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C O N T E N T S

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Criteria based assessment of efficiency of conversion of reciprocating ICE of hybrid vehicle on consumption of biofuels

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***Abstract* – This paper describes the results of a comparative calculation of a complex criteria based assessment of the level of ecological safety of the process of exploitation of a vehicle with hybrid drivind of propeller with diesel reciprocating internal combustion engine and mechanic, electric and mixed transmission mode that consumes a renewable energy source, namely biofuel of plant origin. This comparative calculation study was carried out for six steady models of exploitationof such vehicle - ESC (UNECE Regulations # 49), C1, D1, D2, F and G2 (ISO 8178-4:2017). The physical and chemical properties of biofuels and their impact on the toxicity of exhaust gases was taking into account. On the basis of analysis of quantitative and qualitative results of the calculations rancing of alternative exploitation models for different magnitudes of ratio between duration of transmission mode using was is carried out.**

Key words – hybrid vehicle, ecological safety, biofuels, criteria based assessment, environment protection technologies

I. Introduction

One of the most current global trends in the field of automotive transport is the complex solution of issues of fuel and ecological efficiency of their reciprocating internal combustion engines (RICE), which occurs against the background of the dieselization of the global vehicle park [1, 2]. The first problem directly forms the most of the monetary costs in the exploitation process of vehicle, but it also has two other aspects that indirectly affect the value of ecological safety (ES) indicators.

Firstly, the source of emissions of legislative normalized pollutants with exhaust gas (EG) flow is the combustion process of the motor fuel in the workflow of the RICE, such impact has an extensive side (the higher the exploitation consumption of fuel, the greater the emissions of pollutants, from such vehicle) and intensive side (depending on the quality of the motor fuel depends on both the perfection of the engine workflow and the component composition of EG). Secondly, petroleum-based motor fuel (so-called traditional or mineral) is a non-renewable energy source whose global consumption creates a global problem that is exacerbated year after year by the depletion of natural deposits of crude oil and other hydrocarbons which can be converted into traditional motor fuels.

The first of these disadvantages can be solved in three main ways. The first of them is the use of systems of neutralization of legislative normalized pollutants in the EG flow as part of the exhaust system of vehicle [1]. The second of them is the use of a hybrid drive of the vehicle propulsion with the transfer of part of the functions of the RICE for the production of mechanical energy on the traction electric motor (TEM), which has a number of significant advantages [3]: the consumption of a more ecological efficiency power source for the engine – electric, produced by RICE or other source and stored in the battery; the use of an electric transmission to transfer all the energy from the engine to the propulsion or a part of it, which is much more reliable and ecological efficiency, is easier to manage and assemble than mechanical. The third of them is the rationalization of the exploitation models of such vehicle and its RICE and its separate regimes [1, 2]. The second of these drawbacks can in principle be eliminated by converting their RICE to the consumption of renewable motor fuels (so-called alternative) – pure or in mixion with petroleum-derived (i.e. mixed) fuels. Among such liquid fuels, the most widely used are the methyl and ethyl esters of rapeseed oil [2, 4, 6].

Thus, a complex study of the fuel-ecological effect of the conversion of RICE of hybrid vehicles to the consumption of alternative fuels, comparable for different exploitation models of such RICE, is relevant. This study was performed on the example of a 2Ch10.5/12 autotractor diesel engine, using a improved mathematical apparatus of the criterion and conversion formula of Prof. Igor Parsadanov, regulatory documents [1, 2].

It should be separately noted that these issues are closely related to issues from other stages of the product life cycle, in particular, providing the required design resource [6], ensuring energy and resource savings in the engineering industry [7] and marketing research for the implementation of advertising strategy [8].

Purpose of the study. Determination of fuel-ecological effect of transfer of RICE of hybrid vehicle on consumption of alternative motor fuel. *Object of study*. Fuel-ecological efficiency of the exploitation process of hybrid vehicle with RICE. *Subject of study*. The influence of the type of motor fuel and the type of exploitation model of the RICE of the hybrid vehicle on the object of the study.

