DOI 10.1007/s10749-024-01811-0
Power Technology and Engineering *Vol. 58, No. 2, July, 2024*

EXPERIMENTAL IDENTIFICATION AND EVALUATING THE EFFECT OF VARIOUS OIL SUPPLY SOURCES ON FRICTION IN THE POWER UNIT OF A DIESEL-ELECTRIC GENERATOR SET

S. S. Strelnikova,[1] S. V. Putintsev,[2] and S. P. Demenkova[2]

Translated from *Élektricheskie Stantsii*, No. 1, January 2024, pp. 15 – 24. DOI: 10.34831/EP.2024.1110.1.003

The article presents the results of experiments performed in order to investigate the relevant, though understudied, issues concerning the contribution of various sources of oil supply to the friction of the cylinder piston group (CPG) of a piston engine with a conventional crank mechanism (CM); the relationship between the oil amount supplied to the area of movable contact of parts and their frictional losses. The methodology and equipment used in the experiments are described, and the measurement errors of the control values are estimated. The experimental results enabled identifying the dominant source of oil supply to the CPG parts, as well as verified the reliability of previously obtained calculation data on the uneven distribution of the oil quantity on the loaded and unloaded sides of the cylinder wall. Furthermore, the hypothesis was confirmed that matching the oil quantity supplied to the friction area of the parts with the level of their dynamic loading contributes to minimizing the friction of these parts. Experimental methods and their results are proposed for use in the design and operation of lubrication systems, as well as for improving the efficiency and reliability of modern piston engines, including those operating as power units of electric generating sets.

Keywords: piston engine; diesel engine; oil supply; engine oil; connecting rod; cylinder; friction losses.

The majority of studies into friction losses in piston engines emphasize the essential, if not decisive, role of the lubricant in their formation [1 – 7]. However, extremely little information is available on the sources and quantities of oil entering the area of movable contact between the parts, as well as the effect of this quantity on the friction of the lubricated parts. In the work [8], where various sources of oil supply to cylinder piston group (CPG) parts of high-speed piston engines were analyzed, the feasibility of experimental verification was indicated:

— the dominance of the ejection of oil jets from the clearances of the rotating connecting rod bearing over other sources, which was detected in the course of computational modeling;

— the oil distribution on the inner surface of the cylinder wall;

— the hypothesis that the increase in the oil quantity in the area of the moving parts in proportion to the level of their dynamic loading should lead to a decrease in the friction losses of the lubricated pairings of a high-speed piston engine.

In addition, the oil supply processes of the CPG parts, particularly the cylinder-piston mating, are ambiguously interpreted in various studies on lubrication systems of piston engines [9 – 13]. Therefore, the given provisions based on computational prediction and hypothetical constructions should be experimentally evaluated. Hence, the present study was initiated as a continuation and development of the study [8] by experimental methods and means.

The study aims to obtain experimental data quantitatively characterizing the oil supply process of the cylinder – piston mating of a high-speed diesel engine, thereby establishing the relationship between this process and friction losses in the mentioned mating. In order to achieve this aim, the following objectives were set:

1. Development and application of experimental methods for determining the contribution of particular sources to the total oil supply of the CPG parts (hereinafter — CPG oil supply).

2. Evaluation of the oil quantity distribution, supplied to the cylinder inner surface area by the entire set of oil supply sources, along the circumference and height of the cylinder inner surface area.

[1] Bauman Moscow State Technical University, Moscow, Russia.
[2] Bauman Moscow State Technical University, Moscow, Russia; e-mail: sofya.s.strelnikova@yandex.ru

