The Use of Boride and Silicide Coatings in Fire engines: Technological Aspect

The main regularities of the process of forming on refractory metals the single-phase, multi-phase, multi-layer composite coatings with high heat resistance and durability are examined in the article.

A study of boride coating on refractory metals was conducted, which showed that a single-phase coating is formed on metals that possesses good adhesion to the base. Based on the results of X-ray phase and micro-X-ray spectral methods of analysis, the formation of a monoboride phase on molybdenum and tungsten and a boride phase on niobium and tantalum was revealed. A study of the effect of temperature on the process of diffusion silicification of refractory metals was carried out, which showed that in the range of 950–1100 0C, a single-phase coating is formed, which consists of disilicides of $MeSi_2$ metals. A further increase in the temperature of the saturation process was found to lead to a sharp increase in the thickness of the silicide layer. It was proved that an effective diffusion barrier is the boride phases of refractory metals, which ensure the stability of the diffusion part of the multicomponent coating. The boride phases were determined to be more stable than silicide phases in relation to the metal base. Due to the formation of silicoboride phases at the border of boride and silicide layers, high stability of the borosilicide coating is ensured. The presence of penetrating impurities in the metal matrix leads to poor protection of the oxide film of the diffusion coating and, as a result, to low durability. A mechanism for the transfer of penetrating impurities from the depth of the metal to the boundary of the powder medium is proposed.

The obtained borosilicate-saturated metal technological parameters allow forming a diffusion coating with a fine-grained structure on refractory metals. To ensure high protective characteristics, the formation of the layered part of the coating should be further researched.

engines, metal silicification process, metal boronization process, diffuse layer

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Method of Engine Energy Indicators Estimating when the Cylinders are Disconnected in the Loaded Mode of Operation

Considered modes engine load operations: 1 – test of the original engine; 2 – test with disconnection of four cylinders by stopping the fuel supply; 3 – test with disconnection of four cylinders with simultaneous cessation of fuel supply and absence of pumping losses of the cylinder-piston group (CPG) in the disconnected cylinders.

The feasibility of using the method of disconnecting a part of the working cylinders of the engine, saving fuel at load modes of no more than 70% of the total and with a further increase in the effective power of the engine load, the time consumption of fuel becomes higher than in the variant without disconnection of the cylinders, has been proven.

engine, energy parameters, cylinder shutdown, engine load, pumping losses

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Formulation of the problem. The efficiency of piston engines largely depends on their operating modes [1]. If at nominal or close to it economic indicators usually reach optimal values or close to them, then at partial loads and idling the fuel efficiency of diesel engines can noticeably deteriorate. At the same time, in the operational modes of most vehicles, idling modes and light loads make up a significant share [2].

Every year, the fleet of cars and trucks, road construction, agricultural and other machinery equipped with auto-tractor engines that consume a significant amount of fuel is increasing, in connection with this, the problem of economical use of its resources arises.

Analysis of recent research and publications. The works of E. Chudakov, V. Boltinsky, V. Falkevich, L. Klymenko, D. Rubtsia, V. Arkhangelskyi, M. Lurie et al.

The analysis of publications showed that the solution to this problem was connected with the design of devices for cutting off the supply of fuel to diesel cylinders. Currently, work is underway to create entire systems and complexes with processor control on various types of diesel engines [3].

Many leading institutes of the country, as well as foreign companies (Ford, MTU, BMW, General Motors, Porsche, Mercedes-Benz, and others) conduct research in the field of engine cylinder shutdown for various purposes [4].

Setting objectives. The purpose of this study is to improve the performance of the engine in the load mode by substantiating the number of cylinder shutdowns and determining the energy parameters of its operation.

Achieving the set goal involves solving the following tasks:

– to determine the effect of disconnection of half of the cylinders of a diesel engine on its operating parameters under load;

- to determine the nature of the influence of pumping losses in the CPG when half of the cylinders are turned off on the energy performance of the diesel engine under load.

