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MODELLING OF TOXIC COMPOUNDS EMISSION IN MARINE DIESEL ENGINE DURING TRANSIENT STATES AT VARIABLE ANGLE OF FUEL INJECTION

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Abstract

Transient states are an important part of the spectrum of engine loads, especially the traction engines. In the case of marine diesel engines, transient states are of particular importance in reducing the analysis of motion units for special areas and maneuvering in port, the participation of transient states in the load spectrum significantly increases, also, the emission of toxic compounds from this period increases proportionally. The factors which determine the value of the emission are the forces shaping transient states and the technical condition of the engine itself. This paper presents a description of transient states using multi-equation models, and the analysis of their relevance. It also presents a comparison of toxic compounds concentration at modified angles of fuel injection advance.

Keywords: *diagnostic, theory of experiments, marine diesel engine, exhaust gas toxicity, multi-equation models*

1. Introduction

Transient states are exceptional marine diesel engine operating conditions. They arise in the absence of thermodynamic equilibrium in the engine cylinders and are an important part of the engine load spectrum, especially of traction engines, thereby without affecting the emission of toxic compounds. Engine research in this area is forced because of homologation, where the main problem comes down to the optimization of the combustion course with variable engine load described even through urban driving tests.

In the case of marine diesel propulsion, the importance of transient states, in the above sense, is less prominent because of the relatively small proportion of transients in the engine load spectrum. If, however, such an analysis is subjected to the movement of individuals in specific areas or maneuvering in port, the proportion of transients in the engine load spectrum grows significantly and is worthy of special consideration. Proportionately to this growth increases the emission of toxic compounds, caused by the impact of those states. This should be explained by the fact that transients interfere with cylinder thermodynamic equilibrium, which occurs during the fixed charges. This interrupts the combustion process by causing temporary changes, primarily to the stream of fresh charge of the cylinder, but also the amount of fuel delivered. Thus, the air-fuel ratio changes temporarily, which results in the changes in air excess ratio, leading to increased emissions of combustion products created due to the local oxygen deficit. A further consequence of the appearance of increased amounts of carbon monoxide (CO) and unburned hydrocarbons (HC) is to lower the combustion temperature, which determines the reduced NOx emissions.

The deciding factor in the emissions of toxic compounds derived from transient states is primarily the value of force, which causes these conditions . But this is not the only factor. Another factor affecting the emission of toxic compounds derived from transients that has to be taken into consideration, is the condition of the engine. This condition, described with the structure parameters while using the engine, is constantly changing, which is responsible for the processes of wear. This change enhances the formation of toxic compounds during transient states, as these processes, though short, are so dynamic that the instantaneous concentrations frequently exceed ZT values of the steady states . Therefore, it is expected that the engine with its structure parameters changed due to wear, will be more sensitive to the effects of transients and thus it will be easier to determine its technical condition [5].

The basic parameter deciding about the correctness of combustion process in spark-ignition engines is the fuel injection timing. Even small deviations result in the significant changes in the key indicators of the engine, including the exhaust emission indicators. In the case of conventional engine design, a "self-acting" change of fuel injection timing is rather unlikely. However, in modern constructions, where most of the control parameters is controlled electronically, it is possible for the control system to be damaged and the settings of injection timing to be changed.

The paper will present the modeling of transient states with a variable angle of injection timing and their impact on the changes in the basic concentration of toxic compounds.

2. Identification of a dynamic process of multi-equation model

Building on the experience of authors [6,7,8,9,10] with modeling of toxic compounds concentrations, it was decided to implement the multi-equation models, proven during steady state, for the analysis of dynamic processes, whereby it is assumed that the change process of gas toxicity occurs throughout a time, which makes it dynamic. Therefore, the model can be described as multi-equation system of linear differential equations. Since the measurement of the concentration of toxic compounds is a discrete measurement, discrete-time signal (time series) is a function whose domain is the church of integers. Thus, a discrete-time signal is a sequence of numbers. Such sequences are referred to as recorded in the functional notation. The adoption of such a notation was striving to minimize the impact of errors including the approximation of functions that would have to occur when using the continuous functions.

