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MODELLING OF TOXIC COMPOUNDS EMISSION IN MARINE DIESEL ENGINE DURING TRANSIENT STATES AT VARIABLE PRESSURE 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. To describe the transient states, authors propose the use of multi-equation models, the presented material focuses on the analysis of changes in toxic compound concentrations during transients at varying pressures of the injector opening, which is a typical regulatory parameter that undergoes relatively frequent changes in the process of using the engine. 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 correct course of combustion in the cylinder depends primarily on well-functioning supply system, which is to ensure process repeatability mainly fuel injection. Because of this repetition, not only the beginning and the end of the injection is important, but also its course. The correctness of the first criteria (the beginning and the end of injection), in the classic power systems, is largely protected by the high-pressure fuel pump, through adjustable parameters such as injection timing and fuel dose. These parameters, although significant in view of their impact on the combustion parameters, especially in the case of fuel injection timing, undergo rather small changes during the use of the engine, and if present, they are usually the consequence of an incorrect adjustment of fuel equipment. Authors have examined the issue of the impact of injection timing on the combustion parameters during transients in earlier studies [11]. Although, as previously mentioned, the beginning and end of the injection correspond to the fuel pump, its course corresponds to the injector, and more specifically the parameters that describe its work. The most important regulatory parameter which determines the shape of the injection, its accuracy and above all its repeatability, is the opening pressure of the injector. This parameter, compared to the ones previously mentioned, undergoes the most common changes during the operation of the engine, and despite its effect on the combustion process is incomparably smaller than, for example, that of the fuel injection timing, it still must be taken into account in the analysis of the combustion process. The parameter determines the quality for fuel atomization, and thus determines the preparation of a homogeneous combustible mixture in the cylinder, which is especially important in states of thermodynamic imbalances that occur during transients, when the extortion on the power supply is much larger and this issue it the main topic of this paper. Other parameters, pertaining to the injector and having an impact on the course of the injection, are focused on the parameters that describe the geometry of the atomizer, which, as it stands, also undergoes changes during the engine's operation, e.g. due to erosive fuel interaction. This issue can be found in the earlier studies of the authors [10].

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, 11] 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 was 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.

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

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

$$\mathbf{y}[k+1] = \mathbf{A}\mathbf{y}[\mathbf{k}] + \mathbf{B}\,\mathbf{x}[\mathbf{k}] + \xi \quad (2)$$

where:

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

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

Later denoting:

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

and

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

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

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

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 (opening pressure of the injector) of a single-cylinder test engine [8]. The experimental material was collected by trivalent developed a complete plan [4]. The originality of the presented experimental material lies in the fact that the implementation of the various measurement systems (measuring points) of the aforementioned experiment plan were carried out by a programmable controller, equipped with the dynamometer control system. This 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. The time (about 106 seconds) was selected based on previous experience of the authors.

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 – injector opening pressure p_{wtr} [MPa].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. Injector opening pressure varied by ±3MPa, yielding three values, i.e. face value – 20 MPa, increased regulatory spring tension of the injector, which increased opening pressure of the injector – 23 MPa, and reduced injector opening pressure – 17 MPa. repetitive transients were obtained this way. Graphic interpretation of the test program is shown in Figure 1. 36 repetitive transients were obtained this way. Graphic interpretation of the test program is shown in Figure 1.