Presenting main material. Bench tests of the engine were carried out [5] in the conditions of KHARZ-110 and KHARZ-126 auto repair production in Kharkiv with the direct participation of the department "Technology of mechanical engineering and machine repair" of KhNADU. The brake stand was equipped with measuring devices and control equipment according to GOST 14846-81 [5] and included an electric balancing machine AKB 101-4 with the help of which the load was carried out.

The characteristics were taken according to three variants of tests at different engine crankshaft rotation frequencies:

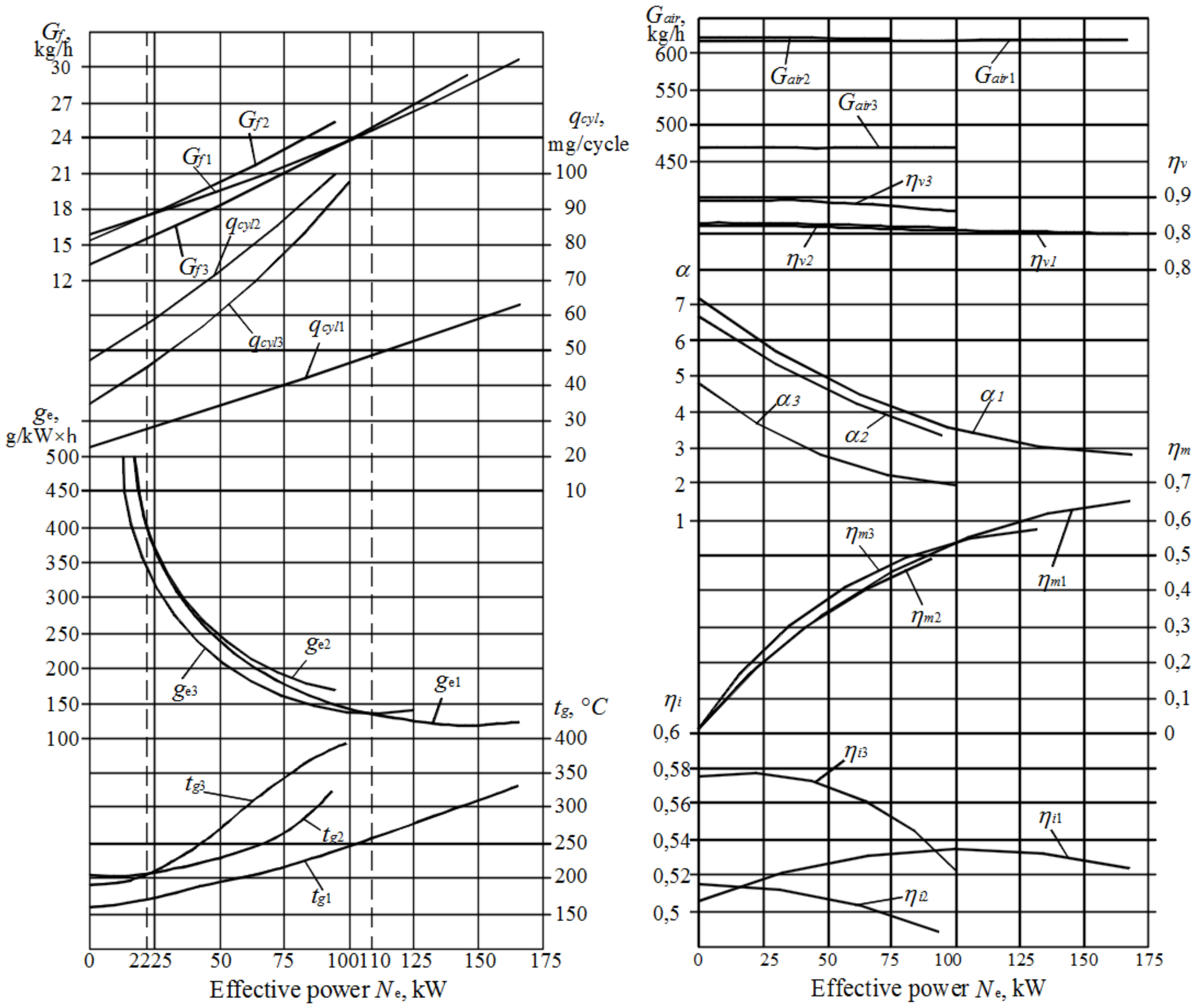
1 – test of the original engine;

2 – test with disconnection of only fuel supply to 1, 4, 6 and 7 cylinders of the engine;

3 – test with the fuel supply cut off and the absence of pumping losses of the cylinder-piston group (CPG) in 1, 4, 6 and 7 disconnected engine cylinders.

