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Research of autonomous generator indicators with the dynamically changing component of a two-fuel mixture

Abstract: Diesel generator engines operate in wide load modes; therefore, it is necessary to change the percentage of the mixture of diesel and biodiesel fuel depending on the operating mode of the engine; this ensures its technical performance at the required level in all operating modes, including starting and stopping the engine. This article describes an algorithm for the operation of a diesel generator and an algorithm for determining the composition of the fuel mixture. During the study, the ratio between the components of the mixture changed, taking into account the load modes of operation of the diesel generator, indicators of fuel supply and the formulation of the fuel mixture to ensure optimal values of technical and economic indicators. To assess the efficiency of the flow

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of working processes in a diesel cylinder, their duration was selected, which is estimated by the duration of the processes of fuel injection, evaporation and combustion. Using the dynamic regulation of the composition of the diesel and biodiesel fuel, the total fuel consumption increased by 5.9%, but the cost of purchasing the fuel is reduced by 10% (at prices as of November 2021) and by 14.6% (based on prices as of the beginning of 2022) compared to engine operation with diesel fuel. This confirms the expediency of using the dynamic adjustment of the composition of the fuel mixture. In addition, even higher economic indicators can be achieved by using an autonomous power plant with a diesel power capacity higher than the generator capacity.

Keywords: diesel fuel, biodiesel fuel, engine working processes, energy efficiency, burning time

Introduction

For remote enterprises, it is often more economically feasible to generate electricity independently than to lay and maintain power grids. This is why the use of diesel generators operating on alternative fuels is promising and relevant. However, to ensure high economic efficiency (Kupchuk et al. 2018; Kaletnik et al. 2020a), it is necessary to comprehensively approach the issue of using alternative fuels, particularly biodiesel fuel (BF) for independent energy sources. An integrated approach to BF use means ensuring the full cycle of raw-material growth (or the use of waste vegetable oils and animal fats) and the production of BF, which in turn is used in diesel generators to ensure the energy independence of enterprises (Sanghamitra and Deshmukh 2019).

The advantage of agricultural enterprises lies in the possibility of BF production arrangements in situ (Kaletnik et al. 2020b). BF production installations are structurally simple and there is the possibility of various capacities, which allows BF production in the volumes required for the enterprise's needs. Such being the case (Bulgakov et al. 2019; Hrushetskyi et al. 2021) fuel price becomes equal to its self-cost – there is no need for its supply and there is no dependence on price fluctuations in the fuel market. The company gets autonomy when it comes to fuel.

Scientists conducted research on the use of mixtures of diesel fuel (80%) and biodiesel fuel (20%). During diesel fuel consumption, an increase of 2% was observed at the proposed mixture. The total cost of fuel purchase at work on the mixture decreased by 5%, compared to working on diesel fuel (Hutarevych et al. 2014). At the same time, the normal flow of working processes in the cylinders including the cold start of the engine was ensured. In an analysis of literary sources, no papers were found concerning the regulation of fuel mix composition during diesel engine operation with its technical parameters being preserved in all operating modes. Therefore, it was proposed to use the dynamic regulation of diesel fuel and BF mix's percentage composition, depending on the operating modes of the engine and the car (Murugesan et al. 2009; Kaletnik et al. 2017).

The aim of the work is to test the expediency of using dynamic regulation of the percentage composition of the fuel mixture for a diesel engine of an autonomous energy source. This goal was achieved by studying the effect of using a mixture of diesel and biodiesel fuels on the technical and economic performance of an autonomous diesel generator.

1. Materials and methods

The object of the study was a mobile power plant equipped with an SMD-15 diesel engine with a three-phase synchronous generator.

In order to test the feasibility of using dynamic regulation of the fuel mix percentage composition for an autonomous diesel power source, the impact on its technical, economic and environmental indicators was investigated (Hutarevych et al. 2014). For the computational study "Engine – power supply system based on the mixture of diesel and biodiesel fuels," a mathematical model was used (Hutarevych et al. 2014; Polyakov et al. 2014; Galushchak O. 2015).