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II. Methodology

1. Analysis of features of hybride vehicle with RICE of exploitation process.

There are several concepts for developing a trackless vehicle on electric traction [3]: 1) electric vehicles with propeller (traction wheels) powered by a traction motor (TEM) that powered by a autonomus (unlike vehicles powered by a contact or contactless electrical network, etc.) chemical source of electricity without the use of RICE (battery, fuel cell, supercapacitor); 2) vehicles with RICE and electric transmission (electrically connected electric generator and TEM), propeller of which exclusively powered by the electric generator that powered by RICE and/or chemical power source; 3) vehicles with combined (hybrid) driving with both RICE, electric accumulator and electric transmission with TEM the propeller of which can be powered from all specified sources both separately and simultaneously in different combinations.

At present, conditions for the widespread distribution of electric vehicles in Ukraine, which require the availability of a developed network of charging stations, service stations and repair of the element base, especially electricity storage units, have not yet been created. Electric power plants have been in use since the middle of the twentieth century, but such a technical solution was used to transmit large power flows (career heavy dump trucks, tractors, armored vehicles), which caused the corresponding mass and dimensions of such power plants. Hybrid-powered vehicles are considered the most promising today, due to the following advantages: a) speed of readiness due to the possibility of using both motor fuel (available and widespread primary energy source) and electricity sources for battery charging; b) intermittent operation of RICE with reduced nominal power and simplified construction, optimized for a narrow range of operating regimes, which increases its fuel and ecological performance (both extensively and intensively), durability, and reduces cost and overall dimension and mass indicators; c) the possibility of using of TEM with less power and a battery of smaller capacity, which reduces their overall dimension and mass and cost indicators; d) variability and flexibility of electronic control of energy production, accumulation and use, possibility of its regeneration during braking, which allows to use the simplified mechanical transmission (and stepless); e) rationalization of transient processes (engine start, moving from place, acceleration, braking, stopping, switching off) possibility of realization of the ideal traction characteristic and shutdown of the RICE at a stop in the traffic flow.

There are several schemes for connecting the engine and the capacitor to the propeller [3, 9], in particular: a) the series, in which the RICE is mechanically connected only to the generator, TEM – only to the propeller, the scheme also contains a battery and a voltage converter connected to each other and with generator and TEM electrically; b) the parallel, in which both the RICE and TEM are mechanically connected to each other and to the propeller by differential and can operate both individually and jointly; c) the sequentially parallel, in which both the RICE, the generator and the TEM are mechanically connected to each other and to the propeller by planetary gearbox, which allows to arbitrarily change the power flows between them.

Most experts in the transport and energy production industries (prognosis of Association for the Peak Oil and Gas Study by data of BP and OPEC statistics, quarterly reports of EIA, Forbes and Bloomberg Analytical Surveys [10]) believe that prospecting and potential fossil fuel resources collectively tend to be depleted, the so-called «crude oil peak» is estimated to have passed in 2005, and the peak production of all conventionally liquid fuels is expected as early as 2019, with the amount of resources not yet extracted estimated at 35 % from the beginning of the number. Two main ways to overcome this situation, as follows from the above, are to use renewable energy sources and to improve energy efficiency. For the transport industry at the present stage of development of vehicle element base and service infrastructure, the first way is realized through the use of biofuels, and the second – through the use of electric or hybrid drive of propeller.

Data from sources [11 – 17] indicate a steady increase in the production of alternative motor fuels, in particular biodiesel, and the corresponding consumption of such fuels both in the transport industry and in the world as a whole. Thus, biofuels make up 14 % of the global consumption balance [11], 80 % of which in the transport sector is biodiesel [12], 60 % of which is consumed by EU countries [13], 15 % of which is produced from rapeseed oil [14].

The data shown in Fig. 1,a from source [11], they show a steady increase in the production of alternative motor fuels, including biodiesel – in 15 times since 2004, although this volume is now less than 3 times that of bioethanol (35 and 105 billion tons).

The main raw material for the production of biodiesel motor fuel is soybean oil (55 % [14]), and in the structure of the distribution of vegetable oil produced, such that is processed into biodiesel fuel began to appear in a significant amount since 2002, with the passage of time the amount of vegetable oil produced increases (in 1.5 times from 120 to 180 million tonnes since 2002), and its portion that is converted to biodiesel fuel (8 times from 4 to 32 million tonnes since 2002, ie from 3.5 to 18 %) – see. Fig. 1,b [15].

