ship's power plant, mainly due to the high price of fuel and lubricating oils [19]. There is a strong relationship between engine reliability and ship safety. A very important issue is also the emission of harmful, including toxic, components of exhaust gases by marine engines and the associated effects on the environment. Taking into account these three aspects (safety of shipping, costs of ship operation and reduction of emissions of harmful and toxic components of exhaust gases), diagnostic methods and equipment are mainly being developed with a focus on the reliability of marine engines, but also on environmental protection [3, 7, 11, 17].

The exhaust gas temperature is the main diagnostic symptom of a marine engine (main and auxiliary). It is an intensive parameter of the state of the thermodynamic (working) medium, which characterises the quality of the process of transforming the chemical energy of fuel into mechanical energy, via work and heat, as a result of the realisation of complex physicochemical processes in its cylinder systems. The temperature of the exhaust gas also determines the quality of the thermal-flow processes taking place in the separated gaseous spaces of the channels for transporting the working medium from the cylinders directly to the environment or indirectly, through the turbine(s) of the turbocharging system. The thermo-chemical reactions that occur during the combustion of fuel in cylinders are essential for the realisation of the working process but, at the same time, they can be the cause of many destructive processes that negatively affect the technical condition of the structural components confining the engine's working spaces. These mainly comprise the corrosive and erosive effects of flowing (hot) exhaust gases. The consequences of successive transformations of the thermodynamic cycle of a compression-ignition engine are cyclically varying thermal and mechanical stresses, resulting in material exhaustion, in turn. Wear processes (tribological, erosive and corrosive) result in the progressive degradation of the engine's design structure, consequently contributing to the state of its operational unfitness [8, 9, 12].

F – STATISTIC AS A TOOL FOR TWO-FACTOR IMPACT SIGNIFICANCE ANALYSIS

An experimental study was carried out, the main purpose of which was diagnostic inference, on the basis of rapidly changing exhaust gas temperature, as a result of the proposed diagnostic measures determined on the basis of the course of rapidly changing exhaust gas temperature. After the single-factor analysis, the next step was to test the significance of the influence of two input factors, varying to a specific degree and determined by the engine's design and operating capabilities. This made it possible to assess which of the analysed input factors has a stronger influence on the output parameter. The matrix of this stage of experimental research is shown in Table 1.

Tab. 1. Matrix of the experimental research program - static randomised block plan with two input factors: engine load P and active cross-sectional area of the intake air flow to the engine A_{dol}

Level of variation of factor I: engine load	Level of variation of factor II: structural parameter			$\bar{h}_i$
	A_{dol1}	A_{dol2}	A_{dol3}	
P_1	h_{11}	…	h_{11}	$\bar{h}_{1w}$
P_2	: ·	: ·	: ·	: ·
P_3	h_{31}	…	h_{33}	$\bar{h}_{3w}$
$\bar{h}_j$	$\bar{h}_{1k}$	…	$\bar{h}_{3k}$	$\bar{h}$

When the number of factors is greater than one, it is said to be a multiple classification, in which the essence of the method remains the same as with a single-factor, but is more complex. The idea of variation analysis for this case is based on decomposing the sum of squares of deviations from the overall average, into components corresponding to the individual factors whose influence was studied [1, 18]. The calculation scheme of the two-factor analysis of variation can be presented in tabular form, see Table 2. Statistical reasoning is carried out analytically, as in the case of one-factor analysis.