The research focused on an autonomous diesel power source equipped with an SMD-15 diesel engine with a synchronous three-phase current generator GSM-60 (Solona et al. 2020). In the course of the research, calculations were performed for diesel engine operation on diesel fuel (Costa et al. 2018; Rutkevych et al. 2022), BF and their mixes with 25, 50, 75% BF content and with adjustments in the composition of the fuel mix during engine operation (Horbay et al. 2018). The criterion for determining the rational composition of the fuel mixture for each engine mode is the duration of the working process, namely the duration of fuel combustion. The maximum use of BP is also provided.

Specifications of the SMD-15 diesel engine, which is used in the computational study, are presented in Table 1.

In remote enterprises or their structural subdivisions, diesel generators are used: as the primary source (in places where there is no centralized power supply); as an emergency energy source; as an auxiliary energy source during the power system's peak loads.

In the first case, the diagram for changes in the load on the diesel generator is proportional to the load on Ukraine's United Power System. Figure 1 shows the diagram of Ukraine's average electricity consumption on working days in November 2021 (Burlaka et al. 2021; Yaropud et al. 2021), from which one can see that electricity consumption function is uneven. Therefore, with the use of a diesel generator, the load therein will also be nonlinear; however, short-term sudden load drops never occur normally (Borysiuk et al. 2021; Gunko et al. 2021).

The diagram (Fig. 1) can be divided into three characteristic zones: minimum loads (at night), average loads and maximum loads. The average load zone is characterized by significant growth in the morning hours, uniform consumption in the middle of the day and decline at the end of the day (Kuznietsova et al. 2020; Kupchuk et al. 2021). The maximum load zone is characterized by a peak increase from the average to the maximum value, then – by decline down to the average. There are usually two maximum loads – one in the morning and another in the evening. The second peak always exceeds the first in terms of magnitude (Borysiuk et al. 2021; Gunko et al. 2021).

Table 1. Specifications of SMD-15 engine

Tabela 1. Dane techniczne silnika SMD-15

No.	Item	Value
1.	Crankshaft's rated speed [rpm]	1800
2.	Torque at rated speed [N·m]	312
3.	Rated power [kW (hp)]	61.1 (83)
4.	Number of cylinders	four
5.	Cylinder positioning	straight
6.	The sequence of cylinder operation	1-3-4-2
7.	Cylinder diameter [mm]	120
8.	Piston stroke [mm]	140
9.	Operating volume [l]	6.33
10.	Compression ratio	17
11.	Crankshaft's minimum rotation speed at idle, no more than [rpm]	600
12.	Crankshaft's maximum rotation speed at idle, no more than [rpm]	1950
13.	Specific fuel consumption in rated power mode [g/kW·h (g/hp·h)]	248 (183)
14.	Injection starting pressure [MPa]	17.5–18
15.	Injection advance angle [degrees]	22

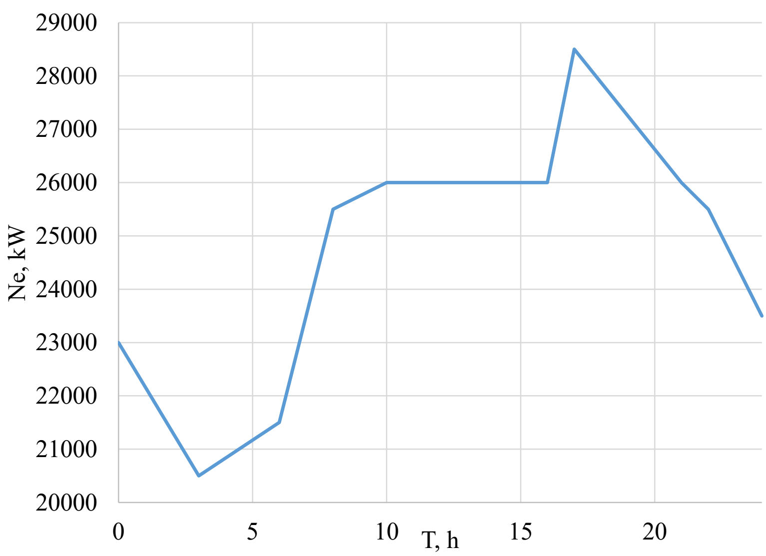

Fig. 1. Diagram of Ukraine's average electricity consumption on weekdays in November

