Determining of optimum operation modes of a diesel engine with a multi-component bio-fuel composition

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Abstract. A problem of reduced number of tests was identified during the determining of optimal load and speed performance of a diesel engine with a multi-component bio-fuel composition. The planning method of the experiment for determining of effective ICE performance was improved. For factor space description, graph analyses were carried out using a semi-rotatable 2nd order Box-Behnken statistical design for three factors. The operation studies of a 4ChN 11,0/12,5 diesel engine were performed with the most stable multi-component bio-fuel composition, including the following ingredients, % wt.: RSO – 34.5; ethanol – 31.0; DF – 34.5. The analysis of regression models and 2D sections of response surfaces provided for determining of the optimum advance angle of fuel injection $\theta_{\text{adv}} = 23.5$ deg. to TDC. By method of superposition of the 2D sections of the response surfaces of the effective efficiency $\eta_e$ and the specific effective fuel consumption $g_e$, a search for a compromise solution on optimum combination of the levels of the factors to be studied. It was found out that the optimum area of the combination of factors is located in the range of the crankshaft rpm $n = 1400...1550$ min$^{-1}$ of the diesel engine and in the effective load range $P_e = 0.68...0.85$ MPa. Under recognition of the variable nature of the load and speed modes of a diesel engine in a real operation environment, the obtained data are of practical interest.

1. Introduction
Among all known alternative energy sources, a special role is assigned to bio-fuels [1-4]. They are usually manufactured from renewable vegetable and animal origin [5], due to that they arouse keen interest of investigators. Due to substantially different physical and chemical properties of bio-fuels from those of the conventional diesel fuel (DT) [6] an adaptation of ICE design is required. The most acceptable way could be the extended applicability of alternative fuels due to the properties of bio-fuels getting closer to DF properties. Using multi-component bio-fuel compositions can also compensate the deviation of the motor property of one ingredient on account of the other one. As a result of prolonged tests, the following composition of the multi-component bio-fuel was recommended, % wt.: RSO – 34.5; ethanol – 31.0; DF – 34.5 [7]. The stability of the above-mentioned composition to coalescence is up to 35 hours. The use of the recommended composition makes it possible to preserve the viscosity/temperature properties of the bio-fuel composition at ambient temperature changes in the framework of the standard in effect [8].

For thorough analysis of the working processes in the diesel engine, modern methods of experiment planning look attractive. It allows for clear definition of admissible operation ranges of the engine at considerably reduced number of test points. Besides that, a possibility appears for assessment of the influence of certain operation mode factors on the other operation mode factors.
2. Literature Review

In paper [9], an algorithm is reported to have been developed for optimization of multi-factor test plans by branch-and-bound method with introduced limitation by an additional criterion. The algorithm allows for accounting of the limiting criterion, superimposed, e.g., on the temporal realization of the plotted plan of the multi-factor experiment, or on the plan value number. The realization of the reported algorithm makes it possible to find two alternative plans: with the minimum value of the first criterion; with the minimum value of the additional limiting criterion.

For analytical and graphical description of the processes under test, as well as for studies of the influence of the factors on the optimization criteria as well as for the search for an optimum combination of the factors under study, paper [10] reports on use of the response surfaces method. Based on the analysis of the obtained data, it appeared possible to model the parameter scattering of transistors during manufacturing.

The authors of paper [11] were studying the composition of Bentonite used in self-reinforced cement for improvement of its purposes. Using of Box-Behnken statistical design of the test allowed for determining of an optimum combination of ingredients in the self-reinforced cement to obtain the maximum compression strength (above 45 MPa). It was found out that the cement composition shall contain 20% of Bentonite, with 0.45 water-to-powder ratio.

The Department of Technologies of the University of Nis [12] reports on studies on optimization of sunflower oil methanolysis conditions in an ultrasonic reactor. Based on Box-Behnken statistical design of the experiment, response surfaces were obtained. The conducted qualitative analysis of the results has delivered a trustworthy substantiation of the temperature value of about 40°C, of 0.7% wt catalyst quantity, of 92.2% wt. of fat-acid methyl ethers (FAME) content and of 7.5:1 methanol-to-oil ratio.

The authors of paper [13] studied the operation mode of an inductor including the following parameters: frequency (f), gap (h) and flux density (J). The planning method of the experiment based on Box-Behnken statistical design, the following optimum combination of factors was identified: f = 1000 Hz, h = 5 mm, J = 45 mm, to provide for the required inductor performance under conditions defined by the process mode.

Paper [14] reports on a study of wheat gluten hydrolysis process (moisture content: 6.8%, protein content (N 5.70): 78.52% in terms of dry substance). Gluten is used for bread quality improvement, as well as as functional protein supplement in various non-bakery products for their structural improvement. The utilization of Box-Behnken statistical design of the experiment enabled the authors to find optimum working process parameters for ferment hydrolysis of wheat gluten. The data have demonstrated that optimum functional properties of gluten hydrolysates may be achieved at a reaction temperature equal to 40°C, pH = 9 and at a ferment-gluten ratio equal to 0.5 a.u./g of gluten.