Tab. 2. Calculation scheme for two-fold analysis of variation

Variation	Sum of squares	Number of degrees of freedom	Empirical variation
relative to the rows	$S_I = q\ \bar{h}_i^2 - p \cdot q \cdot \bar{h}^2$	p−1	S_I^2
relative to the columns	$S_I = p \sum_{j=1}^{q} \bar{h}_j^2 - p \cdot q \cdot \bar{h}^2$	q−1	S_{II}^2
residual (error)	$S_R = \sum_{i=1}^{p} \sum_{j=1}^{q} h_{ij}^2 - q \sum_{i=1}^{p} \bar{h}_i^2 - p \sum_{j=1}^{q} \bar{h}_j^2 + p \cdot q \cdot \bar{h}^2$	(p−1)·(q−1)	S_R^2

where $\bar{h}_i$ is the average specific enthalpy from the results of the measurements in the i-th row, $\bar{h}_i$ is the average specific enthalpy from the results of the measurements in the j-th column, $\bar{h}$ is the average specific enthalpy of the results from all measurements, h_{ij} is the value of the j-th specific enthalpy at the level of i, p and q are the number of levels of variation of input factor I (engine load) and input factor II (active cross-sectional area of inlet air flow to the engine), accordingly.

At the level of variation of the first factor, the same number of experiments must be performed as for the level of variation of the second factor, and the individual experiments should be performed in random order. Mathematical processing of the results carried out for the discussed program consisted of calculating the value of the F_{obl} coefficient for the two input factors under study, according to the equations [5]:

$$F_{obl\_I} = \frac{S_I}{S_R} \cdot \frac{(p-1)\cdot(q-1)}{(p-1)}$$
$$F_{obl\_II} = \frac{S_{II}}{S_R} \cdot \frac{(p-1)\cdot(q-1)}{(p-1)} \quad (1)$$

After calculations according to (1), the obtained values of the coefficients were compared with the critical value of the statistic determined on the basis of Fisher-Snedecor's F-distribution tables, with the assumed significance level α and the number of degrees of freedom for the denominator:

$$f_2 = f_m = (p-1)\cdot(q-1) \quad (2)$$

and for the numerator (for factor I and factor II, respectively, e.g. P and A_{dol}):

$$f_{1I} = p - 1$$
$$f_{1II} = q - 1 \quad (3)$$

where p and q are the numbers of levels of variation in factor I and factor II, respectively.

The influence of the considered input factor on the result factor is deemed significant when the empirical value for a given factor calculated from (1), F_{obl}, was greater than or equal to the critical value Fkr [5].

To complement the statistical analysis, the values of the impact significance confidence factor ΔF were determined as a measure of the power of the statistical test, i.e. the difference between the value of the F_{obl} statistic, calculated for the input factor under study, and the critical value for the assumed values of the numerator and denominator degrees of freedom and the significance level:

$$\Delta F_I = F_{obl\_I} - F_{krI}$$
$$\Delta F_{II} = F_{obl\_II} - F_{krII} \quad (4)$$

Comparing the values of the confidence coefficients ΔF_I and ΔF_{II} made it possible to assess which of the two input factors has a greater influence on the output parameters, with the previously proven significance of the influence of both input factors.

RESEARCH PROCEDURE

Analysis was carried out on the effects of changes in structural parameters using the DIESEL-RK program on selected engine operating parameters, such as flame temperature, temperature and pressure of the working medium in the cylinder, and the temperature and chemical composition and speed of the exhaust gas in the exhaust channel [10, 13]. Literature searches were also carried out on the most common states of inoperability of functional engine systems [19]. It was concluded that the most critical functional systems of a marine compression-ignition engine are the fuel supply system [4, 6], the intake air duct [19] and the structural elements that limit the combustion chamber [2, 20]. On the basis of the above analyses, in the next step, tests were conducted during which the most common malfunctions in the functional systems of a diesel engine were simulated (Table 3). The empirical research was carried out on a laboratory test stand comprising a single-cylinder, type D10 four-stroke Farymann Diesel marine engine, as described in the first part of the article [15]. The input variables were the structural parameters listed in the same article and shown in Table 3 and Figure 1.

