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EXPERIMENTAL RESEARCH ON DIESEL ENGINE WORKING ON A MIXTURE OF DIESEL FUEL AND FUSEL OILS

Summary. This article considers the possibility of spirit fusel oil being used as an addition to agile fuels. Results of experimental research on diesel engines working on mixtures of diesel fuel and fusel oils are given. The fuel economy and ecological indexes of engines working on mixtures of diesel fuel and fusel oils were improved.

1. INTRODUCTION

In the foreseeable future, motor transport will be powered using oil as the main raw material. Consequently, in the production and consumption of motor-car fuels, there is a need to find solutions to the dilemma of saving valuable resources and search for alternative sources of raw material, together with finding solutions to reduce negative impacts on the environment.

From the results of the analysis of the most prospective types of alternative fuels for combustion engines conducted by the authors from the perspective of resource saving, optimal utilization of harmful industrial wastes, and improvement of technical-operating indexes of the performance of combustion engines, the possibility of using alcoholic fusel oils as additions to agile fuels was evaluated [1].

Experimental research on the operating indexes of different types of fusel oils containing mixtures of petrol and diesel were conducted by the authors earlier [1]. The research studies show that there are certain optimum compositions of mixtures; the economic impact of the use of such fuels was studied on a petrol engine, and a research of ecological indexes from their work was conducted on the modes of idling.

The research studies cited aimed to estimate the impact of addition of fusel oils to diesel fuel on basic technical, operating, and ecological parameters in a diesel engine Д21А1.

2. REVIEW OF THE LITERATURE

Paper [2] is devoted to the determination of the efficiency of a diesel engine’s working and to the research of changing troop landings of harmful matter with exhaust gases while using bio-diesel fuel. During the test, the proportion of bio-diesel fuel in a mixture ranged from B0 (oil-diesel fuel) to B10, B20, B30, B50, and B100. The results show that there is a decline in troop landings of hard particles while using mixture B10 and a sharp reduction of troop landings of oxide to hydrocarbon while using mixture B20. The results also showed a reduction in troop landings of oxides of nitrogen.

Changes in technical, economic, and ecological indexes of engines working on a combination of diesel fuel and sunflower-seed oil and that of diesel fuel and oil were studied in paper [3].

The results of this research show that troop landings of oxides of carbon CO diminish but the troop landings of carbon dioxide CO_2 and oxides of nitrogen NO_x multiply; torque and engine power reduce on average by 5.87 % and the specific expense of fuel increases by 9.07 % on average.

Paper [4] studied the influence of harmful matter in exhaust gases on troop landings during bio-diesel fuel use in trucks.

The results show that using a mixture of diesel and bio-diesel fuel (B35) (35% bio-diesel fuel and 65% diesel fuel) leads to a reduction in troop landings of oxides of carbon SO to 12% on average [4]; this results in better working of the cylinders of the engine due to higher oxygen levels in bio-diesel fuel.

Using a mixture of diesel and bio-diesel fuel (B35) results in a concentration of troop landings of hard particles in exhaust gases of 25%. It is necessary to note that an insignificant increase in troop landings of oxides of nitrogen NO_x, achieved by a mixture of diesel and bio-diesel fuel, has shorter time of delay of occupation.

Consequently, using a mixture of diesel and bio-diesel fuel in the engines of cars is suitable in auto transport. According to the data derived by many researchers, diesel and bio-diesel fuel can interfuse well with each other in any proportion and form a stable mixture [5]; however, long-term storage of such a mixture is impossible because of the difference in densities of these fuels, which leads to its division into layers.

Y. He and Y.D. Bao, in study [6], assert that a mixture of 70% diesel and 30% bio-diesel (B30) is optimum for effective working of a car engine and for stability and homogeneity of the mixture.

Research paper [7] is devoted to addressing specific expenses of mixture B30 in terms of four regulated parameters: corner of closing of the induction valve, corner of opening of the final valve, corner of passing of injection of fuel, and pressure of injection. Analysis of the literature shows that the most important parameter that affects the specific expense of the mixture of fuels is the corner of passing of injection.

Biodiesel, defined as the monoalkyl esters of long-chain fatty acids, has received considerable attention worldwide as an alternative to pure diesel fuel made from petroleum. The techno-economic aspect of using bio-diesel fuel from vegetable oils was analyzed in studies [8, 9]. These studies explored the dependence of critical indicators of profitability from production capacity.

Considerable attention is now being given to bio-diesel fuel with the use of bioethanol produced from biomass, as it does not interfere with the food industry and can provide raw material at a low price. The University of Florida conducted an analysis on the production of ethanol from sugarcane [10].

The use of ethanol obtained from fermented barley straw is analyzed in [11]. The main obstacles to the hydrogen process are its low productivity and low energy efficiency.

