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Evaluation of the impact of supplying a marine diesel engine with a mixture of diesel oil and n-butanol on its efficiency and emission of toxic compounds

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The article presents the results of research on the impact of feeding marine reciprocating internal combustion engines with blends of diesel fuel and n-butanol on their performance parameters. The study includes a research plan and empirical results, in which the engine efficiency and emissions of harmful compounds in the exhaust gases were determined. A promising aspect is also the decrease in the concentration of NO_x, which has a positive impact on reducing the toxicity of exhaust gases. An important aspect of the passive defence of a vessel is the reduction of exhaust gas temperature under nominal loads.

Key words: *marine diesel combustion engine, engine efficiency, n-butanol, Box-Behnken plan, NO_x*

1. Introduction

Fuel can be simply defined as a substance (solid, gas, liquid) that releases a large amount of heat energy during the combustion process [16]. This energy can be utilized for heating purposes or technological applications. One of the main applications of fuels is in internal combustion engines, where they convert chemical energy into mechanical energy.

One of the major users of fuels is maritime transport. It is estimated that maritime transport accounts for 3.5–4% of greenhouse gas emissions, primarily carbon dioxide. In terms of total global air pollution emissions, shipping "produces" 18–30% of nitrogen oxides and 9% of sulphur oxides. In the context of European transportation, maritime and inland waterway shipping account for 13.5% of greenhouse gas emissions (including approximately 18% of total CO_2 emissions and around 24% of total NO_x emissions – data referring to global maritime transport in 2018) – according to the report by the European Environment Agency and the European Maritime Safety Agency [4, 15]. In April 2018, the IMO (International Maritime Organization) established a strategy to reduce total greenhouse gas emissions from shipping by at least 50% compared to 2008 [5].

Due to the unstable geopolitical situation (including the armed conflict in Ukraine) and the global trend towards minimizing (eliminating) toxic compounds in exhaust gases, alternative solutions to fossil fuels are being sought. Alternative solutions include harnessing energy from wind, solar power, geothermal sources, nuclear reactions, fuel cells, and alternative fuels.

One of the most forward-thinking ways to reduce pollution and improve engine efficiency is to use alternative fuels. Over the years, extensive research has been conducted on alternative fuels such as alcohols, methyl tert-butyl ether (MTBE), and n-butanol [1, 8].

Alcohol-based fuels, which can be combined with conventional fuels, have the potential as alternative transportation fuels. Previous interest has focused on the use of simple alcohol-gasoline blends in internal combustion engines. Alcohols have a higher octane rating, making them suitable for spark-ignition engines. The combustion properties of alcohols in spark-ignition engines are better than gasoline. However, due to the different physical and chemical properties of alcohols compared to gasoline and diesel fuels, their use may require modifications to engines and fuel systems. On the other hand, blends of up to about twenty percent usually do not require any changes [1, 14, 17].

The idea of using n-butanol and its isomers to create fuel blends is not new, but it has not been sufficiently explored in the case of powering marine reciprocating internal combustion engines.

Iso-butanol has been used as a surfactant to increase the stability of methanol/gasoline and ethanol/gasoline blends [10, 18]. In the past, it was used in a 1:2 ratio with methanol as a co-solvent to eliminate phase separation issues that occur when mixing methanol with gasoline [8]. Bata and his team found that when testing an engine with a 20% isobutanol blend, there was only a 2.5% reduction in thermal efficiency. They was also a 6.5% increase in specific fuel consumption compared to gasoline under the same experimental conditions. They showed that butanol is superior to methanol and ethanol in terms of thermal efficiency and lower specific fuel consumption. They also found that isobutanol has a higher stoichiometric air-to-fuel ratio than lighter alcohols, which allows for higher proportions of isobutanol in blends as an additive without requiring significant engine modifications [1, 17].

The primary economic advantage of butanol is the fact that it is a renewable fuel. An additional benefit is its physicochemical properties, including its ability to blend with hydrocarbon fuels. Research studies on fuel blends with n-butanol have been conducted in various research fields [6].

Labeckas et al. [9] studied the effects of n-butanol-oil fuel blends on engine performance and exhaust emissions. They compared engine performance using a traditional diesel fuel and mixtures with n-butanol. This allowed them, based on the interpretation of various quantities such as ignition delay angle, torque, and emissions of NO_x and CO, to determine potential trends in the utilization of the tested fuel blends [6, 9].

Pielecha et al. [13] applied a non-conventional system for creating gasoline blends with ethanol, n-butanol, or n-heptane using dual direct injection. The interpretation of combustion process indicators led to the conclusion that the fuel blend with n-butanol was the most efficient and resulted in a 6.1% increase in efficiency compared to pure gasoline combustion [6].

Elfasakhany and Mahrous [2] investigated the impact of two-component blends (fuel with n-butanol) and three-component blends (fuel, n-butanol, methanol) at various concentrations on the efficiency and exhaust emissions of spark-ignition engines. The key finding of the research was the unfavourable effect of using the three-component blend compared to the two-component blend (both with low alcohol content) on engine efficiency and the emission of toxic compounds. However, for three-component blends with higher alcohol content (> 10%), the engine efficiency and emission of toxic compounds were found to be more favourable compared to the two-component blend (n-butanol > 10%).