Tab. 3. Values of engine load and its structural parameters, which are input factors in the diagnostic tests carried out

Structural parameter (input factor)	Desig-nation	Unit	Reference value	Assigned changes
Engine load	P	W	1200 ($0.2 \cdot P_{NOM}$)	768 ($0.64 \cdot P_{REF}$) 432 ($0.36 \cdot P_{REF}$)
Active cross-sectional area of the inlet air channel flow	A_{dol}	mm^2 (%)	(100%)	603 ($0.75 \cdot A_{REF}$) 401 ($0.5 \cdot A_{REF}$)
Opening pressure of the injector	p_{wtr}	MPa	12	10
Compression ratio	ε	-	22:1	22:1

In order to obtain the value of the F_{obl} statistic and the confidence coefficient ΔF, and thus to answer the key question about the significance of the influence of selected input factors (structural engine parameters) on the defined diagnostic measures, the procedure was followed according to the developed scheme for the implementation of statistical tests (Figure 1). The recorded signal of exhaust gas temperature in the first step was subjected to mathematical processing, the purpose of which was to remove disturbances from the measurement network using the method of least sum of squares. An important element when evaluating the dynamic properties of the thermocouple is to determine its response to the sinusoidal forcing of the exhaust gas temperature of the compression-ignition test engine (the phase shift and amplitude of the temperature changes recorded by the thermocouple in relation to the forced, real exhaust gas temperature changes) [16]. Diagnostic measures were determined from the obtained waveform of the real and disturbance-free fast-changing exhaust gas temperature. By using the complete randomised plan, non-significant input values were extracted and eliminated from further diagnostic analyses [15]. The final stage of the study was the implementation of the block randomised plan and the statistical and merit analysis of the significance of