Study [12] conducted a techno-economic analysis of using ethanol derived from cellulose in ionic liquids [12]. It is a relatively new technology for the production of bioethanol from biomass. Its drawback is that ionic liquids are expensive.

It is thus clear from the results of the literature research that the mixing of diesel fuel with alternative fuels is promising as it does not entail substantial changes in the system of engine feeding and it improves some of the indexes.

Prospective alternative fuels are mixtures of commodity fuels and matter. They have physical-technical characteristics similar to commodity fuels, they are a good source of raw material, and they are inexpensive. Fusel oils, which are waste matter from the alcohol industry and harmful to the environment, possess such qualities. Alcohol plants in Ukraine accumulate fusel oils averaging 3.5 – 4.5 thousand m^3 in a year.

The real problem lies in determining the optimal quantity of fusel oils to be used; further, the application of new technologies for the use of fusel oils as additions to motor fuels, in particular to diesel fuel, remains an unsolved dilemma.

3. MATERIAL RESEARCH

Research methods were developed taking into account the basic physical and chemical properties of fusel oils. All experiments in this work were executed on the fusel oils of the Ivano-Frankivsk regional state association of alcoholic and liqueur-vodka distillery industry "Knyagynyn". Basic properties of the fusel oils were determined in a chemical laboratory of the enterprise (tab. 1). Indexes of fusel oils are given in tab. 1 and they approximate to descriptions of commodity motor fuels.

Table 1

Basic physical and chemical properties of fusel oils

Name of index	Experimental values
Temperature limits of distillation at pressure 101,325 kPa (760 mm Hg), not less	120
Density at 20 ºC, kg/m^3, no more	834
Viscidity, m^2/s	$4{,}44 \cdot 10^{-6}$
Component composition of fusel oils, %: - ethanol; - n-propanol; - izoboutanol; - izoamilol; - water;	 9 15 11 57 8
Pressure of saturated steam, mm Hg	44
Acidity, pH	5,7
Indexes of refraction, n_d^{20}	1,397
Spark temperature, ºC	42
Temperature of spontaneous combustion, ºC	-
Low heat of combustion, kJ/kg	34240

The process of mixing fusel oils with a commodity diesel fuel was carried out in an old closed tub using a mixer with an electric drive for 5 min. This duration was enough for complete dissolution of fusel oils in the diesel fuel. Mixing was performed at temperatures of 20-21 ^{o}C and atmospheric pressures of 735-740 mm Hg.

Complete dissolution of fusel oils in the diesel fuel was ensured. The formed mixtures were maintained in hermetically closed old glass tubs for 30 days at a temperature of 21 ^{o}C. At these conditions, storage of the mixtures was not fixed; stratifications of commodity fuel and fusel oils and non-homogeneities in all volume of mixtures were observed.

To confirm adherence to technical-economic and operating indexes and to test the possible application of such fuel mixtures on an engine, it is necessary to carry out comparison of basic indexes of the working of an engine on a clean fuel and on fuel mixtures. Using the most optimum compositions of mixtures of diesel fuel and fusel oils, as given by authors, research on the composition of exhaust gases of the experimental diesel engine D21A1, a short technical description of which is given in tab. 2, was performed.

A diagram of the experimental plant is given in fig. 1. Loading for a diesel engine (5) is created by a fourfold compressor (9) (model K-5M); power on the compressor billow is regulated in the range of 2 to 34 kW, which allows a load of 100% on the diesel engine. Torque from the engine to the compressor is passed by the box of transmissions (5) and by the carding transmission (7).

For determination of mass expense of fuel *according to experimental plant diagram at figure 1* weight (1) for a tank with fuel (2) is used. We measured the volume of air expended using a gas-meter (4).

We expect the sentinel expense of fuel to follow the formula:

$$G_T = \frac{\Delta G_T \cdot 3{,}6}{\tau}, \qquad (1)$$

where ΔG_T is the expenditure of fuel during the course of the experiment; and g; τ is the duration of the experiment, in s.