Discrete-time signal $x[k]$ is often determined by sampling $x(t)$, a continuous signal in time. If the sampling is uniform, then $x[k] = x(kT)$. Constant T is called the sampling period. Course of the dynamic process in time depends not only on the value of force at a given time but also the value of extortion in the past. Thus, the dynamic process (system) has a memory where it stores consequences of past interactions.

The relations between the input signals $x_1[k], x_2[k], \cdots, x_n[k]$, and output signals $y_1[k], y_2[k], \cdots, y_m[k]$, $k = 0,1,2,\ldots$, will be described by a system of linear differential equations.

$$\begin{cases} y_1[k+1] = a_{11}y_1[k] + a_{12}y_2[k] + \cdots + a_{1m}\, y_m[k] \ + b_{11}x_1[k] + b_{12}x_2[k] + \cdots + b_{1n}x_n[k] + \xi_1 \\ y_2[k+1] = a_{21}y_1[k] + a_{22}y_2[k] + \cdots + a_{2m}\, y_m[k] \ + b_{21}x_1[k] + b_{22}x_2[k] + \cdots + b_{2n}x_n[k] + \xi_2 \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ y_m[k+1] = a_{m1}y_1[k] + a_{m2}y_2[k] + \cdots + a_{mm}y_m[k] + b_{m1}x_1[k] + b_{m2}x_2[k] + \cdots + b_{mn}x_n[k] + \xi_m \end{cases} \tag{1}$$

where:

$y_i[k], i = 1,2,\ldots,m$ - output signal values at k,

$x_j[k]$, $j = 1,2,\ldots,n$ - input signal values at k,

a_{ij} – is a coefficient found in i-th equation with j-th output signal, $i, j = 1,2,\cdots,m$

b_{ij} - is a coefficient found in i-th equation with j-th input signal, $i = 1,2,\cdots,m,\quad j = 0,1,\cdots,n$,

ξ_i - is a non-observable random component in i-th equation.

In analogy to (1), the system of equations (2) can be written in matrix form

$$\mathbf{y}[k+1] = \mathbf{A}\mathbf{y}[\mathbf{k}] + \mathbf{B}\,\mathbf{x}[\mathbf{k}] + \boldsymbol{\xi} \tag{2}$$

where:

$$\mathbf{B} = \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1m} \\ b_{21} & b_{22} & \cdots & b_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ b_{m1} & b_{m2} & \cdots & b_{mm} \end{bmatrix}, \qquad \mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ a_{m1} & a_{m1} & \cdots & a_{mn} \end{bmatrix},$$

$$\mathbf{y}[k] = \begin{bmatrix} y_1[k] \\ y_2[k] \\ \cdots \\ y_m[k] \end{bmatrix}, \quad \mathbf{y}[k+1] = \begin{bmatrix} y_1[k+1] \\ y_2[k+1] \\ \cdots \\ y_m[k+1] \end{bmatrix}, \quad \mathbf{x}[\mathbf{k}] = \begin{bmatrix} x_1[k] \\ x_2[k] \\ \cdots \\ x_n[k] \end{bmatrix}, \quad \boldsymbol{\xi} = \begin{bmatrix} \xi_1 \\ \xi_2 \\ \cdots \\ \xi_m \end{bmatrix} .$$

Later denoting:

$$\boldsymbol{C} := [\boldsymbol{A}|\boldsymbol{B}] = [c_{ij}]_{m\text{x}(m+n)} \tag{3}$$

and

$$\boldsymbol{z}[k] := \begin{bmatrix} \boldsymbol{y}[k] \\ \boldsymbol{x}[k] \end{bmatrix},$$

the system of equations (1) is shown in reduced form

$$\boldsymbol{y}[k+1] = \boldsymbol{C}\boldsymbol{z}[k] + \boldsymbol{\xi} \tag{4}$$

Identification of the system of equations (1) and (4) will be based on the selection of the coefficients using the set of measurements on the real object of input and output signals. The problem of aforementioned selection the authors present, among others, in [6,7,8,9,10].