It is known [6] that the load characteristic is the dependence of the specific fuel consumption and other indicators of engine operation on the effective power or on the average effective pressure at a constant crankshaft rotation frequency. Figures 1 a, b shows the results of research at the crankshaft rotation frequency n = 2600 min^{-1}

The hourly fuel consumption (Fig. 1 a) can be determined according to the dependence [7]



a b

1 – with all working cylinders; 2 – when the fuel supply to 50% of the cylinders is cut off;
3 – with fuel cut-off in 50% of the cylinders and the absence of pumping cylinders in the CPG
a – G_f – hourly fuel consumption, q_{cyl} – cyclic fuel supply, g_e – specific effective fuel consumption,
$t_g = f(N_e)$ – exhaust gas temperature; b – G_{air} – actual air consumption,
η_v – cylinder filling factor, α – coefficient of excess air, η_m – mechanical efficiency,
$\eta_i = f\left(N_e\right)$ – indicator efficiency

Figure 1 –Load characteristics of a diesel engine ($n = 2600$ min^{-1})

Source: developed by the author

$$G_f = g_e \cdot N_e = \frac{3600}{H_u \cdot \eta_e} \cdot \frac{P_e \cdot V_h \cdot i''_{cyl} \cdot n}{30 \cdot \tau} = K \cdot \frac{P_e \cdot V_h \cdot i''_{cyl} \cdot n}{\eta_e} = $$
$$= K \cdot \frac{\left(P_i - P_{ml}\right) \cdot V_h \cdot i''_{cyl} \cdot n}{\eta_i \cdot \eta_m}, \text{ kg/h} , \qquad (1)$$

where $K = \frac{3600}{H_u \cdot 30 \cdot \tau} = \frac{3600}{42{,}7 \cdot 30 \cdot 4} = 0{,}7$ – constant for this diesel engine;

$\tau = 4$ – the number of beats;

$H_u = 42{,}7$ – lower calorific value of diesel fuel, MJ/kg;

g_e – specific effective fuel consumption, g/kWh;

N_e – effective power, kW;

P_e – average effective pressure, MPa;

P_i – average indicator pressure, MPa;

P_{ml} – conventional pressure of mechanical losses, MPa;

η_e – effective efficiency;

η_i – indicator efficiency;

η_m – mechanical efficiency;

V_h – volume of one cylinder in liters;

n – crankshaft rotation frequency, min^{-1};

$i^{"}_{cyl}$ – the number of working cylinders.

Hourly fuel consumption G_{f2} when only the fuel supply is turned off (option 2) compared to option 1, it is 7% less, in the power range from 0 to 22 kW, due to the improvement of the combustion process, and then it becomes more. When the fuel is turned off and there are no CPG pumping losses in the disconnected cylinders (option 3), the time consumption of fuel G_{f3} at low modes, the load decreases, compared to the first option, by 1.73 kg/h, or 21%, which is explained by the increase in indicator and mechanical efficiency, and the decrease in pumping losses in disconnected cylinders. With a further increase in effective power over 110 kW, the time consumption of fuel becomes higher than in option 1.

Cyclic fuel supply q_{cyl} (Fig. 1 a) can be determined by the dependence [7]

$$q_{cyl} = \frac{10^4 \cdot G_f \cdot \tau}{1,2 \cdot n \cdot i^{"}_{cyl}} = \frac{10^4 \cdot 4 \cdot G_f}{1,2 \cdot n \cdot i^{"}_{cyl}} = 3,3 \cdot 10^4 \cdot \frac{G_f}{i^{"}_{cyl} \cdot n}, \text{ mg/cycle.} \tag{2}$$

When the load changes at the nominal crankshaft rotation frequency (2600 min^{-1}) for all test options, the cyclic fuel supply increases, since G_f increases, and $n = \text{const}$.

