Recueil De Mécanique
El Wancharissi University
of Tissemsilt

ISSN: 2507-7589 ○ EISSN: 2507-7619

Research Paper DOI : 10.5281/zenodo.7207557 Open access

Improving the operational efficiency of marine high-speed diesel engines

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ARTICLE INFO

Article history :

Received 03 September 22

Accepted 11 October 22

Keywords:

Marine diesels, calculation methods, engine cost, economic efficiency, diesel quality, power calculation, modernization of marine high-speed diesels.

ABSTRACT

In the course of the research, a comparative analysis of the operating parameters of high-speed ship diesel engines, including cost ones, was carried out. The technical characteristics of the ship's high-speed diesel engines of domestic production are analyzed, as well as the directions of their modernization are proposed, including structural measures and ways of organizing work processes for various variants of combustion chambers, variants of execution (main, auxiliary). The method of calculating the power of the main engine of the vessel on the basis of valid indicator diagrams is proposed. The calculation method is proposed and the concept of the economic efficiency coefficient of a ship's small-sized diesel engine is introduced. A method for assessing the quality of marine diesel engines is proposed, as well as a method for calculating the cost of diesel based on its main functional indicators. The ways of modernization of marine high-speed diesel engines are determined.

1 Introduction

The technical level of marine high-speed diesel engines (MHSDE) is largely determined by the organization of a highly efficient working process, which includes the formation and development of a fuel flare with a large fraction of a fine component, its interaction with hot and moving air and the walls of the combustion chamber (CC), heating and evaporation of fuel and the formation of a close to homogeneous working mixture. Russian and foreign engine-building companies use all types of mixture formation in their products, with the exception of film (near-wall) – volumetric, combined (film-volumetric), and vortex with the corresponding CC designs.

Improving manufactured and creating new models, problems related to increasing the compression ratio, maximum cycle pressure, fuel injection pressure and the size of spray nozzle openings are solved. High fuel and economic indicators were achieved by using modern high-quality materials, using advanced and innovative MHSDE production technologies, using structural and technological methods to reduce power losses to overcome friction forces, and solving problems of dynamics and strength.

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Currently in Russia there are problems with the production of MHSDE with a capacity of 5 ÷ 110 kW (plants "Dagdiesel", "Volzhsky diesel named after Mamin", "Bogorodsky Machine-building Plant", "Barnaultransmash", "Zvezda"). Engines of types Ch8,5/11 and Ch9,5/11 are used on sea and river vessels, boats, lifeboats, fishing boats, river vessels with a displacement of 3 to 45 tons as main, emergency and auxiliary diesel engines. At the moment, domestic MHSDEs in the range of capacities under consideration can only meet the needs of shipbuilding to a limited extent. Few engines are produced, within a limited range, and their parameters do not meet modern requirements.

Engines of types Ch8,5/11 and Ch9,5/11 are produced with two methods of mixing: vortex – with a vortex combustion chamber located in the cylinder head, the volume of which is 90% of the volume of the combustion chamber; and combined – with a semi-divided combustion chamber located in the piston.

2 Comparative analysis of the operating parameters of MHSDE

Comparative characteristics of domestic and foreign diesel engines that are similar in purpose and dimension at first glance indicate the undoubted advantages of foreign machines.

Comparative assessment of the quality of internal combustion engines by a certain set of their parameters is one of the tasks that engine engineers often have to face (for example, when certifying quality, justifying plans for creating new equipment, analyzing competitiveness in the foreign market, etc.).

Regardless of the final goals, the general algorithm for solving the problem is the same: one or several analogs are selected for the engine being evaluated, after which the numerical values of their indicators are compared; the individual estimates obtained in this way are either considered differentially, or reduced to a total index and serve as the basis for making a decision on the level of quality or competitiveness of this engine. The most objective and reliable assessment would be obtained by conducting comparative tests of analog engines using a single methodology and under the same conditions, as well as on the basis of generalized data on their operational experience. However, in practice, there is often no comprehensive, documented data about the engine samples themselves, and the main information sources are prospectus and catalog materials of manufacturers. Moreover, companies issue advertising brochures for new models even at the design stage, before the production of prototypes.

The disparity of available information materials is caused not only by different degrees of reliability, but also by differences in existing national standards and norms. Therefore, comparison of some parameters is possible after they are brought to a comparable form in terms of external conditions, engine completeness, etc. Analysis of literature data shows that only due to atmospheric conditions stipulated by the standards of many countries, the power of the same engine can vary up to 16%.

It is most difficult to compare domestic and foreign diesel engines by resource indexes, since each company uses its own approach to the volume and complexity of maintenance and repair of its engines. So, for example, in the same collection of materials from the Swedish company "Volvo Penta" you can find the expected service life before the complete bulkhead of diesel generators of 20,000 hours and the recommended interval between full bulkheads of 12,000 hours. Such discrepancies in the resource values of the same machines, sometimes amounting to 100% or more, can introduce serious errors in the results of a comparative assessment of the technological level. Foreign companies attach great importance to linking the supplied engines to their operating conditions. A number of companies specify the preferred mode of operation of the engine during the guaranteed service life and climatic conditions, zones of operation.

This leads to the conclusion that in a comprehensive assessment of the quality of a particular engine, first of all, one should proceed from an expert assessment of the significance (weight coefficient) of a particular index, depending on atmospheric and external conditions, characteristic indicators of the operating mode, the possibility of performing qualified and timely maintenance, and the trouble-free operation resource requested by the consumer. An expert method for determining the weighting coefficients of indicators by ranking them is recommended in the theory and practice of qualimetry [2, 3].

The most unobvious of the evaluation criteria for diesel engines is specific weight. With the existing engines variety by type and purpose, designers face completely different tasks. While weight reduction is the most important factor for aircraft engines or diesel engines installed on hydrofoils, for example, for stationary or conventional marine engines, economy, reliability, low noise and vibration levels are primarily required, which is facilitated by more massive structures.

The advertised power is usually specified according to ISO conditions without specifying the power consumption for driving auxiliary mechanisms mounted on the engine, which leads to an additional" increase" in power by 5-9%. As a result, the advertised power of foreign diesel engines significantly exceeds the actual long-term power sold by the consumer, which results in an underestimation of the specific weight of the engine.

Thus, when comparing estimates of domestic and foreign diesel engines based on heterogeneous information materials, a large number of disparity factors come into force, the combined effect of which gives these estimates a very approximate character [4]. Therefore, the most appropriate way to assess the quality of machines is to use a hypothetical standard that combines the best values for each of the indicators. Such a standard is objective, stable, universal and easy to calculate, and the problem of selecting an objective analog for comparing the quality indicators of the machine being evaluated methodically does not present any fundamental difficulties. The difficulties are related only to the lack of information and the need to bring the available information to a comparable level. Thus, there is a need for a method of comparative assessment of the quality of marine diesel engines, which could be used in various circumstances: in quality certification; justification of plans for creating new equipment; analysis of competitiveness [5, 6], etc.