3. Study of dynamic process in engine fuel supply system through multi-equation models

The object of this research was the engine fuel supply system (fuel injection) of a single-cylinder test engine 1-SB installed in the Laboratory of the Exploitation of Marine Power Plants at the Naval Academy [8]. The experimental material was collected by trivalent developed a complete plan [4]. The implementation of specific measuring systems (measuring points) of the above experiment design were performed using a programmable controller, which allowed a high repeatability of dynamic processes. The period between an onset of the clipping of injection system components and the re-stabilization of output quantities was adopted as the duration of the dynamic process. This period was chosen through a series of experiments, and it averaged to about 106 seconds.

In order to identify the impact of the technical condition of the fuel supply system on the parameters of the engine power during dynamic processes, sets of input quantities (preset parameters) and output quantities (observed parameters) were defined. For the purpose of this study a set of input quantities X was limited to three elements, that is: x_1 - engine speed n [r/min]; x_2 – engine torque T_{tq} [N·m]; x_3 – fuel injection timing α_{ww} [ºREC]. The study was conducted in accordance with the approved complete plan, for three values of speed, ie 850, 950 and 1100 [r / min]. For each speed, torque (T_{tq}) increased and thus created a transient state, consequently for the load of 10, 20, 30, 50, 70 [N]. For speed of 850 r / min, afraid of a large engine overload, the loads of 50 and 70 N were omitted. Similarly, this was done to the speed of 950 r / min and a 70 N load. Fuel Injection timing varied by ± 5 ºREC, yielding three values, i.e. face value - N, accelerated angle - W, delayed angle - P. 36 repetitive transients were obtained this way. Graphic interpretation of the test program is shown in Figure 1.

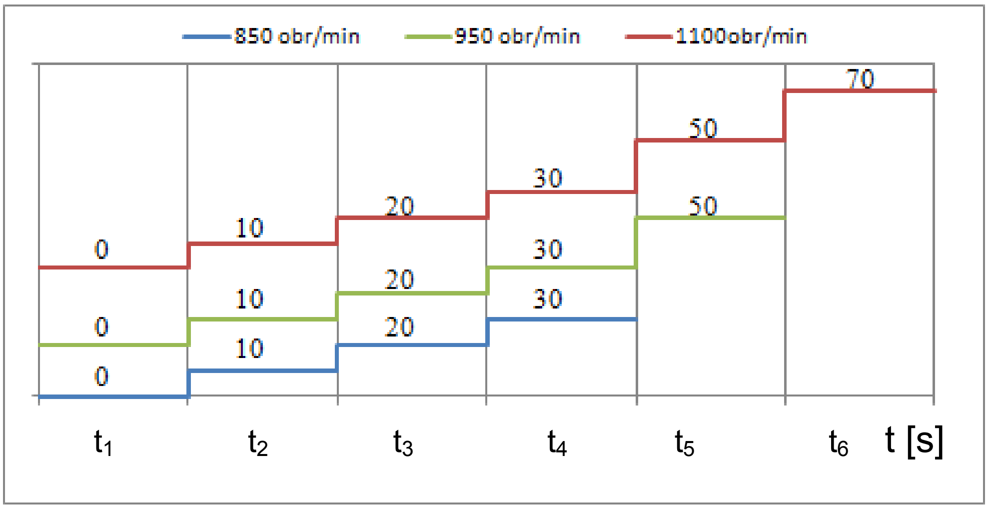

Figure 1. Schematic of the program of research

Similar treatment was applied to the set *Y* of output quantities, limiting the number of its elements to only the primary toxic compounds in exhaust manifold: y_1 – concentration of carbon monoxide in the exhaust manifold $C_{CO(k)}$ *[ppm]; y_2* – concentration of hydrocarbons in the exhaust manifold $C_{HC(k)}$ *[ppm]; y_3* – concentration of nitrogen oxides in the exhaust manifold $C_{NOx(k)}$ *[ppm], y_4* – tsp exhaust gas temperature [º C], y_5 – air-fuel ratio λ.

