



Results of an experimental statistical study of the influence of hydrogen on the CO release and on the fuel consumption of a marine diesel engine. Quantitative analysis

Part I

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Abstract: The application of the Regression Analysis and the results of the study and evaluation of the influence of Hydrogen 5.0 F50 P200 on the CO release and the fuel consumption under variable load operation of a marine diesel engine SKL 3NVD24 with two types of fuel are considered. A technology for quantitative analysis is proposed.

Key words: efficiency, marine diesel fuels, mathematical models, hydrogen technology

1. Introduction

The use of hydrogen as an energy source in recent years has occupied a central place in energy consumption in all areas as a starting material, fuel or energy carrier, as well as a means of energy storage. It has many possible applications in industry, transport, and energetics. One of the operational objectives set out in the Roadmap, underlying the analyses conducted in recent years and presented in the special Report "Assessment of the Potential for Development of Hydrogen Technologies in the Republic of Bulgaria" is to promote the effective introduction of technologies for the production, transportation and use of green hydrogen in our industry, energetics and transport. Bulgaria ranks eighth in the European Economic Area in terms of its share in hydrogen production, with less than 5% [2,3].

Significant success has been achieved in the implementation of hydrogen fuel in the operation of car engines and in transport in general worldwide [1,4]. There is a lack of data on the use of hydrogen in ship engines. There are no complete studies of the influence of hydrogen on the environmental performance of ship diesel engines. The current research is devoted to the analysis and comparison of the influence of hydrogen, in comparison with ordinary diesel fuel, on the emitted carbon monoxide of a medium-frequency ship diesel engine SKL 3NVD24: four-stroke, 3 cylinders, rated power at 600 (min-1) – 44.1 kW, cylinder volume – 5.76 (dm³), at different loads. For the purposes of the study, 10 experiments were conducted at loads in the entire load range of the diesel engine and CO registration [7,8,9].

1. Study of the influence of engine load G (kg) on the emitted carbon monoxide CO (ppm) when using diesel fuel

The search for a qualitative mathematical model linking emitted carbon monoxide CO and engine load in this case includes two first and second order models. The Regression Analysis method was used to verify their qualities. The results and subsequent conclusions are given in tabular form (Table 1), which includes: type of the model; results of verification of the qualities of the model by adequacy, standard error SY, value of the Pearson correlation coefficient Ryx,

as well as verification of the conditions for applying Regression Analysis: normality, absence of correlation, stationarity and $\sum e_i=0$ of the residuals, after processing the data with the Least Squares method (**LSM**). For universality in the entries in all tables following the analysis, **x** denotes the values of the load factor G, and **ya** denotes the objective functions.

G=[0 2.3 4.1 6.2 8.0 10.4 12.5 14.2 16.6 18.9];

CO=[370 441 498 545 608 657 699 1052 1650 1890];

Results of the study of the influence of the load G, on CO (ppm) of a marine diesel engine SKL 3NVD24, when using diesel fuel

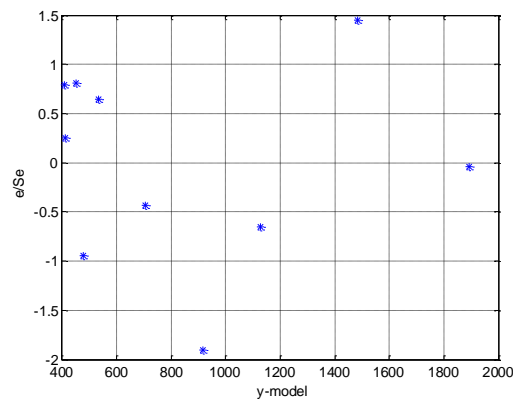
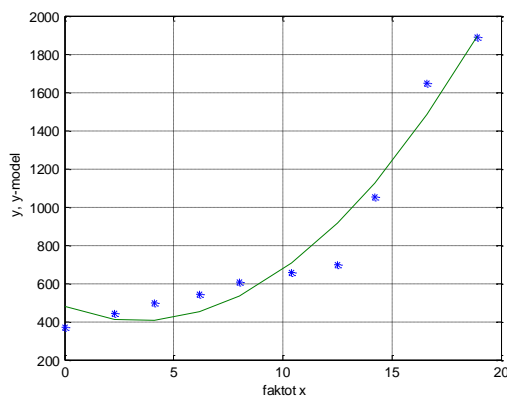
Table 1