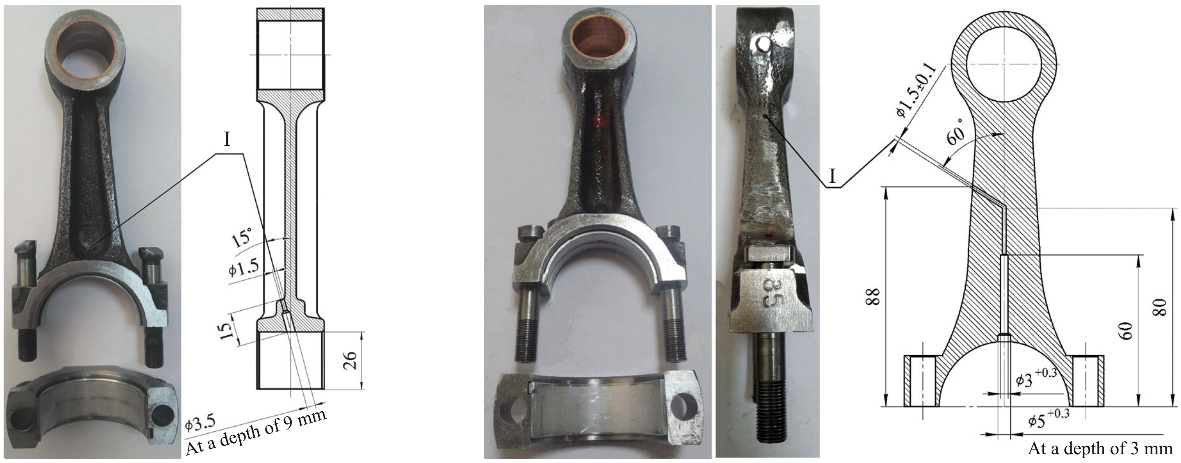

Fig. 1. Photo and sketch of commercial (*a*) and modernized (*b*) connecting rod: I, oil supply hole.

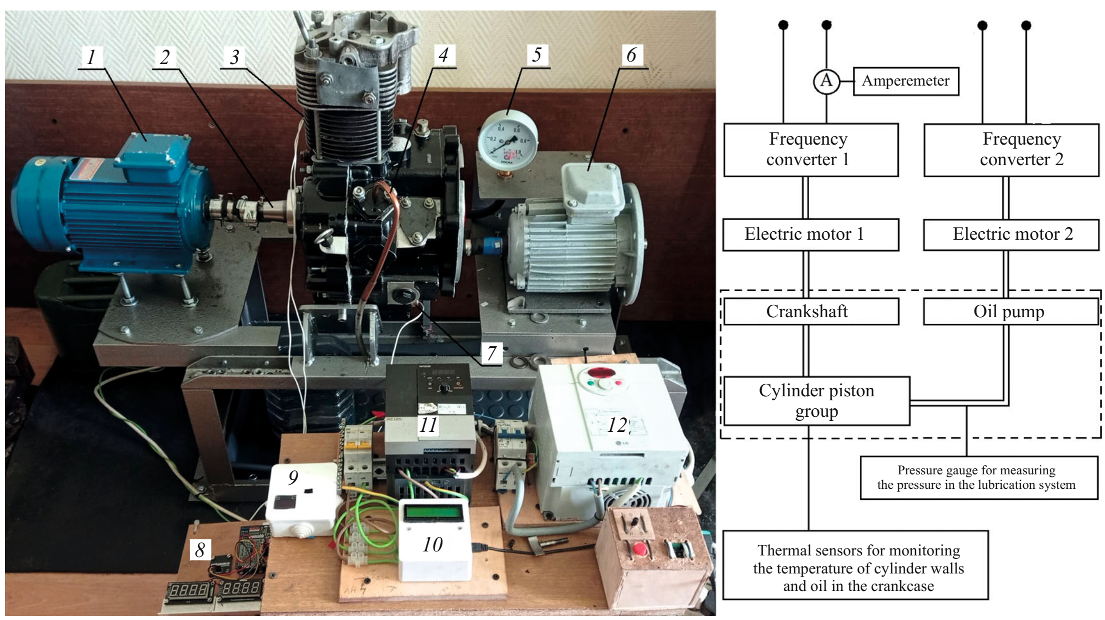

Fig. 2. General view (*a*) and schematic diagram (*b*) of the layout unit based on diesel engine 1 × 8.5/8.0.

3. Verification of the hypothesis that harmonizing the amount of oil supply to the level of dynamic loading of lubricated parts can lead to a reduction in friction losses.

Study objects, equipment, and test methods

The general object of the study was the process of CPG oil supply of high-speed diesel engine of size 1 × 8.5/8.0, operating as part of diesel-electric generator sets of AD4-230VM2, AD4-T230VM2, and AD4-T400VM2 types.

A modernized connecting rod of the specified diesel engine was a particular research object. The efficiency of the modernized connecting rod was evaluated on the basis of comparative tests with a commercial connecting rod. It can be seen in Fig. 1 that both versions of the connecting rod (commercial and modernized) are equipped with oil-supply channels and holes for splashing oil into the cylinder area. However, the axes of these oil lines lie in different planes, at different angles to the central axis of the connecting rod, and on different heights relative to the plane of separation of its crank head.