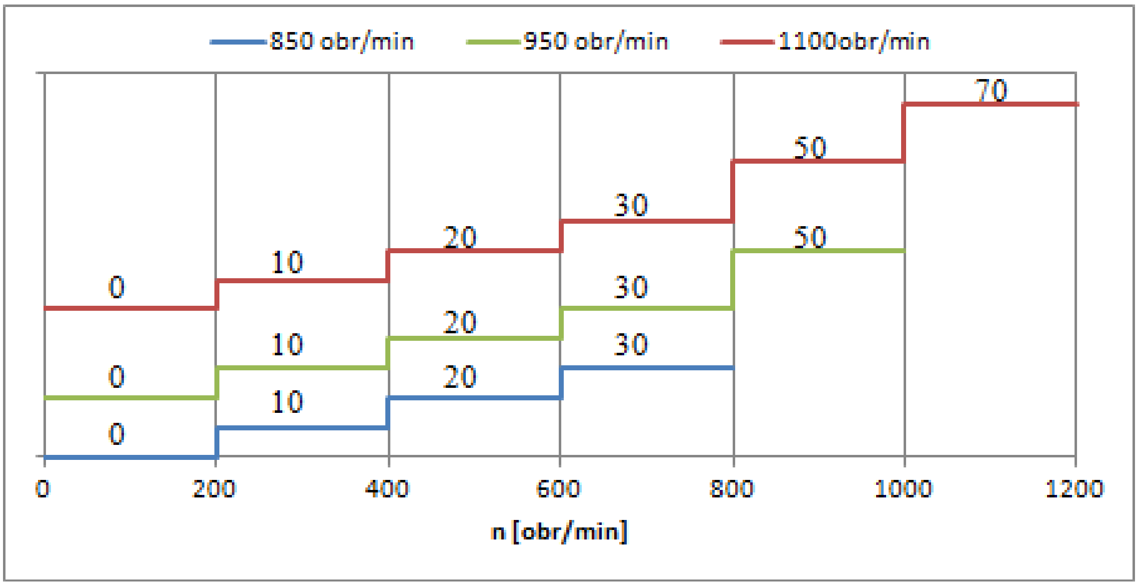

Fig.1. Diagram of the research program

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.

Figure 2 and figure 3 show a graphical representation of transients recorded at a speed of 1100 [rev/min] and the change in torque from 30 to 50 [Nm] (Fig. 2), and from 50 - 70 [Nm] (Fig. 3) for concentrations of CO and HC.

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, as well as due to the authors' detailed methodology of the analysis, for the purpose of this study presented are only the most characteristic of cases which occur at the highest loads that have been achieved during the experiment.

From the analysis of the experimental material as well as the multi-equation models describing it, it is clear that both the concentration of carbon monoxide C_{CO}, hydrocarbon concentrations C_{HC}, and concentrations of nitrogen oxides C_{NOx} are correlated primarily with excess air ratio λ and with the size of the input of the presented experiment - an injector opening pressure p_{wtr}. This arrangement seems to be obvious, as it is the amount of oxygen in the combustion chamber that determines the concentration of a particular ZT value. In turn, the value of the excess air ratio in the combustion chamber, especially its local values, is determined by the correctness of the fuel supply, in particular the correctness of the spray. As demonstrated in the introduction, the decisive factor affecting the correctness of the fuel atomization is the injector opening pressure.