Table 2

Brief technical description of diesel engine D21A1

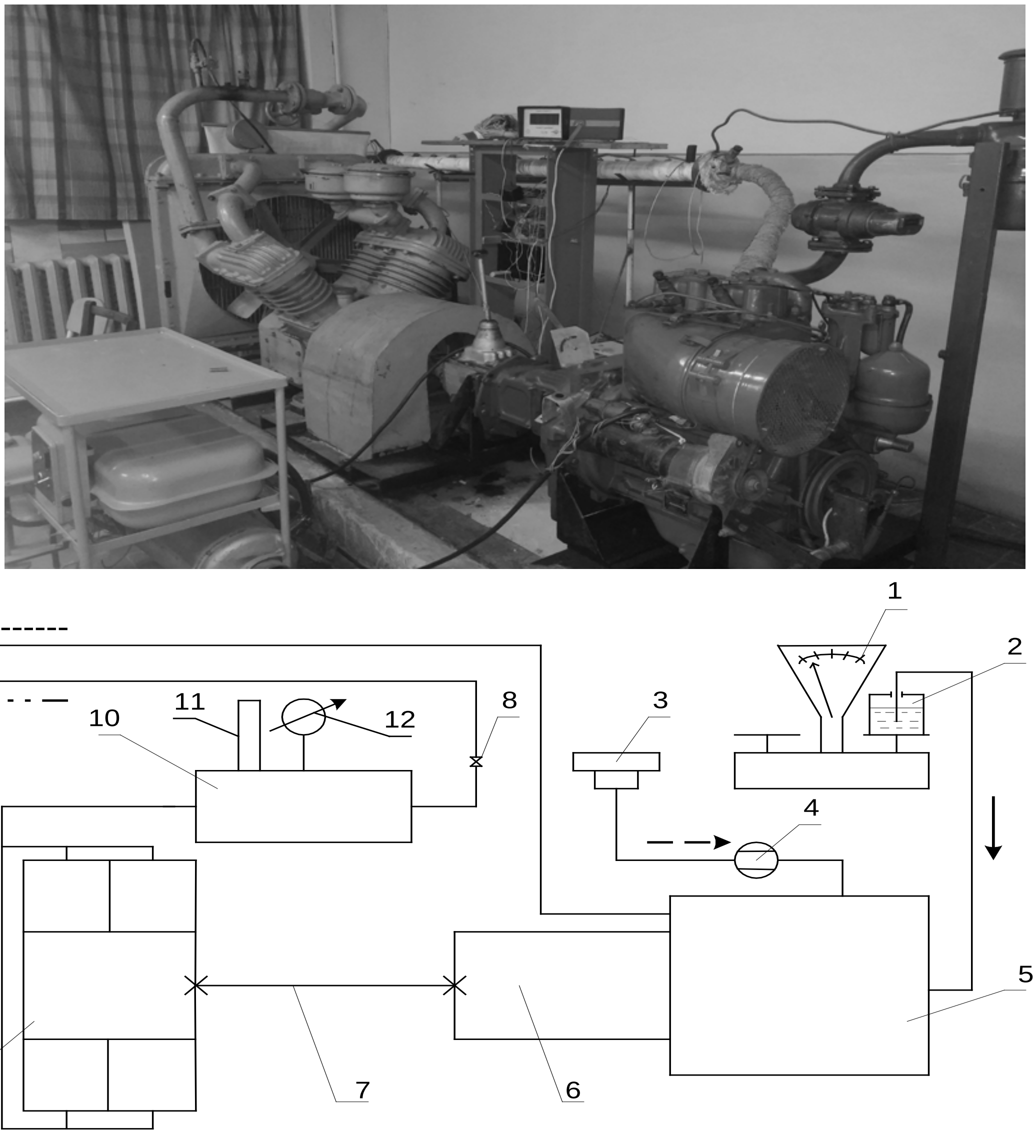
№	Name of parameter	Units of measuring	Value
1	Type of diesel	-	Fourfold
2	Method of mixture formation	-	Inseparable combustion chamber with the direct injection of fuel.
3	Direction of rotation of crankshaft	-	Right (clockwise).
4	Operating engine (capacity) horse power	kW h.p.	18 25
5	Specific expenditure of fuel	g/ kW·h g/h.p.·h	253 186
6	Frequency of rotation of engine crankshaft at operating capacity	rev./min.	2800
7	Frequency of rotation of engine crankshaft on idling: a) maximal b) minimum	rev./min.	 2950 800
8	Mass of diesel (no less than)	kg	280

Fig. 2 shows the external speed description, which was built as a thermal calculation of the diesel engine D21A1, using a clean fusel oil and clean diesel fuel as the fuel source. Shaded regions in the graph of fig. 2 specify the change in indexes of the working of the engine. As seen in fig. 2, the working of the diesel engine on fusel oils is accompanied by a partial loss of power Ne, torque Me, growth of sentinel expense of fuel Gt and specific expense of g. Such a change in indexes of the working of the engine is explained by the lower heat of combustion of fusel oils in comparison with diesel fuel.

Taking into account the optimum composition of the fuel mixture [3] and the engine on which research is conducted containing only 6% fusel oil by volume, the impact of diesel on power is insignificant.

Technical indexes of modern diesel engines – namely, their measure of compression and high speed – allow increasing the volume of fusel oils in a fuel source by 10-15 %, which will lead to an improvement in fuel economy by 15%. It is also possible to improve the economy in fuel usage by utilizing diesel fuel of low quality in the fuel mixtures, with low cetane number improving the value of the given indexes by addition of a greater amount of fusel oils.