The cyclic supply curve when only fuel is turned off (option 2) is higher than the initial one, this is explained by the fact that when turning off the fuel supply in the cylinders to maintain the engine shaft speed and load q_{cyl} was increased due to more pressure on the gas pedal.

Cyclic supply curve q_{cyl3} when fuel is turned off and pumping losses are eliminated in cylinders 1, 4, 6, and 7, it is located slightly lower, which is associated with a decrease in the power of mechanical losses by the amount of pumping losses in the four disconnected cylinders.

Specific effective fuel consumption g_e (Fig. 1a) with all variants of tests at low load modes, about 1200-1400 min^{-1} equals infinity, since $\eta_m \approx 0$. As the load increases g_e sharply decreases, as the mechanical and indicator efficiency increases [7]

$$g_e = \frac{G_f \cdot 10^3}{N_e} = \frac{3600}{H_u \cdot \eta_m \cdot \eta_i}, \text{ g/kW·h.} \tag{3}$$

In the second version of the tests, compared to the original one, g_e does not change, and when the fuel is turned off and pump losses are eliminated, the specific effective fuel consumption g_{e3} the lowest due to an increase in indicator and mechanical efficiency (Fig. 1 b).

Exhaust gas temperature t_g (Fig. 1 a) increases with increasing load in all test options, and according to the second and third options t_g higher than the initial one, as the amount of released heat changes due to an increase in the cyclic supply of fuel. In the second option, the temperature is lower than in the third due to the mixing of exhaust gases with the air coming out of idle cylinders.

Actual air consumption G_{air} (Fig. 1 b) in all test options with increasing load changes very little. This is caused by a slight decrease in air density due to heating in the intake manifold. When turning off only the fuel supply G_{air2} practically does not change compared to the original option, but with the third option G_{air3} almost twice as low as in the first and second options due to disconnection of the supply of fresh charge to cylinders 1, 4, 6 and 7.

Fill factor $\eta_v = G_{air}/G_{Tair}$ (Fig. 1 b) practically does not change with all three options, since the ratio of the actual and theoretical amount of air does not change significantly.

Excess air factor α (Fig. 1 b) decreases due to a slight decrease in actual air consumption and an increase in hourly fuel consumption (Fig. 1 a) [7]

$$\alpha = {G_{air}}\Big/{14,7 \cdot G_f} \,. \tag{4}$$

When disconnecting only the fuel supply (option 2) α_2 practically does not change. When the fuel supply is turned off and the pumping losses are eliminated, the coefficient of excess air α_3 lower, which is associated with a significant decrease in air flow (due to the installation of a bypass valve in the disconnected engine cylinder), although fuel consumption also decreases, especially in the load operating mode with a rotation frequency of 1200-1400 min^{-1}.

Mechanical efficiency η_m (Fig. 1 b) in all test options increases due to an increase in the indicator power, since the power of mechanical losses is assumed to be independent of the load [7]

$$\eta_m = \frac{N_e}{N_{in}} = 1 - \frac{N_{ml}}{N_{in}} \,, \tag{5}$$

where N_{in} – indicator power, kW;

N_{ml} – power of mechanical losses, kW.

With all options η_m changes in the same way, since the power of mechanical losses [8], which depends mainly on the frequency of rotation of the crankshaft, remains constant. According to the third option, the mechanical efficiency is higher to a greater extent due to a reduction in the power of mechanical losses (reduction in pumping losses).

Indicator efficiency η_i (Fig. 1 b), which characterizes the perfection of the combustion process, first increases and then decreases. Reduction η_i at low loads, it is explained by the deterioration of mixture formation caused by low temperature (deterioration of fuel evaporation), impaired atomization and possible fuel injection failures (due to insignificant cyclic fuel supply); reduction η_i at nominal loads is explained mainly by the deterioration of the combustion process due to a lack of air, which is also evidenced by the coefficient of excess air: α below 1.4 leads to incomplete combustion of fuel, increased smoke of exhaust gases. Incomplete combustion is accompanied by the prolongation of the combustion process according to the expansion stroke and, as a result, overheating of the parts of the cylinder-piston group, coking of the fuel and excessive soot deposition.