Separately, we should focus on the cost indicators. This is the most private data, which is virtually impossible to obtain information about even from manufacturers ' catalog materials, and which is often revealed only in contract negotiations. And these data are urgently needed already at the stage of initial development of the project. Hence, it is necessary to solve the following particular problem-to develop a methodology for analytical determination of the cost of marine diesel engines based on their known functional indicators set out in the prospectus and catalog materials of manufacturers.

In addition, in practice, there are situations when in order to achieve a high technical level of products and maintain it further, it is necessary to make such large financial contributions that it is not possible to compensate for them in the future, let alone receive profit from operation. And it is not a new optimization task to link the volume of investment in design, production and financing of operational maintenance with those indicators of the technical level of the product that will be necessary and sufficiently accurate, both to ensure its normal profitability in operation and to maintain operational indicators at acceptable values during the established service life [4].

The technical level values of modern and promising marine diesel engines achieved so far are based on high and ultra-high values of workflow indicators, design and technological solutions for the skeleton elements, cylinder-piston group, fuel supply system and materials used. This approach leads to a high level of costs for research, design and production of diesel engines and is typical for fundamentally new machines, and the achieved indicators are essentially marginal for a significant future due to design, technological, materials science and economic constraints. In this regard, it is very rational to improve the functional indicators based on the introduction of well-known or new technical solutions into the production of mass-produced or upgraded engines. Each such solution can give a small quantitative increase in operational indicators, but when applied together, due to the superposition principle, they can have a tangible effect.

Astrakhan State Technical University has conducted a series of studies on the organization of MHSDE work processes [7-10]. Certain results have been achieved in improving fuel efficiency, reducing loads on CPG parts by reducing the maximum cycle pressures [7], increasing the specific power characteristics of MHSDE without the use of supercharging and significant structural changes [10], experimental models of MHSDE with combined mixture formation and forced ignition [7], with combined mixture formation and compression ignition [10] have been created.

The International Convention for the Safety of Life at Sea, called SOLAS, was adopted by the International Maritime Organization in 1960 as an International Convention. The most effective collective life-saving appliances (CLSA) capable of ensuring a rescue operation in a short time and the departure of the crew and passengers to a safe distance from the ship in distress and fully meeting the SOLAS convention requirements are motor lifeboats, equipped with reliable power plants (PP) based on small-sized diesel engines (SSDE). In emergency situations, a prerequisite for successful rescue operations is, first of all, trouble-free and efficient operation of the CLSA PP diesel engine.

The efficiency of the PP is determined by indicators that characterize the engine motility required for the CLSA to move at a conventional speed and the operation of its life support systems, the balance of power and efficiency of the PP in terms of specific fuel and oil consumption. Important indexes are also: the total efficiency of the propulsive complex (η_{pc}) – which characterizes power losses in the engine (η_e), reverse gear transmission (η_t), shaft line and propeller (η_s), pumps of dehumidification and irrigation systems (η_p), generators of on-board power supply, radio stations, and batteries charge (η_g), loss to overcome the resistance of the movement of CLSA hull and power reserve (η_k).

The specified nomenclature of PP evaluation indicators differs significantly from the generally accepted nomenclature of PP evaluation indicators for general purposes, which is explained by the specific functions performed by the PP during the implementation of a rescue operation.

It is advisable to include in the nomenclature of estimated characteristics for the CLSA PP: external and propeller law of the PP; starting characteristics, the dependence of the start-up duration on various design and operational factors such as ambient temperature, crankshaft speed, cyclic fuel supply, fuel injection start-up angle, etc.

The listed set of indicators and characteristics takes into account the main features of PP and makes it possible to assess their compliance with international and national requirements. The full range or part of the proposed evaluation indicators can be used for research, development, factory and other types of tests. OJSC "Plant "DAGDIESEL" is the only enterprise in the Russian Federation that serially produces engines for collective life-saving appliances of sea and river vessels, both for commercial and military purposes. And if shipping companies, even those belonging to the United Shipbuilding Corporation (USC), allow themselves to purchase imported equipment at the expense of the state budget, then the Russian Navy should rely only on its own manufacturer. In this regard, improving the quality and performance of life-saving engines is an important and urgent task not only for the plant's specialists, but also for all scientists and engineers working in this field.

Among the numerous modifications of boat engines, there are two main diesel engine sizes: 4ChSP9,5/11 (Kaspiy 40) with film-volumetric mixing and a semi-separated combustion chamber in the piston (Ne = 25 kW, at n = 41.6 s^{-1}) and 4CHSP9,5/11 (Kaspiy 30M) with a volumetric vortex-type mixing (Ne = 22 kW, at n = 41.6 s^{-1}).

Engines with a CC in the piston have two indisputable advantages over eddy-chamber diesels: fast start-up and good fuel efficiency.

Their comparative analysis shows that switching to the piston combustion chamber reduces specific fuel consumption by 20-30 g/(kW·h). At the same time, the combustion pressure p_z increases by no more than 0.5-0.7 MPa, and the diesel engine operates steadily and stably over the entire load range, the spread of p_z values in subsequent cycles does not exceed 4%.

These machines (engines of rescue vehicles) are a class of one-time machines with a short period of operation, i.e., having fulfilled their function and provided rescue of people in the course of a maritime disaster, they are no longer needed, and their subsequent use as a means of rescue at sea does not matter. But at the same time, the engines of collective rescue vehicles technically, technologically, and in course of material science repeat more or less successful models of small-size marine diesel engines.

As for fuel efficiency, this factor does not prevail in the implementation of rescue operations. And with the use of fast-igniting liquids based on dimethylether during pre-start operations, as well as maintaining the system of glow plugs, the starting advantages of an engine with a chamber in the piston are leveled. Nevertheless, there are still a number of opportunities to bring the starting and maneuvering qualities of the 4ChSP9,5/11 eddy-chamber diesel engine (Kaspiy 30M) to the level of SOLAS and ICLSA requirements. These opportunities are expected to be implemented in the future. In addition, vortex-chamber machines have a number of significant advantages, namely:

- Create a lower level of noise and vibration due to the lower values of the pressure build-up rate during the combustion of the working mixture ($dp/d\varphi$), which is important for providing more comfortable conditions for the passengers of the boat;
- These engines have a lower level of smoke due to good mixing;
- These engines are equipped with a simple design and reliable fuel equipment that is not too demanding for fuel quality.

3 Calculation method for determining the power of the ship's main engine

In the practice of sea trials of ships and thermotechnical tests of ship power plants, there are cases when, at the request of supervisory authorities (the Russian Maritime Register of Shipping or the Russian River Register), it is necessary to make a direct assessment of the effective power of the main engine. Usually, the rated effective power of the main engine of a ship during sea trials is estimated by indirect indicators – hourly fuel consumption G_h (kg/h), exhaust gas temperature – T_g *or* t_g (K or °C), maximum combustion pressure, p_z (MPa), according to the engine's passport data, at rated speed progress bar.