Statistical identification was made using GRETL [1]. Estimation of the equation coefficients for specific output variables was performed using the least-squares method and it had to verify the significance of its parameters and, consequently, the rejection of insignificant values, which consequently led to a significant simplification of the models. Given the large amount of experimental material, for the purpose of this study is selected the most typical cases, while limited to the greatest loads that occur during the experiment. Tables 1, 2, 3, 4 are coefficients of equations for nominal output variable injection timing. Significance values of model parameters are shown in the last column of the tables. Equations describing the changes in concentration of hydrocarbons (y_2) and the concentration of nitrogen oxides (y_3) have undergone the greatest simplification. (Table 1, 2, 3). In the case of equations describing changes in carbon monoxide and hydrocarbons, they depend on the excess air ratio λ (y5) significantly, a parameter directly related to the parameter of the structure, which was the fuel injection timing (x3). Both CO and HC significantly dependent on each other. Furthermore, in the case of CO, speed has a greater impact, while in the case of HC it is the load, which seems to be logical, considering the creation processes of these compounds in the cylinder.

Table 1. Least-squares estimation of the dependent variable y_1

Variable	*Coefficient*	*Mean error*	*Student t*	*p value*	*i significance*
x1_1	0,785212	0,297116	2,6428	0,00952	***
y5_1	-640,111	84,9526	-7,5349	<0,00001	***
y2_1	6,00076	0,536841	11,1779	<0,00001	***

Table 2. Least-squares estimation of the dependent variable y_2

Variable	*Coefficient*	*Mean error*	*Student t*	*p value*	*i significance*
y5_1	52,7105	9,26814	5,6873	<0,00001	***
x2_1	2,23258	0,472489	4,7252	<0,00001	***
y1_1	0,0605765	0,0102887	5,8876	<0,00001	***

Table 3. Least-squares estimation of the dependent variable y_3

Variable	*Coefficient*	*Mean error*	*Student t*	*p value*	*i significance*
x2_1	0,104014	0,0251446	4,1366	0,00007	***
x1_1	0,216752	0,00166072	130,5167	<0,00001	***
y4_1	0,025725	0,00437145	5,8848	<0,00001	***

Table 4. Least-squares estimation of the dependent variable y_4

Variable	*Coefficient*	*Mean error*	*Student t*	*p value*	*i significance*
x1_1	-0,483745	0,23243	-2,0813	0,03994	**
y1_1	-0,0155244	0,00653628	-2,3751	0,01943	**

y3_1	4,6947	0,975664	4,8118	<0,00001	***
y5_1	-118,888	10,9896	-10,8182	<0,00001	***

The graphical presentation (Fig. 2) of the matching can prove having a good model fit to the values obtained in the experiment on the engine, as well as equal distribution of residuals from the regression of mean values (Fig. 3).