The results of computational modeling of the CPG jet oil supply of the specified diesel engine presented in [8] revealed an abnormal distribution of engine oil on the opposite sides of the cylinder wall. The loaded (L) side of the cylinder wall received almost 3 times less oil in comparison with the side unloaded (UL) by the piston lateral force. As a result,

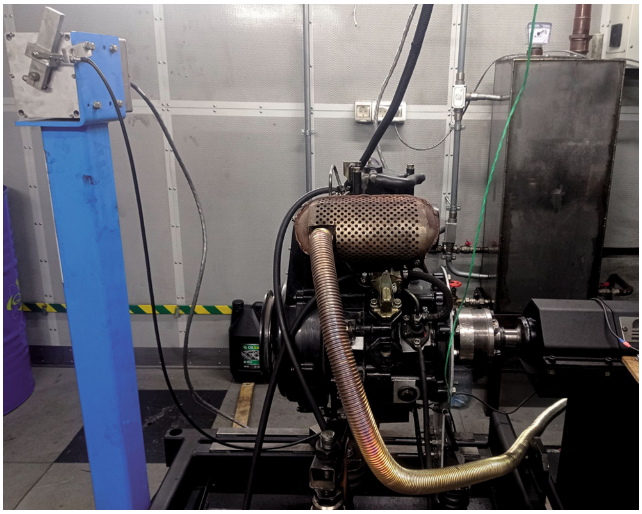

Fig. 3. Engine stand with diesel engine 1 × 8.5/8.0 and test equipment.

the scheme and, consequently, the design of the production connecting rod were modernized to eliminate this anomaly.

Two test tools were used for the study. The first is a layout unit used to measure the parameters of the oil supply process of the moving parts and friction losses in the CPG and crank mechanism (CM) of the diesel engine in the cranking mode (Fig. 2). The second is an engine stand for the final comparative evaluation of friction losses of the diesel engine with the commercial and modernized connecting rods, respectively.

The layout unit is equipped with (Fig. 2): two electric motors *1* and *6* for autonomous drive of the crankshaft *2* of the diesel engine and its oil pump, respectively, frequency converters *11* and *12* for controlling these electric motors, amperemeter *10* for measuring the current in the circuit of the electric motor *1*, thermocouples *3* in the cylinder wall and modules *8* and *9* for processing their signals. To control the pressure and oil level in the lubrication system manometer *5* and pipe *4* were used, respectively. The electric crankshaft drive carried out cranking of the diesel engine at the required speed mode. The autonomous drive of the oil pump provided for visual and quantitative assessment of some indicators of the jet oil supply in quasi-stationary conditions, which are more convenient for measurements.

The engine stand consisted of a diesel engine 1 × 8.5/8.0 in a complete set, devices for controlling the fuel rail and measuring fuel consumption by weight method (Fig. 3). To control the crankshaft speed, a combined tachometer TachoLiner THM-30 was used.

The mass of lubricant m (in g) supplied into the corresponding friction area for the fixed time of tests was used as a control value when estimating the indicators of CPG oil supply. While estimating the friction, the total power of friction losses N (in kW) in the CPG and CM at the layout unit was considered, as well as the one-hour fuel consumption at idling G_t (in kg/h) according to the state standard GOST 14846–2020.

Based on the accuracy classes of the applied instruments and methods for determining the control values, an analysis of measurement errors was performed to obtain confidence intervals. The exceedance of these intervals when carrying out comparative tests (only concerning the commercial and modernized connecting rods) implied the exceedance of the limits of significant difference in the results, i.e., the difference subject to consideration. Thus, for the control values determined by friction, the absolute Δ and relative δ values of the confidence intervals of measurement error I were as follows:

— for friction loss power N — $I_{\Delta N} = 0.08$ kW, $I_{\delta N} = 3\%$;

— for fuel consumption G_t — $I_{\Delta N}$ $G_t = 0.01$ kg/h, $I_{\delta N} = 2\%$.

Methods and conditions for experimental study

Stage 1. Study of the CPG oil supply process of the diesel engine. At this stage, in order to experimentally determine the amount of lubricant supplied to the rubbing surface of the cylinder by a particular oil supply source, two methods were developed and sequentially applied.

The first method involved determining the relative contribution of natural sources of this process (oil mist, oil ejection from the clearances of main and connecting rod bearings) to the CPG oil supply. To that end, a special insertion device was developed, i.e., a cartridge with oil-absorbing elements, which was tightly inserted into a commercial cylinder (Fig. 4*a*, *b*). The dimensions of these elements were determined by the areas of oil distribution on the cylinder walls, considering the geometric features of the location of the elements. The amount (mass) of settled oil was estimated by weighing the absorbent elements prior to and following the experiment. Since the cartridge prevented the presence of the piston in the cylinder, the piston was removed from the connecting rod, while the connecting rod itself was replaced by a simulator of the connecting rod crank (Fig. 4*c*) to reproduce the actual picture of oil supply due to the inertial ejection of oil jets from the gaps of the rotating connecting rod bearing.