Direct assessment of the effective power, if necessary, is carried out by instrumental measurement of the effective engine torque using torsiographs or dynamometric couplings [11, 12, 13, etc.]. Such methods for assessing the effective power are cumbersome and not always possible due to the design features of ship shaft lines. Therefore, as an alternative, a method based on indexing and calculating the internal losses of the engine is proposed. Obviously, the proposed method can be applied for engines equipped with indicator cranes, as well as for diesel engines with electronic systems for monitoring engine performance.

Engine power at idle is spent only on overcoming internal losses (power losses for making pumping strokes of the piston, power losses for overcoming friction forces in all nodes, power losses for driving auxiliary mechanisms), then the area of the idling indicator diagram expresses the work that went to overcome internal losses. The indicator diagram of an engine in rated power mode determines its indicator operation per cycle, i.e., operation, that takes into account heat losses during the operating cycle, but does not take into account internal losses in the engine when converting the reciprocating motion of the piston to the rotational motion of the crankshaft. Then, subtracting the engine idling indicator operation from the rated power indicator operation, we get the effective engine operation per duty cycle, as well as the effective power. To a first approximation, this approach to the problem of determining the effective engine power is valid.

However, there is one discrepancy. If the power losses for pumping and driving auxiliary mechanisms can be assumed to be the same both at idle and at rated power, then the power losses for overcoming friction forces differ. Power losses to overcome friction forces consist of a number of components [14]:

$$N_{fp} = N_{cpg} + N_g + N_{gdm} + N_b + N_{hpfp} \tag{1}$$

In the formula under consideration, N_{fr} is the total power loss to overcome the friction forces in the engine; N_{cpg} is the power loss to overcome the friction forces in the cylinder-piston group; N_g is the power loss to overcome the friction forces in mechanical gears; N_{gdm} is the power loss to overcome the friction forces in the gas distribution mechanism; N_b is the power loss power losses to overcome frictional forces in plain bearings; N_{hpfp} – power loss to overcome the friction forces in the high-pressure fuel pump.

The components $N_g + N_{gdm} + N_b + N_{hpfp}$, as an assumption, can be considered independent of the engine operating mode, while N_{cpg} increases along with the load due to the increase in the "lateral" force N. The lateral force N determines the work of friction in the cylinder-piston group (the friction of the piston rings and the friction of the piston skirt about cylinder sleeve). The force N is a function of the total force P_Σ, applied to the connecting rod piston head.

$$N = P_\Sigma \cdot \tan\beta\,,\ where\ P_\Sigma = \left|P_g + P_j\right| \tag{2}$$

Here P_g is the gas pressure force at each moment of the cycle, according to the indicator diagrams, N. P_j is the inertia force of translationally moving masses (piston, rings, piston pin and the upper part of the connecting rod), N. β is the angle of inclination of the connecting rod shaft to the cylinder axis. The sum (2) is algebraic, since the inertia force is directed opposite to the gas pressure force.

For a particular engine and vessel, indicator diagrams should be taken at idle, with the crankshaft speed corresponding to the rated power mode of operation. In addition, an indicator chart should be removed for the approximate rated power mode based on indirect indicators – the nominal speed of the vessel, hourly fuel consumption, exhaust gas temperature (according to the engine's passport data). Based on the indicator diagram taken under load, it is necessary to calculate the force change function N. So, the values of the inertia force are determined, for example, every 5° of the angle φ of rotation of the crankshaft. In this case, the force P_g is taken from the indicator diagram, and the force P_j is calculated as follows.

$$P_j = -Gr\omega^2(\cos\alpha + \lambda\cos 2\alpha) \tag{3}$$

In formula (3), G is the total mass of translationally moving parts of the CPG, kg (piston, piston rings, piston pin, 1/3 of the connecting rod mass – according to the drawings of these parts); r is the crank radius, m; ω is the angular speed of rotation of the crankshaft, s^{-1}; λ is the mechanism constant, $\lambda = r / l$ (l is the connecting rod length between the centers of the piston and crank heads, m).

Thus, the inertia forces are determined after a certain interval by the angle of rotation of the crankshaft with the corresponding sign and taking the gas pressure forces according to the indicator diagram, find the values of the force P_Σ as a function of the angle α. From here, the values of the lateral force N are found by formula (2). However, it is inconvenient to operate with the values of β in calculations, since they must be additionally calculated depending on α. In this case, the formulas of the expression β through α [14] are used:

$$\sin\beta = \lambda \sin\alpha, \qquad \cos\beta = 1 - 0{,}5\lambda^2 \sin^2\alpha$$

As a result of the calculations, a function of the values of the force N per cycle from the angle of rotation of the crankshaft is obtained. Planimetry of this graph will give the total value of the force N per cycle, or N_Σ.

The action of force N causes the appearance of a friction force F that acts in the direction opposite to the movement of the piston and applied in the plane of contact of the piston with the cylinder, which is determined in accordance with the Coulomb-Amonton law:

$$F = Nf \tag{4}$$

In formula (4), f is the proportionality coefficient or coefficient of friction (in this case, sliding friction), depending on the materials of the friction pair, their geometry, the parameters of the rubbing surfaces, the presence and properties of lubricants, etc.

For example, an aluminum piston with cast-iron piston rings moves in a cast-iron cylinder sleeve, pressed against it by force N. The height of each of the k rings is l_1. The length of the piston in contact with the cylinder is l_2. Total length of contact of the piston group with the cylinder, $l = kl_1 + l_2$. The piston and cylinder are in contact and according to the theory of mechanisms and machines, contact is made along a line. By making this assumption, the specific linear pressure in the contact zone can be determined as $p = N_\Sigma/l$, N/m. From this, we can determine the fractions of force N_Σ that fall on the rings and on the piston:

$$N_{\Sigma r} = pnl_1, \qquad N_{\Sigma p} = pl_2 \tag{5}$$

Then, the friction force in contact of the piston with the cylinder will be

$$F_p = N_{\Sigma p} f_{aci}\,, N$$

where f_{aci} is the coefficient of sliding friction of aluminum over cast iron, taking into account lubrication,

$$F_r = N_{\Sigma r} f_{cici}$$

where f_{cici} is the coefficient of sliding friction of cast iron over cast iron, taking into account lubrication.

The total friction work in the cylinder-piston group at the nominal operating mode will be:

$$L_{\Sigma fr.cpg.n} = \left(F_p + F_r\right)4S, Nm.$$

where S is the piston stroke, m.

In the works of a number of researchers [21, 22], the relations of power losses due to friction in the CPG with internal losses in the engine are analytically and experimentally established. Thus, it is shown in [15, 16] that the friction work in the cylinder – piston group is 47% of the work of all internal engine losses, in [1-7] – 50%, in [18] - 53-54%. Figures 1 and 2 show indicator diagrams of the operating cycle of the 2Ch9,5/11 diesel engine in idle mode at n = 1500 rpm (here n is the crankshaft rpm) and in rated power mode – N_e = 11.5 kW, at n = 1500 rpm.