Otaka et al. [12] conducted a research study using a blend of biobutanol with marine fuel on a single-cylinder compression ignition engine. The results of the study showed an extended ignition delay for the used blend and an increase in hydrocarbon and CO emissions, primarily in the low engine load range.

Wang et al. [20] investigated the impact of alternative fuel blends used in two-stroke slow-speed marine diesel engines on their performance. They discovered that by introducing a certain amount of n-butanol into the fuel, it is possible to reduce NO_x emissions, and increasing the concentration of n-butanol leads to a decrease in CO_2 emissions.

Kniaziewicz et al. [10] conducted research on a marine internal combustion engine fuelled with a blend of F–75 marine fuel and n-butanol. They demonstrated that n-butanol improves combustion conditions and has a beneficial impact on the emission of toxic compounds. The empirical research was supported by a mathematical model analysed using artificial neural networks.

The results of Zhang et al. [22] demonstrated that blends of diesel fuel and methanol and n-butanol had a key effect on fuel dispersion and combustion. Fuel containing methanol and n-butanol had a longer ignition delay, higher maximum heat and higher in-cylinder pressure release rate compared to diesel fuel. The authors concluded that the optimal fuel mixture ratio was 70% diesel + 20% methanol + 10% n-butanol. According to the above, the mixture of diesel fuel with methanol and n-butanol allows to improve the combustion and emission parameters of the engine.

Tipanluisa et al. [19] conducted a study on the application of a single-zone combustion model along with Wiebe triple functions to analyze the effects of blends of diesel and n-butanol as drop-in fuel in a four-cylinder heavy-duty diesel engine (HDDE). Blends of 5%, 10% and 20% n-butanol were used at varying speed and load conditions. All n-butanol blends reduced CO and particulate emissions, regardless of operating conditions, while NO_x emissions increased primarily at full load.

The article continues the work of previous researchers to find the optimal blend of marine fuel with n-butanol and its application in marine reciprocating internal combustion engines. The authors decided to conduct empirical and modeling research on a single-cylinder research engine to analyse the obtained efficiency and emission levels of toxic compounds for marine fuel and its blend with n-butanol.

During laboratory tests, a single-cylinder engine test rig was used, which was driven by a planetary gearbox and equipped with an electric dynamometer brake. The engine, gearbox, and brake were equipped with the necessary measurement equipment for analysing torque, crankshaft speed, fuel and oil temperature, gravimetric fuel consumption measurement, exhaust gas analysis, and cylinder pressure indication.

2. Research plan and research object

2.1. Research plan

Following the methodology of conducting research, a research plan was developed that included the research object, the measurement apparatus used, and the measured parameters of the research object, i.e., in the case of the examined engine, the crankshaft rotational speed, engine load by torque, fuel consumption, and indicated pressure, the content of toxic compounds in exhaust gases and their temperature.

Design of experiments (DoE) is often used to create empirical models. It reduces the number of necessary measurements, which translates into reduced consumption of the tested object, and ultimately – cost reduction. It systematically and structurally explains cause-and-effect relationships in the processes being studied, which allows this method to be the most effective in solving problems. A properly selected research plan allows for obtaining precise and validated results, i.e., mathematical relationships describing selected process variables [3, 21].

One of the strategies used in experimental design is the response surface methodology (RSM). The Box-Behnken design, chosen by the authors of the article, is based on this method. It is used for modeling and analysing phenomena in which multiple variables interact with the output variable [3]. The chosen experimental design is suitable for the assumption that the engine is a non-linear object due to the emission of exhaust gases. A non-linear object is best described by a non-linear equation with at least three input values [6].

One of the stages of experimental planning is determining a set of characteristic quantities for the object under study (Fig. 1), which was selected by introducing the following simplifications:

1. Constant values, due to their invariable effect on output values, are not taken into account
2. The disturbing factors are omitted due to conducting tests under identical external conditions
3. The set of input variables was defined as follows:
    - crankshaft rotational speed n = 800–1200 rpm
    - concentration of n-butanol as a percentage by weight C_b = 0–35%
    - rated brake power (input power to the engine measured at the output shaft) N_z = 0–6 kW.

4. The output quantities are limited to the quantities:
   - mean induced torque T_i [Nm]
   - average fuel consumption b_s [g/s]
   - fuel rail setting [%]
   - ignition angle α_{ign} [°OWK]
   - maximum indicated pressure angle α_{pmax} [°OWK]
   - exhaust gas temperature $t_{exh.}$ [°C]
   - nitrogen oxides concentration in the exhaust gas NO_x [ppm]
   - nitrogen oxide concentration in the exhaust gas NO [ppm]
   - nitrogen dioxide concentration in the exhaust gas NO_2 [ppm]
   - carbon monoxide concentration in the exhaust gas CO [ppm]
   - carbon dioxide concentration in the exhaust gas CO_2 [%].

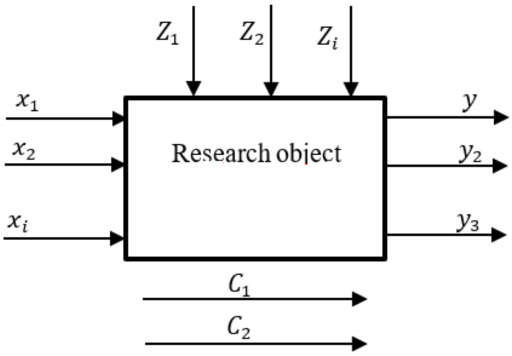

Fig. 1. Research object – structure. x-input quantities, y – output quantities, Z – disturbing quantities, C – constant values

Input parameters (k in number) within the specified ranges during the experiments took on three levels of variability, allowing for the construction of a mathematical model of the studied process in the form of a second-order polynomial [7]:

$$y = b_0 + \sum b_k x_k + \sum b_{kk} x_k^2 + \sum b_{kj} x_k x_j \qquad (1)$$

where: y – dependent output factor, x – j-th independent input factor, b – regression function coefficient.