In this experiment, while retaining the principle of oil collection into the drain pipes placed in the cylinder wall as applied earlier in [14], the number of oil drain pipes in the cylinder was increased whereas their arrangement scheme was changed (Fig. 4*d*). Thus, oil distribution can be seen not only along the circumference, but also along the height of the cylinder wall.

The total contribution of all natural and special sources to the CPG oil supply, such as the jet oil supply from the oil supply hole in the connecting rod, was determined. The contribution of this source to the total CPG oil supply was determined as the difference in the mass of oil in the drain pipes before and after sealing of the mentioned hole.

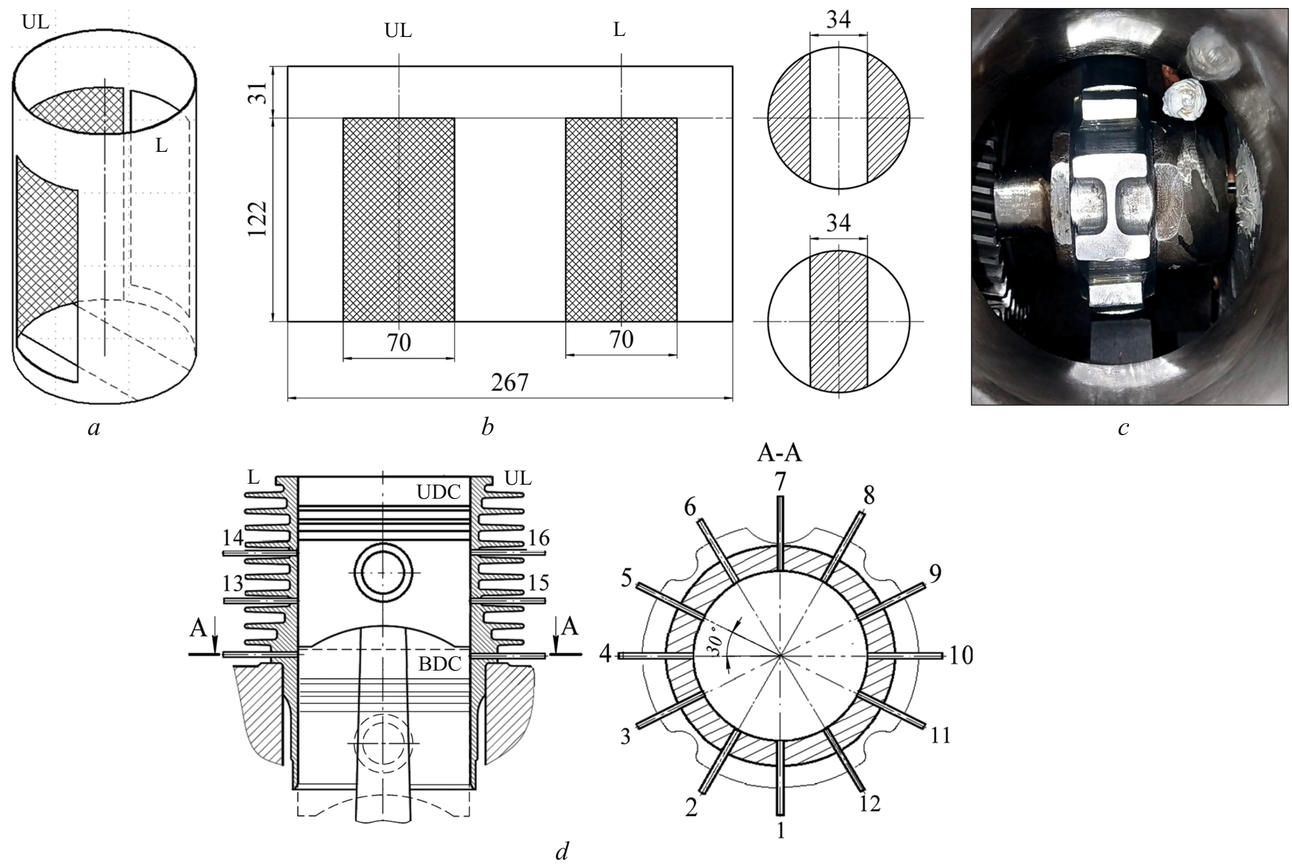

Fig. 4. Device components for the exploration of CPG oil supply process: *a*, general view of the cartridge; *b*, layout of the cartridge surface with oil-absorbing elements and screens for oil volume separation; *c*, simulator of the connecting rod crank head; *d*, oil drain pipes in the cylinder wall (1 – 16 — pipe numbers).