Cetane number of fusel oils of Ivano-Frankivsk regional state association of alcoholic and liqueur-vodka distillery industry "Knyagynyn" is approximate 70-71 units. So, for creation of fuel mixtures of fusel oils and diesel fuel a domestic summer diesel fuel is taken as its cetane number has the lowest value and during formation of mixtures and incineration of them the maximal quantity of fusel oils will be utilized in a diesel engine. Cetane numbers were measured using an octanometer (model PE-7300). On the basis of the results of the research, we built graphic dependences of the cetane number of diesel-fuel mixture with fusel oils from the volume maintenance of fusel oils V_{fo} (fig. 3).



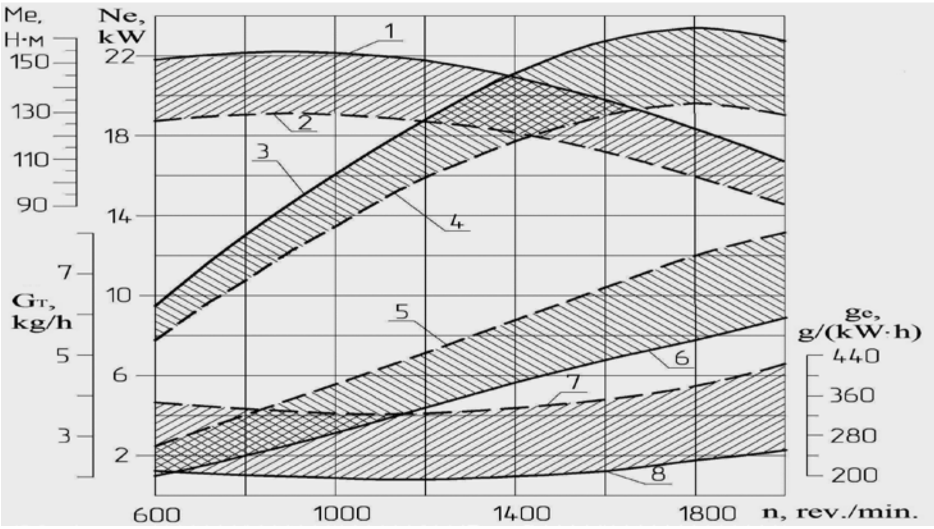
⟶ – direction of motion of fuel in the system of feed; – – ▸ – direction of motion of air in the system of feed; – · ⟶ – motion of air to receiver; ◂ · · – – motion of air in to an environment; ◂-------- – motion of exhaust gases in an environment; 1 – weight; 2 – tank for fuel; 3 – air filter; 4 – gas-meter; 5 – diesel engine; 6 – gear-box; 7 – carding transmission; 8 – valve; 9 – compressor; 10 – receiver; 11 – mercury thermometer; 12 – manometer.

Fig. 1. External appearance and diagram of the experimental plant for research of ecological indexes of diesel working on fuel mixtures

On the basis of the results of the cetane numbers of diesel fuel mixtures and fusel oils, the following equation was obtained:

$$Cet = 49{,}9 - 0{,}1366V^2_{fo} + 2.5532V_{fo}, \qquad (2)$$

where *Cet* is of diesel fuel mixtures and fusel oils.



—— – curve of change of parameters in the engine while functioning on diesel; – – – – curve of change of parameters in the engine while functioning on fusel oils; 1, 2 – the crooked changes of torque; 3, 4 – the crooked changes of power; 5, 6 – the crooked changes of sentinel expense of fuel; 7, 8 – the crooked changes of specific expense of fuel

Fig. 2. External speed characteristic of diesel D21A1 while functioning on diesel fuel and fusel oils

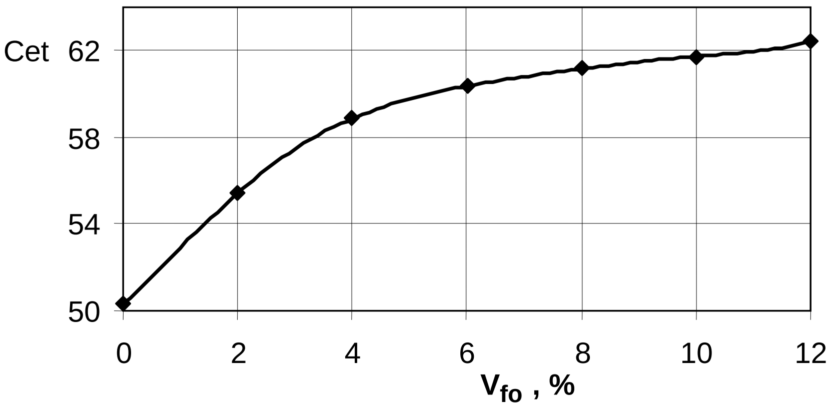


Fig. 3. Experimental dependence of cetane number Cet of the mixture of diesel fuel with fusel oils by volume maintenance of fusel oils (V_{fo})