To determine the efficiency of the studied system for the applied mixtures, the calorific value of the mixture was determined for each mass percentage concentration of n-butanol using the KL-11 calorimeter (Fig. 2).

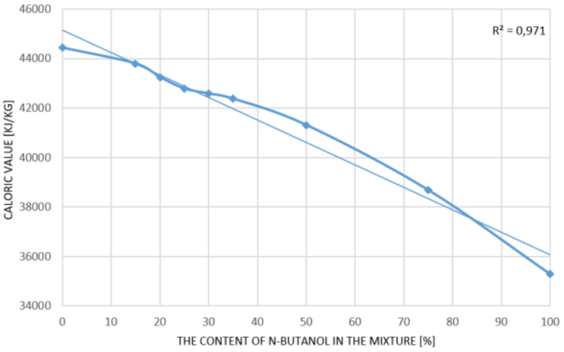

Fig. 2. The calorific value of marine fuel mixture with n-butanol

By analyzing the course of the calorific value curve, the most favorable concentrations of n-butanol in the mixture were chosen, i.e. 15% and 35%. The area between 15% and 35% has a fault, which can affect efficiency as well as of toxic compounds.

The experiment was carried out according to the appropriate set of input parameter values for the selected experimental plan (Table 1).

Table 1. The experimental plan

The Box-Behnken Plan 3**(3–1)						
TEST	A	B	C	crankshaft rotational speed [rpm]	concentration of n-butanol [%]	rated brake power [kW]
1	–1	–1	–1	800.0	0.0	0.0
2	–1	0	1	800.0	15.0	6.0
3	–1	1	0	800.0	35.0	3.0
4	0	–1	1	1000.0	0.0	6.0
5	0	0	0	1000.0	15.0	3.0
6	0	1	–1	1000.0	35.0	0.0
7	1	–1	0	1200.0	0.0	3.0
8	1	0	–1	1200.0	15.0	0.0
9	1	1	1	1200.0	35.0	6.0

The Box-Behnken plan was used because it is very economical and therefore particularly useful when taking measurements is expensive and their number should be limited to the really necessary. The researcher were able to perform as few as nine tests, which made it possible to satisfactorily analyze the results obtained. In this plan:

- A is crankshaft rotational speed
- B is concentration of n-butanol
- C is rated brake power.

Number –1, 0 and 1 means lowest, middle and highest value of parameters A, B and C.

2.2. Research object

Empirical and model studies were carried out for the same engine operating parameters (requested power, fuel mixture and crankshaft speed).

The research object was a laboratory single-cylinder engine installed on a stand at the Institute of Naval Architecture and Marine Engineering of the Polish Naval Academy. The basic data of the engine are grouped in Table 2, while the laboratory setup is shown in Fig. 3. The control panel of the single-cylinder engine setup is presented in Fig. 4.

Table 2. Technical data of the engine used in the tests

Cylinder arrangement and quantity	single-cylinder, vertical
Piston stroke	160 mm
Cylinder bore	135 mm
Cylinder displacement	2290 cm^3
Compression ratio	16:1
Specific fuel consumption	215 g/kWh
Rated torque at rated power	127 Nm
Injection pressure	17.17 MPa
Rated power	20 kW at 1500 rpm

Fig. 3. Laboratory engine stand

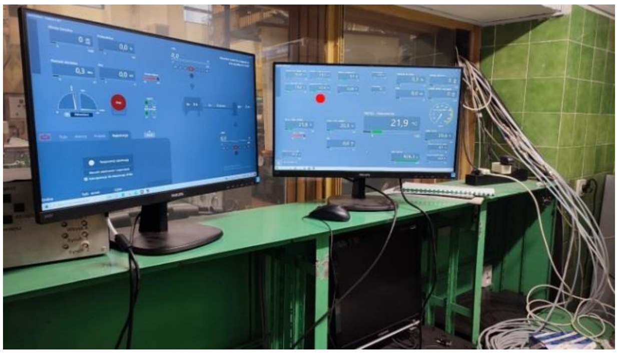

Fig. 4. Single-cylinder engine stand control panel

3. Results

3.1. The significance of input parameter influence

Following the established research plan, all listed engine operating parameters were measured and recorded for specified rotational speeds, n-butanol concentrations, and loads (brake power).

After the tests, the obtained output values were analysed using STATISTICA software. A modified quadratic model was selected for fitting, containing only statistically significant elements. The significance of the effect of each input parameter and its interaction was determined by analysis of variance (ANOVA). The next step was to determine the level of fit of the obtained models to the measured values for a specific experimental design, which was defined based on the coefficients of determination R^2 and the standard deviation of the residual component s [3, 7, 11].

The approximated polynomials (1) allowed for determining the relationships between individual variables, including the calculation and evaluation of the influence of n-butanol concentration in the fuel mixture on engine performance indicators (correlation determination). It can be assumed that this method allows for optimizing the selection of n-butanol concentration in the fuel mixture to achieve better engine performance and reduce exhaust toxicity, as indicated by Pareto charts [9, 20].