Stage 2. Study of the impact of the CPG oil supply on the friction of the lubricated parts of the diesel engine. This stage involved two-level comparative tests of the commercial and modernized connecting rods. The first test was carried out on the layout unit using the electrodynamic method, while the second one was performed on the engine stand by taking and comparing of the typical idle speed characteristics. These characteristics, which are regulated by the previously mentioned GOST, involved the dependences of hourly fuel consumption on the crankshaft speed under the conditions of piston engine operation without external load.

The electrodynamic method involved measuring the current force in the electric motor drive circuit, with this force being converted into the power spent on cranking the diesel crankshaft. The specified power, numerically equal to the intensity of work to overcome all types of resistance to the movement of parts, was reasonably considered as the total power of friction losses in the CPG and CM cranking diesel engine. To adjust the viscosity of the lubricant in layout tests to the level of viscosity of engine oil under actual operation conditions of the diesel engine with combustion, a super low-viscosity lubricant was used, with kinematic viscosity from 40 to 10 cSt in cranking temperature conditions (from 30 to 60°C), which corresponded to the viscosity of engine oil recommended by the diesel engine manufacturer in the range of operating temperatures (from 65 to 95°C) (Fig. 5).

The method of registering and comparing idle characteristics is based on the fact that when a piston engine operates in the idling mode (with no external loading of the piston engine), all thermal energy of the combusted fuel is spent to overcome the resistance to the movement of parts, i.e., the value of the measured fuel consumption is an indicator of friction losses. Thus, the value and character of the change in fuel consumption G_t depending on the crankshaft speed n at idle speed are identical to those for friction losses. Consequently, the fuel consumption in this mode can be used to scientifically justify the level of friction losses of the engine according to the rule stating that the lower fuel consumption, the lower losses, and vice versa.

RESULTS AND DISCUSSION

The first stage consisted in determining the relative contribution of various sources to the total oil supply of CPG parts. In this work, all the sources were considered, natural (ejection of oil jets from the crank and main crankshaft bearing clearances, as well as oil mist) and special sources, such as oil jetting from the connecting rod hole. Table 1 and Fig. 6

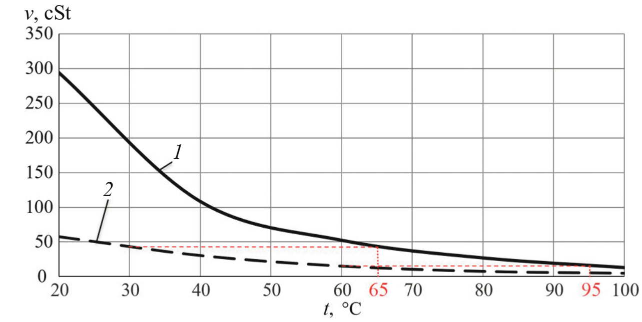

Fig. 5. Comparison of viscosity and temperature characteristics (dependence of kinematic viscosity ν on oil temperature *t*) of M-10G2 engine oil (*1*) recommended for use in diesel engine 1 × 8.5/8.0 and lubricant (*2*) produced by diluting M-10G2 oil with diesel fuel.

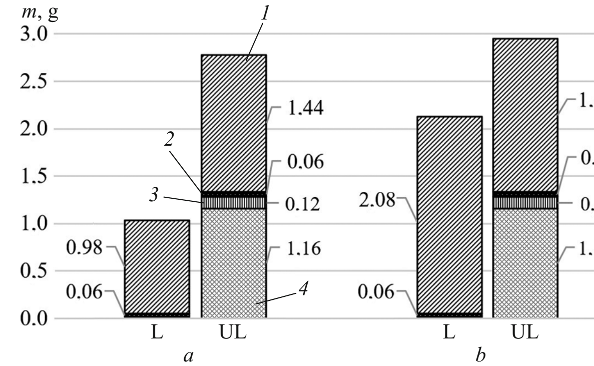

Fig. 6. Distribution of the contribution of different sources to the cylinder oil supply: *a*, commercial connecting rod; *b*, modernized connecting rod; *1*, jet outflow from a designed hole in the connecting rod; *2*, oil mist; *3*, *4*, ejection from the clearances of main and connecting rod bearings, respectively.

demonstrate the distribution of the contribution of various sources to the total oil supply to the loaded and unloaded sides of the cylinder wall by the piston lateral force in two different (commercially available and modernized) connecting rod designs.

According to the presented data (Fig. 6, Table 1), a specially organized ejection of oil from the connecting rod hole (from 52 to 97%) makes the greatest contribution to the oil supply on both the loaded and unloaded sides of the cylinder.