CO (ppm)						
Model	Adequacy	Standard error SY	Normality check on Jacques-Bera curve	Homoskedasticity according to Glaser's criterion	Pearson's Ryx	DERBIN-WATSON correlation check
$y_d = 143.7761 + 74.8094 \cdot x$	Fem = 31.1686 F(0.05;1;8)=5.32 Conclusion: yes	252.3775	JBem= 0.6202 JB τ (0.05;2) = 5.99 Conclusion: Normal distribution	FFem =4.3080; F τ (0.05;1;8) = 5.32 Conclusion: yes	0.89205	d = 0.5780 alfa=5%; dL= 0.879 dU= 1.32 0<d<dL Conclusion: positive autocorrelation
$y_d = 477.5098 - 42.7234 \cdot x + 6.2261 \cdot x^2$	Fem =70.7815 F(0.05;2;7)=4.74 Conclusion: yes	129.5878	JBem =0.4510 JB τ (0.05;2) = 5.99 Conclusion: Normal distribution	FFem = 0.0528 F τ (0.05;1;8) = 5.32 Conclusion: yes	0.97616	d = 1.4744 alfa=5%; dL= 0.824 dU= 1.32 dU<d<4-dU=2.68 Conclusion: No autocorrelation available



Both models are adequate, with large values of the Pearson correlation coefficients R_{yx} . The verification of the conditions for the application of Regression Analysis (RA): the criteria of Jacques-Bera, Glaser, Pearson are satisfied and $\sum e_i = 2.2737e-013$, taken as zero. However, the Durbin-Watson criterion shows a positive correlation of the residuals for the linear model, which is a drawback.

The results of the obtained second-order nonlinear model are given in the second row of table 1, and below in fig. 1 of the dependence of the experimental data (*) and that of the model (-). Here, the dependence of the normalized error e/Se has a random nature and does not show a change in the nature of the selected mathematical model. The requirements for the application of the Least Squares method (LSM) are satisfied.



Figures 1. Results of a nonlinear model

The parabolic model is more accurate, with a smaller standard error $S_Y = 129.5878$ and a large Pearson correlation coefficient 0.97616 , which is the reason for choosing it as a Regression model of the relationship between engine load G (kg) and CO released during combustion. The model in real variables has the form (1)

$$CO = 477.5098 - 42.7234 \cdot G + 6.2261 \cdot G^2 \quad (1)$$

2. Study of the influence of engine load G (kg) on carbon monoxide released CO (ppm) when using *Hydrogen 5.0 F50 P200*

The following data were used, recorded as row vectors:

$$G = [0 \quad 2.1 \quad 4.1 \quad 6.4 \quad 8.1 \quad 9.9 \quad 12.0 \quad 14.1 \quad 15.6];$$

$$CO = [254 \quad 315 \quad 377 \quad 433 \quad 455 \quad 476 \quad 482 \quad 734 \quad 975];$$

The conducted research and the subsequent conclusions are given in tabular form, Table 2.



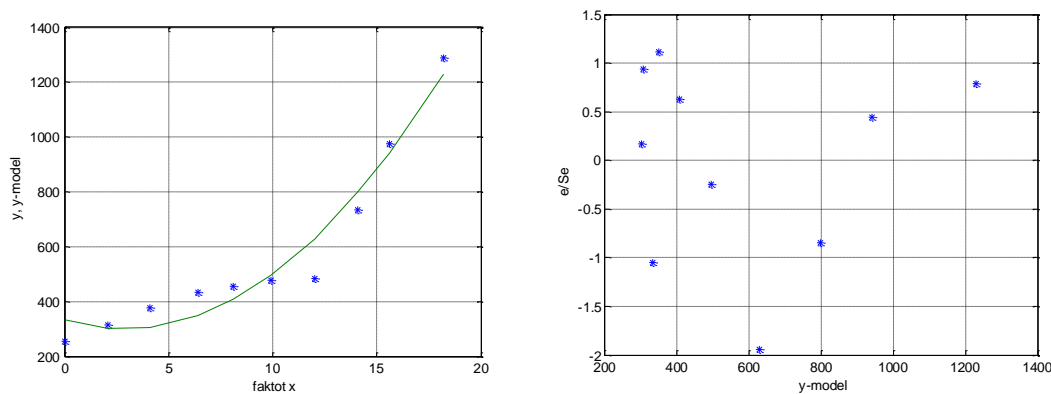
Results of the study of the influence of the load G, on CO (ppm) of a marine diesel engine SKL 3NVD24, when using fuel Hydrogen 5.0 F50 P200

Table 2

CO (ppm)						
Model	Adequacy	Standard error SY	Normality check on Jacques-Bera curve	Homoskedasticity according to Glaser's criterion	Pearson's Ryx	DERBIN-WATSON correlation check
$y_v = 138.3276 + 48.7041 \dots x$	Fem = 32.3448 F(0.05;1;8)=5.32 Conclusion: yes	154.1914	JBem= 0.1186 JBtr(0.05;2) = 5.99 Conclusion: Normal distribution	FFem = 4.3080; Ft(0.05;1;8) = 5.32 Conclusion: yes	0.89538	d = 0.5763 alfa=5%; dL= 0.879 dU= 1.32 0<d<dL Conclusion: positive autocorrelation
$y_v = 333.3270 - 23.0617 \dots x + 3.9755 \dots x^2$	Fem = 61.3306 F(0.05;2;7)=4.74 Conclusion: yes	86.01	JBem = 1.0249 JBtr(0.05;2) = 5.99 Conclusion: Normal distribution	FFem = 0.0244 Ft(0.05;1;8) = 5.32 Conclusion: yes	0.97263	d = 0.9941 alfa=5%; dL= 0.824 dU= 1.32 dU<d<dU Conclusion: Test is nonconclusive

Table 2 gives the results of the mathematical modeling of the influence of the load G on the CO obtained from combustion with *Hydrogen 5.0 F50 P200* fuel. The two adequate models obtained have large values of the Pearson correlation coefficients Ryx, indicating significant levels of the relationships of the considered dependencies. The results of the obtained nonlinear second-order model are

given in the second row of Table 2, and below in Fig. 2, the type of dependence of the experimental data (*) and that of the nonlinear model (-). Here, the dependence of the normalized error e/Se has a random distribution character and does not show a change in the character of the selected mathematical model [5,6].