Figure 2 shows fuel economy depending on engine crankshaft speed at different loads.

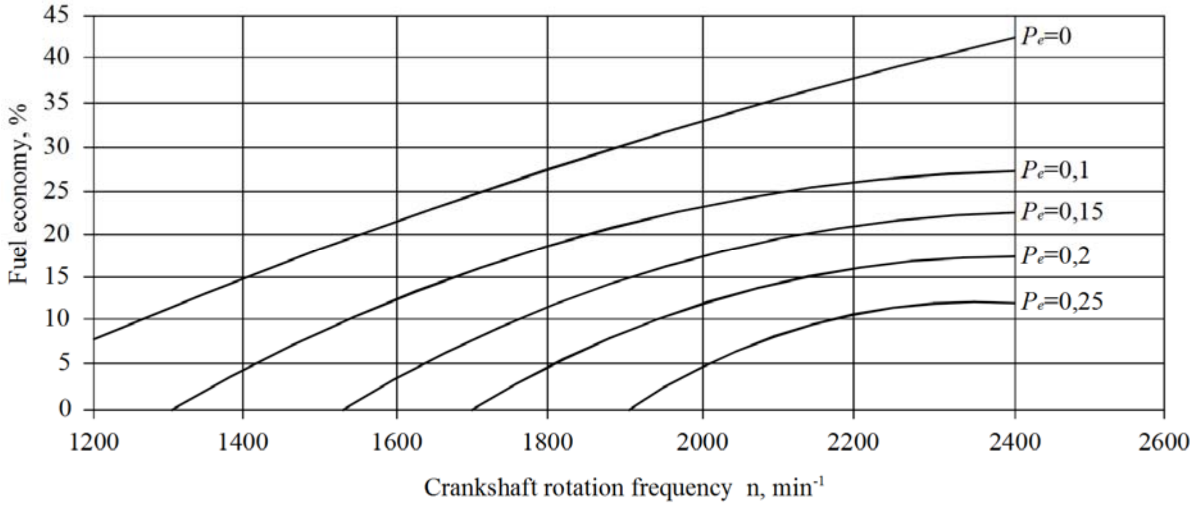


Figure 2 – Fuel economy depending on the speed of rotation crankshaft under different loads

Source: developed by the author

As can be seen from Figure 2, the maximum fuel economy occurs at a low load mode at the crankshaft rotation frequency $n = 1400$ min^{-1} ($P = 0$), moreover, the greater the frequency of rotation of the engine shaft, the less the economy, at the nominal frequency the fuel economy ΔG_f reaches 1.73 kg/h. As the load increases, fuel economy decreases and at $P_e = 0,25$ ($n = 2600$ min^{-1}) becomes minimal – 0.39 kg/h, and with a further increase in the load, fuel consumption occurs.

One of the measures to ensure the dynamic properties of wheeled vehicles and power on their drive wheels while reducing fuel consumption is the operation of the automobile and tractor engine in the mode of disconnection of the cylinders. Insufficient attention is paid to this problem, there are no studies of the load process and the method of control of vehicle engine systems, which affect the reliability and functional stability of the wheeled machine, and methods of diagnosis.

The work is aimed at solving the current scientific and practical problem of ensuring the reliability and functional stability of wheeled vehicles in the mode of disconnection of the cylinders. An effective method of further improving the fuel efficiency of the vehicle engine when disconnecting part of the cylinders at low loads and speeds can be the transition to neural networks controlled by the fuel supply system, which have feedback using the sensors of the standard on-board system. The use of an artificial neural network also allows to improve the latest technologies for monitoring and diagnosing the technical condition of the elements of wheeled vehicles, in particular internal combustion engines.

The combination of the method of disconnecting part of the cylinders and the latest technologies for monitoring and diagnosing the technical condition of the elements of wheeled vehicles will provide the required level of technical characteristics, which determines the relevance and prospects.

Conclusions.