Rys. 1. Średnie zużycie energii elektrycznej w Ukrainie w dni powszednie w listopadzie

In the computational study, these specificities of electricity consumption were taken into account and a diagram of the diesel generator's load changes over the course of 24 hours was drawn up (Fig. 2), taking into account recommendations for its operation (Burlaka et al. 2021; Paziuk et al. 2021).

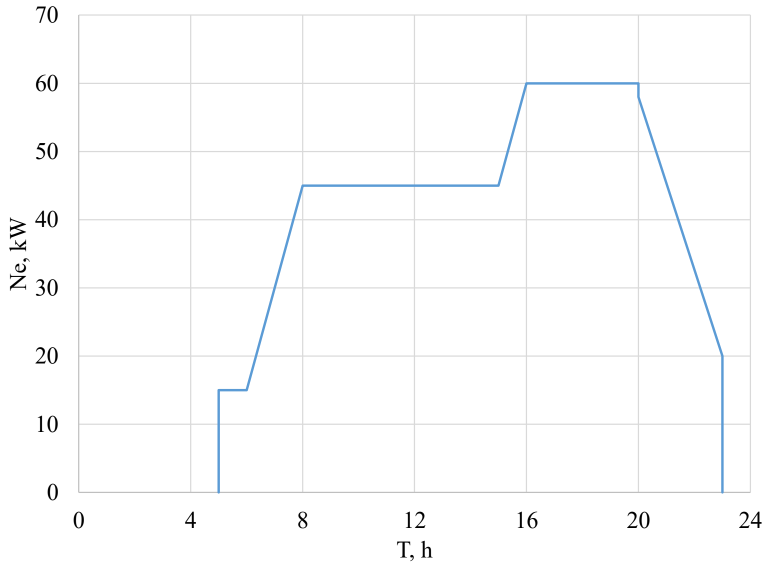

Fig. 2. Changes in diesel generator load

Rys. 2. Zmiany obciążenia generatora diesla

According to the recommendations, the load on the diesel generator should be increased gradually at regular intervals: every 5 to 7 minutes in summer and every 10 to 12 minutes in winter (Manzanera et al. 2008; Burlaka et al. 2021). After starting the diesel generator, a 25% load is applied. At appropriate intervals – 50, then 75 and 100%.

It is not recommended to operate diesel generators at less than 30% of the loads recommended in the unit's specifications, since when diesel generators operate at low loads, the KPI decrease significantly and fuel consumption increases. The optimal load is around 40 to 75%.

Let us consider the algorithm of diesel-generator operation. It was assumed in the computational study that firstly, the diesel engine runs at idle. To increase the crankshaft speed to the level required for the generator's correct operation, the cyclic fuel supply increases until the crankshaft speed reaches 1,500 rpm, whereupon cyclic fuel supply decreases to the level that ensures the diesel engine's operation at a given crankshaft speed. After that, the generator is served with a load equal to 25% of the maximum, which is 15 kW. The diesel generator operates for 10 minutes in this mode. During this time, the diesel engine warms up, after which, the load is changed in accordance with the graph shown in Figure 2.

2. Results and discussion

Figure 3 shows the graph of dependence between the hourly fuel mix consumption and the time of day when the diesel generator is operating at a given load using fuel mixes of various compositions, with the composition of diesel and biodiesel fuel mix being adjusted in the course of engine operation. Figure 4 shows the graph's section, which details the dependence between the fuel mix's hourly consumption from the moment of the diesel engine starting until the moment the load is served on the generator.