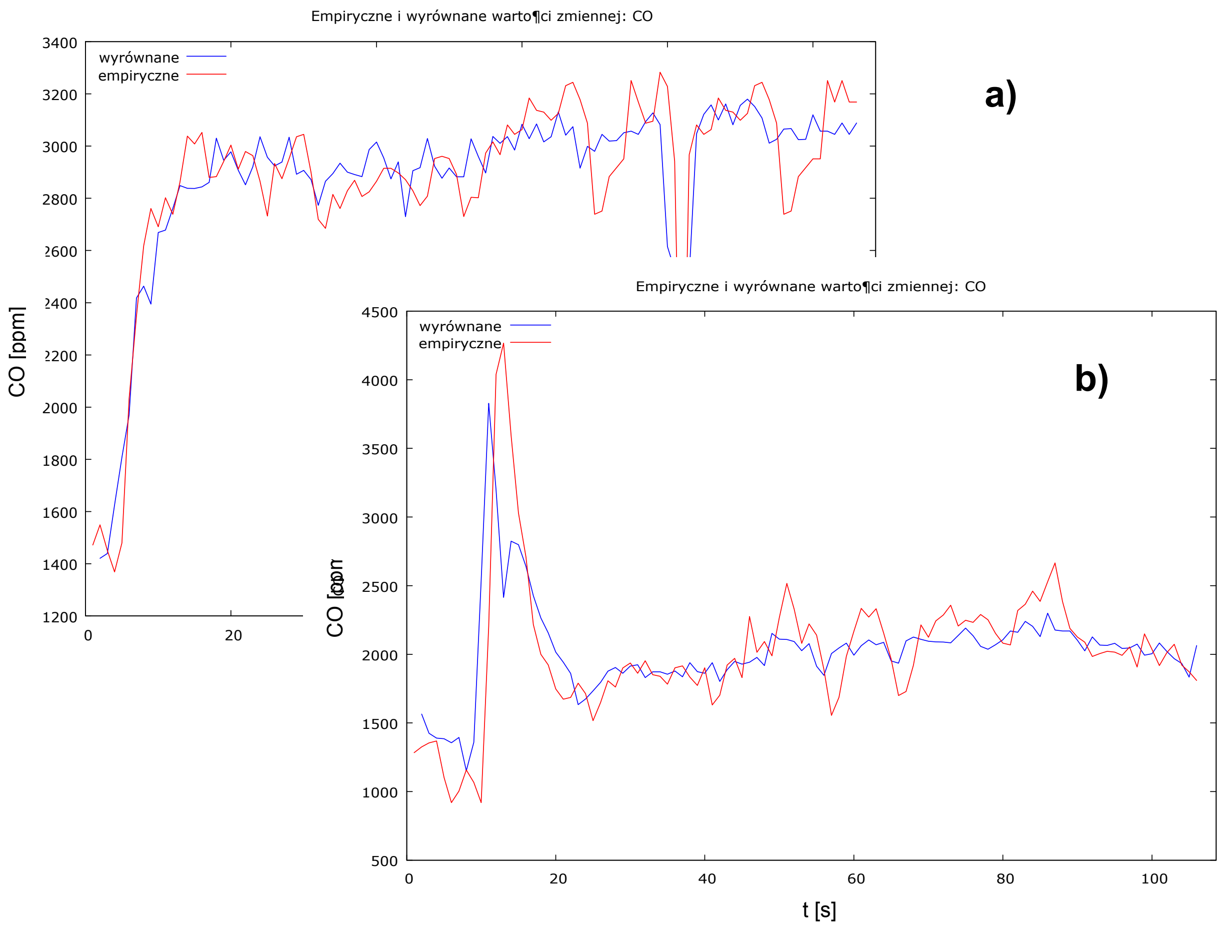

Figure 2. Graphical matching of the CO model to the empirical data for the transient at n = 1100 r / min and load change with Ttq = 50 to N = 70 N Ttq a) delayed (P) injection timing angle, b) accelerated (W) injection timing angle

The analysis of Figure 3 shows that the worse adjustment, due to the higher residue values, exists for accelerated (earlier) fuel injection timing angle.

The results of the presented analysis highlight the significant advantage of multi-equation models, the possibility of multi-criteria analysis of the variables in the case where these values are in mutual correlation. Analysis of these relationships in one model reflects the reality more accurately (because there are obvious interactions between, for example, CO and HC and, for example, λ), and thus allows for a broader interpretation of the test problem.

Despite the undeniable advantages of multi-equation models do not provide direct information on the quality of changes, in this case, differences between the concentration of various toxic compounds due to changes in fuel injection timing. Only the juxtaposition of courses of the experiment or the analysis of the obtained models provides some picture of the phenomenon. Nonetheless, analysis still remains difficult due to the similarity of transient waveforms, irrespective of the value of extortion.