The oil supply to the unloaded side of the cylinder provided by the connecting rod bearing clearances (about 40%) is comparable, although less in quantity, to the one considered. However, this source is not involved in the oil supply to the loaded side of the cylinder, where full lubrication is much more important.

The oil flow contributions from main bearing clearances and due to condensation of the liquid fraction of oil mist are extremely small, not exceeding 5 and 4%, respectively. This implies that the main interest lies in studying and dealing with oil flow from the connecting rod journals and from the oil feed hole in the connecting rod.

Note that natural sources of oil supply, such as inertial oil ejection from connecting rod journals, are rather difficult to control. The only possible way to affect this process quantitatively is to change the operating mode of the lubrication system. Meanwhile, the qualitative characteristic of the oil supply will remain practically unchanged. On the contrary, specially organized methods of oil supply can affect both quantitative and qualitative aspects of the CPG parts lubrication process. However, the advantages of a specially designed solution can be diminished by not considering natural sources, while a successful combination of natural and special oil supply methods can lead to the best results.

In the process of connecting rod modernization, it was decided not to change the connecting rod inserts, due to the risk of reducing the mechanical strength of the insert and the possibility of oil pressure drop in the main oil line below the critical value. As a result, the process of CPG jet oil supply was improved by selecting a rational location of the oil supply hole in the connecting rod. Using the CRJet calculation program [15], which visualizes the process of oil jetting from the connecting rod and determines the amount of oil flowing into the typical friction areas of CPG parts, the most efficient, technological solution for modernization of the commercial connecting rod was selected that, according to calculations, did not reduce the strength of the part (Fig. 1).

The proposed change in the scheme of CPG jet oil supply provided a more significant (1.7 times) increase in the amount of oil supplied to the loaded side of the cylinder (Table 1, Fig. 6), while the oil supply to the unloaded side of this part increased insignificantly (by 6%).

The method of drain pipes was used to draw diagrams of engine oil distribution both along the circumference and

TABLE 1. Contribution of Different Sources to the CPG Oil Supply

Source	Commercial connecting rod		Modernized connecting rod	
	L	UL	L	UL
The connecting rod jet	0.98/95	1.44/52	2.08/97	1.62/55
Oil mist	0.06/5	0.06/2	0.06/3	0.06/2
Main bearings	0.0/0	0.1/4	0.0/0	0.12/4
Connecting rod bearing	0.0/0	1.16/42	0/0/0	1.16/39
Total	1.04/100	2.78/100	2.14/100	2.96/100

Note. Numerator indicates mass in grams, denominator indicates percentage.

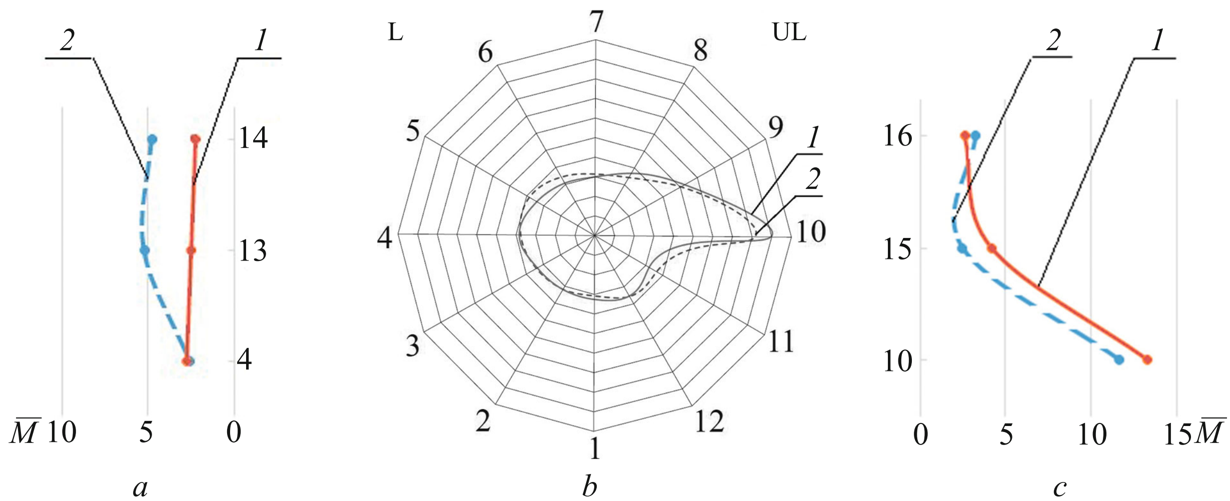

Fig. 7. Distribution diagrams of the relative amount of engine oil along the circumference (*b*) and along the height (*a*, *c*) of the cylinder: *1*, commercial connecting rod; *2*, modernized connecting rod; pipe numbering corresponds to Fig. 4*d*.

height of the cylinder (Fig. 7). To display the data in Fig. 7 more conveniently, the relative oil quantity parameter $\overline{M}$, defined by the formula, was introduced:

$$\overline{M} = m_i/m_{av},$$

where m_i is the mass of collected lubricant from the ith pipe; m_{av} is the arithmetic average value of the mass of engine oil from each pipe.