1. The criteria are substantiated and a method of evaluating the energy indicators of the engine when the cylinders are disconnected in the loaded mode of operation is proposed. The following modes are considered engine load operations: 1 – test of the original engine; 2 – test with disconnection of four cylinders by st opping the fuel supply; 3 – test with

disconnection of four cylinders with simultaneous cessation of fuel supply and absence of pumping losses of the cylinder-piston group (CPG) in the disconnected cylinders.

2. It was established that when the engine is operating under load, the hourly fuel consumption when only the fuel supply is turned off is 7-0% less, in the power range from 0 to 22 kW, due to the improvement of the combustion process, and then increases.

3. It was also established that when the fuel is turned off and CPG pumping losses are eliminated in the disconnected cylinders, the time consumption of fuel at low load modes decreases, compared to the first version of work, by 1.73 kg/h, or 21%, which is explained by the increase in indicator and mechanical efficiency, the decrease in pumping losses in disconnected cylinders.

4. The feasibility of using the method of disconnecting a part of the working cylinders of the engine, saving fuel at load modes of no more than 70% of the total and with a further increase in the effective power of the engine load, the time consumption of fuel becomes higher than in the variant without disconnection of the cylinders, has been proven.

List of references

1. Полянський О.С., Молодан А.О., Власенко О.В. Підвищення паливної економічності колісних машин відключенням частини циліндрів двигуна . *Технічний сервіс агропромислового, лісового та транспортного комплексів*. 2017. № 9. С. 57-61.
2. Polyanskii A., Molodan A., Potapov N. Cause and investigative failure analysis in nominal engine operation and partial disabling of cylinders . *Транспорт, екология – устойчиво развитие*: сб. докл. XXVI научн.-техн. конф. с межд. участ. Варна: Технически университет, 2020, 8-10 октября. С. 132-137.
3. Капралов Б.И., Красильников А.С., Мазинг М.В. Оптимизация параметров топливной аппаратуры дизеля грузового автомобиля . *Двигателестроение*. 1987. №5. С. 20-22.
4. Драгунов, Г.Д., Медведев А.Н. Метод оценки эффективности отключения цилиндров автомобильного дизеля . *Двигателестроение*. 2007. № 4(230). С. 20-22.
5. Молодан А.А. Оценка технического состояния цилиндро-поршневой группы двигателя с учетом разделения потоков газов, проходящих в картер: дис. … канд. техн. наук. Харьков, ХНАДУ, 2011. 184 с.
6. Молодан А.О. Наукові основи забезпечення надійності і функціональної стабільності колісних машин в режимі відключення частини циліндрів: дис. … д-р техн. наук:. 05.22.20 / Харківський національний автомобільно-дорожній ун-т . Харків, 2021. 387 с.
7. Molodan A., Polyanskyi O., Potapov M.. Change of power and mechanical losses of a wheel vehicle engine with cylinders cutout . *MOTROL. Commission of Motorization and Energetics in Agriculture*. 2018. Vol.20. No.1. P. 99-103.
8. Куций П.В. Поліпшення експлуатаційних показників транспортних засобів в неусталених режимах оптимізацією способу регулювання дизелів: дис. … канд. техн. наук : 05.22.20 / Національний ранспортний ун-т. Київ, 2015. 206 с.

References

1. Polyansky, O.S., Molodan, A.O. & Vlasenkoб O.V. (2017). Improving fuel economy wheeled vehicles disconnection of cylinder [Pidvyschennia palyvnoi ekonomichnosti kolisnykh mashyn vidkliuchenniam chastyny tsylindriv dvyhuna]. *Tekhnichnyj servis ahropromyslovoho, lisovoho ta transportnoho kompleksiv – Technical service of agro-industrial, forest and transport complexes : Scientific journal*, *9*, 57-61 [in Ukrainian].
2. Polyanskii, A., Molodan, A. & Potapovб N. (2020). Cause and investigative failure analysis in nominal engine operation and partial disabling of cylinders . Transport, ecology - sustainable development *: XXVI nauchno-tekhnycheska konferentsyia s mezhdunarodno uchastye (2020, 8-10 Oktomvry) – Sat. report XXVI Scientific&Technical. Conf. From Int. Participation* (Pp.132-137). Varna: Tekhnychesky unyversytet [in English].
3. Kapralov, B.I., Krasil'nikov, A.S. & Mazing, M.V. (1987). Optimizacija parametrov toplivnoj apparatury dizelja gruzovogo avtomobilja [Optimization of the parameters of the fuel equipment of a truck diesel engine]. *Dvigatelestroenie – Engine building, 5,* 20-22 [in Russian].