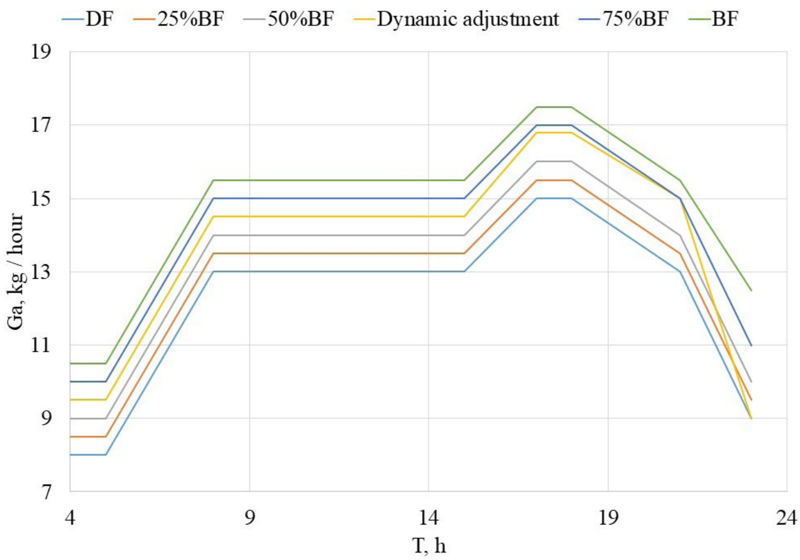

Fig. 3. Dependence between the fuel mix's hourly consumption Gn and the time of day T in the course of diesel generator operation

Rys. 3. Zależność godzinowego zużycia mieszanki paliwowej Gn od pory doby T w trakcie pracy agregatu prądotwórczego

The dependence between the change in the fuel mixes, the hourly consumption of each of its components and the time of day during the diesel generator's operation is shown in Figure 5.

The increase in the fuel mix's hourly consumption after starting the diesel engine (Fig. 3, 4) is caused by the increase in the fuel mix's cyclic supply with the increase in the diesel engine crankshaft's rotational speed from 600 rpm to 1,500 rpm. When the crankshaft speed reaches 1,500 rpm, the hourly consumption of the fuel mix decreases to the level at which effective torque can be maintained, which in turn compensates the mechanical loss momentum. Further on, with the increase in the load on the diesel engine's crankshaft, in order to maintain its rotational speed at a level of 1,500 rpm, the fuel mix's hourly consumption increases, which depends

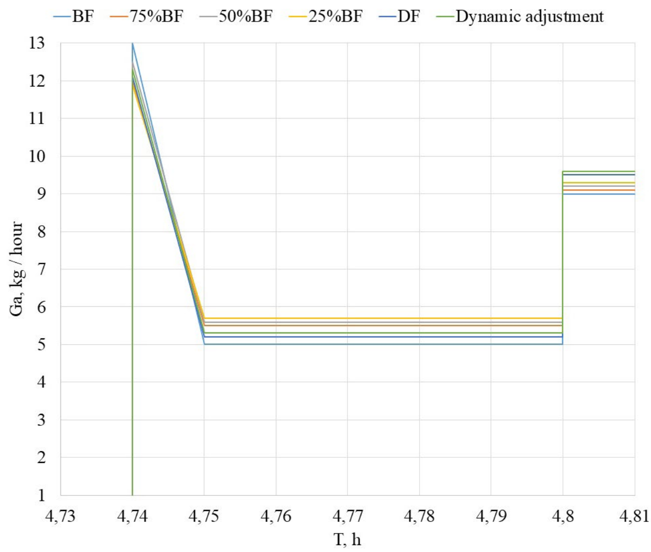

Fig. 4. Dependence between the fuel mix's hourly consumption Gn and the time of day T in the course of diesel generator operation (detailed)

Rys. 4. Zależność godzinowego zużycia mieszanki paliwowej Gn od pory doby T w trakcie pracy agregatu prądotwórczego (szczegółowo)