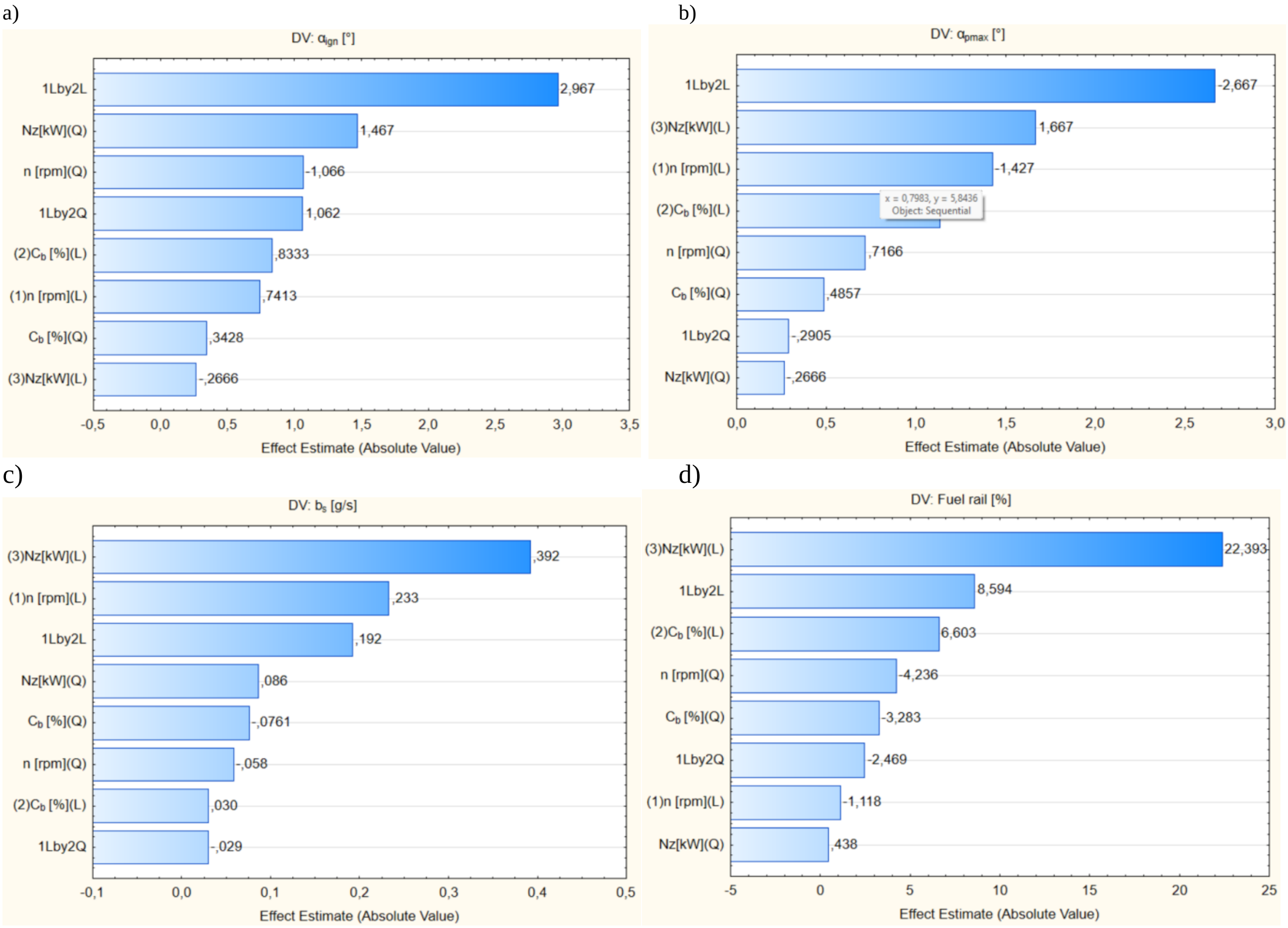

Fig. 5. Pareto charts of concentration of a) ignition angle, b) maximum indicate pressure angle, c) average fuel consumption, d) fuel rail

Pareto analysis (charts) is a technique that helps to visually present and rank individual independent variables affecting the output variable [18].

Figure 5 shows the influence of individual independent factors and their interactions on engine performance indicators (including those related to combustion quality). The input variables are represented on the vertical axis of the graph. Number 1 is crankshaft rotational speed, 2 – concentration of n-butanol in the blend fuel, 3 – rated brake power. The notation "L" indicates that the coefficient value is assigned to the linear term of the polynomial, "Q" – to the quadratic term, and "by" – in relation to a reference value. The main influence is seen from the linear relationship of rotational speed n to n-butanol concentration C_b.

Figure 6 shows the influence of individual independent factors and their interactions on the content of toxic compounds in engine exhaust. The obtained main results and interactions demonstrate the existing relationship between the concentration of n-butanol in the fuel and the concentration of toxic compounds in the engine exhaust.

3.2. Evaluation of the influence of n-butanol concentration on engine performance indicators

Based on the obtained data, surface plots were created and changes in the investigated parameters were presented as functions of n-butanol concentration in the fuel and rotational speed for the specified brake power $N_z = 3$ kW. Due to the repeatability of the function course for $N_z \in \langle 0,6 \rangle$ kW surface plots were not presented for $N_z = \{0,6\}$ kW.