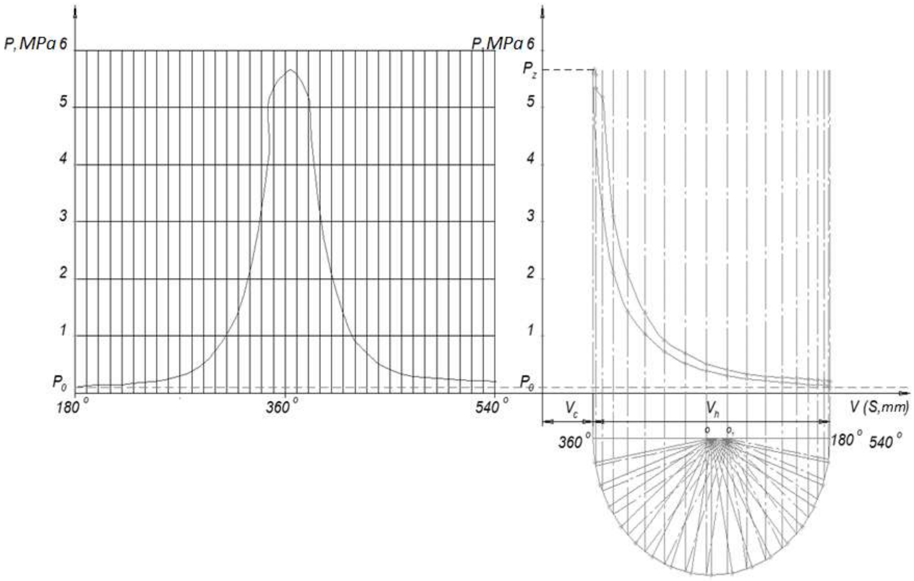

Fig. 1 – Expanded and collapsed indicator diagrams in idle mode.

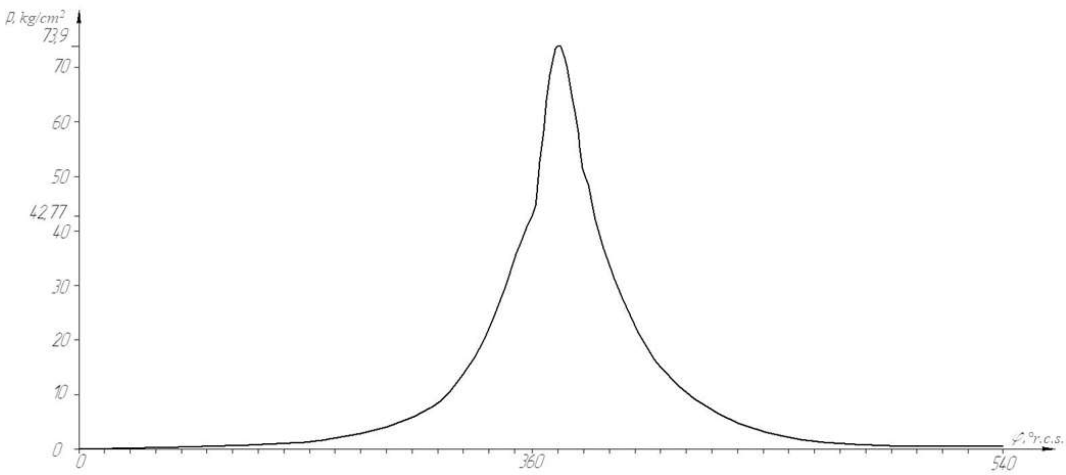

Fig. 2 – Diesel indicator diagram at rated load.

It is obvious that at the same loss levels $N_g + N_{gdm} + N_b + N_{hpfp}$ at idle and under load, the friction losses in the CPG will differ significantly due to differences in *pz*. Therefore, it is necessary to perform the same actions described above to determine the total friction work in the cylinder-piston group at idle – $L_{\Sigma fr.\ cpg.i.}$ Then, from the indicator engine operation at idle (Fig. 1), we subtract the amount of work corresponding to $L_{\Sigma fr.\ cpg.i.}$ and to the remainder we add the value $L_{\Sigma fr.\ cpg.n.}$ The result obtained will represent the sum of the internal losses of the engine in the rated power mode. Subtracting from the indicator operation of the engine in the rated power mode (Fig. 2) the work of internal losses, we get the cylinder effective operation L_{ec}, and, as a consequence, the cylinder effective power N_{ec}. Multiplying the results by the number of cylinders, we get the effective operation and effective power of the engine as a whole – L_e and N_e.

The proposed method seems cumbersome at first glance, but this section presents the procedure (algorithm) and a set of source data, on the basis of which you can create an appropriate program, i.e. automate the calculation process. Moreover, automated calculation programs for many stages of the method are already available (calculation of forces N, P_g, P_j, P_Σ and other components).

4 Economic efficiency of production and operation of heat engines

The complex energy efficiency of heat engines is expressed by a number of efficiency coefficients, which generalize to the effective efficiency or η_e. Its value is determined by the well-known formulas:

$$n_e = Q_e/Q_f = n_i n_m = \eta_t \eta_o \eta_m = q_e/q_f,$$

where Q_e is the amount of heat equivalent to the effective engine power; Q_f is the available amount of heat contained in the consumed fuel; n_i is the indicator efficiency of the operating cycle; η_t is the thermal efficiency of the cycle; η_o is the relative efficiency of the cycle; η_m – is the mechanical efficiency of the engine; q_e is the specific amount of heat equivalent to a unit of effective engine power; q_f is the specific amount of heat contained in the consumed fuel, attributed to the unit of engine power.

When talking about the energy efficiency of a heat engine, the concept of exergy is also used [23], as a measure of the total energy of the working fluid or the heat supplied to it, which can be converted into work under the conditions of this engine. In irreversible processes that are characteristic of piston heat engines, the total amount of exergy entering the thermodynamic system is greater than the amount diverted from it. This difference determines the loss of exergy $\Delta_{e1\rightarrow2}$ due to the irreversibility of the process, and the exergetic efficiency of the process - η_{ex} will be expressed as follows:

$$\eta_{ex} = 1 - \left(\Delta_{e1\rightarrow2}/e^{(+)}_{1\rightarrow2}\right),$$

where $e^{(+)}_{1\rightarrow2}$ is the exergy obtained by the system.

However, these indicators characterize only the level of technical perfection (or imperfection) of the engine and do not take into account the amount of costs – in design, manufacture, operation, which must be invested to achieve it. In practice, it is not uncommon such large financial investments to be made in order to achieve a high technical level of products and maintain it further, which cannot be compensated in the future, not to mention making a profit from operation. And it is not a new optimization task to link the volume of investment in the design, production and financing of operational maintenance with those indicators of the technical level of the product that will be necessary and sufficient, both to ensure its normal profitability in operation, and to maintain operational indicators at acceptable values during the established service life period. New, updated or improved methods can be used to estimate costs and the total revenue generated from the operation of the product or the resulting profit.