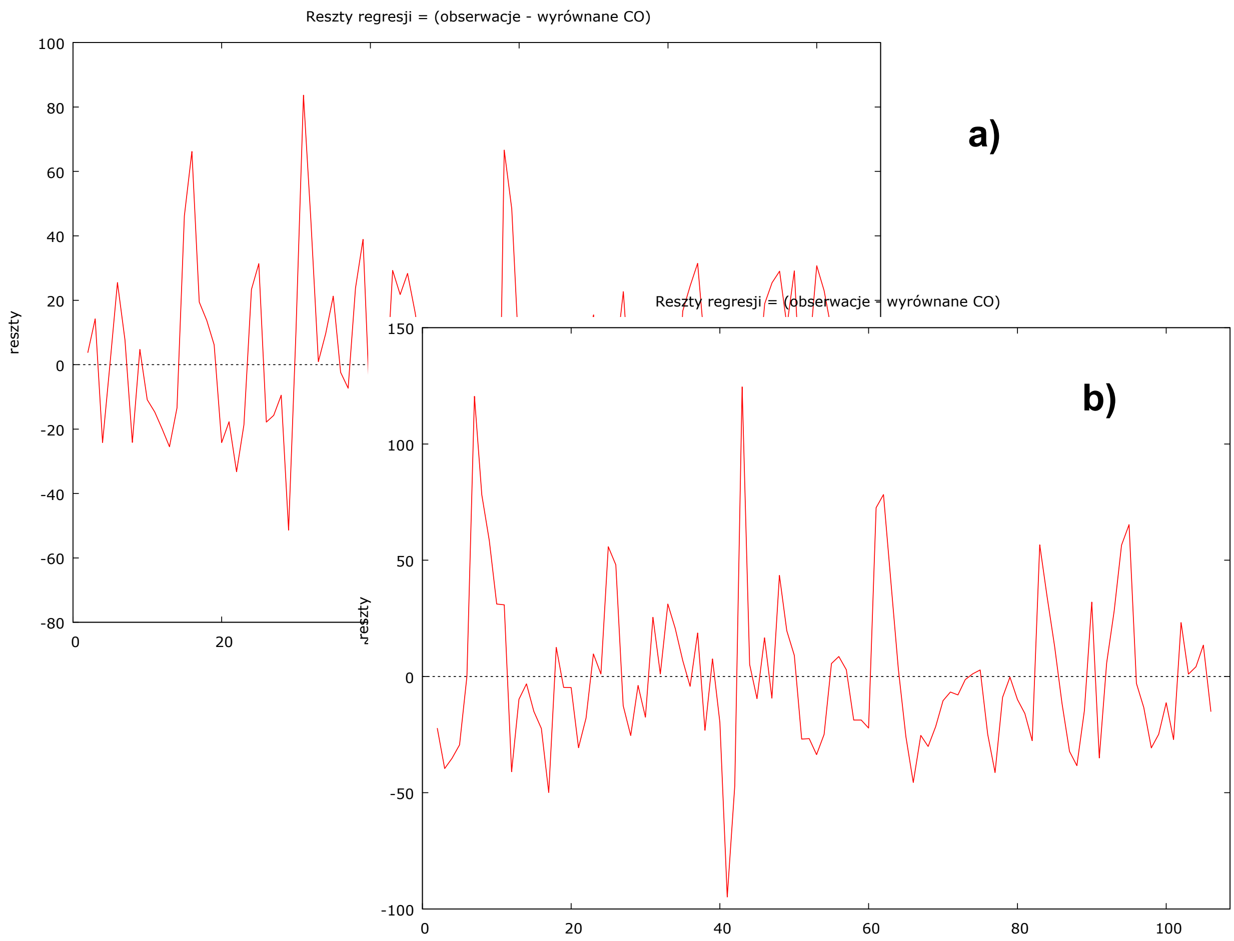

Figure 3. Graph of the CO regression residuals for the transient at n = 1100 r / min and load change from T_{tq} = 50 N to T_{tq} = 70 N a) delayed (P) injection timing, b) accelerated (W) injection timing.

In such case, it is desired to apply the criteria that would be useful in the objective assessment of the comparative levels or emissions from transients. The use of an evaluation index is one of the commonly used methods in such cases. The basic hourly evaluation is an individual emission of toxic fumes, which is calculated by the formula [3]:

$$E_{i,j} = a_j \cdot C_{j,i} \cdot G_{sp,i} \text{ [g/h]} \tag{5}$$

where:

j – CO, HC, NO_x,

a_i – characteristic factor for a given compound j:

a_{CO} = 0,000966, a_{HC}=0,000478, a_{NOx}=0,001587,

$C_{j,i}$ – concentration of individual compounds [ppm],

$G_{sp,i}$ – exhaust gas flow [kg/h].

This evaluation is, however, difficult to apply in the case of the analysis of transient processes, since determining the exhaust flow would require the estimation, thus introducing significant errors, which obviously excludes this method. Another view was proposed by the authors in [3], using the following relationship evaluation:

$$W_i = a_i \int_0^t C_{j.i}(t)dt \qquad (6)$$

where:
$C_{j,i}(t)$ – the concentration of any toxic compound in time t [ppm],
t – the duration of the transient state [s].