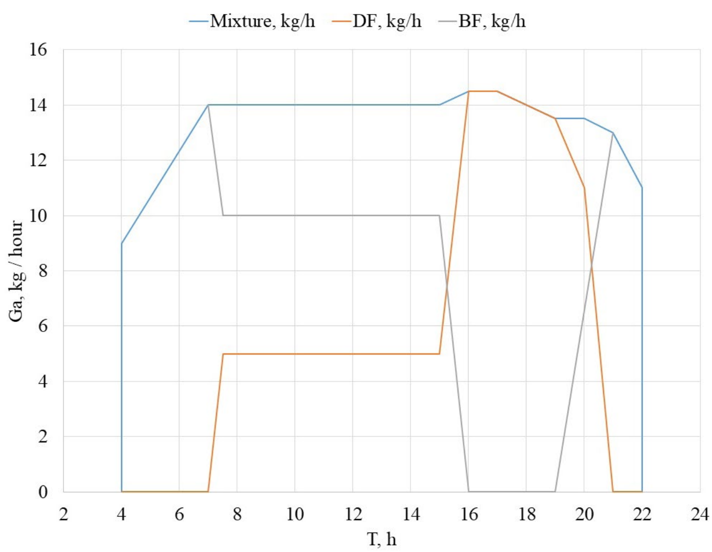

Fig. 5. Dependence between fuel mix's Gn and each of its components' hourly consumption and the time of day T in the course of diesel generator operation

Rys. 5. Zależność między godzinowym zużyciem mieszanki paliwowej Gn i każdym z jej składników a porą doby T w trakcie pracy agregatu prądotwórczego on diesel fuel and BF percentage composition (Fig. 5). Diesel engine starting and stopping, when a dynamic regulation of the fuel mix's percentage composition is applied, occurs with the diesel fuel.

Diesel engine's economic performance (Table 2) is estimated by fuel mix ($G_{F\Sigma}$), and the total consumption of DF ($G_{DF\Sigma}$) and BF ($G_{BF\Sigma}$) during its operation, which is determined using the following formulas:

$$G_{F\Sigma} = \sum_{i=1}^{k} i_c \frac{n_{d(i-1)} q_{c(i-1)} + n_{di} q_{ci}}{14,400} \tag{1}$$

$$G_{DF\Sigma} = \sum_{i=1}^{k} i_c \frac{n_{d(i-1)} q_{cDF(i-1)} + n_{di} q_{cDFi}}{14,400} \tag{2}$$

$$G_{BF\Sigma} = \sum_{i=1}^{k} i_c \frac{n_{d(i-1)} q_{cBF(i-1)} + n_{di} q_{cBFi}}{14,400} \tag{3}$$

where:

n_{di}, $n_{d(i-1)}$ – the crankshaft speed at the current and previous calculation stage,

q_{ci}, $q_{c(i-1)}$ – cyclic supply of a mixture of fuels at this and at the previous stage of calculation [g/cycle],

q_{cDFi}, q_{cBFi}, $q_{cDF(i-1)}$, $q_{cBF(i-1)}$ – cyclic supply of diesel and biodiesel fuel at the current and previous calculation stage [gm/cycle].

TABLE 2. Results of calculating the fuel mix consumption during diesel generator's operation under given load* (Fig. 2)

TABELA 2. Wyniki obliczeń zużycia mieszanki paliwowej podczas pracy generatora spalinowego pod zadanym obciążeniem* (rys. 2)

Fuel mix composition	Fuel mix consumption		Consumption by components		Fuel purchase expenses [UAH]	Costs reduction [%]
	total [kg]	increase in fuel consumption [%]	DC [kg]	BC [kg]		
DT	240.75	–	240.75	–	6741	
25% BF	246.12	2.23	184.59	61.53	6,399.12	5.07
50% BF	252.59	4.918	126.3	126.3	6,062.4	10.07
75% BF	260.21	8.08	65.05	195.16	5,724.6	15.08
BF	268.69	11.61	–	268.69	5,373.8	20.28
Dynamic regulation	254.94	5.89	120.63	134.31	6,063.84	10.05

* In prices as of November 2021.