Increasing of cetane number according to increasing of maintenance of fusel oil gets to facilitation of starting of diesel engine and increases of maximal pressure of combustion fuel. The considerable increasing of cetane number indicates increasing of the specific expense of the fuel, toxic smoke and exhaust gases. According to this index, the optimum proportion of fusel oils in diesel fuel is 4-10% of volume. As a result of the advances made in diesel engines, the measure of compression in them is multiplied, which allows the use of diesel fuel with a higher cetane number. Therefore, in the high-forced engines of passenger cars, it is possible to heave up the proportion of fusel oils in diesel fuel to 12%.

For the sake of financial viability of efficiency of using fusel oils as a part of diesel fuels at economic efficiency of addition of fusel oils financial charges on a fuel influence to the commodity diesel fuels at that time both other charges in the process of exploitation of car (on an olive, depreciation deductions, repair, burden costs, charges on motor-car tires and others like that) as on a commodity fuel and on the mixture of commodity fuel with fusel oils will be practically identical.

The expedience of the addition of fusel oils to diesel fuel was determined by the formula:

$$P_f \geq (P_{fm} \cdot g_{fm} + P_{fo} \cdot g_{fo}) \cdot k, \quad (3)$$

where P_f – retail price of one ton of commodity fuel equivalent to cetane number of fuel mixtures of commodity fuel with fusel oils, $ /t; P_{fm} – retail price of one ton of commodity fuel used in fuel mixtures, $/t; P_{fo} – retail price of one ton of fusel oils, $ /t. In calculations the accepted cost of one ton of fusel oils is – 290 $/t (from data of state business concern "Ukrspirt" by the state on 01.06.2016); g_{fm} – mass particle of commodity fuel in an alternative fuel; g_{fo} – mass particle of fusel oil in an alternative fuel; k – coefficient, which takes into account the increase in the expense of an alternative fuel, which is determined from the heat balance that is contained in a commodity and in alternative fuels.

We find low heat of combustion mixtures of commodity fuel and fusel oils of $h_{АП}$ using the formula

$$h_{fo} = h_f \cdot g_f + h_{fm} \cdot g_{fm}, \quad (4)$$

where $h_{НТП}$ is the low heat of combustion of commodity fuel; for a diesel fuel we accept 42,6 MJ/kg; $h_{НСМ}$ is the low heat of combustion of fusel oils, which is 34,2 MJ/kg.

According to formula (4) we get

$$k = \frac{h_{fo}}{h_f \cdot g_f + h_{fm} \cdot g_{fm}}. \quad (5)$$

The value of coefficient k, depending on the mass particle of fusel oils in mixtures with a commodity diesel fuel, is given in tab. 3.

The basic index of diesel fuels that substantially affects its cost is the cetane number. This index indicates the capacity of diesel fuels to spontaneously combust after their injection into the combustion chamber of the engine, and determines the period of delay of spontaneous combustion of the mixture from the moment of injection to the start of burning. The higher the cetane number the faster the combustion process; the delay in spontaneous combustion is shorter as the fuel mixture burns softly and smoothly. In Ukraine and Europe, diesel fuel is produced with a cetane number of nearly 51. The price of one ton of diesel fuel with a metanovim number 51 in Ukraine is 750 $/t (wholesale price of railway party from data of business concern "Ukrnafta" by the state on 01.06.2016).

Table 3

Value of coefficient of k depending on the mass particle of fusel oils
in fuel mixtures with diesel fuel

g_{fo}	0,02	0,04	0,06	0,08	10	12
k	1,004	1,008	1,012	1,016	1,02	1,024

For the estimation of the economic efficiency of using fuel mixtures of diesel fuel and fusel oils, the dependencies of change of cost of fuel (P_{fm}), which is used for formation of fuel mixtures from the percentage of cetane number, were expected (fig. 4).