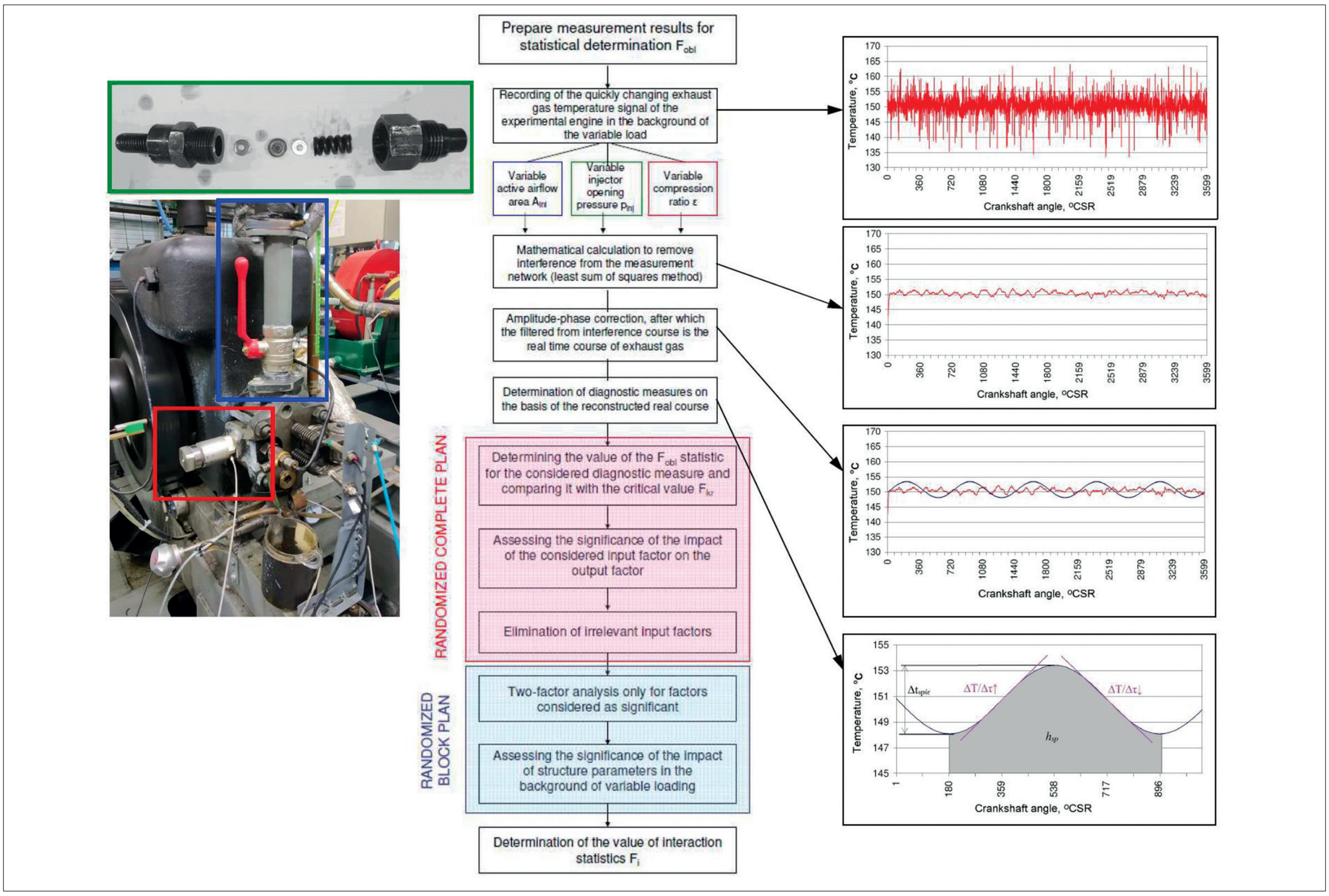

Fig. 1. Steps for determining the F-statistic of the Fisher-Snedecor distribution for diagnosing a diesel test engine

the effect of the structural parameters on the defined diagnostic measures in the background of the changed load condition (presented in this article), The determination of the interaction coefficient of significance will be described in the next part of the article and will allow assessment as to whether and how two input factors statistically affect the output factor.

RESULTS

In the case of two-factor statistical analysis, the simultaneous effect of the structural parameter (A_{dol}, p_{wtr}, ε) in the background of the variable engine load P on the defined diagnostic measures ($h_{spśr}$, $\Delta T_{spśr}$, $(\Delta T/\Delta\tau\uparrow)_{śr}$) was evaluated. Accordingly, the following null hypotheses were formulated:

H01: the value of the analysed structural parameter with a background of variable load has no influence on the value of the specific enthalpy of the exhaust gas stream, averaged over one engine operating cycle ($S_{II}^2 = S_I^2$).

H02: the value of the analysed structural parameter with a background of variable load has no influence on the peak-to-peak value of the exhaust gas stream temperature within one engine operating cycle ($S_{II}^2 = S_I^2$).

H03: the value of the analysed structural parameter with a background of variable load has no influence on the value of the intensity of changes in the exhaust gas temperature within one engine operating cycle ($S_{II}^2 = S_I^2$).

Table 4 shows the results of the statistical analysis, evaluating which of the two input parameters (the engine load P or the structural parameter (A_{dol}, p_{wtr}, ε) has a greater effect on the determined diagnostic measures ($h_{spśr}$, $\Delta T_{spśr}$, $(\Delta T/\Delta\tau\uparrow)_{śr}$). Calculations were performed according to the algorithm presented in this article (1-4).

In the first step, a statistical analysis was performed to evaluate which of the two input parameters (engine load P or active cross-sectional area of the intake air channel A_{dol}) has a greater impact on all diagnostic measures ($h_{spśr}$, $\Delta T_{spśr}$, $(\Delta T/\Delta\tau\uparrow)_{śr}$). The number of degrees of freedom for the denominator f_2 was 4 and the number of degrees of freedom for the numerator of the first factor (P) was $f_{II} - 2$. The number of degrees of freedom was the same for the numerator of the second factor (A_{dol}) f_{III}. The number of levels of variation of both factors p and q was the same, i.e. 3. The critical value of the statistic read from the tables was for rows and columns $F_{kr(0,05;2;45)} = 3.20432$ (table data [5]).