One can see from Table 2 and Figures 3 to 5 that with an increase in the percentage of BF in the fuel mix, its consumption increases proportionally.

The fuel mix percentage composition is determined taking into account the impact on the working process flow (Wallner et al. 2018; Burlaka et al. 2021) and the diesel cylinder, their duration is chosen, which is estimated by the duration of fuel injection, evaporation and combustion processes. Since the permissible value of the duration of these processes varies depending on the fuel mix injection advance angle, for the sake of convenience it is advisable to evaluate the diesel cylinder's working process flow efficiency by the value of diesel engine's crankshaft rotation angle (c.r.a.) at the end of fuel mix combustion φ_{bu}:

$$\varphi_{zg} = 360° - \theta_{ing} + \varphi_{ing} + \varphi_z \tag{4}$$

where:

- $\theta_{ing} = f(\phi_i)$ – fuel injection advance angle [°],
- φ_{ing} – injection duration [°],
- φ_z – duration of fuel mix combustion [°].

The dependence between the injection duration and the cycle feed is as follows (Paziuk et al. 2021):

$$\varphi_{ing} = 6 n_d \tau_{ing} \tag{5}$$

$$\tau_{ing} = \frac{q_c}{\mu_c f_c \sqrt{2\rho_n \Delta P}} \tag{6}$$

where:

- τ_{ing} – injection duration [s],
- μ_c – discharge ratio of nozzle openings' flow sections,
- f_c – nozzle openings' cross-sectional area [m^2],
- ρ_n – fuel mix density [kg/m^3],
- ΔP – the difference between the average injection pressure and the ambient pressure.

Duration of fuel mix combustion:

$$\varphi_z = 6 n_d \tau_z \tag{7}$$

$$\tau_z = \frac{A_z}{b_{t.k.} a^{0.6}} \tag{8}$$

where:

- τ_z – duration of large droplets' evaporation and combustion [s],
- $A_z = 2.4$ – large droplets' evaporation duration constant,

$b_{t,k}$ – relative theoretical constant of fuel evaporation [s^{-1}],
α – air excess ratio (Yaropud et al. 2021).

Fuel mix auto ignition delay period $\Delta\varphi i$ is determined by an empirical formula (Polyakov et al. 2014):

$$\Delta\varphi_i = (0.36 + 0.22C_n)\exp\left(E_a\left(\frac{1}{RT_H\varepsilon^{m-1}}\right) - \left(\frac{21.2}{P_H\varepsilon^m - 12.4}\right)^{0.63}\right) \quad (9)$$

where:

C_n – the average piston speed [m/s],
E_a – fuel activation energy [kJ/mol],
$R = 8.31$ – universal gas constant [J/kg·K],
T_H – gas temperature at injection commencement K,
P_H – gas pressure at injection commencement [MPa].

The algorithm for choosing the mix composition can be generalized as follows. BF use during diesel-engine operation with low loads provides the required amount of heat while maintaining the working processes' effective flow. With load increases, in order to maintain the diesel engine's technical parameters, it is necessary to increase the amount of heat supplied to the diesel cylinder and thus also the BF's cyclic supply until the working processes' effective flow is achieved. Further increases in the amount of heat requires increase in the diesel fuel content in the mix. With the load close to the maximum, it is impossible to provide the required amount of heat with the fuel mix; therefore, to maintain the diesel engine's technical parameters, the use of diesel fuel is required.

Figure 6 shows diagrams of dependence between effective torque, the fuel mix percentage composition n_{BF}, the value of the c.r.a. angle at the end of fuel mix combustion in the diesel cylinder (φ_{bu}), and the time of day. Let's take a closer look at the diagram.

After the starting of the diesel engine, there is no load moment thereon. The increase in cycle fuel supply leads to increases in the effective torque, which exceeds the torque of mechanical losses. φ_{bu} value increases to 440° c.r.a. Crankshaft speed increases from 600 to 1,500 rpm, after which, to maintain a crankshaft speed of 1,500 rpm, cycle fuel supply decreases, which leads to the effective torque decrease, φ_{bu} value (up to 400° c.r.a.). The engine runs on diesel fuel.