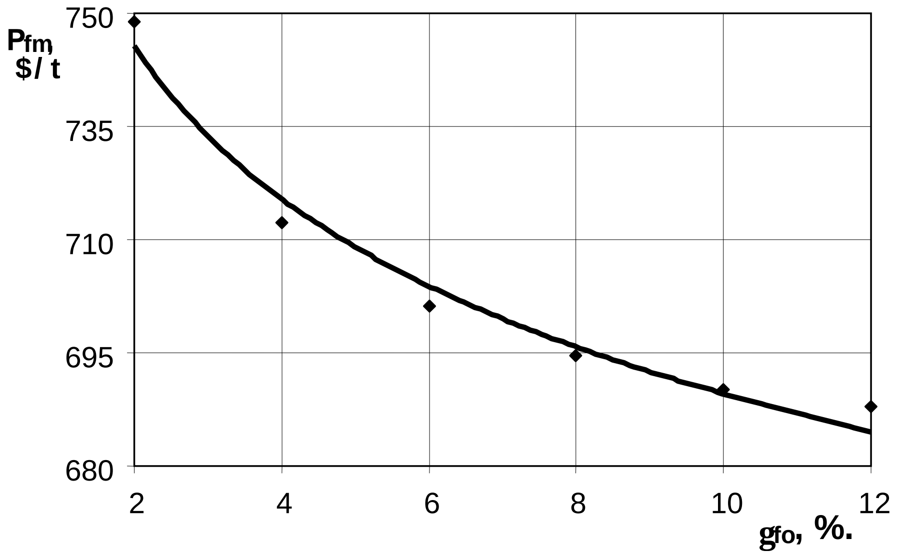
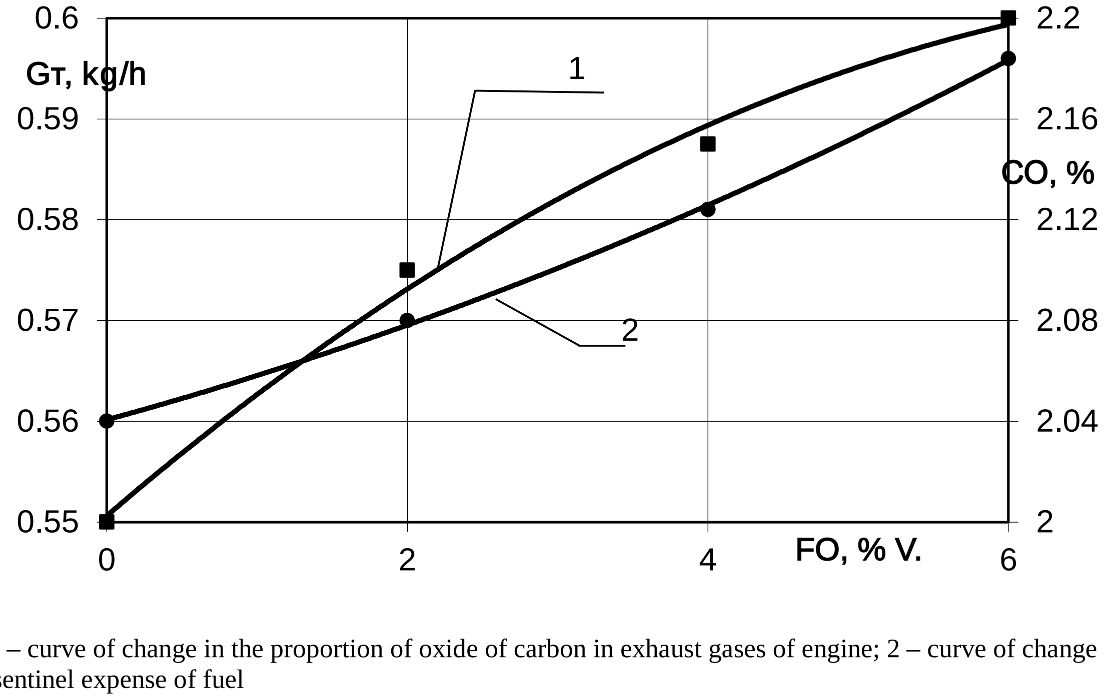


Fig. 4. Change of price of formed fuel mixture P_{fm} in dependences on mass maintenance of fusel oil g_{fo}

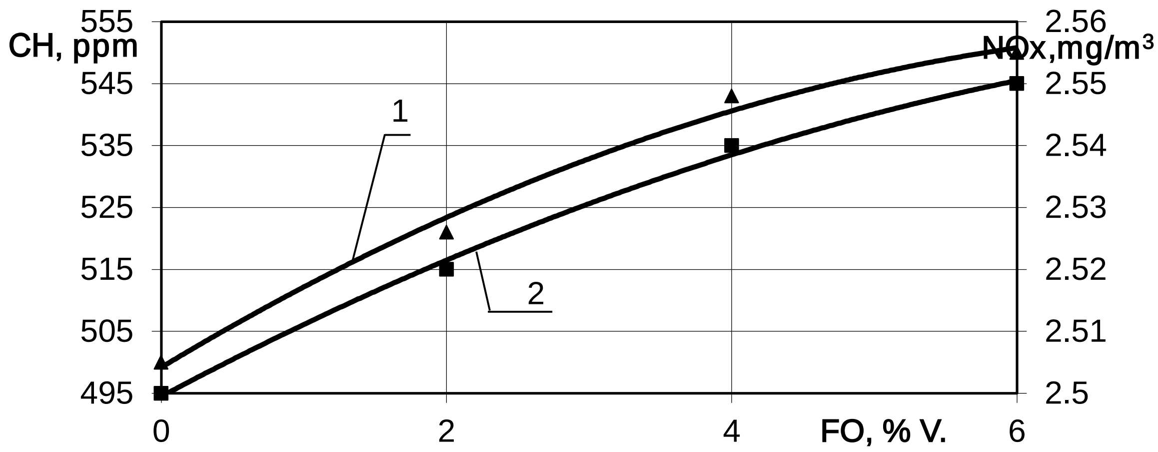
Therefore, for the accepted price of a diesel fuel and fusel oil and for our calculations, it is clear that with an increasing percentage of fusel oil in the fuel mixtures of diesel fuel and fusel oil, an increase in economic efficiency is achieved because of the use in the fuel mixtures of diesel fuel with a low cetane number and, accordingly, of low cost.