The value of the efficiency of money invested in the production of products by means of a given engine (let's call it economic efficiency - η_{ec}) can be taken by analogy with the effective efficiency - $\eta_e = Q_e/Q_f = (Q_f - Q_l)/Q_t = 1 - Q_l/Q_f$. Here, Q_e is the amount of heat equivalent to the effective engine power; Q_f is the available amount of heat contained in the consumed fuel; Q_l is the amount of heat equivalent to all types of losses during energy conversion. Then, the value of economic efficiency can be determined bypthe formula:

$$\eta_{ec} = C_{con}/C_e \tag{6}$$

In formula (6) $C_{con} = C_e - C_f$, then $\eta_{ec} = 1 - C_f/C_e$, where C_e is the total cost of converting the chemical energy of the fuel into mechanical workeremoved by the consumer from the power take-off flange, C_{con} is the cost of the system for converting the chemical energy of the fuel in the heat energy of the working fluid, and more specifically, in mechanical work, and C_f is the cost of fuel.

However, in order to be able to make a comparative estimate ηec for different types and sizes of engines, it is advisable to determine the cost values of C_e, C_f and C_{con}, bringing them to the same time and power unit. Then, the value of η_{ec} will be defined as $(c_e - c_f)/c_e$, where c_f is the cost of fuel consumed by the engine during the year, reduced to a unit of motor power.

That is, $c_f = C_f$. year/N_e. The unit cost of energy conversion - c_{con}, will consist of the following components:

- The share of the engine price p_e (it can be taken as the price of the engine - P_e, relative to the unit of its rated power - N_e and to one calendar year of operation, based on the assigned service life - R, i.e. $p_e = P_e/N_e{\cdot}R$;
- The cost of engine maintenance during the year – C_o, attributed to the unit of power, i.e. $c_o = C_o$ year/N_e;
- The share of the cost of all engine repairs - C_{rep}, during the assigned service life, attributed to the power unit and to the service life ($c_{rep} = C_{rep}/N_e{\cdot}R$).

Based on the above, the unit cost of converting energy can be represented in summ

$$c_{con} = p_e + c_o + c_{rep}$$

Then the economic efficiency will have the form:

$$\eta_e = (p_e + c_o + c_{rep})/(c_f + p_e + c_o + c_{rep}) \tag{7}$$

This indicator can serve as an assessment of the efficiency of funds involved in the design, production and operation of various types of heat engines and will be a rational addition to the indicators of their technical efficiency.

5 Comparative assessment of the quality and cost of marine diesel engines

Comparative assessment of the quality of machines based on a certain set of their parameters is one of the tasks that machine builders often have to face. Regardless of the final goals, the general algorithm for solving the problem is the same: one or more analogs are selected for the machine being evaluated, after which the numerical values of their indicators are compared. The resulting individual ratings are considered differentially or reduced to a total indicator and serve as the basis for making a decision on the level of quality and competitiveness of this machine. The most objective and reliable assessment could be obtained by conducting comparative tests of similar machines using a single methodology and under the same conditions, as well as on the basis of generalized data on their operational experience. However, in practice, there are often no machine samples themselves or comprehensive documented data about them and the main information sources are prospectus and catalog materials of manufacturers.

It follows that in a comprehensive assessment of the quality of a particular machine, first of all, one should proceed from an expert assessment of the significance (weight coefficient) of a particular indicator, depending on atmospheric and external conditions, characteristic indicators of the operating mode, the possibility of performing qualified and timely maintenance, and the failure-free service resource requested by the consumer. An expert method for determining the coefficients of a set of indicators by ranking them is recommended in the theory and practice of qualimetry.

As is customary in the world practice, in accordance with the requirements of quality standards and metrics, the assessment of the weighting coefficients of quality indicators was carried out by an expert method. An expert panel consisting of the authors and leading technical specialists of the manufacturer, and based on the assigned qualification data, production and operating conditions, as well as market conditions, assessed the significance of the quality indicators of the QMS (Table 1).

Due to the lack of data for analogs for all indicators, the following main indicators and their weighted coefficients were used for further analysis: specific mass power – N_m, kW/kg ($m_1 = 0.145$); liter power – N_l, kW/l ($m_2 = 0.09$); specific overall power – N_g, kW/m^3 ($m_3 = 0.055$); specific fuel consumption – g_e, kg/(kWh) ($m_4 = 0.22$); specific oil consumption – g_m, kg/(kWh) ($m_5 = 0.1$); service life up to the first bulkhead – T_1, hour ($m_6 = 0.07$); resources before major repairs – T_2, hour ($m_7 = 0.06$); unit cost – C, rub./kWh ($m_8 = 0.057$).

Separately, we should focus on the cost indicators. This is purely private data, which is virtually impossible to obtain information about even from manufacturers catalog materials, and which is often disclosed only in contract negotiations. And these data are urgently needed already at the stage of initial development of the project. The author, based on the results of research on the production features of marine and industrial diesel engines of the Ch8,5/11 and Ch9,5/11 types, proposed a formula for calculating the cost (C) based on their main functional indicators [19].

Table 1 - Expert assessment of the significance of quality indicators for small and medium-sized businesses.

№	Internal combustion engine quality indicators	Weight coefficients of exhibits, *mi*		
		№1	№ 2	№ 3
1.	Specific power, kW/kg	0.15	0.14	0.15
2.	Liter capacity, kW/l	0.09	0.05	0.06
3.	Specific overall power, kW/m^3	0.057	0,05	0.05
4.	Specific fuel consumption, kg/kW·h	0.22	0.22	0.21
5.	Specific oil consumption, kg/kW·h	0.073	0.1	0.12
6.	Operating time to failure, h	0.07	0.08	0.08
7.	Continuous service life, h	0.04	0.05	0.05
8.	Service life up to the first bulkhead, h	0.07	0.07	0.07
9.	Service life before major repairs, h	0.06	0.05	0.05
10.	Unit cost, rub/kW·h	0.06	0.06	0.05
11.	Specific labor intensity, n-h/kW·h	0.03	0.06	0.05
12.	Ergonomic and aesthetic indicators, score	0.08	0.07	0.06
13.	Sum of coefficients	1.0	1.0	1.0

$$C = K\,(N_e^{0.073}T^{0.086}M^{0.763})/(g_e^{2.446}g_m^{1.138}S^{0.466}) \qquad (8)$$

In formula (8) N_e is the rated effective engine power, kW; T is the service life up to the first bulkhead, h; M is the mass, kg; g_e is the specific effective fuel consumption at the rated power mode, kg/(kWh); g_m is the specific effective oil consumption on the mode of rated power, kg/(kWh); S – serial number of output, in conventional units (serial number for marine diesels is 10, for industrial diesels is 25); K – portionality coefficient, 0.023. The calculation results for a group of diesels are given in Table 2. The degree indicators characterize the weight of each argument in the formula.

Table 2-Indicators and ratio of factory and estimated prices of diesel engines.