Thus, by integrating the area under the curve obtained from an experiment or from a model, an indicator that accurately describes the direction of change was obtained. On the other hand, this indicator continues to not describe the nature of the changes. As is known from observation, depending on the value of force, the course of the transient can vary significantly. These differences depend largely on the intensity of the experience of individual phases of the transient. Frequently, in the course of a typical transient, two phases can be noticed. First, characterized by the highest growth rate, accompanied by a sharp increase in the concentration of TS, typically several times more than the concentration in the steady state. The second phase of the transient is characterized by a much less violent course, it has a monotonic character and approaches the steady-state of concentrations in an asymptotic manner.

As mentioned above, the concentrations of individual toxic compounds derived from transients are characterized by a certain regularity and repetition, and therefore a tool had to be found that would be deprived of the above-mentioned disadvantages of the indicators, while being able to be described in the precise and objective nature of the changes in the concentrations of individual toxic. It seems that the described method would be the analysis of the correlation of individual transients. This method determines the correlation of the researched transient state and that of the transient adopted as a model describing the phenomenon. Analysis of the correlation function allows you to specify the degree of correlation and its nature. Analyzing the components of the function can infer the said transient nature, that is, the participation and intensity of the individual phases.

The graphic imagining of the analysis correlation is a scatter diagram presented in Figure 4 and 5. Figure 4 shows the linear correlation function of the concentration of unburnt hydrocarbons HC at early injection timing angle (30 ° HVAC - red) relative to the nominal injection timing (26 º HVAC) , where the correlation coefficient was r = 0.75. The color green indicates the correlation function and the HC concentration at the delayed angle (22 º HVAC) also with respect to the nominal injection timing. The correlation coefficient in this case was smaller, and was r = 0.59. Smaller values of the correlation coefficient were affected by the dispersion of points around the correlation function, which indicates an unstable transient process (matching multi-equation model is significant even in this case, as the greatest value of the residue is 60 ppm). Analogously, correlation analysis may be performed for NOx (Fig. 5).

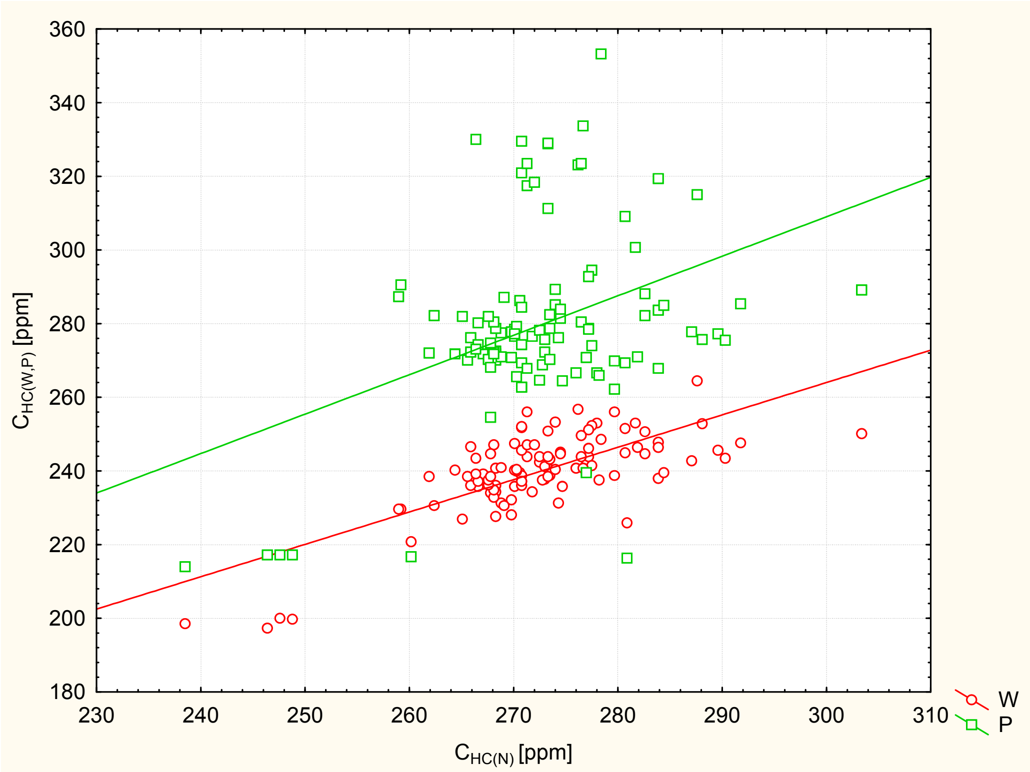

Figure 4. The concentration of hydrocarbons HC for the transient at n = 1100 r / min and load change from T_{tq} = 30 N to T_{tq} = 50 N: P - late, W - accelerated injection timing, CHC (N, S, P) - HC concentration for (N) nominal, (W) accelerated, (P) delayed injection timing