Ecological indexes of the working of a diesel engine on fuel mixtures without loading are shown on fig. 5, 6.



1 – curve of change in the proportion of oxide of carbon in exhaust gases of engine; 2 – curve of change of sentinel expense of fuel

Fig. 5. Graphic representation of changing of time expense of fuel and oxide of carbon in exhaust gases of engine depending on volume percentage in fusel oils



1 – curve of change of proportion of hydrocarbons in exhaust gases of an engine; 2 – curve of change of maintenance of oxides of nitrogen in exhaust gases of the engine

Fig. 6. Graphic dependence of change of hydrocarbons and oxides of nitrogen in exhaust gases of the engine depending on volume percentage in the fuel of fusel oils

It should be noted that during the functioning of an engine, there is an insignificant growth in the proportion of harmful components in exhaust gases on single turns. For a diesel exhaust to become clear, above all, it is necessary to purge it of the oxides of nitrogen, dioxide of sulfur, and soot.

Toxic components of diesels, in general, constitute 0.2-5.0 % [13] of the volume of exhaust gases, depending on the type of engine and the duration for which it runs. Soot is in itself non-toxic but it adsorbs hydrocarbons of particles of carcinogenic polycyclic compounds, including benzopiren, on its surface, which makes it most harmful [7].

Earlier, the comparatively low levels of oxides of carbon, hydrocarbons and oxides of nitrogen in exhaust gases of diesel did not require special devices for the reduction of toxic compounds. However, the norms for diesel engines have become more stringent in the last few years. Therefore on models of cars that satisfy ecological norms of Euro-5 approaches and landing aids toxic of exhaust gases which include reticulation exhaust gases appeared at diesel engines with catalytic neutralization and special filter of soot [13]. It is known that the efficiency of catalytic neutralization reduces, on average, all harmful components by nearly 80 % [13].

In the system developed by Volkswagen for neutralization of exhaust gases of diesel engines, the regeneration takes place because of the use of dioxide of nitrogen, which is contained in the catalyst of oxidization. The catalyst of oxidization, located next to the engine, purges exhaust gases from the oxides of carbon and hydrocarbons. At this time, another catalyst, the dioxin of nitrogen, necessary for oxidization of hard particles of oxides of carbon and hydrocarbons, appears intensively. For the decline in exhaust gases of gaseous oxides of nitrogen catalyst of oxides of nitrogen was used with, efficiency of clearing of such system near 85 % [7, 13].

The system of cleaning exhaust gases of diesel engines, which has been developed by Peugeot, includes a system of management of the engine and pressure sensors, a system of dosage of the special additive to the fuel, and a system of feeding the common rail and filter that purges exhaust gases from soot and executes the function of catalytic neutralization [15].

One of the alternative methods of neutralization of exhaust gases is the use of low-temperature plasma. Research in Japan, the USA, and in Russia resulted in development of experimental standards of equipment based on plasma technologies [15]. It has thus succeeded in providing an ever-higher efficiency of absorption of soot particles – up to 100 % – in all ranges of turns of diesel engines. From the oil separator part, exhaust gases can be sent to an inlet collector (recirculation). It brings down the proportion of oxides of nitrogen in exhaust gases.

On the basis of previous calculations, plasma cleaning will be 1.5 – 2 times cheaper, compared with the cost of existent multicomponent devices. It is not required to use noble metals, the resource of the systems of neutralization will considerably increase and time on their technical service will be shorter [14, 15].

4. CONCLUSIONS

The important task of maximizing fuel economy and improving the indexes of the working of diesel engines by using a mixture of diesel and fusel oils has been discussed and a solution has been reached in the article.

Increasing the share of fusel oil share in commodity diesel fuel reduces the dynamic indexes of the engine D21A1 slightly, but is compensated by low cost.