Engine model	Indicators					Price, rub.	
	***Ne*, W**	***T*, h**	***ge*, kg/kW·h**	***gm*, kg/kW·h**	***M*, kg**	**factory**	**calculated**
8D6 (6Ch9,5/11)	33100	14000	0,260	0,0019	485	144000	144283
10D6 (6ChSP9,5/11)	44100	14000	0,263	0,00184	485	148300	148588
DS25 (4ChSP8, 5/11)	18400	18000	0.269	0.00177	420	126000	126236
DP30 (4Ch9,5/11)	22000	15000	0,260	0,0015	350	93600	93785
DP31 (4Ch9,5/11)	22500	22000	0,261	0,0015	350	96000	96177

A similar formula structure for determining the cost of making decisions about purchasing diesels at the design stage can be recommended for other types of engines. At the same time, the average quadratic error of the model does not exceed 7%.

The author selected the main indicators of small-sized marine diesel engines (with a cylinder diameter ≤ 100 mm – aggregate power, average effective pressure, crankshaft speed, average piston speed, specific fuel and oil consumption, weight, dimensions, service life) of the most famous companies (USA, Great Britain, Japan Sweden, France, Finland, Czech Republic, etc.), which can be used as analogs in terms of their classification data and time of production. A promising marine diesel engine 4ChN9,5/11, developed jointly by JSC "Plant "DAGDIZEL" and FSUE NC "NAMI" (rated power, N_{erat}= 75 kW, rated speed of the crankshaft, n_{rat} = 3000 rpm) was selected as the evaluated engine. In order to improve the functional performance of marine diesel engines of the Ch8,5/11 and Ch9,5/11 types, without radically changing their design, manufacturing technology and without replacing the materials of the main elements, the Laboratory of Problems of Motor Power Engineering (LPME) in Astrakhan (joint Institute of Physics of the Dagestan Scientific Center of the Russian Academy of Sciences and Astrakhan State Technical University) in coordination with the manufacturer of these types of diesel engines, OJSC "Plant "DAGDIZEL" and the Russian Maritime Register of Shipping (Astrakhan branch) carried out work on boosting diesel 4Ch9,5/11 at average effective pressure by gas turbine supercharging, taking into account the requirements of RMRS for marine diesel engines. Currently, OJSC "Plant "DAGDIZEL" is working on the creation of a new boost engine. The object of research in the LMPE was a ship diesel 4Ch9,5/11 with a two-circuit, water-water, combined cooling system (forced circulation of the coolant in the head of the cylinder and thermosiphon in the block) and eddy-chamber mixing. The engine was equipped with a TKR-6 turbocharger with all necessary communications. The braking device was a DC generator P-81 loaded with a package of thermal electric heaters. The stand was equipped with a standard set of control and measuring devices. For research and analysis of internal cylinder processes, the stand was equipped with a measuring complex for taking indicator diagrams.

The calculation model presented above makes it possible to justify the cost of a motor based on the specified indicators by calculation, or to determine the value of one of the indicators based on the specified cost and the accepted values of the remaining indicators. For the estimated engine, the cost determined by formula (8) is 190,620 rubles, while the cost of the "ideal" engine is 126,000 rubles.

Based on the indicators of the selected engines, the specific indicators of the evaluated diesel, analog diesels and ideal diesel were calculated.

The generalized quality coefficient of an ideal hypothetical engine will be equal to the sum of the weight coefficients of the eight considered indicators (n = 8), i.e.:

$$K_{\Sigma E} = \Sigma_{mi} = 0.797$$

The missing amount value of 0.203 refers to indicators for which it is almost impossible to find data for analogs (time to failure, labor intensity, etc.).

Generalized quality factor of the engine being evaluated.

$$K = N_m m_1/N_{me} + N_l m_2/N_{le} + N_g m_3/N_{ge} + g_{ee} m_4/g_e + g_{\text{м}e} m_5/g_m + T_1 m_6/T_{1e} + T_2 m_7/T_{2e} + \text{C} m_8/S_e \ = \ 0.994,$$

where N – values of specific mass, liter and overall power; g – values of specific fuel and oil consumption; T – values of resources; C – value of cost.

The ratio of quality factors equal to

$$a = (0.203\ +\ K_\Sigma)/(0.203\ +\ K_{\Sigma E}) = 1.198 \approx 1.2,$$

shows that the estimated engine is 20% superior in terms of its technical level to the ideal hypothetical engine.

Thus, the given method of comparative assessment of the quality of the marine diesel engine being created and the principle of choosing a standard showed the real competitive advantages of the evaluated machine even at the design stage. The actual quality level will be determined by the degree of compliance of the real indicators of the new machine with the specified ones and the time it is put into production.

6 Directions for improving the MHSDE based on an analysis of the comparison of their cost and operating costs

The current state of diesel construction in Russia is deeply depressing. Many diesel plants, and there are currently 10 of them, have lost their production capacity due to the failure to fill the natural and forced outflow of specialists, extreme wear and failure to fill technological equipment, tooling and tools. An extremely negative factor is the lack of a federal research center for diesel engineering, which could develop promising models of diesel engines, analyze the needs of domestic and foreign markets, coordinate the activities of individual design organizations, that is, perform functions that were previously performed by the Central Research Diesel Institute (TsNIDI, Leningrad).

Improvement of reciprocating internal combustion engines should go in the direction of improving the totality of known indicators characteristic of these types of heat engines: increasing the service life; increasing liter capacity; reducing specific and hourly fuel and oil consumption; reducing weight and size parameters; adaptive workflow management based on microprocessor systems and others. An indicator of the efficiency of the use of financial resources (E) invested in the design and production of engines, taking into account the provision of high operational indicators, can be estimated by comparing the operating costs (OC) per unit cost of the engine (C_e).

$$E = OC/C_e \tag{9}$$

Operating costs are the sum of the cost of engine maintenance during the service life – C_o, the cost of repairs – C_r, the cost of fuel – C_f. However, in order to be able to compare E for different types and sizes of engines, it is advisable to determine the cost values of C_o, C_r and C_f, giving them to a single time and power unit. Then, the value of c_f is the cost of fuel consumed by the engine during the year, reduced to a power unit, $c_f = C_f$ year/N_e, where N_e is the effective engine power, kW. The share of the cost of the engine – c_e, it can be taken as the cost of the engine – C_e, attributed to the unit of its rated power – N_e and to one calendar year of operation, based on the assigned service life – R, i.e. $c_e = C_e/N_eR$. The cost of engine maintenance during the year – C_o, attributed to the power unit, i.e. $c_o = C_o$ year/N_e. The cost of all engine repairs – C_r, during the assigned service life, attributed to the power unit and to the service life, $c_r = C_r/N_eR$. Then, formula (9) will take the form

$$e = \left(c_o + c_r + c_f\right)/c_e \tag{10}$$

This formula (10) will reflect the level of efficiency of engine design and production costs expressed in terms of minimizing annual operating costs.

Let's analyze the calculations made on the example of two specific engines, domestic and foreign production.