The uneven distribution of engine oil along the circumference of the inner surface of the cylinder, mentioned earlier in [7], was quantified using the degree of unevenness σ, which is defined by the ratio of the difference between the maximum and minimum values of the oil quantity *m* and its average value (Fig. 7*b*). For the commercial and modernized connecting rods, this value was $\sigma = 4.1$ and $\sigma = 3.6$, respectively (decreasing and approaching of σ value to unity means a decrease in the unevenness of distribution of the studied quantity).

According to these results, the proposed modernization of the connecting rod leads to a 14% reduction in the unevenness of oil distribution along the cylinder circumference. In addition, a quantitative increase (by 52%) in oil supply on the loaded side of the inner surface of the cylinder (Fig. 7*a*) and a decrease (by 6%) in the amount of excess lubricant on the unloaded side of the cylinder inner surface (Fig. 7*c*) were observed when switching from the commercial to the modernized connecting rod. Therefore, the modernization of the connecting rod was found to improve the matching of the amount of supplied engine oil with the character of dynamic loading of the cylinder-piston mating in the plane of the connecting rod motion. Furthermore, the effect of the improved CPG oil supply on the friction-induced mechanical losses of the diesel engine was evaluated.

At the second stage of the experimental study, an electrodynamic method implemented on the layout unit (Fig. 2) was used to conduct preliminary comparative tests of the commercial and modernized connecting rods. The test procedure [13] included two consecutive steps, which involved cranking the diesel engine at a constant crankshaft speed ($n = 1000$ rpm) during 60 min and registering the characteristic of mechanical losses in the speed range from 1000 to 2000 rpm with a 200 min pitch during 10 min. The test results (Fig. 8) demonstrate a significant (from 9 to 14%) reduction of friction loss power *N* when the commercial connecting rod is replaced with the modernized version.

In order to exclude the possible impact of the methodology and conditions of the experiment on the comparison results of the tribological efficiency of connecting rods, for the final verification of the results of layout tests, the investigated objects were subjected to testing on a full-size diesel engine 1 × 8.5/8.0 in the course of its engine stand tests in the idling mode (Fig. 9).

Figure 9*a* shows that at the speed mode from 1000 to 2000 rpm, the values of the fuel consumption difference (friction losses) caused by replacing the commercial connecting rod with the modernized one, hardly exceed the limits of the confidence interval. However, a significant (assuredly exceeding the measurement error) relative decrease in fuel consumption at operation of the diesel engine with the modernized connecting rod occurs starting from 2000 rpm. Presumably, it is due to the fact that the proposed modernization of the connecting rod was calculated for the conditions of operation of the diesel engine at crankshaft speed $n = 3000$ rpm, which refers to the main (nominal) speed mode of operation of diesel engine 1 × 8.5/8.0 when using it as a power unit of an alternating current electrical generator set with a frequency of 50 Hz. Therefore, the effect of modernization was less pronounced at much lower, compared to nominal, speeds of crankshaft rotation of the diesel engine.

For the entire period of tests (over the entire range of idle characteristic), when using the modernized connecting rod,