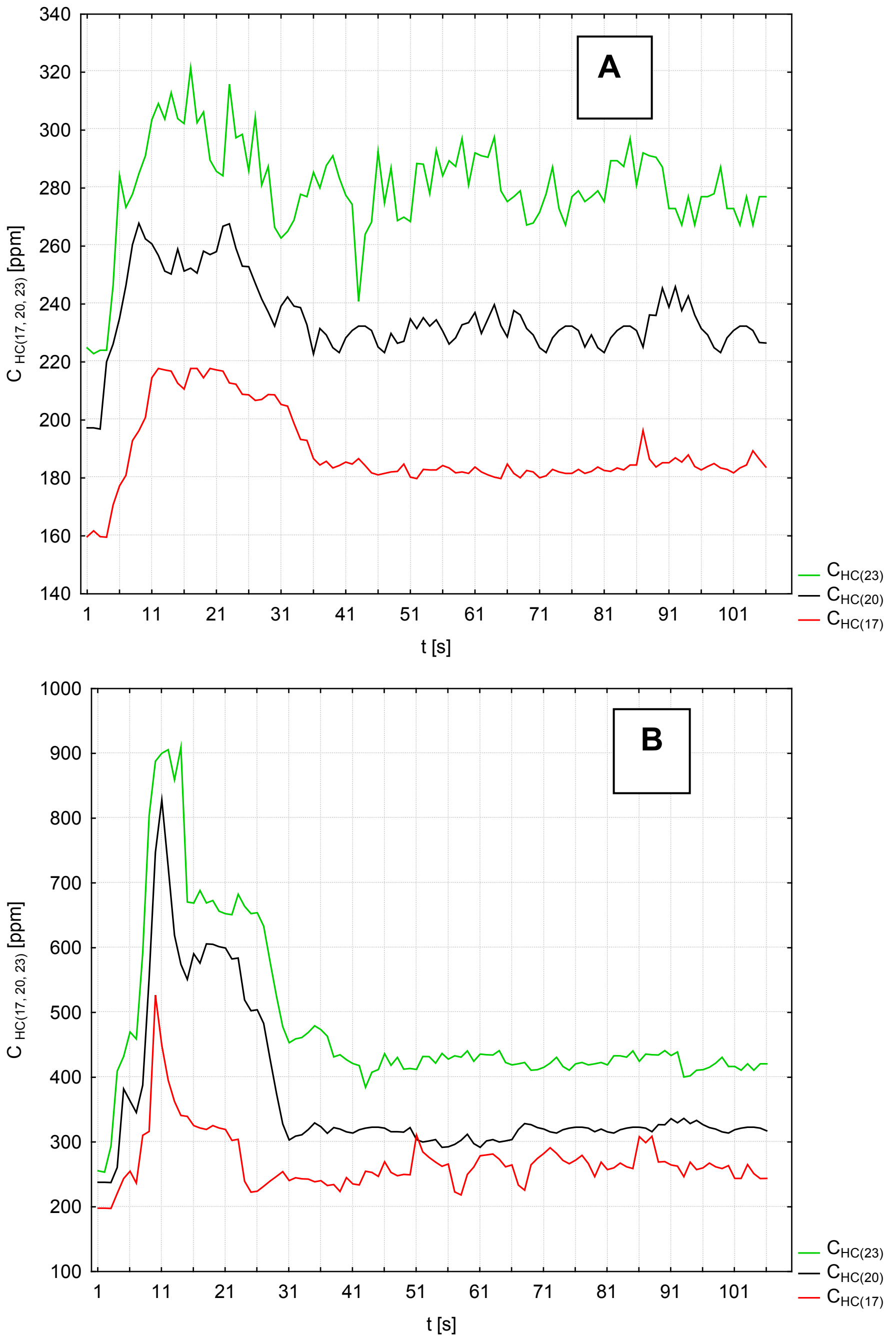

Figure 2. The concentration of hydrocarbons HC for the transient at n = 1100 r / min and load change from A: T_{tq} = 30 Nm to T_{tq} = 50 Nm; B: Ttq = 50 Nm to Ttq = 70 Nm. $C_{HC\ (17,\ 20,\ 23)}$ – HC concentration for the (17) reduced, (20) nominal, (23) increased opening pressure of the injector, where t - the time of the transient

The resulting relevance values of model parameters are similar to those presented in previous works of injection timing interactions [11], wherein the interaction is far greater, especially in the case of the NO_x concentration. Similarities are also found in the case of the impact of other input values of the experiment. It has been observed, inter alia, that the rotational speed has a greater effect on the concentrations of CO, and in the case of HC an important factor determining the value of its concentration is the load (particularly evident in the case of the maximum torque load).

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. In the present case, significant interactions were observed between the concentration of CO and HC and a negative correlation between the concentrations of these compounds and NO_x concentration, which seems to be logical considering the processes of formation of these compounds in the cylinder.

Having a good model fit to the values obtained as a result of the experiment on the engine is indicated by a small value of the sum of residuals between these results. These values, in the case of raw residues, for a model describing the concentration of HC are a maximum of 30 ppm. In the case of models describing the concentration of CO, the maximum error does not exceed 80 ppm, which is a very good value considering the maximum value of indicators that, during the experiment, was 3000 ppm. A uniform distribution of the regression residuals from the average values also indicates a proper fitting of the models.