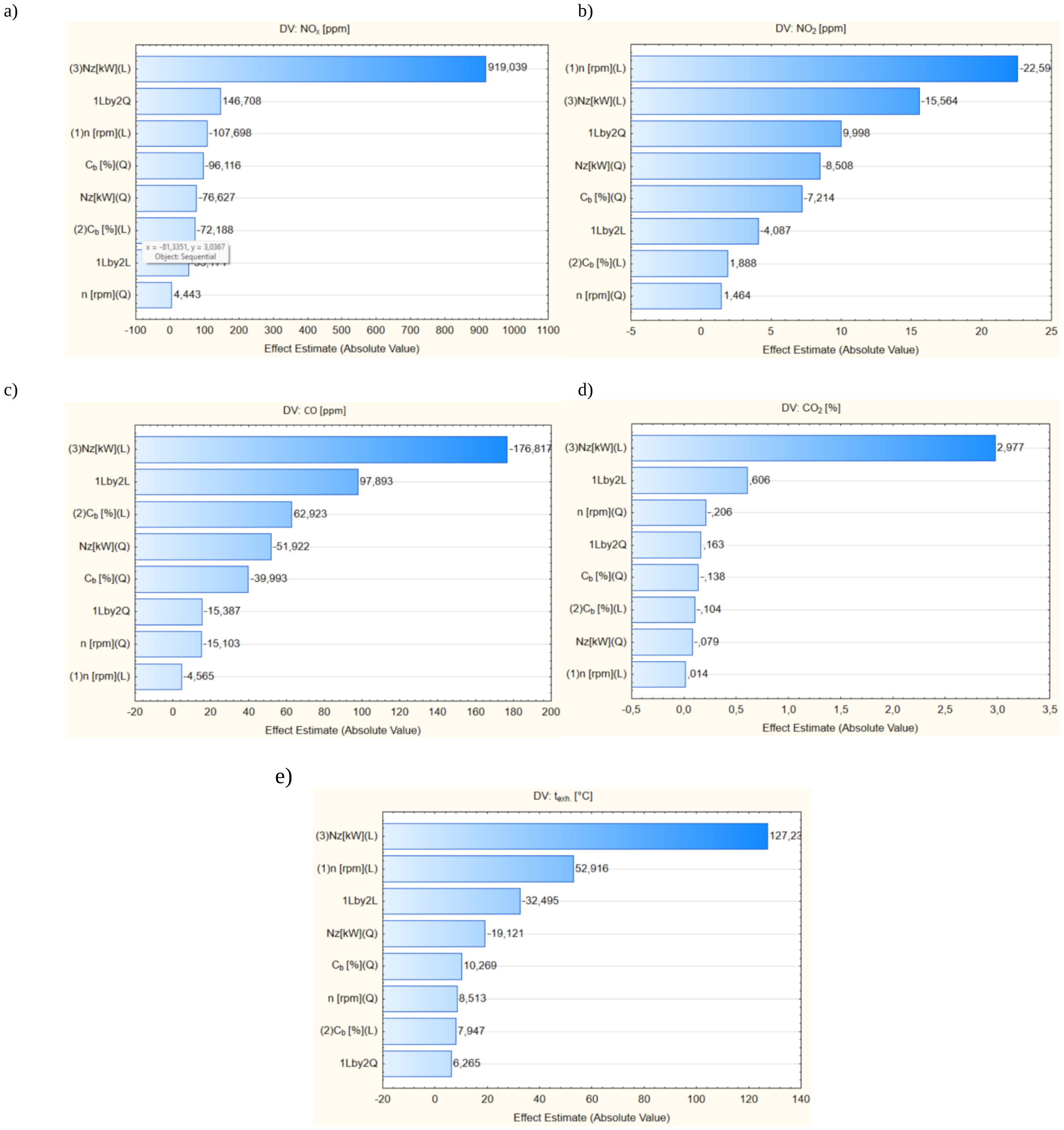

Fig. 6. Pareto charts of concentration of a) nitrogen oxide, b)) nitrogen dioxides, c) carbon monoxide, d) carbon dioxides, e) exhaust temperature

The ignition angle α_{ign} (Fig. 7) for an n-butanol-rich mixture decreases with increasing engine speed. It reaches a minimum in the range of $C_b \in \langle 25{,}35 \rangle$. Similarly, the maximum indicated pressure angle α_{pmax} (Fig. 8) for the same range of n-butanol concentration C_b decrease.

It follows that regardless of the set load, the ignition angles and maximum indicated pressure angle approached the TDC, which has a positive effect on the combustion process, efficiency (Fig. 9c), and reducing the level of toxic exhaust components (Fig. 10a–d).