The authors of paper [15] report on a study of lead removal process from coal (leaching) excavated in Enugu, using different acids as leaching agents in different conditions. The leaching of coal samples prior to combustion or use in a power plant is required to remove the most part of microelements in this coal to mitigate the risk of environment pollution. Based on orthogonal Box-Behnken statistical design of 2nd order, parameters were obtained allowing for maximum lead removal. It was found out that nitric acid HNO3 in 0.5 mole concentration should be used, thereby, the leaching time is 32 hours with 63 μm admissible particle size of the coal and the required volume of the leaching agent not exceeding 40 ml (solid/liquid ratio).

3. Research objectives

The objective of the study was to determine admissible mode performance specifications of a diesel engine with a multi-component bio-fuel composition.

The mission of the study was to determine the most efficient fuel injection advance angle, optimum load and speed operation ranges of the diesel engine.
4. Methods and materials

General appearance and list of equipment and instruments, see figures 1, 2 and Table 1.

**Table 1.** Instrumentation and equipment as part of experimental fixture.

| Type of test          | Equipment                        | Designation     | Note                     |
|-----------------------|----------------------------------|-----------------|--------------------------|
| Time of physical      | Stop-watch                       | SOP Pr-2a-2-010 | "AGAT" Accuracy ± 0.1 sec|
| stability             |                                  | "AGAT" Accuracy |                          |
| Bench tests           | Automotive/tractor diesel engine | D-245.S2        | Power 70 kW              |
| Fuel efficiency       | Flowmeter                        | ACE-50          | Accuracy ± 1 %           |
| Frequency of rotation | Tachometer                       | AVL DIS-speed 492 | Accuracy ± 5 rpm         |
| Loading of diesel     | Scale                            | RAPIDO          | Error ± 0.2 kg           |
| engine                |                                  |                 |                          |

**Figure 1.** Control panel of diesel engine.  
**Figure 2.** Diesel engine D-245 in the test bench.

The laboratory tests of the stability assessment of the bio-fuel composition were carried out in the chemical laboratory of FGBOU VO Vyatka State University. Experimental studies were carried out in the test laboratory of UO Byelorussian State Agricultural Academy.

For description of the factor space with regression models, revealing of regularities of the influence of the loading and the speed mode of the diesel engine on its performance (effective efficiency $\eta_e$, specific effective fuel consumption $ge$) and determining of optimum factor values, a semi-rotatable Box-Behnken statistical design of 2nd order was selected and implemented for three factors. Factors and their levels (Table 2) were selected by a priori ranking method based on the results of one-factor experiments.

**Table 2.** Factors, levels of fixation and intervals of their variation.

| Coded designation of factors | Names of factors, their designations and units of measure | Levels of factors | Intervals of variation |
|-----------------------------|----------------------------------------------------------|-------------------|------------------------|
| $x_1$                       | Effective loading, $P_e$, MPa                            | 0                 | 0.47 0.94 0.47         |
| $x_2$                       | Rotation frequency of the crankshaft, $n$, rpm            | 1.40 1.60         | 1.800 200              |
| $x_3$                       | Advancing angle $\Theta$ of fuel injection, deg.         | 10 18 26           | 8                      |

The statistical processing of the experimental data, the calculation of regression coefficients, the plotting of the response surfaces and their 2D sections were realized by means of "STATGRAPHICS+" software [16].
5. Result and discussion

As a result of the experimental series of the test design, trustworthy (р = 0.95 after Fisher's F-criterion) [17,18] models of a 2nd order regression analysis of effective efficiency $\eta_e$ measurement and $r$=the specific effective fuel consumption $g_e$ measurement were obtained:

$$\eta_e = 33.0 + 15.3x_1 - 1.3x_2 + 0.5x_3 - 12.3x_1^2 - 0.7x_1\cdot x_2 + 0.6x_1\cdot x_3 - 0.06x_2^2 - 0.1x_2\cdot x_3 - 0.7x_3^2$$  

(1)

$$g_e = 258.7 - 230.6x_1 + 9.8x_2 - 3.8x_3 + 208.1x_1^2 + 4.3x_1\cdot x_2 - 4.2x_1\cdot x_3 + 0.3x_3^2 + 0.6x_2\cdot x_3 + 4.8x_3^2$$  

(2)

After exemption of negligible coefficients from the regression models (1) and (2), and inclusion of the rest coefficients, get the following appearance:

$$\eta_e = 33.0 + 15.3x_1 - 1.3x_2 + 0.5x_3 - 12.3x_1^2 - 0.7x_1\cdot x_2 + 0.6x_1\cdot x_3 - 0.7x_3^2$$  

(3)

$$g_e = 258.7 - 230.6x_1 + 9.8x_2 - 3.8x_3 + 208.1x_1^2 + 4.3x_1\cdot x_2 - 4.2x_1\cdot x_3 + 4.8x_3^2$$  

(4)

The analysis of the regression models (3) and (4) demonstrates (fig. 3) that in the experimental area of studies, the maximum value of the effective efficiency $\eta_e$ = 39.6%, whereas the minimum specific effective fuel consumption $g_e$ = 180.2 g/kWh is observed at almost equal values of the factors being studied.