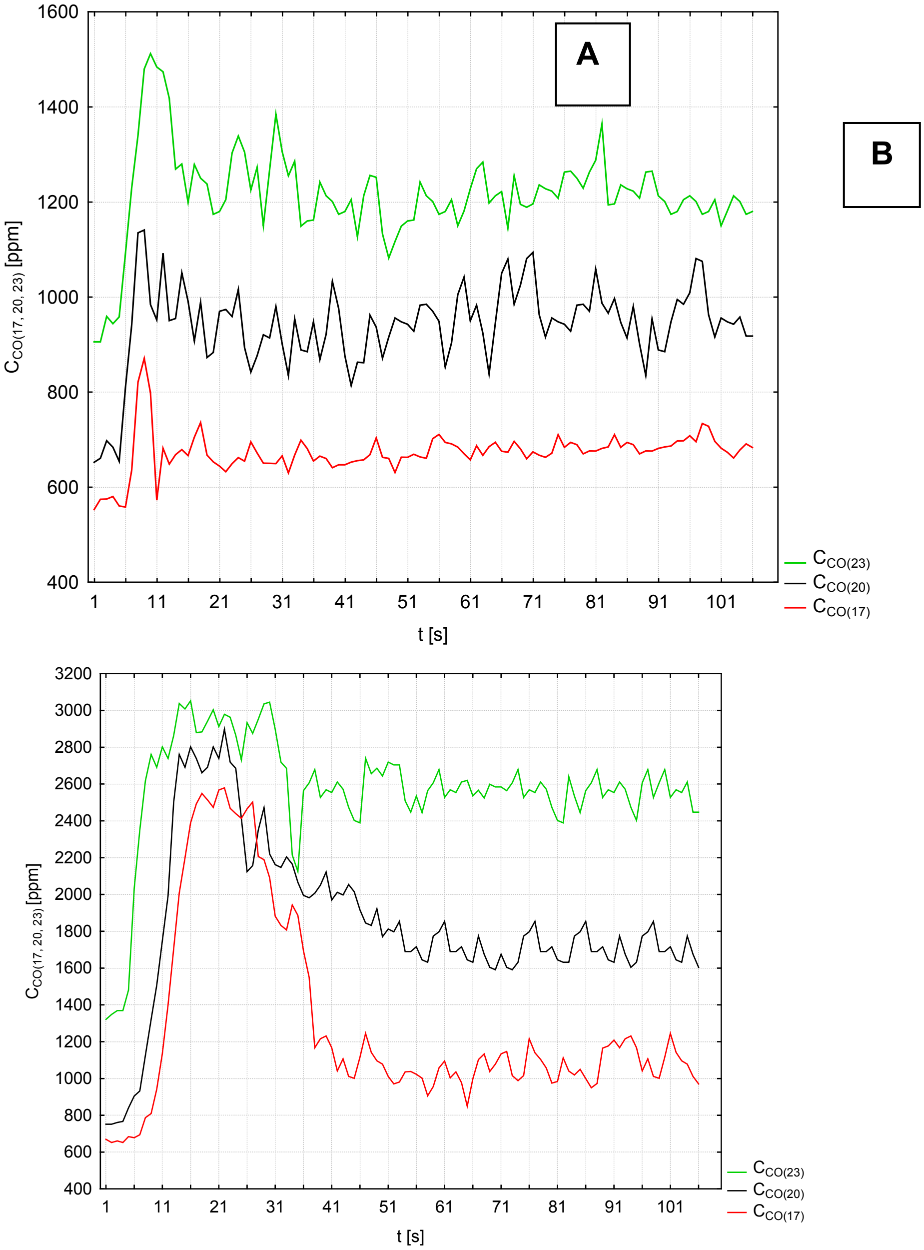

Fig. 3. The concentration of carbon monoxide CO for the transient at n = 1100 r/min and load change: A: T_{tq} = 30 Nm to T_{tq} = 50 Nm; B: T_{tq} = 50 Nm to T_{tq} = 70 Nm: CCO (17, 20, 23) - the concentration of CO for the (17) reduced, (20) the nominal, (23) increased opening pressure of the injector, where t - the time of the transient