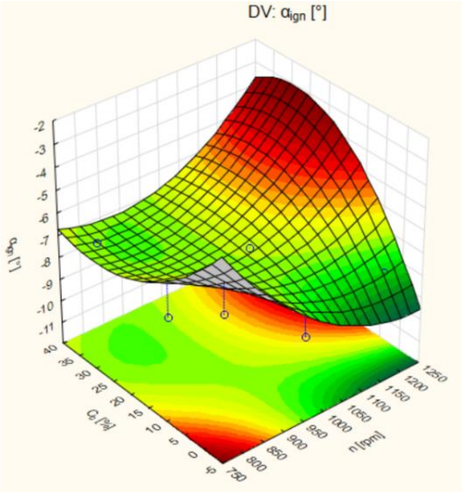

Fig. 7. Dependence of ignition angle on concentration of n-butanol and crankshaft rotational speed

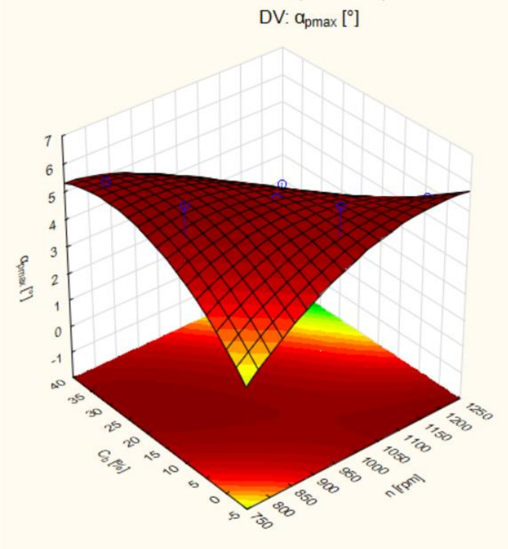

Fig. 8. Dependence of maximum indicate pressure angle on concentration of n-butanol and crankshaft rotational speed

The study showed that in the tested range of load and rotational speed, an increase in n-butanol concentration in the fuel mixture results in an increase in the load index, and thus greater fuel consumption (Fig. 9a–b). This means that the calorific value of the fuel mixture is lower compared to the marine fuel used, which is confirmed by the study of calorific values of the used mixtures (Fig. 2). However, it should be noted that the use of an n-butanol mixture resulted in an increase in engine efficiency (Fig. 9c).

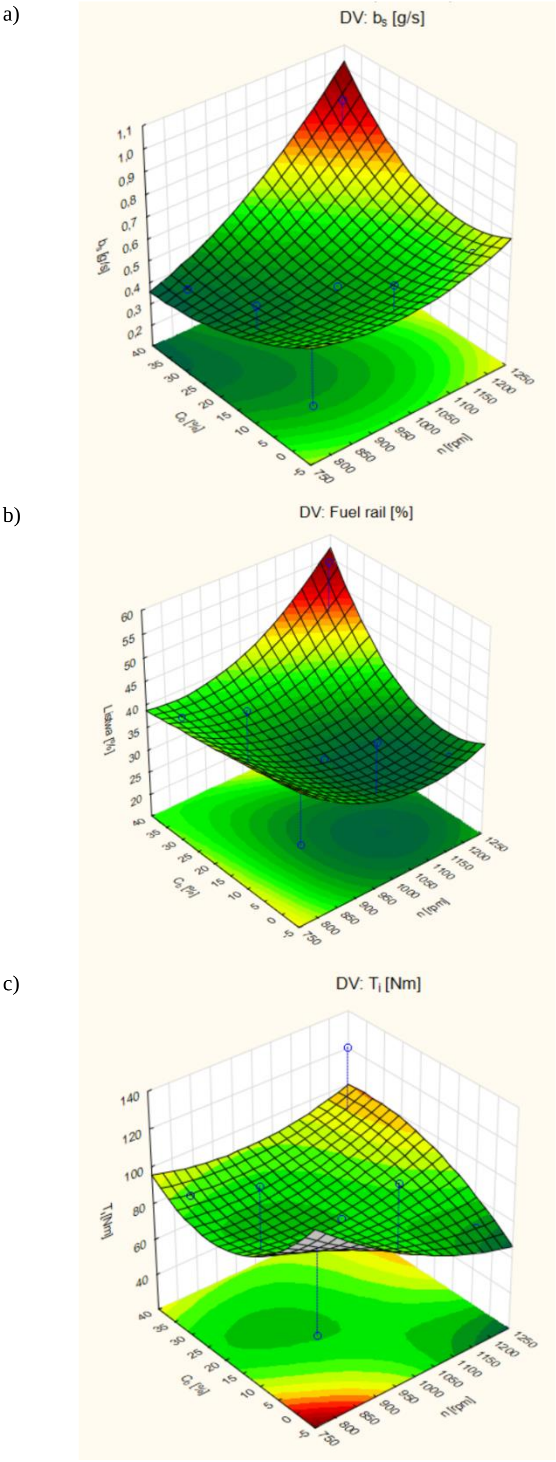

Fig. 9. Dependence of a) average fuel consumption, b) load indicator, c) indicated torque on concentration of n-butanol and crankshaft rotational speed

In the load and speed range studied, it was observed that raising the rotational speed resulted in a decrease in the concentration of both NO and NO_2 (Fig. 10a–b). This effect was particularly noticeable for NO_2. It should be noted that at low rotational speeds, the content of NO_x significantly increases for high C_b concentrations, which is related to the values of the ignition and maximum indicated pressure angles (Fig. 7, 8).

The influence of n-butanol content is visible for CO emissions (a significant increase for upper input limits) and $\mathrm{CO_2}$ – the gradient of the increase takes smaller values (Fig. 10c–d). The increase in CO concentration may be caused by the individual influence of specific carbon, hydrogen, and oxygen atoms in the structure of n-butanol and its mixture with the ship fuel [6].