Thus, the maximum efficiency $\eta_{max}$ is achieved at $x_1 = 0.7$ ($P_e = 0.66$ MPa), $x_2 = -1$ ($n = 1,400$ rpm) and $x_3 = 0.6$ ($\Theta_{inj} = 23.5$ deg. to TDC). The minimum value of the specific effective fuel consumption $g_{min}$ is obtained at the following factor values $x_1 = 0.6$ ($P_e = 0.56$ MPa), $x_2 = -1$ ($n = 1,400$ rpm) and $x_3 = 0.6$ ($\Theta_{inj} = 23.5$ deg. to TDC).

The obtained results rest on real physical sense. The presence of ethanol and rapeseed oil in the multi-component bio-fuel composition causes a certain reduction of its total cetane number. During the operation of the diesel engine, a growth of the fuel ignition delay period will be observed, as well as the shift of the combustion beyond the TDC. To compensate the occurring processes, a certain upturning of the advance angle of fuel injection relative to its standard value $\Theta_{inj} = 22$ deg.

The operation of the automotive/tractor diesel engine is the most efficient in overload mode, that is, in the crankshaft rpm decrease range from the rated value $n = 1,800$ rpm down to the maximum torque rpm $n = 1,400$ rpm.

Naturally and significantly, both the effective efficiency $\eta_e$, and the value of the specific effective fuel consumption $g_e$, are influenced by the change of the effective load $P_e$. Thereby, the dependency curves of the parameters $\eta_e$ and $g_e$ on the parameter $P_e$, demonstrate a kink at $P_e = 0.5…0.7$ MPa and a variance of the two remaining factors across the entire experiment area.

This result can be explained by the circumstance that the most economical operation of a piston ICE is usually obtained in the loading range of 60…80% of the rated load.
Figure 4. Dependences of effective efficiency $\eta_e$ (a) and specific effective fuel consumption $g_e$ (b) on effective load $P_e$ and crankshaft rpm value $n$ at advance angle of fuel injection $\Theta_{inj} = 23.5$ deg.

For example, at diesel engine crankshaft rpm $n = 1,400$ rpm and advance angle of fuel injection $\Theta_{inj} = 23.5$ deg to TDC, a change of the effective load from 0.47 MPa to 0.6 MPa leads to an increase of the effective efficiency $\eta_e$ from 5.6% to 39.6% and to the decrease of the specific effective fuel consumption $g_e$ from 694 g/kWh to 180 g/kWh (fig. 4). At further growth of the effective load $P_e$ up to 0.94 MPa, the value of the effective efficiency $\eta_e$ goes back to 38.2%, whereas the value of the specific effective fuel consumption $g_e$ grows up to 220 g/kWh.

A search for a compromise solution of an optimum combination of the level of the studied factors was carried out by the method of superposition of 2D sections of the response surfaces of the effective efficiency $\eta_e$ and the specific effective fuel consumption $g_e$ (figure 5).

Figure 5. Bidimensional sections of response surfaces of effective efficiency $\eta_e$ (——) and specific effective fuel consumption $g_e$ (− − −) at advance angle of fuel injection $\Theta_{inj} = 23.5$ deg.

It is evident that the optimum area of the combination of the studied factors (shaded area in fig. 5) is located in the variable crankshaft rpm range of the diesel engine $n = 1,400...1,550$ rpm and in the variability range of the effective load $P_e = 0.68...0.85$ MPa at advance angle of fuel injection $\Theta_{inj} = 20...25$ deg. to TDC. At such combination of the factors, an almost practical effective efficiency $\eta_e$ in the experimental range (at least, 38%) at a low specific effective fuel consumption $g_e$ of max. 200 g/kWh is provided for.

Conclusions

For description of the factor space and reduction of the number of tests during the determining of optimal load and speed performance of a diesel engine with a multi-component bio-fuel composition, the method of experiment design was improved.
The optimum area of the combination of the factors is located in the variable crankshaft rpm range of the diesel engine $n = 1,400 \ldots 1,550$ rpm and in the variability range of the effective load $P_e = 0.68 \ldots 0.85$ MPa at advance angle of fuel injection $\theta_{inj} = 23.5$ deg. to TDC.

Under recognition of the alternating nature of the load and the speed modes of the diesel engine in real operation environments, the data of diesel engine operation as part of a traction vehicle are of practical relevance.

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