Figures 2. Results of the nonlinear model

The parabolic model is more accurate, with a smaller standard error $SY = 86.01$ and a large Pearson correlation coefficient $R_{yx} = 0.97263$, which is the reason for choosing it as the Regression model of the relationship between engine load G (kg) and combustion emissions CO (ppm). The model in real variables has the form (2)

$$CO = 333.3270 - 23.0617 \cdot G + 3.9755 \cdot G^2 \quad (2)$$

3. Quantitative analysis of the influence of fuel Hydrogen 5.0 F50 P200 on the environmental performance of a marine diesel engine SKL 3NVD24. Evaluation of the efficiency of use

The algorithm of the study is reduced to the implementation of the following sequence: creation of qualitative mathematical models of the "cause - effect" type for both types of fuels and calculation of predicted target functions based on them. After their analysis, a relative error is determined, which is compared with the error from the experiment and a decision is

made on the significance of the influence of the studied fuel Hydrogen 5.0 F50 P200.

In the previous two sections, the following two mathematical models were created, reflecting the statistical relationship of the influence of the engine load G (kg) when using the two types of fuel on carbon monoxide CO (ppm).

$$CO1 = 477.5098 - 42.7234 \cdot G + 6.2261 \cdot G^2 \quad (1)$$

$$CO2 = 333.3270 - 23.0617 \cdot G + 3.9755 \cdot G^2 \quad (2)$$

The designations $CO1$ and $CO2$ are necessary, since a comparison of the processes is made in pairs. According to the equations, when the load changes in the load range $G = [0 \ 2 \ 4 \ 6 \ 8 \ 10 \ 12 \ 14 \ 16 \ 18]$, representing research interest, the values for $CO1$ and $CO2$ were obtained, given as row vectors:

$$CO1 = 1.0e+003 \cdot [0.4775 \quad 0.4170 \quad 0.4062 \quad 0.4453 \quad 0.5342 \quad 0.6729 \quad 0.8614 \quad 1.0997 \quad 1.3878 \quad 1.7257];$$

CO₂ = 1.0e+003 * [0.3333 0.3031 0.3047
0.3381 0.4033 0.5003 0.6291 0.7897
0.9821 1.2063];

The relative error between the two processes in percentage is

$$CO_e\% = (CO_e / CO_1) * 100$$

CO_e % = [**30.1947** 27.3071 24.9968
24.0809 24.5094 25.6545 26.9715
28.1929 29.2365 30.1010];

The maximum relative error is 30.1947 %, at idle, G= 0 kg. Provided that the error with which the experimental data are taken is 5%, it follows that the difference CO_e% between the values of carbon monoxide CO₁, when working on diesel fuel and CO₂, when working on Hydrogen fuel 5.0 F50 P200 is significantly above this value, indicating the significant influence of hydrogen.

CO reduction due to the use of Hydrogen 5.0 F50 P200 fuel can be realized in the entire engine load range. To determine it in a certain operating mode, the following approach can be used. It is assumed that due to disturbing factors the load varies in the interval G₁ – G₂. The average value of carbon monoxide CO_{cp} is determined. After taking into account (1) and (2) and solving the integral, the average value of the difference in the released CO for the two types of fuel will be

$$CO_{cp} = \frac{1}{G_2 - G_1} \int_{G_1}^{G_2} (CO_1(G) - CO_2(G)) \cdot dG =$$

$$\frac{1}{G_2 - G_1} [144.1828 \cdot (G_2 - G_1) - 9.8309 \cdot (G_2^2 - G_1^2) + 0.7502 \cdot (G_2^3 - G_1^3)].$$

Using the average value of carbon monoxide CO_{cp} during the operating time in this interval Δt, the carbon monoxide “savings” resulting from the use of Hydrogen 5.0 F50 P200 fuel is determined, i.e. CO_И = CO_{cp} * Δt

2. Conclusion

The proposed technology and research results allow us to state with high confidence that the use of Hydrogen 5.0 F50 P200 fuel in a marine diesel engine leads to a 25-30% reduction in carbon monoxide values. The research and results refer to a specific type of marine engine. The report shows the logical consequence of the statistically analyzed data, presented clearly and concisely, and tempered by an honest assessment of the study's limitations. Also offer insights into the potential practical applications and implications of the findings.

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