An equally important factor in the applicability of biodiesel fuel is its cost compared to the cost of diesel fuel of petroleum origin, which are determined by the cost of raw materials – respectively, crude oil and vegetable oil. Recently, there has been a tendency to reduce the price of biodiesel blended fuel, which is explained by the increase in demand for it and the improvement of its production technologies and reflected in Fig. 2,c by the data on the dynamics of price changes on traditional and mixed diesel fuel and natural gas in the world from 2005 to 2012, described in the source [17].

An analysis of the trends for the decade (from 2007 to 2017) in the source [18] shows that the nature of the change in the price of traditional diesel motor fuel exactly repeats the nature of the change in the price of crude oil (see Fig. 2,a), and the difference between them is the sum of the cost and profitability of the actual process of processing crude oil into diesel fuel. The dynamics of changes in the price of crude oil, as the «primary source» of prices for its products, is extremely difficult to predict, since its formation contains subjective, first of all – geopolitical, factors.

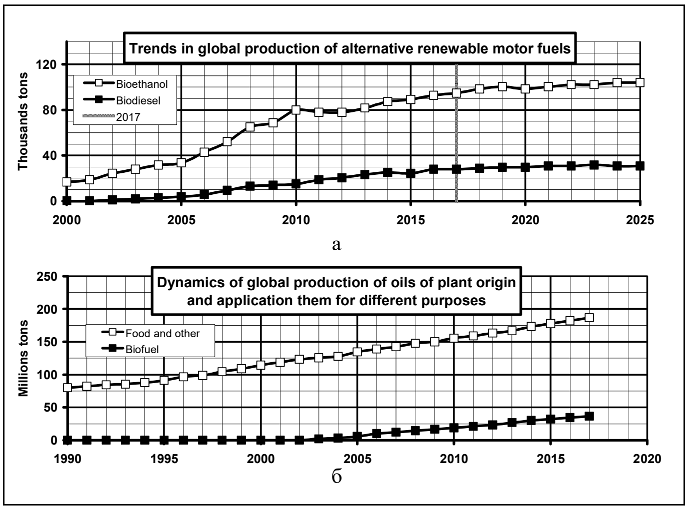

Fig. 1. Dynamics of production of motor biofuels and raw materials for it in the world according to [11, 15]

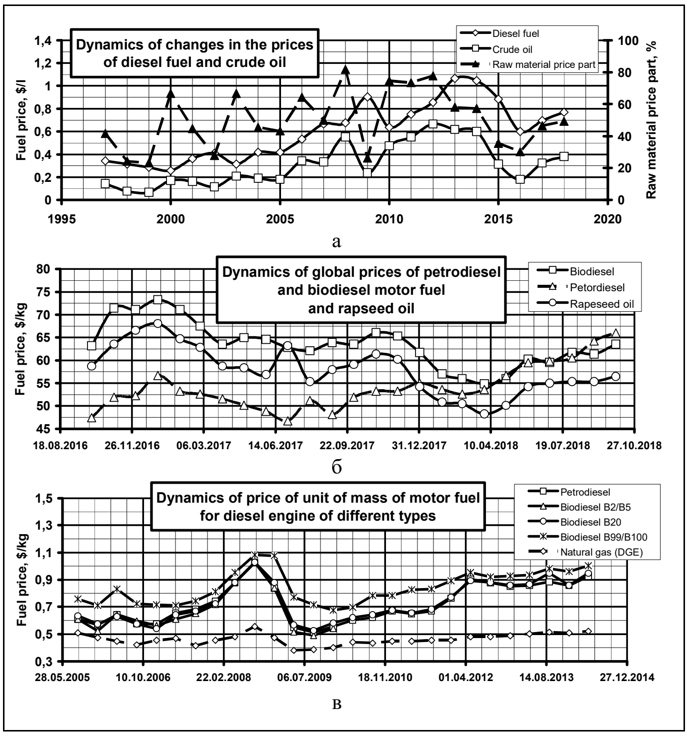

Fig. 2. Dynamics of price changes for different types of diesel fuel and its raw materials according to [16 – 18]

An analysis of the dynamics of changes in the price of traditional, alternative diesel fuels and pure rapeseed oil in the world from 2016 to 2018 (see Fig. 2,b) in [16] shows that the dynamics of changes in the price of biodiesel fuel are traced such prices of rapeseed oil (as with the other pair of raw material and product considered above), the prices themselves go down, unlike the price of diesel oil of petroleum origin, and at some point in time the price of alternative fuel became lower than the price of traditional fuel.