The load moment is increased to 95.5 N·m, φ_{bu} value to 409° c.r.a., whereupon remaining unchanged. In this mode, the diesel engine runs on diesel fuel for 10 minutes. Further on, the power system succeeds to operation on fuel mix with dynamic adjustment of its percentage composition. Within 30 seconds, the fuel mix percentage changes from 100% diesel fuel to 100% BF. This leads to an increase in the φ_{bu} value from 409° c.r.a. to 422° c.r.a. During this time, the entire mixture from the supply system fuel lines will be used and replaced with diesel fuel (Galushchak O.O. and Galushchak D.O. 2014; Horbay et al. 2018).

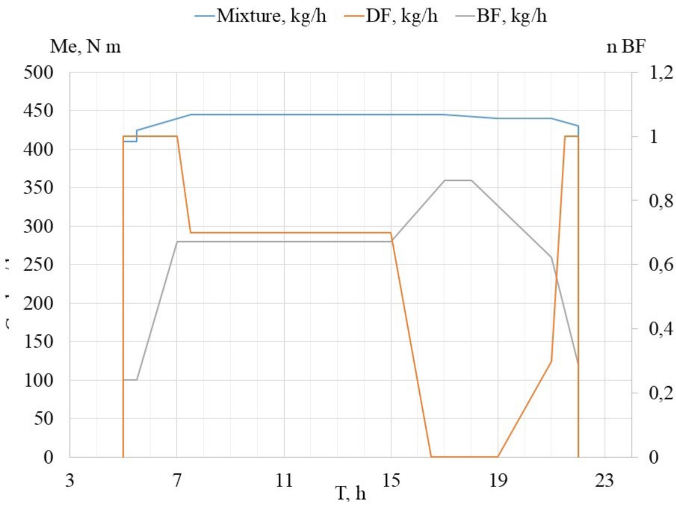

Fig. 6. Diagram of dependence between effective torque Me, fuel mix percentage composition nBF and crankshaft rotation angle value at the end of fuel mix combustion φ_{bu} in the diesel cylinder, and the time of day

Rys. 6. Zależność momentu efektywnego Me, procentowego składu mieszanki paliwowej nBF i wartości kąta obrotu wału korbowego na końcu spalania mieszanki paliwowej φ_{bu} w cylindrze diesla od pory dnia

Over three hours of diesel engine operation, load torque increases linearly from 96 to 287 N·m, with the φ_{bu} value growing from 422° c.r.a. up to the maximum permissible value of 445° c.r.a. Having reached the maximum φ_{bu} value, there occurs a gradual decrease of BF content in the fuel mix to 67% (33% diesel fuel, 67% BF), which, with increasing load, ensures a constant φ_{bu} value at 445° c.r.a.

For seven hours, the diesel engine operates in a steady mode: the load moment is 287 N·m, the φ_{bu} value is 445° c.r.a. with BF percentage in the fuel mix being 67% (33% diesel fuel and 67% BF). For one hour, the diesel engine operates in a steady mode: the load moment is 382 N·m, φ_{bu} value is 445° c.r.a. with the fuel mix percentage being 100% DF.

For 3.5 hours, the load moment decreases linearly from 382 to 287 N·m. The fuel-mix percentage composition remains unchanged (100% DF) with φ_{bu} value not decreasing to 440° c.r.a. (the range if 5° c.r.a. is set to prevent changes in the fuel mix percentage at minor φ_{bu} fluctuations). A constant φ_{bu} value at the 440° c.r.a. level, with the load decrease, is maintained due to the change in the fuel mix percentage composition from 100% diesel fuel (100% diesel fuel) to 34% BF (66% diesel fuel and 34% BF).

Within 1 hour 55 minutes, the load moment decreases linearly from 287 to 133 N·m, with the BF content in the fuel mix increasing from 34% (66% DF and 34% BF) to 100% BF (0% DF and 100% BF). The φ_{bu} value remains at 440° c.r.a. As soon as 100% BF in the fuel mix (0% diesel fuel and 100% BF) is reached, the φ_{bu} value decreases from 440° c.r.a. to 429° c.r.a.