In the case of statistical analysis of the diagnostic parameters, which are the average peak-to-peak value $\Delta T_{spśr}$ and the average intensity of changes of exhaust gas temperature $(\Delta T/\Delta\tau)_{śr}$, which of the two input parameters (engine load P or injector opening pressure p_{wtr}) has a greater influence on the diagnostic measures was evaluated. The number of degrees of freedom for the numerator of the first factor (P) was $f_{II} - 2$, the number of degrees of freedom for the numerator of the second factor (p_{wtr}) was $f_{III} - 1$, and the number of degrees of freedom for the denominator f_2 was 2. The number of levels of variation of the factors was p = 3 and q = 2, respectively. The critical value of the statistics read from the tables was for rows $F_{kr(0.05;\,2;\,18)} = 3.55456$ and columns $F_{kr(0.05;\,1;\,18)} = 4.41387$ (table data [5]).

Table 4 also shows the results of the statistical analysis for evaluating which of the two input parameters, the engine load P or its compression ratio ε, has a greater effect on all diagnostic measures ($h_{spśr}$, $\Delta T_{spśr}$, $(\Delta T/\Delta\tau)_{śr}$) within one engine cycle. The number of degrees of freedom for the denominator of f_2 was 2, the number of degrees of freedom for the numerator of the first factor (P) f_{1I} was also 2, the number of degrees of freedom for the numerator of the second factor (p_{wtr}) f_{1II} was 1, and the number of levels of variation of the input factors was: p = 3 and q = 2. The critical value of the statistic was for rows $F_{kr(0.05;\,2;\,18)} = 3.55456$, while for columns $F_{kr(0.05;\,1;\,18)} = 4.41387$ (table data [5]).

In all three cases, a significance level of α = 0.05 was applied and a right-hand critical area was assumed. Confidence coefficient values ΔF_I and ΔF_{II} were calculated, based on the significance of the effect of the two input factors on the determined diagnostic measures.

Tab. 4. Values of the confidence coefficient ΔF for the simultaneous influence of the engine load P (first input factor - index 'I') and the structural parameter (second input factor - index 'II') on the diagnostic measures considered

Input factors influencing simultaneously	The value of the confidence coefficient ΔF for the diagnostic measures		
	$h_{spśr}$	$\Delta T_{spśr}$	$(\Delta T/\Delta\tau)_{śr}$
P (I)	$\Delta F_I = 1011.55$	$\Delta F_I = -3.19$	$\Delta F_I = -3.19$
A_{dol} (II)	$\Delta F_{II} = 559.80$	$\Delta F_{II} = 53.57$	$\Delta F_{II} = 53.57$
P (I)		$\Delta F_I = 12.81$	$\Delta F_I = 1.65$
p_{wtr} (II)		$\Delta F_{II} = 486.66$	$\Delta F_{II} = 309.73$
P (I)	$\Delta F_I = 432.53$	$\Delta F_I = 8.75$	$\Delta F_I = 8.75$
ε (II)	$\Delta F_{II} = 65.83$	$\Delta F_{II} = 273.84$	$\Delta F_{II} = 274.30$

Based on the numerical data summarised in Table 4, it was possible to observe (within the analysed range of variation of input parameters) a very significant effect of engine load P on the specific enthalpy of the exhaust gas stream $h_{spśr}$ (confidence coefficient $\Delta F_I = 1011.55$). The value of the active cross-sectional area of the intake air flow A_{dol} on the specific enthalpy of the exhaust gas stream hspśr was also statistically significant ($\Delta F_{II} = 559.8$). When the effects of the engine load P and the active cross-sectional area of the intake air flow A_{dol} on the diagnostic measures of the average peak-to-peak value of the exhaust gas temperature $\Delta T_{spśr}$ and the value of the average intensity of changes in the exhaust gas temperature $(\Delta T/\Delta\tau)_{śr}$ are evaluated, the conclusions for both measures are analogous. A significant effect of the A_{dol} cross-sectional area on both diagnostic measures $\Delta T_{spśr}$ and $(\Delta T/\Delta\tau)_{śr}$ was observed, with a confidence coefficient ΔF_{II} of 53.57. However, there was no effect of engine load P on these diagnostic measures ($\Delta F_I = -3.19$).