The correctness of the chosen ways of overcoming the mentioned ecological problems of the transport industry is confirmed by the data on the analysis of the dynamics of the growth of sales volume of hybrid vehicles in [19] (see Fig. 3,a), which in the period since 2013 increased cumulatively in 7 times in all major regions of the world – US, EU and China. In 2018, there are 4 million such vehicles sold in the world, representing 1.5 – 4.0 % of the total number of vehicles sold [19].

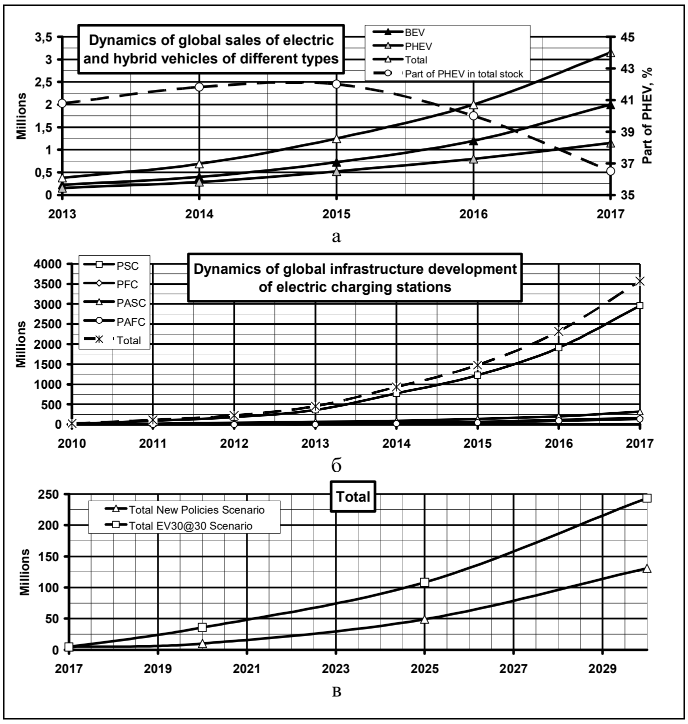

Fig. 3. Dynamics and forecast of production and sales of hybrid and electric vehicles and number of charging stations in the world according to [19]

Forecasts based on the existing trends in [19] (see Fig.3,c), predict an increase of such sales by another 45 times, and in the EV30@30 scenario (reaching the 30 % mark in the overall structure by 2030) – in 85 times. At the same time, as of 2016, electrically driven vehicles in the world market structure are now over 65 % of hybrids, in particular the Toyota Prius [20]. According to information from [22], currently in the territory of Ukraine the number of registered electric vehicles is about 18 thousand, half of which are full-fledged electric vehicles, 16 % are plug-in hybrids and the rest are ordinary hybrids.

The processes described above are also facilitated by a worldwide upward trend in the number of charging stations for electric vehicles and plug-in hybrids in 35 times since 2010 (see Fig. 3,b [19]). Electricity charging stations in Ukraine are now registered more than 1.2 thousand, while in EU countries – over 8 thousand, in Japan – 7,5 thousand, in the USA – 50 thousand, in China – 160 thousand. [22]. The current distribution of electric charging stations of different types for electric trucks throughout Ukraine provides a resource [21].

Thus, it is determined that for the current stage of development of road and service infrastructure in Ukraine, the most promising are cars with hybrid drive, built on the use of a combined scheme.

2. Selection of variants of exploitation model for hybride vehicle with RICE and different modes of propeller dirving

Based on the above, we can conclude that in a hybrid electric vehicle, there are several ways of operating all of the main components listed above – RICE, generator, TEM and battery both individually and in any combination. These methods are implemented in different modes of motion of the same vehicle. This study will apply a simplified approach based on the assumption that the RICE can drive the propeller in one of two ways (while the combined operation of TEM and RICE is not realized, the battery does not charge from RICE and transmit stored energy to the TEM): A) through a mechanical transmission (as in a traditional vehicle); B) through electric transmission; C) alternately through mechanical and electrical transmission.