4. Dragunov, G.D. & Medvedev, A.N. (2007). Metod ocenki jeffektivnosti otkljuchenija cilindrov avtomobil'nogo dizelja [Method for evaluating the efficiency of turning off the cylinders of an automobile diesel engine]. *Dvigatelestroenie – Engine building, 4(230)*, 20-22. [in Russian].
5. Molodan, A.A. (2011). Otsenka tekhnycheskoho sostoianyia tsylyndro-porshnevoi hruppы dvyhatelia s uchetom razdelenyia potokov hazov, prokhodiashchykh v karter [Assessment of the technical condition of the cylinder-piston group of the engine, taking into account the separation of gas flows passing into the crankcase]. *Candidate's thesis.* Kharkiv, KhNADU [in Ukrainian].
6. Molodan, A.O. (2021). Naukovi osnovy zabezpechennia nadiinosti i funktsionalnoi stabilitii kolisnykh mashyn v rezhymi vidkliuchennia chastyny tsylindriv [Scientific bases of ensuring the reliability and functional stability of wheeled vehicles in the mode of disconnection of part of the cylinders]. *Doctor's thesis*. Kharkiv, KhNADU [in Ukrainian].
7. Molodan, A., Polyanskyi, O. & Potapov, M. (2018). Change of power and mechanical losses of a wheel vehicle engine with cylinders cutout . *MOTROL. Commission of Motorization and Energetics in Agriculture, Vol.20, No. 1*, 99-103 [in English].
8. Kutsyi, P.V. (2015). Polipshennia ekspluatatsiinykh pokaznykiv transportnykh zasobiv v neustalenykh rezhymakh optymizatsiieiu sposobu rehuliuvannia dyzeliv [Improvement of operational indicators of vehicles in unstable modes by optimizing the method of regulating diesel engines]. *Candidate's thesis*. Science Kyiv: NTU [in Ukrainian].

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Метод оцінки енергетичних показників двигуна при відключенні циліндрів в навантаженому режимі роботи

Метою даного дослідження є підвищення ефективності роботи двигуна в режимі навантаження шляхом обґрунтування кількості відключень циліндра та визначення енергетичних параметрів його роботи. Досягнення поставленої мети передбачає вирішення наступних завдань: визначити вплив відключення половини циліндрів дизеля на параметри його роботи під навантаженням; визначити характер впливу насосних втрат в ЦПГ при вимкнених половині циліндрів на енергетичні характеристики дизеля під навантаженням.

Ефективність поршневих двигунів значною мірою залежить від режимів їх роботи. Якщо при номінальних або близьких до них економічні показники зазвичай досягають оптимальних або близьких до них значень, то при часткових навантаженнях і холостому ході паливна ефективність дизелів може помітно погіршуватися. При цьому в режимах роботи більшості транспортних засобів значну частку складають режими холостого ходу та невеликі навантаження. В роботі розглянуті режими роботи навантаження двигуна: 1 – випробування вихідного двигуна; 2 – випробування з відключенням чотирьох циліндрів припиненням подачі палива; 3 – випробування з відключенням чотирьох циліндрів одночасним припиненням подачі палива і відсутністю насосних втрат циліндро-поршневої групи (ЦПГ) у відключених циліндрів.

Доведено про доцільність використання способу відключення частини працюючих циліндрів двигуна, економії палива на режимах навантажень не більш як 70% від загального та при подальшому збільшенні ефективної потужності навантаження двигуна часова витрата палива стає вище, ніж у варіанті без відключення циліндрів.

двигун, енергетичні параметри, відключення циліндрів, навантаження двигуна, насосні втрати

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