The analysis of the research results also revealed the influence of the percentage concentration of n-butanol $\mathrm{C_b}$ on the oxygen content in the exhaust gases $\mathrm{O_2}$ and on the exhaust gas temperature $\mathrm{t_{spal.}}$. The decrease in exhaust gas temperature for $\mathrm{C_b} > 15\ \%$ at high rotational speeds is a desirable effect in military applications due to the limitation of thermal fields of tanks, vehicles, ships, and aircrafts.

3. Conclusion

Both empirical and model-based research indicates that it is reasonable to use fuel blends containing n-butanol. N-butanol positively affects the combustion conditions (α_{ign} and α_{pmax} angles approach TDC) and efficiency, which shows Fig. 9c. A promising aspect is also the decrease in the concentration of $\mathrm{NO_x}$, which has a positive impact on reducing the toxicity of exhaust gases. An important aspect of the passive defence of a vessel is the reduction of exhaust gas temperature under nominal loads.

The prospective results encourages to continue and expand the research. The focus will be put on optimizing the selection of n-butanol concentration in the fuel blend, introducing an additional component to the blend to minimize the concentration of toxic compounds in exhaust gases and confirming the use of fuel blends in military applications (minimizing the physical fields of ships, including the thermal field).

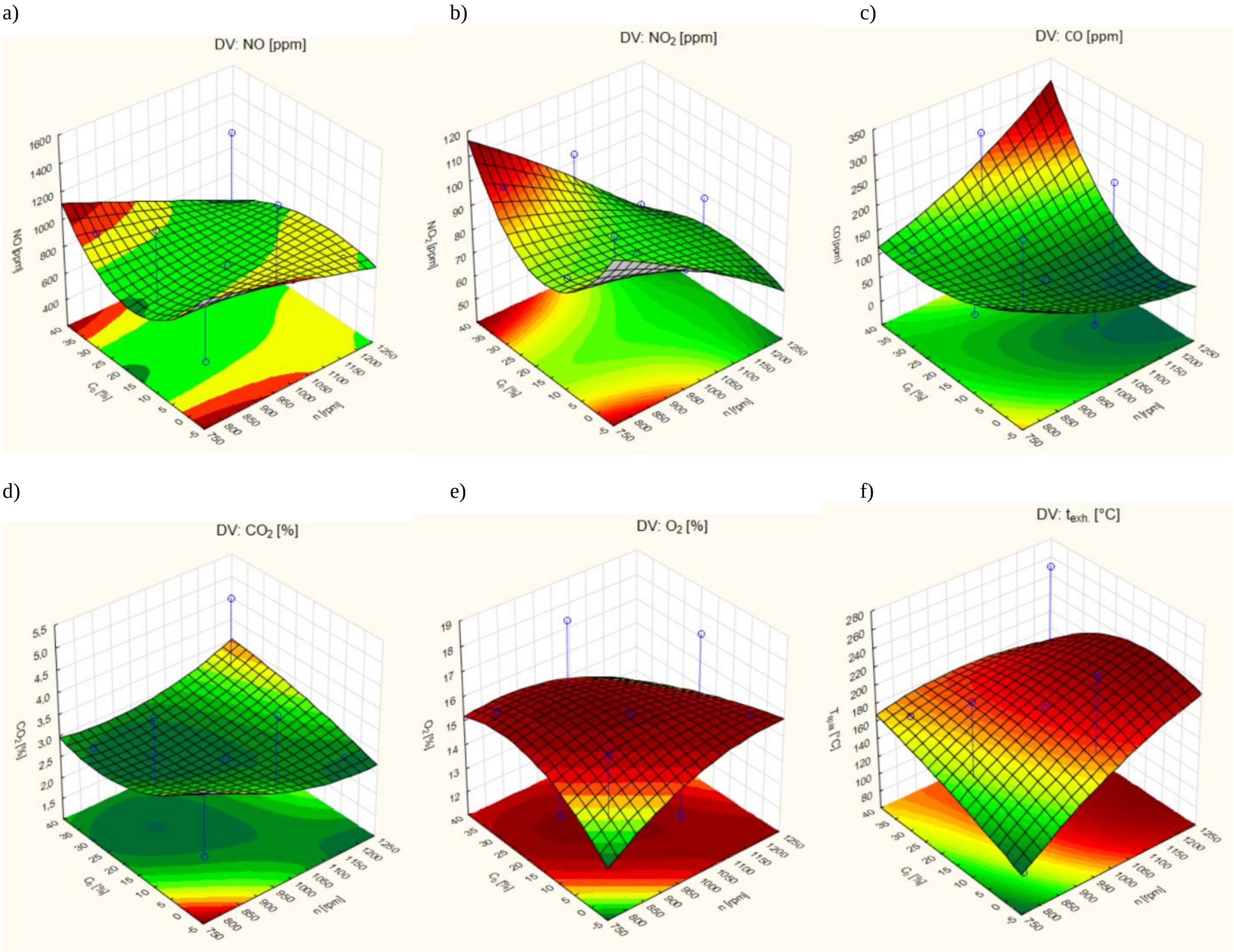

Fig. 10. Dependence of a) nitrogen monoxide, b) nitrogen dioxides, c) carbon monoxide, d) carbon dioxides, e) oxygen, f) exhaust temperature on concentration of n-butanol and crankshaft rotational speed