The highly significant effect of injector opening pressure pwtr on the average peak-to-peak value of exhaust gas temperature $\Delta T_{spśr}$ was also confirmed (confidence coefficient $\Delta F_{II} = 486.66$). The value of engine load P also had a statistically significant effect on the same diagnostic measure ($\Delta F_I = 12.81$). Based on the data presented in Table 4, it is also possible to confirm the highly significant effect of injector opening pressure pwtr on the average intensity of changes in exhaust gas temperature $(\Delta T/\Delta\tau)_{śr}$; the confidence coefficient $\Delta F_{II} = 309.73$. Statistically significance was also affected by the change in engine load P on $(\Delta T/\Delta\tau)_{śr}$ but the value of the confidence coefficient was much smaller ($\Delta F_I = 1.65$).

The results summarised in Table 4 allow us to conclude that there is a very significant effect of engine load P on the specific enthalpy of the exhaust gas stream $h_{spśr}$ (confidence coefficient $\Delta F_I = 432.53$) but the value of compression ratio ε on the specific enthalpy $h_{spśr}$ was also statistically significant ($\Delta F_{II} = 65.83$). The results of the calculations summarised in Table 4 also allow confirmation of a highly significant effect of the compression ratio ε on the average peak-to-peak value of the exhaust gas temperature $\Delta T_{spśr}$ (confidence coefficient $\Delta F_{II} = 273.84$). A statistically significant effect of engine load change P on the same diagnostic measure ($\Delta F_I = 8.75$) was also confirmed. The data allows confirmation of a highly significant effect of the compression ratio ε on the average intensity of change in exhaust gas temperature $(\Delta T/\Delta\tau)_{śr}$ (confidence coefficient $\Delta F_{II} = 274.3$). The effect of engine load P on $(\Delta T/\Delta\tau)_{śr}$ was also statistically significant at $\Delta F_I = 8.75$.

To evaluate the significance of the influence by means of two-factor statistical analysis (Figure 2a), for the question as to which of the input parameters (the load P or the active cross-sectional area of the intake airflow A_{dol}) has a greater effect on the diagnostic measures studied, the result is not so clear. It can be seen that some values of the F_{obl} statistic are below the critical value of F_{kr}, which means that there is no significant influence of these input factors on the determined measures of the diagnostic signal of the quickly changing exhaust gas temperature. These include the effect of engine load P on the average intensity of changes in exhaust gas temperature $(\Delta T/\Delta\tau)_{śr}$ and on the average peak-to-peak value of exhaust gas temperature $\Delta T_{spśr}$. In other cases, however ($F_{obl} > F_{kr}$), different values of the confidence factor ΔF are evident for the evaluation of the effect of A_{dol} on $\Delta T_{spśr}$ and $(\Delta T/\Delta\tau)_{śr}$, where the confidence factor was less than 54. Meanwhile, the effect of A_{dol} on $h_{spśr}$ is greater than that for $(\Delta T/\Delta\tau)_{śr}$ and $\Delta T_{spśr}$. It is also interesting to note that the specific enthalpy of the exhaust gas stream is more influenced by the engine load than by the amount of air supplied to the combustion chamber, but both input factors interacting simultaneously have a significant effect, as the values of the confidence factor ΔF are very high (559.8 and 1011.55).