Four-cylinder diesel DS32 (4CHSP9,5/11) with eddy-chamber mixing, produced by JSC "Plant "DAGDIESEL", Russia:

Cost (C_e) = 232450 rub.; rated power ($N_{e\ rat}$) = 23.5 kW; crankshaft speed (n) = 1900 min^{-1}; service life before major repairs (R_{mr}) = 18000 h.; service life before write-off (R) = 12 years; average cost diesel fuel (C_f) = 37 rubles/liter; specific effective fuel consumption g_e = 0.28 kg/(kWh); maintenance cost during the year 30,000 rubles; cost of major repairs 85,000 rubles; number of major repairs during the service life – two.

Three-cylinder diesel MD2030 (Russian marking 3ChSP7,6/7,2) with volume-film mixing and combustion chamber in the piston, produced by AB "VOLVO-PENTA", Sweden:

C_e = 11000 USD (660,000 rubles); $N_{e\ rat}$ = 21 kW; n = 3600 min^{-1}; Rmr = 18000 h; R = 12 years; C_f = 1USD (60 rubles)/per liter; specific effective fuel consumption g_e = 0.245 kg/(kWh); maintenance cost during the year 30,000 rubles;

cost of major repairs 110,000 rubles; number of major repairs during the service life-two (characteristics are taken from the factory forms of diesel engines and price lists of manufacturers). Fuel consumption during the year was taken from the condition of eight-hour operation per day for a valid calendar annual fund of working days in the rated power mode.

Then, for DS32: c_e = 824.3 rubles/(kW year); c_o = 1277 rubles/(kW year) ; c_r = 603 rubles/(kW year); c_f = 22400 rubles/(kW year). Hence, e = 29.5.

For MD2030: c_e = 2619 rubles/(kW year); c_o = 1430 rubles/(kW year) ; c_r = 873 rubles/(kW year); c_f = 29400 rubles/(kW year). Hence, e = 12.1.

Thus, it can be seen that the DS32 engine in terms of operating costs per unit of engine cost is more than twice as high as the similar indicator of the MD2030 engine. Therefore, there are two ways to reduce this indicator: reduce operating costs and increase the cost of the engine. These paths are interrelated, because it is impossible to reduce operating costs, without investing in production upgrades, design upgrades or major upgrades to both the machine design and the production process, which will significantly affect the cost of the engine in the direction of its increase. It should be noted that the difference in liter capacity shows that the DS32 is almost twice as good as the Swedish engine in this indicator, i.e. 8.3 kW/l for the DS32 versus 15.44 kW/l for the MD2030 with a mass of DS32 is 395 kg, while the mass of the MD2030 is 152 kg. This shows that the level of design and technological development of the Swedish car is much higher than that of its Russian counterpart, which leads to a higher cost of the MD2030 engine. The current trend in the development of the engine industry is such that the engine should not be cheap, but the level of its functional indicators should be such that operating costs are minimized over the entire service life. Some enterprises that produce obsolete machines can improve their performance to acceptable values by deep modernization of the design using existing equipment, tooling and tools. As an example, we can cite diesel engines of the Ch8,5/11 and Ch9,5/11 types produced by JSC "Plant "DAGDIESEL", where the technological base has been preserved, albeit outdated, but in good condition.

The DS32 diesel engine was taken as the object of research. One of the options for modernizing diesel engines is to boost it according to the average effective pressure by gas turbine supercharging, performed at the Department of Shipbuilding and Marine Engineering Energy Complexes of the Astrakhan State Technical University [20].

Tests of the upgraded diesel engine were carried out in the load and propeller law modes, at which the effective power value N_e = 35 kW was obtained. Thus, a liter capacity of 12.37 kW/l was achieved. A further increase in power was not possible due to the achievement of the cooling water and lubricating oil temperature limits. During the tests, the temperature condition of the cylinder sleeve and exhaust valve plates was measured using chromel-copel thermocouples, which showed overestimated temperatures of these parts. It can be argued that the firing bottom temperatures of the cylinder heads will also be exceeded. Since the DS32 diesel engine is a vortex-chamber machine, its analog with a volume-film mixture formation and a combustion chamber in the piston were tested. After refining the design of the cooling system through the use of a more powerful heat exchanger from the 6Ch9.5/11 engine, during testing, it was possible to achieve an effective power, N_e = 40 kW and, consequently, a liter capacity of N_l = 14.1 kW/l. Thus, it is clear that there are reserves for qualitative improvements through deep modernization of existing diesel engine designs. However, along with this, there are also problems, associated with ensuring sufficient resistance of parts of the cylinder-piston group, cylinder covers, multi-hole spray nozzles to high mechanical and thermal loads.

The given example of comparing the level of operating costs attributed to the cost of engines indicates their high values for domestic serial diesels in comparison with foreign analogues. Along with the development and production of new lines of diesel engines, or instead at a specific stage, it is quite possible for enterprises to deeply modernize the mastered production models, as a result of which their operational performance will increase.

It is necessary to revive the unified scientific and technical center of diesel engineering, which could develop promising models of diesel engines, analyze the needs of domestic and foreign markets, and coordinate the activities of individual design organizations and industrial enterprises.

The proposed option of deep modernization of marine diesel engines of the Ch9,5/11 type is quite feasible within the framework of a specific diesel-building enterprise, on the existing technological base, provided a new approach to the formation of the design of the cylinder head, cylinder sleeve and other elements of the cylinder volume.

7 Conclusion

As a result of the performed studies, it was established:

- The layout of diesel engines of the Ch8,5/11 and Ch9,5/11 types generally corresponds to modern trends in marine small-size diesel construction, but a number of structural and technological solutions are outdated and do not meet the requirements of quality, reliability, efficiency and, in general, competitiveness;
- The initial indicator for ensuring highly efficient operation of reciprocating internal combustion engines will be the internal energy of the working mixture;
- The calculation method for estimating power losses to overcome friction forces in the cylinder-piston group of the internal combustion engine and determining the effective power of the main engine of the vessel based on actual indicator diagrams is proposed;
- The concept of an economic efficiency factor is introduced, which will be a rational addition to the indicators of their technical efficiency, the concept of criteria for optimal structure of a complex technical system is introduced, using the example of a low-power marine diesel engine, and an acceptable technical solution is one that ensures the fulfillment of the set goal with a minimum of costs;
- The method of comparative assessment of the quality of the marine diesel engine being created and the principle of choosing a standard, which showed the real competitive advantages of the evaluated machine at the design stage, were developed;
- Based on the results of research on the production features of marine and industrial diesel engines of the Ch8,5/11 and Ch9,5/11 types, a formula for calculating the cost based on their main functional indicators is proposed;
- At a specific stage of the company's development, a deep modernization of the mastered production models is quite possible, as a result of which their operational performance will increase and operating costs will decrease.