Research on fuel expenses in a diesel engine D21A1 when using mixtures of diesel fuel and fusel oils shows that despite increasing the share of fusel oils the cost of fuel grows, and it depends on the lower heat of combustion of fusel oils in comparison with diesel fuel.

Also, increasing the share of fusel oils leads to an increase in CO, C_nH_m, and NO_x; however, it is suggested that modern methods of purifying exhaust gases of a diesel engine, and accounting for small losses of power while using fusel oils as addition to diesel fuel, can improve the economic index by 2 – 15%.

References

1. Мельник, В.М. Альтернативні палива дизельних двигунів нафтогазової галузі. *Розвідка та розробка нафтових і газових родовищ*. 2005. No 4. P. 92-94. [In Ukrainian: Melnyk, V.M. Alternative fuels of diesel engines of oil and gas industry. *Search and development of oil and gas deposits*].
2. Wirawan, S. & Tambunan, A. & Djamin, M. & Nabetani, H. The Effect of Palm Biodiesel Fuel on the Performance and Emission of the Automotive Diesel Engine. *Agricultural Engineering International: the CIGR Ejournal*. Manuscript EE 07 005. 2008. Vol. X.
3. Karabektas, M. & Ergen, G. & Hosoz, M. The effects of preheated cottonseed oil methyl ester on the performance and exhaust emissions of a diesel engine. *Applied Thermal Engineering*. 2008. No. 28. P. 2136-2143.
4. Wang, W. & Lyons, D. & Clark, N. & Gautam, M. Emissions from nine heavy trucks fueled by diesel and biodiesel blend without engine modification. *Environmental science & technology*. 2000. Vol. 34, No. 6. P. 933-939.
5. Westbrook, S.R. *An Evaluation and Comparison of Test Methods to Measure the Oxidation Stability of Neat Biodiesel*. National Renewable Energy Laboratory. 2005. 34 p.
6. He, Y. & Bao, Y. Study on rapeseed oil as althernative fuel for a single-cylinder diesel engine. *Renewable Energy. An international journal*. 2003. No. 28. P. 1447-1453.
7. Матейчик, В.П. Енергоустановка транспортного засобу: системний підхід до дослідження. *Автошляховик України: окремий вип*. 2002. No 5. P. 33-35. [In Ukrainian: Mateychyk, V.P. Power plant of transport vehicle: systems approach to research. *Autoshliahovyk of Ukraine: separate issue*].
8. Apostolakou, A. & Kookos, I. & Marazioti, C. & Angelopoulos, K. Techno-economic analysis of a biodiesel production process from vegetable oils. *Fuel Process Technology*. 2009. No. 90 (7) P. 1023–1031.
9. Tang, Z. & Zhenzhou, L. & Zhiwen, L. & Ningcong, X. Uncertainty analysis and global sensitivity analysis of techno-economic assessments for biodiesel production. *Bioresour Technology*. 2015. No. 175. P. 502–508.
10. Gubicza, K. & Nieves, I. & Sagues, W. & Barta, Z. & Shanmugam, K. & Ingram, L. Techno-economic analysis of ethanol production from sugarcane bagasse using a Liquefaction plus

Simultaneous Saccharification and co-Fermentation process. *Bioresour Technology*. 2016. No. 208. P. 42-48.

11. Ljunggren, M. & Wallberg, O. & Zacchi, G. Techno-economic comparison of a biological hydrogen process and a 2nd generation ethanol process using barley straw as feedstock. *Bioresour Technology*. 2011. No. 102 (20). P. 9524–9531.
12. Klein-Marcuschamer, D. & Simmons, B. & Blanch, H. Techno-economic analysis of a lignocellulosic ethanol biorefinery with ionic liquid pre-treatment. *Biofuels, Bioproducts and Biorefining*. 2011. No. 5. P. 562–569.
13. Шапко С.В. *Підвищення стабільності екологічних показників дизельного автомобіля, обладнаного каталітичним нейтралізатором*. PhD thesis. Львів: НУ «Львівська політехніка». 2004. 156 p. [In Ukrainian: Shapko, S.V. *Increasing of stability of ecological indexes of the diesel car equipped by catalytic neutralizer*. PhD thesis. National university «Lvivska Politehnica»].
14. Pontikakis, G. & Stamatelos A. Mathematical modelling of catalytic exhaust systems for EURO-3 and EURO-4 emissions standards. *Proc. Inst. Mech. Engrs*. 2001. Part D. Vol. 215. P. 1005-1015.
15. Orlyk, S.M. & Soloviev, S.O. Palladium in GasPhase Processes of Environmental Catalysis in «Palladium: Compounds, Production and Applications». *Nova Science Publishers. Series: Material Science and Technology.* 2011. P. 57–103.

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