Five minutes prior to diesel engine stopping, while still operating under load, the BF content in the fuel mix is reduced to 0% (100% DF). The change in the fuel mix percentage composition occurs in the course of 30 s, φ_{bu} decreasing from 429° c.r.a. to 416° c.r.a. The load moment continues to decrease linearly from 133 to 127 N·m and the φ_{bu} value further decreases to 415° c.r.a.

The diesel engine runs on diesel fuel. The load moment becomes zero, the φ_{bu} value is equal to 340° c.r.a. The diesel engine stops.

Mobile power plants are equipped with diesel engines of predominantly higher power than generators themselves, and this leads to the fact that when diesel generators operate at the maximum load, the engines operates at a partial load with a crankshaft speed being close to the nominal one. Accordingly, diesel engines operate in the modes in which it is advisable to use fuel mixes with a high BF content. Diesel power systems with the dynamic adjustment of the composition of the fuel-mix percentage ensuring the efficient operation of power plants in all their operating modes, easy start-ups with diesel fuel even at low temperatures, and helps eliminate the negative effects of BF use in cold engines.

Conclusion

As a result of the application of the dynamic regulation of the percentage composition of the fuel mixture in the diesel-generator, the power of which is close to the diesel engine, the overconsumption of the fuel mixture as compared to the use of diesel fuel is 5.9%. At the same time, the cost of fuel acquisition is reduced by 10% (prices as of November 2021), which is the best result compared to the results obtained for the use of the mixture with constant composition diesel fuel (80%) and biodiesel fuel (20%), which were received by other researchers (Hutarevych et al. 2014) (reduction by no more than 5%).

The criterion for determining the rational composition of the fuel mixture was chosen for the duration of the combustion process. The mixture composition correction consists of the maximum use of biodiesel fuel in the maintenance of the working process duration, as in the operation of the engine on the diesel fuel. If the content of the biodiesel fuel in the mixture is increased, the efficient flow of working processes at maximum load is disrupted and the cold start of the engine is difficult. Therefore, the use of dynamic control of the composition of the fuel mixture at mobile power plants is expedient and economically more profitable in comparison with the use of the fuel mixture of permanent composition.

When using mobile power plants, where the power of the engine is higher than the power of the generator, the economic effect is greater. Taking into account the change in the cost of diesel (about 58 UAH per l) and biodiesel fuel (about 41,2 UAH per l) in 2022 (Zorkin 2022) the economic effect of the application of the dynamic regulation of the percentage composition of the fuel mixture is higher at 14.6%.

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Badanie wskaźników generatora autonomicznego z dynamicznie zmieniającym się składnikiem mieszanki dwupaliwowej

Streszczenie

Silniki Diesla pracują w szerokim zakresie obciążenia, dlatego konieczna jest zmiana procentowej mieszanki oleju napędowego i biodiesla, w zależności od trybu pracy silnika, co zapewni jego osiągi techniczne na wymaganym poziomie we wszystkich trybach pracy, w tym uruchamianie i zatrzymywanie silnika. W artykule opisano algorytm działania generatora diesla oraz algorytm wyznaczania składu mieszanki paliwowej. W trakcie badań zmieniały się proporcje między składnikami mieszanki, biorąc pod uwagę obciążeniowe tryby pracy agregatu prądotwórczego oraz wskaźniki podawania paliwa i tworzenia mieszanki paliwowej, aby zapewnić optymalne wartości wskaźników technicznych, ekonomicznych i środowiskowych. Do oceny wydajności przebiegu procesów roboczych w cylindrze diesla dobrano czas ich trwania, który szacowany jest czasem trwania procesów wtrysku, odparowania i spalania paliwa.

Słowa kluczowe: generator diesla, olej napędowy, paliwo biodiesel, tryb obciążenia, mieszanka, proces roboczy