Despite the obvious advantages, multi-equation models do not provide direct information on the quality of changes, in this case - changes in the concentration of various toxic compounds resulting from the changes in opening pressure of the injector. Only comparing the courses of the experiment, or the analysis of the obtained models, gives a picture of the phenomenon. As it is known from observation, depending on the value of force, the course of the transient can vary significantly. These differences are largely in the intensity of the course of each phase of the transient. Most frequently the course of a typical transient can be divided into two phases. The first one is characterized by the highest growth rate, accompanied by a sharp increase in ZT concentration, which is usually several times higher than the concentration in the steady state. The second phase of the transient is characterized by a much less violent course, with a monotonic character and approaches the value of the steady state concentrations in an asymptotic way (fig. 2, 3).

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 methods used commonly in similar cases. In earlier studies, the authors present a proposal for such indicators [11], however they do not exhaust the topic, and may be a separate source of discussion.

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. Graphic representation of the correlation analysis is a scatter diagram presented in figures 4 and 5.

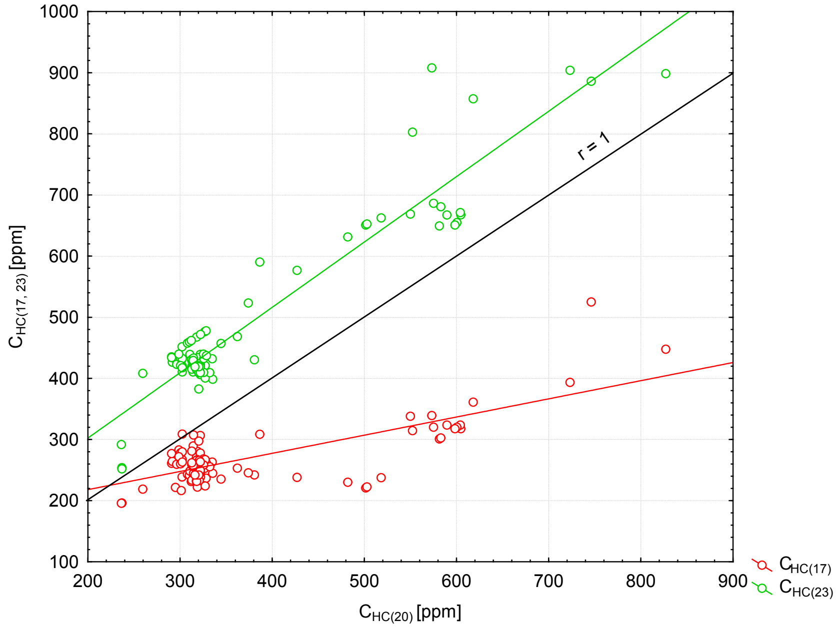

Fig. 4 The concentration of hydrocarbons HC for the transient at n = 1100 r / min and load change from Ttq = 30 Nm to Ttq = 50 Nm: CHC (17, 20, 23) – HC concentration for (17MPa) reduced (20 MPa) nominal, (23MPa) increased opening pressure of the injector

Figure 4 shows the linear correlation function of the concentration of unburnt hydrocarbons HC at an injector opening pressure of 23 MPa (green) relative to the nominal injector opening pressure (20 MPa), where the correlation coefficient was r = 0.95. Black color indicates a correlation r = 1 (for the nominal values of the injector opening pressure), while the red color indicates the correlation function of HC concentration at reduced pressure to open the injector (17 MPa) also relative to the nominal opening pressure of the injector. The correlation coefficient in this case was smaller, with r = 0.75. Smaller values of the correlation coefficient were affected by the dispersion of points around the correlation function, which indicates an unstable transient process (multi-equation model fit is nevertheless significant because the largest residual value is 22 ppm). Analogously, correlation analysis may be performed for the carbon monoxide (fig. 5).