To implement a complex criteria-based assessment of fuel-ecology efficiency of exploitation process of RICE in such vehicle when using motor fuel of both mineral and biological origin, it is necessary to have a model of exploitation of such RICE for methods A and B, and method C is a combination of the first two. The analysis of the nomenclature and parameters of the known exploitation models of RICE, described in the sources [1, 2], allowed:

– method A to comply with the ESC standardized steady test cycle described in UNECE Regulations No. 49, which is used to build the vehicle test program and contains 13 steady-state regimes of engine operation;

– method B to comply with one of the following cycles of ISO 8178-4: 2017 «Reciprocating internal combustion engines, Part 4: Test cycles for different engine applications»: C1 «Engines for off-road transport and off-road industrial equipment» (diesel) (contains 8 regimes), D1 «Engines with constant crankshaft rotation for power plants» (diesel) (contains 3 regimes), D2 «Engines with constant crankshaft rotation for electrical installations with variable load» (diesel including short-loaded diesel generators load (intermittent, hopping), ship and locomotive auxiliaries (not for traction)) (contains 5 regimes), F «Locomotive engines» (diesel, including heavy duty dump trucks with electric transmission) (contains 3 regimes) or G2 «Industrial engines with power less than 20 kW» (diesel, including portable diesel generators) (has 6 regimes).

3. Initial data and mathematical apparatus for comparative calculated criteria based assessment

The most relevant for such assessment among the known is the complex fuel-ecological criterion of Prof. Igor Parsadanov K_{fe}, described in the monograph [2]. To solve these problems, the author of this study has improved the mathematical apparatus of this criterion, which is described in the monograph [1], which was successfully used in the study to expand the range of ES factors taken into account [23].

Parameters of the ESC cycle regimes for 2Ch10.5/12 diesel engine according to UNECE Regulation No. 49 have been obtained and described in previous studies [24 – 26]. The distribution of the magnitudes of technical, economic and ecological performance of the 2Ch10.5/12 autotractor diesel engine, as well as the K_{fe} criterion and its monetary components in the field of its operating regimes obtained experimentally and calculated are given in the monograph [1]. From such data, a set of initial data was generated to investigate the operating regimes described by the C1, D1, D2, F, and G2 test cycles. Differences in the physical and chemical properties of diesel motor fuels of biological and traditional origin, as well as the technical, economic and ecological indicators of diesel 2Ch10.5/12 on 100 % biodiesel fuel obtained experimentally, have been described, illustrated and analyzed in a previous study [24].

III. Results and Discussion

Results of the calculated assessment of the fuel-ecological effect from the transfer of the RICE of a hybrid vehicle to the consumption of motor fuel of biological origin, determined by the use of the selected modified criteria-based apparatus, are illustrated for all the studied exploitation models on Fig. 4 – 7.

On Fig. 4 shows the histograms of distribution of K_{fe} criterion for the 2Ch10.5/12 diesel engine consumption of 100 % conventional and 100 % alternative motor fuel in ESC cycle regimes (i.e., RICE exploitation model for model A of propeller driving), as well as a graph of the relative values of changes of this the criterion δK_{fe} (i.e. fuel-ecological effect of transferring diesel engine from one fuel to another), as well as for cycles C1, D1, D2, F and G2, i.e. alternatives for the RICE exploitation model for model A of propeller driving.

n Fig. 5 contains the results of the calculated assessment of the average (i.e., characterizing the test cycle as a whole) values of the criterion K_{feme} when using both motor fuels and the fuel-ecological effect δK_{feme} for all investigated exploitation models. On Fig. 6 shows the results of the calculated assessment of the relative difference magnitudes of the midle exploitation values of the criterion δK_{femeC} and the fuel-ecological effect δK_{femeE} for cycles C1, D1, D2, F and G2 compared to the ESC cycle.