Nomenclature

ANOVA	analysis of variance
DV	dependent variable
DoE	design of experiments
IMO	International Maritime Organization
MTBE	methyl tert-butyl ether
TDC	top dead centre
RSM	response surface methodology

Bibliography

[1] Bata RM, Elrod AC, Rice RW. Emissions from IC engines fueled with alcohol-gasoline blends: a literature review, engine emissions, J Eng Gas Turbines Power. 1989;111(3):424-431. https://doi.org/10.1115/1.3240271

[2] Elfasakhany A, Mahrous A-F. Performance and emissions assessment of n-butanol–methanol–gasoline blends as a fuel in spark-ignition engines. Alexandria Engineering Journal. 2016;55(3):3015-3024. https://doi.org/10.1016/j.aej.2016.05.016

[3] Habrat W, Żółkoś M, Świder J, Socha E. Forces modeling in a surface peripheral grinding process with the use of various design of experiment (DoE). Mechanik. 2018;91(10):929-931. https://doi.org/10.17814/mechanik.2018.10.165

[4] Hydrogen bulk carrier, battery container ship. https://mlodytechnik.pl/technika/29907-masowiec-na-wodor-kontenerowiec-na-baterie

[5] Initial IMO Strategy on the Reduction of GHG Emissions From Ships. Resolution MEPC.304(72), 2018.

[6] Kniaziewicz T, Zadrąg R, Bogdanowicz A. Environmental characteristics of marine diesel engine fueled by butanol. Renewable Energy. 2022;182:887-899. https://doi.org/10.1016/j.renene.2021.10.068

[7] Korzyński M. Experiment methodology. Planning, implementation and statistical elaboration of the results of technical experiments (in Polish). Wydawnictwo WNT, Warsaw 2017.

[8] Kozak M. Exhaust emissions from a diesel passenger car fuelled with a diesel fuel-butanol blend. SAE Technical Paper 2011-28-0017. 2011. https://doi.org/10.4271/2011-28-0017

[9] Labeckas G, Slavinskas S, Rudnicki J, Zadrąg R. The effect of oxygenated diesel-n-butanol fuel blends on combustion, performance, and exhaust emissions of a turbocharged CRDI diesel engine. Pol Marit Res. 2015;25:108-120. https://doi.org/10.2478/pomr-2018-0013

[10] Lee RC. Effect of compression ratio, mixture strength, spark timing, and coolant temperature upon exhaust emissions and power. SAE Technical Paper 710832. 1971. https://doi.org/10.4271/710832

[11] Online Statistics Handbook. https://www.statsoft.pl/textbook/stathome_stat.html

[12] Otaka T, Kukisaki M, Fushimi K, Kinoshita E, Yoshimoto Y. Combustion characteristics of DI diesel engine fueled with marine diesel oil and 1-butanol blends. J Japan Inst Mar Eng. 2015;50(6):135-141. https://doi.org/10.5988/jime.50.840

[13] Pielecha I, Wierzbicki S, Sidorowicz M, Pietras D. Combustion thermodynamics of ethanol, n-heptane, and n-butanol in a rapid compression machine with a dual direct injection (DDI) supply system. Energies. 2021;14:2729. https://doi.org/10.3390/en14092729

[14] Puzdrowska P. Evaluation of the influence of the opening pressure of a marine diesel engine injector on the results of numerical simulation of the working cycle and their comparison with the results of the laboratory experiment. Combustion Engines. 2023;193(2):9-14. https://doi.org/10.19206/CE-155873

[15] Report: shipping accounted for 13.5 percent of greenhouse gas emissions from transport in the EU. https://www.cire.pl/artykuly/serwis-informacyjny-cire-24/raport-zegluga-odpowiadala-za-135-proc-emisji-gazow-cieplarnianych-z-transportu-w-ue

[16] Rychter W. Dzieje samochodu. WKiŁ, Warszawa 1983.

[17] Sriram SSP, Bata RM. A performance study of iso-butanol-, methanol-, and ethanol-gasoline blends using a single cylinder engine. SAE Technical Paper 932953. 1993. https://doi.org/10.4271/932953

[18] Sriram SSP, Bata RM. A technical assessment of alcohol fuels – alternate fuels Committee of the Engine Manufacturers Association. SAE Technical Paper 820261. 1982, https://doi.org/10.4271/820261

[19] Tipanluisa L, Thakkar K, Fonseca N, Lopez J-M. Investigation of diesel/n-butanol blends as drop-in fuel for heavy-duty diesel engines: Combustion, performance, and emissions. Energ Convers Manage. 2022;255:115334. https://doi.org/10.1016/j.enconman.2022.115334

[20] Wang SY, Yao L, Zhang JD. Homogeneous charge compression ignition combustion and emissions of methyl decanoate and n-butanol in low-speed diesel engine. Tuijin Jishu/Journal Propuls Technol. 2020;11:2558-2565. https://doi.org/10.13675/j.cnki.tjjs.200367

[21] What is a planned experiment and can almost anything be improved with it? https://sigmavalue.blog/planowany-eksperyment-doe/

[22] Zhang Z, Tian J, Xie G, Li J, Xu W, Jiang F et al. Investigation on the combustion and emission characteristics of diesel engine fueled with diesel/methanol/n-butanol blends. Fuel. 2022;314:123088. https://doi.org/10.1016/j.fuel.2021.123088

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