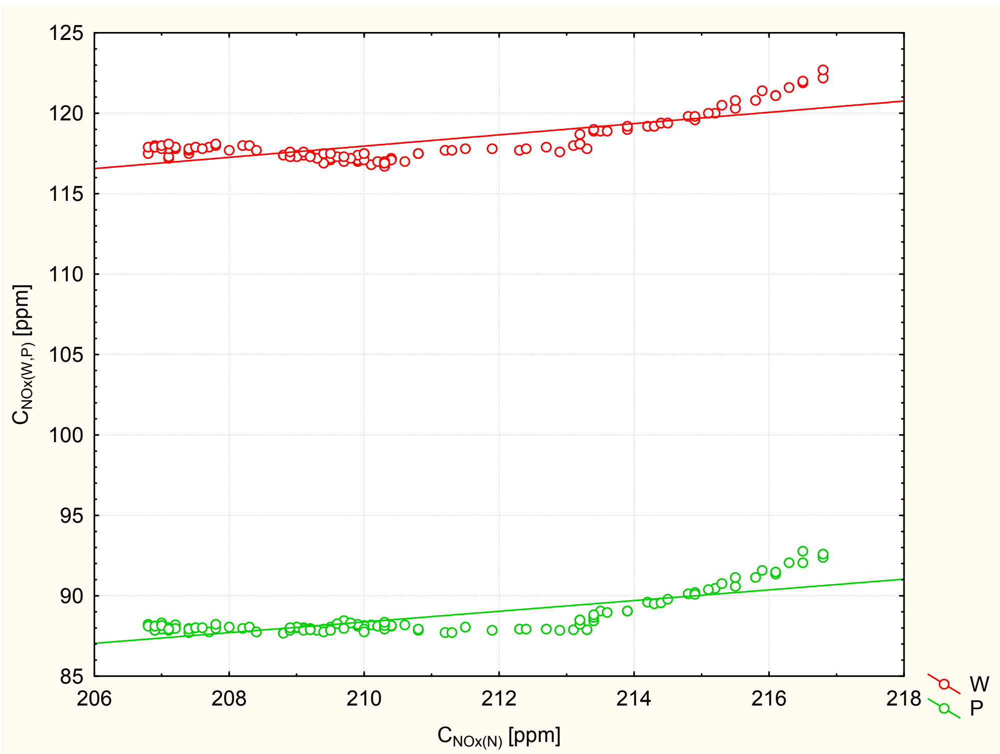

Figure 5. The concentration of NOx for the transientat n = 1100 r / min and load change from T_{tq} = 30 N to T_{tq} = 50 N: P - late, in - accelerated injection timing, CNOx (N, S, P) - NOx concentration (N) nominal, (W) accelerated, (P) delayed injection timing

The correlation coefficients indicate a high matching of correlation functions in the two cases. And, for the accelerated angle (red), correlation coefficient is r = 0.79, while for delayed angle, r = 0.80. Another regularity can be noted, namely, much higher concentrations of NOx fall for the former angle, which of course is consistent with the theory of combustion (with the increase of injection timing, the share of kinetic combustion increases, at the same time increasing the pressure and temperature of combustion) , are thus improved conditions , at which nitrogen oxides are formed. For HC the situation is reversed (Fig. 4), delayed injection timing results in a higher proportion of diffusion combustion, which often goes into burnout and thus creates favorable conditions for the formation of unburned hydrocarbons.

4. Summary:

In the course of this study, the following conclusions have raised:

- multi-equation models provide a good match to the empirical results,
- using a multi-equation model makes it possible to predict, and thus greaten the modeling of concentration change (emission) during the transient,
- a discussion of the accuracy of different methods to estimate emissions, even using the method of spline functions is possible.

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