When using two-factor statistical analysis (Figure 2b) to assess the significance of the influence which the input parameters engine load P and injector opening pressure p_{wtr} have on the considered diagnostic measures, the result is more clear. It can be seen that all the values of the confidence coefficient ΔF are positive and so $F_{obl} > F_{kr}$, which means there is a significant simultaneous influence of these input parameters on the determined diagnostic measures. Figure 2b also indicates the result of two-factor analysis for a diagnostic measure such as $h_{spśr}$, despite its elimination after the first stage of statistical testing (one-factor analysis). The result of the two-factor analysis indicates that both input factors (interacting simultaneously) have a significant effect on this diagnostic measure. By analysing the values of the confidence coefficient ΔF, it is apparent that p_{wtr} has a much more significant effect on $(\Delta T/\Delta\tau)_{śr}$ and $\Delta T_{spśr}$ than on $h_{spśr}$, and the opposite is true for the effect of load.

In the case of evaluating the significance of the influence as a result of two-factor statistical analysis (Figure 2c), to answer the question as to which of the input parameters (engine load P or compression ratio ε) has a greater influence on the diagnostic measures considered, the result is also quite clear. A significant influence of both input factors on all diagnostic measures is evident; however, the values of the confidence coefficient ΔF differ significantly. In the case of engine load P, the greatest influence occurs for $h_{spśr}$ (ΔF = 432.53), while the degree of compression ε had the most significant effect on $(\Delta T/\Delta\tau)_{śr}$ and $\Delta T_{spśr}$ (ΔF = 274.3 and ΔF = 273.84).

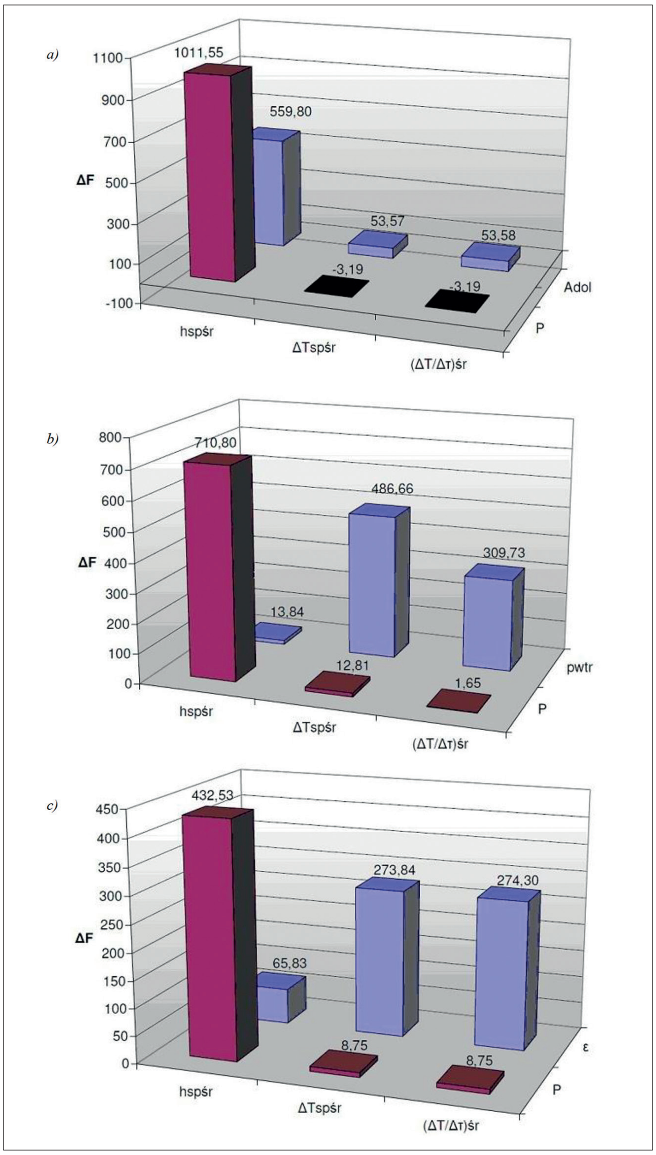

Fig. 2. Values of significance coefficient ΔF for two-factor analysis of the simultaneous effect of engine load P and structural parameters: active cross-sectional area of intake airflow A_{dol} (a), injector opening pressure p_{wtr} (b), and compression ratio ε (c) on values of defined diagnostic measures