Nomenclature

MHSDE	Marine high-speed diesel engines
CC	Combustion chamber
ISO	International Organization for Standardization
CPG	Cylinder-piston group
CLSA	Collective life-saving appliances
SOLAS	The International Convention for the Safety of Life at Sea
SSDE	Small-sized diesel engines
PP	Power plant
η_{pc}	Total efficiency of the propulsive complex [%]
η_e	Power losses in the engine [%]
η_t	Power losses in reverse gear transmission [%]

η_s	Power losses in shaft line and propeller [%]
η_p	Power losses in pumps of dehumidification and irrigation systems [%]
η_g	Power losses in generators of on-board power supply, radio stations, and batteries charge [%]
η_k	Loss to overcome the resistance of the movement of CLSA hull and power reserve [%]
OJSC	Open joint-stock company
USC	United shipbuilding corporation
Ne	Rated engine power [kw]
n	Engine speed [revolutions per minute] or [s^{-1}]
p_z	Maximum combustion pressure [mpa]
ICLSA	International Code for Life-Saving Appliances
$dp/d\varphi$	Pressure build-up rate during the combustion of the working mixture
G_h	Hourly fuel consumption [kg/h]
T_g	Exhaust gas temperature [K]
t_g	Exhaust gas temperature [°C]
N_{fr}	Total power loss to overcome the friction forces in the engine [N]
N_{cpg}	Power loss to overcome the friction forces in the cylinder-piston group [N]
N_g	Power loss to overcome the friction forces in mechanical gears [N]
N_{gdm}	Power loss to overcome the friction forces [N]
N_b	Power loss power losses to overcome frictional forces in plain bearings [N]
N_{hpfp}	Power loss to overcome the friction forces in the high-pressure fuel pump [N]
N	The lateral force, ot the work of friction in the cylinder-piston group [N]
P_Σ	The total force, applied to the connecting rod piston head [N]
P_g	Gas pressure force at each moment of the cycle, according to the indicator diagrams [N]
P_j	The inertia force of translationally moving masses [N]
β	Angle of inclination of the connecting rod shaft to the cylinder axis [°]
G	Total mass of translationally moving parts of the CPG [kg]
r	Crank radius [m]
ω	Angular speed of rotation of the crankshaft [s^{-1}]
λ	The mechanism constant [unit]

l	Connecting rod length between the centers of the piston and crank heads [m]
α	Angle of inclination of the connecting rod shaft to the cylinder sleeve [°]
N_{Σ}	Total value of the lateral force per cycle [N]
F	Friction force in CPG [N]
f	The proportionality coefficient or coefficient of friction [unit]
k	Number of piston rings [unit]
l_1	Height of each piston ring [m]
l_2	Length of the piston in contact with the cylinder [m]
l	Total length of contact of the piston group with the cylinder [m]
p	Specific linear pressure in the contact zone [N/m]
$N_{\Sigma r}$	Fractions of total value of the lateral force per cycle [N]
F_p	Friction force in contact of the piston with the cylinder [N]
f_{aci}	Coefficient of sliding friction of aluminum over cast iron [unit]
F_r	Friction force in contact of the piston rings with the cylinder [N]
f_{cici}	Coefficient of sliding friction of cast iron over cast iron [unit]
$L_{\Sigma fr.cpg.n}$	Total friction work in the cylinder-piston group at the nominal operating mode [J]
S	Piston stroke [m]
$L_{\Sigma fr.\ cpg.i}$	Total friction work in the cylinder-piston group at idle mode [J]
L_{ec}	Cylinder effective operation [J]
N_{ec}	Cylinder effective power [kw]
L_e	Effective operation [J]
N_e	Effective power of the engine [kw]
Q_e	Amount of heat equivalent to the effective engine power [J]
Q_f	Available amount of heat contained in the consumed fuel [J]
η_e	Effective efficiency [unit]
n_i	Indicator efficiency of the operating cycle [unit]
η_t	Thermal efficiency of the cycle [unit]
η_o	Relative efficiency of the cycle [unit]
η_m	Mechanical efficiency of the engine [%]

q_e	Specific amount of heat equivalent to a unit of effective engine power [J]
q_f	Specific amount of heat contained in the consumed fuel, attributed to the unit of engine power [J]
$\Delta_{e1\to2}$	Loss of exergy [J]
η_{ex}	Exergetic efficiency of the process [unit]
$e^{(+)}{}_{1\to2}$	Exergy obtained by the system [J]
η_{ec}	Value of the efficiency of money invested in the production of products by means of a given engine [unit]
Q_l	Amount of heat equivalent to all types of losses during energy conversion [J]
C_e	Total cost of converting the chemical energy of the fuel into mechanical workeremoved by the consumer from the power take-off flange [rub]
C_{con}	Cost of the system for converting the chemical energy of the fuel in the heat energy of the working fluid [rub]
C_f	Cost of fuel [rub/l]
c_f	Cost of fuel consumed by the engine during the year, reduced to a unit of motor power [rub year/kw]
c_{con}	Unit cost of energy conversion [rub year/kw]
p_e	Share of the engine price [rub/kw year]
P_e	Price of the engine [rub]
R	Assigned service life [year]
C_o	Cost of engine maintenance [rub]
c_o	Cost of engine maintenance during the year [rub year/kw]
C_{rep}	Cost of all engine repairs [rub]
c_{rep}	Share of the cost of all engine repairs during the assigned service life, attributed to the power unit and to the service life [rub/kw year]
N_m	Specific mass power [kw/kg]
N_l	Liter power [kw/l]
N_g	Specific overall power [kw/m^3]
g_e	Specific fuel consumption [kg/(kwh)]
g_m	Specific oil consumption [kg/(kwh)]
T_1	Service life up to the first bulkhead [hour]
T_2	Resources before major repairs [hour]
C	Unit cost [rub/kwh]
N_e	The rated effective engine power [kw]

T	Service life up to the first bulkhead [h]
M	Mass [kg]
S	Serial number of output [conventional units]
K	Portionality coefficient [unit]
N_{erat}	Rated engine power [kw]
n_{rat}	Rated speed of the crankshaft [rpm]
LPME	Laboratory of Problems of Motor Power Engineering
TKR	Radial turbocharger
DC	Direct current
$K_{\Sigma E}$	The generalized quality coefficient of an ideal hypothetical engine [unit]
Σ_{mi}	Sum of the weight coefficients of the eight considered indicators [unit]
K	Generalized quality factor of the engine [unit]
a	The ratio of quality factors [unit]
TsNIDI	Central research diesel institute
E	Indicator of the efficiency of the use of financial resources [unit]
OC	Operating costs [rub]
C_e	Cost of the engine [rub]
C_o	Cost of engine maintenance during the service life [rub]
C_r	Cost of repairs [rub]
C_f	Cost of fuel [rub/l]
c_f	Cost of fuel consumed by the engine during the year, reduced to a power unit [rub year/kw]
e	Level of efficiency of engine design and production costs expressed in terms of minimizing annual operating costs [unit]

Greek symbols

$\sum$	Total
η	Total efficency

Subscripts

mi	Weight coefficients of main indicators

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