On Fig. 4 it can be seen that the values of the K_{fe} criterion for the ESC cycle modes vary from 4.1 to 71.3 ‰ for the case of consumption of 100 % of traditional fuel, and the fuel-ecological effect δK_{fe} from the transition to consumption of 100 % of alternative fuel – in the range from 1.1 to 10.7 %. This is due to the fact that the proposed exploitation models contain regimes with low and zero effective power N_e, which show the least intense growth of δK_{fe} magnitudes (see [24]), and a significant number of regimes with a magnitudes of N_e in the range 20...40 %, where a moderate increase in δK_{fe} magnitudes is observed, and this effect is significantly achieved in regimes with values of N_e in the range of 40…60 %, where the dependence of K_{fe} on N_e moderately increases and «goes on the shelf». The greatest effect is achieved on regimes with N_e magnitudes in the range of 60…100 %, where K_{fe} magnitudes from N_e are almost independent. In all ESC regimes, the value of the effect of δK_{fe} is positive. On Fig. 4 shows that the features obtained in the analysis of the distribution of the values of K_{fe} and δK_{fe} by the regimes of the ESC cycle are inherent in the cycles C1, D1, D2, F and G2.

From the above on Fig. 4 and 5 show that the middle exploitation magnitudes of the K_{fe} criterion for all investigated exploitation models are of the same order of magnitude – varying in the range from 61.8 to 68.4 ‰, which is explained by the nature of the distribution of the criterion magnitudes across the field of operating regimes of the RICE (see [24]) and the closeness of the structure and parameters of such models (see monograph [1]).

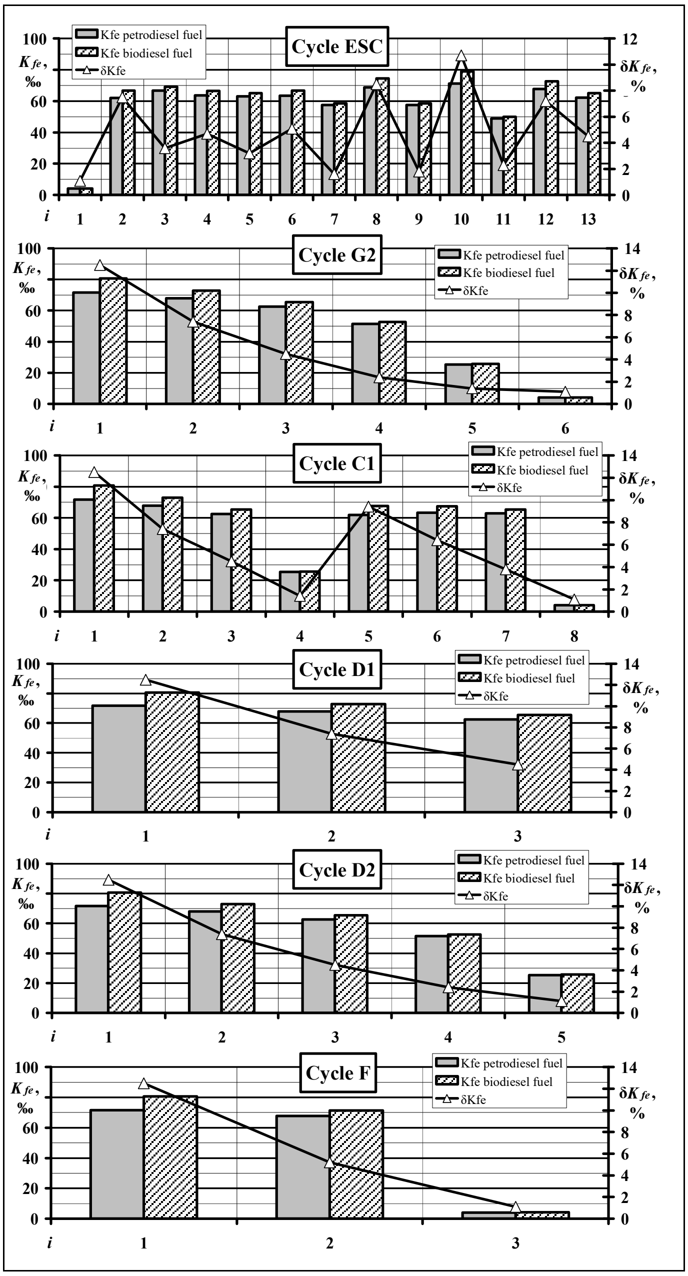

Fig. 4. Results of the study for cycles ESC, G2, C1, D1, D2 and F

On Fig. 5 shows that the middle exploitation magnitudes of the fuel-ecological effect δK_{fe} for all investigated exploitation models are positive and fluctuate in the range from 6.6 to 10.7 %, which is a result of the different direction of change of the fuel (increasing) and ecological (decreasing) components of the K_{fe} criterion during the transition in consumption from 100 % conventional to 100 % alternative motor fuel.