In summary, it is possible to formulate the following general conclusions for the two-factor analysis, where the input factors are engine load P and engine structure parameters (A_{dol}, p_{wtr}, ε):

1. Injector opening pressure and compression ratio affects $(\Delta T/\Delta\tau)_{śr}$ and $\Delta T_{spśr}$ more significantly than engine load, which should be interpreted as the high sensitivity of these two diagnostic measures to their (p_{wtr} and ε) changes in the range being studied. Thus, a change in p_{wtr} and ε causes an evident increase in the fluctuation of the course of the rapidly changing exhaust gas temperature.
2. Both A_{dol} and load P have the strongest effect on $h_{spśr}$, which is due to the direct and simultaneous influence of these two input factors on the value of the quickly changing exhaust gas temperature.

From the statistical hypotheses tested, it is also possible to conclude the following methodological findings, which are also presented graphically in Table 5:

1) During diagnostic investigations, the engine should be loaded to the maximum degree, then the specific enthalpy of the exhaust gas stream within one engine cycle $h_{spśr}$ responds most strongly.
2) The loss of permeability of the inlet channel, e.g. as a result of its pollution, demonstrated by a reduced value of the active cross-sectional area of the inlet air channel flow A_{dol}, is best indicated by the specific enthalpy of the exhaust gas stream within one engine cycle $h_{spśr}$.
3) The greatest diagnostic sensitivity to reduced injector opening pressure pwtr is characterised by the average peak-to-peak value $\Delta T_{spśr}$ and the average intensity of change in exhaust gas temperature $(\Delta T/\Delta\tau)_{śr}$. At higher engine loads, the sensitivity of these diagnostic measures is greater.
4) Damage or impurities (carbon deposits), which can result in a reduced value of the compression ratio ε, can best be inferred on the basis of the average inter-peak value $\Delta T_{spśr}$ and the average intensity of changes in exhaust gas temperature $(\Delta T/\Delta\tau)_{śr}$. These measures show high diagnostic sensitivity over the entire range of specified engine load changes.
5) Inference on the basis of the proposed diagnostic measures can be made for measurements made with a thermocouple with sufficiently low values of the time constant, of the order of a few to a few tens of milliseconds, designed for measurements of rapidly changing exhaust gas temperatures [14]. It is crucial to apply the proposed mathematical and statistical processing of the recorded signal.

Tab. 5. Criterion for the selection of a diagnostic measure depending on the analysed parameter of the structural design of a diesel engine: blue boxes indicate a diagnostic measure especially recommended for inference with a significant influence on the selected parameter of the structure, pink boxes indicate a diagnostic measure with low significant influence

Diagnostic measure Load / Structure parameter	$h_{spśr}$	$\Delta T_{spśr}$	$(\Delta T/\Delta\tau)_{śr}$
P			
A_{dol}			
p_{wtr}			
ε			

FINAL REMARKS AND CONCLUSIONS

In the proposed one-factor and two-factor analysis, it was shown that the quickly changing temperature of the exhaust gas from a compression-ignition engine is a suitable diagnostic parameter. The proposed diagnostic measures allow the diagnostic inference of selected malfunctions of engine systems with a reduced active cross-sectional area of intake airflow A_{dol}, a reduced injector opening pressure p_{wtr} or with a reduced engine compression ratio ε. The two-factor analysis method presented in this article introduces a lot of diagnostic information about the condition of selected engine functional systems, but it is worth developing further. Therefore, in the next part of this article, the interaction value of the statistic F_i and the interaction confidence coefficient ΔF_i will be characterised, allowing us to assess whether, and how much, the two input factors 'interact' with each other, affecting the output factor, and the results of the presented statistical analyses will also be discussed. Conducting the analysis in three stages allows us to present a method for diagnosing selected functional systems of engines similar to the one researched, based on the course of the quickly changing exhaust gas temperature.

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