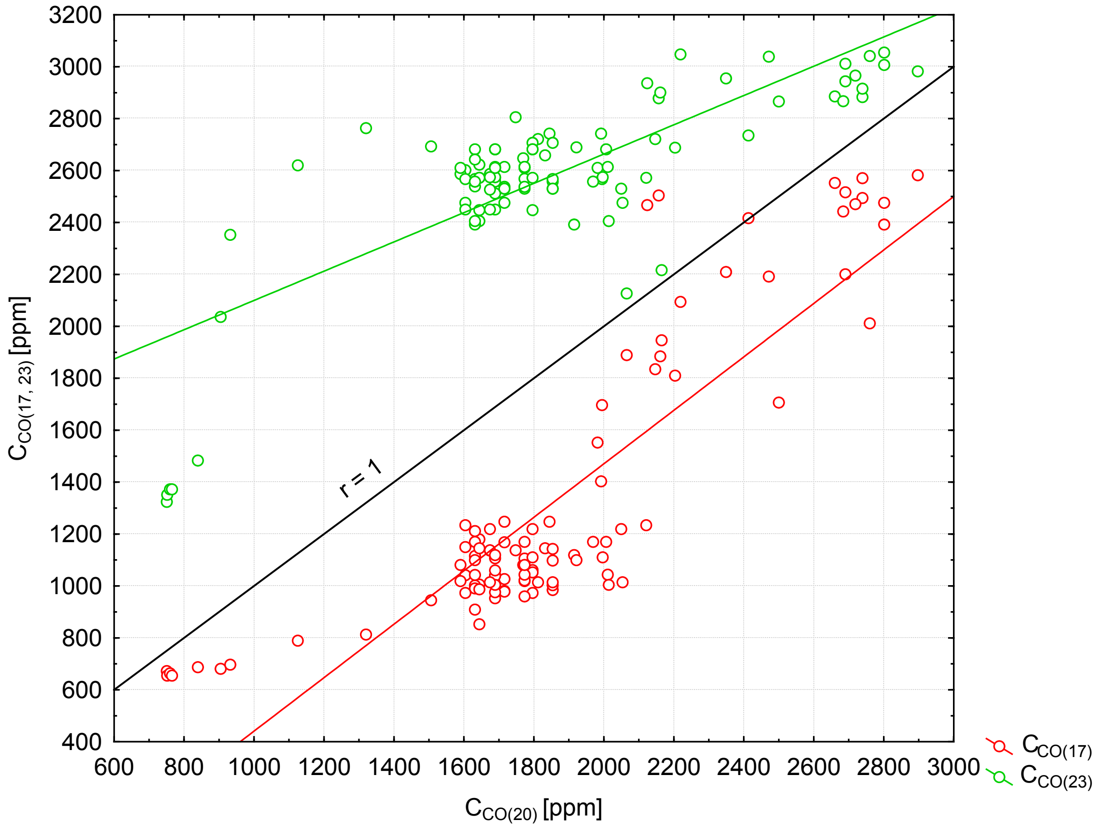

Fig. 5 The concentration of carbon monoxide for transient n = 1100 rev / min and load change with T_{tq} = 50 Nm to T_{tq} = 70 Nm: CCO (17, 20, 23) - the concentration of CO for (17MPa) reduced (20 MPa) nominal, (23MPa) increased opening pressure of the injector

The correlation coefficients indicate a high match of the correlation functions in the two cases under consideration. And so, for increased opening pressure of the injector (green), the correlation coefficient is r = 0.78, while for the reduced pressure, r = 0.87.

While analyzing the collected material, another regularity can be seen, namely, the higher the opening pressure of the injector, the higher the concentrations of CO and HC, and higher exhaust temperature. Accompanied by a decline in the value of excess air (measured in the exhaust manifold), which, despite seemingly better fuel fragmentation and thus a better mix of cargo, should be explained by a decrease in the local values of air ratio with the entry into burning more mass of (better prepared) fuel. It is evidenced by the increase of dynamics of combustion (which rises along with the increase of the opening pressure of the injector). At the same time a NO_x concentration decrease can be noticed, to whose creation at least a local excess of oxygen is neccessary.

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,
- there is a need for a thorough analysis of the correlation of the dependent variables throughout the experiment,
- a discussion of the accuracy of different methods to estimate emissions, even using the method of spline functions is possible.

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