From the contents of Fig. 6 it follows that when comparing the parameters of cycles C1, D1, D2, F and G2 as alternative models of exploitation of the RICE of a hybrid vehicle operating in the mode of a current generator for electric transmission (method B of driving vehicle propeller), cycle parameters of the ESC as a model of exploitation of the RICE of a hybrid vehicle operating in the mode of power source for mechanical transmission (method A of driving vehicle propeller), the most favorable value of the K_{fe} criterion is the cycle D1 (higher by 8.6 %), the least advantageous – cycle F (lower by 1.9 %).

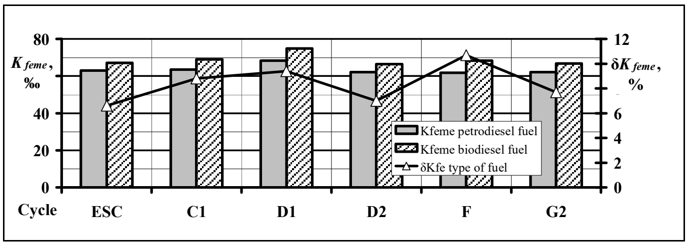

Fig. 5. Middle exploitation magnitudes of the K_{fe} criterion and fuel-ecological effect δK_{fe}

Ranking of alternative variants of exploitation models of diesel-generator						
A sign of ranking	Fuel and ecological efficiency of the ICE exploitation process in drive mode of electrical transmission in comparison with the drive mode of the mechanical transmission					
Indicator	δK_{fe}(cycle), %	8,6	0,8	–1,3	–1,4	–1,9
Model of exploitation		D1 →	C1 →	G2 →	D2 →	F
A sign of ranking	Fuel and ecological effect of application of alternative fuel					
Indicator	δK_{fe}(fuel), %	62,1	42,4	33,3	16,7	6,1
Model of exploitation		F →	D1 →	C1 →	G2 →	D2
Priority of application		Higher →				Lower

Fig. 6. Results of ranking of alternative exploitation models

The magnitude of the fuel-ecological effect δK_{fe} from the transfer to the consumption of alternative motor fuel in comparison with the ESC cycle is the most favorable cycle F (higher by 62.1 %), second place – cycle D1 (higher by 42.4 %), and least favorable – cycle D2 (higher by 6.1 %). In view of the above considerations, the results of the study were ordered by ranking the C1, D1, D2, F and G2 cycles with respect to the ESC cycle according to the priority of use of the selected criterion and effect, the results of which are shown in Fig. 6.

CONCLISIONS

Summarizing the above, it can be noted that in the present study a comparative description of the quantitative and qualitative aspects of the RICE operation of a hybrid vehicle on alternative exploitation models and the effect of transferring it to the use of a renewable energy source were made, based on the results of the analysis of the calculated complex criteria-based assessment.

For the first time, the approach is proposed for the assessment of fuel and ecological efficiency of the process of exploitation of diesel RICE in the composition of a hybrid vehicle with taking into account the influence of the type of fuel consumed by it, the type of exploitation model and the relative part in the modes of mechanical and electric transmission in duration of exploitation process.

Proposed approach is suitable for carrying out such an assessment in cases of transfer of the engine of such vehicle to other known or promising types of alternative fuels, both pure and mixed; to evaluate these effects in the rationalization of the structure of known or newly created models of exploitation of hybride vehicles and their engines; application of other mathematical mathematical apparatuses.

For the first time, well-known standardized steady models of exploitation of a diesel generator are ranked for the case of its operation in a hybrid vehicle, both on the basis of fuel-ecological efficiency of its exploitation process, and with the sign of the magnitude of the effect of transferring of such object on the consumption of alternative fuel.

The results of the ranking of known models of exploitation of the diesel generator can be taken into account in the development of the algorithm of operation of the engine electronic contril system as part of a hybrid vehicle and the assessment of the amount of cost for fuel and ecological damage during the exploitation process of such objects.

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