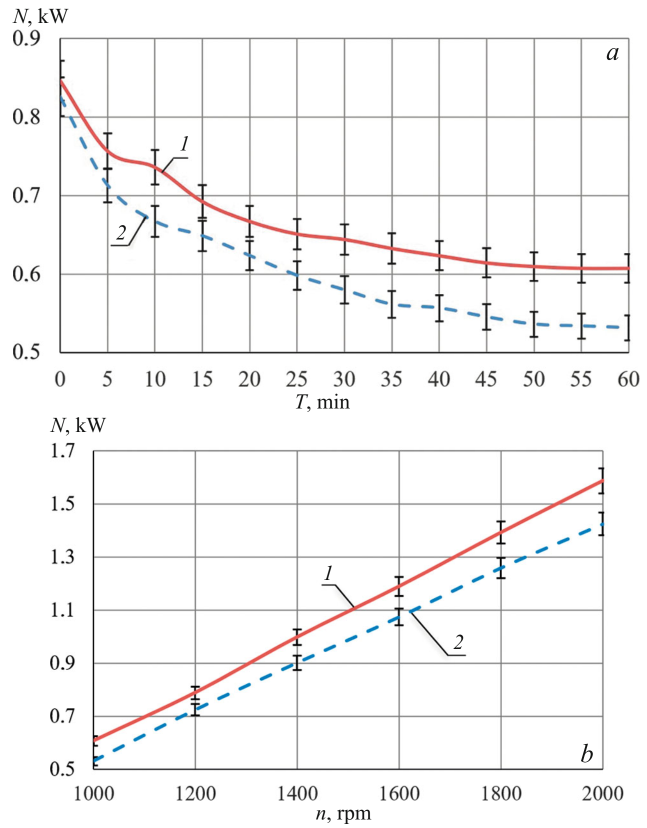

Fig. 8. Dependence of mechanical loss power *N* on cranking duration *T* (*a*) and crankshaft speed *n* (*b*): *1*, commercial connecting rod; *2*, modernized connecting rod.

the average decrease in fuel consumption in the idling mode, i.e., the reduction of friction losses, was 0.42 – 0.37 = = 0.05 kg/h, or 12% (Fig. 9*b*), whereas at the nominal speed of the diesel engine of 3000 rpm, the relative decrease in G_t remained at the same level of 12% (Fig. 9*a*). Figures 8 and 9 show that the obtained results of the positive reduction of losses caused by replacing the commercial connecting rod with the modernized one are satisfactorily correlated when tested both on the layout unit and on the full-size diesel engine (engine stand).

A similar diesel engine model was previously used for comparative tests of various objects directly affecting mechanical losses, such as antifriction additives to engine oils, pistons with different skirt profile and number of piston rings, engine oils of different viscosity, etc. The array of the obtained results proves the existence of a rigid and stable relationship between the relative change in fuel consumption G_t in the idling mode and the relative change in the effective power N_e and, respectively, the specific effective fuel consumption g_e when the diesel engine operates under load (for example, in the mode of removing the external speed characteristic).

The results of friction loss reduction obtained by a simple and economical method of idle characteristic can be used to make a scientifically substantiated calculation of the values improved as a result of friction loss reduction of the main energy and economic indicators of the engine (N_e and g_e) operating under load, i.e., under conditions of high temperatures and force impact on the rubbing parts.

With this position and the results of previous comparative tests of antifriction additives to engine oil performed on a similar model of diesel engine (Table 2), a positive and quantitatively expressed forecast of energy efficiency improvement for diesel engine 1 × 8.5/8.0 at rated speed mode of operation under load is obtained (Fig. 10).

According to Fig. 10, when switching from commercial to modernized connecting rod, the effective power of diesel engine N_e at generator high-speed mode of operation (3000 rpm) will increase from 7.7 to 8.0 kW (by 4%). Hence, taking into account the constancy of hourly fuel consumption G_t in conditions of unchanged high-speed mode, specific effective fuel consumption of diesel engine g_e will proportionally decrease by the same 4%, from 248 to 238 g/(kW · h).

The ratio between the relative reduction of mechanical losses obtained in this study (12%) and the predicted relative increase in specific fuel efficiency (4%) is 0.33, which does not contradict the known ratio of 0.45, derived from the theory of internal combustion engine operating processes, including the natural prediction error (the non-convexity does not exceed 27%).

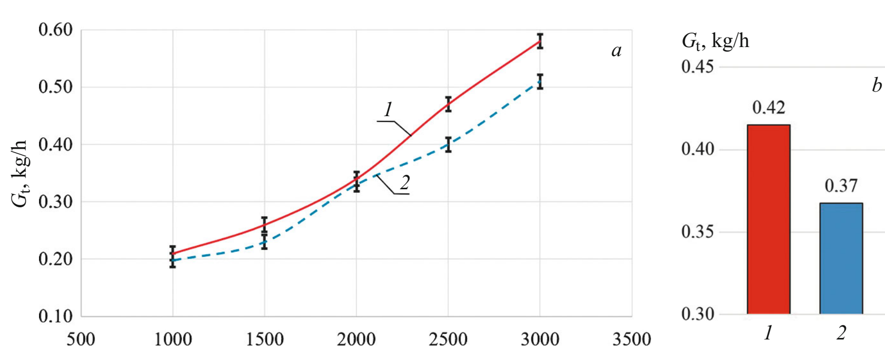

Fig. 9. Dependence of G_t fuel consumption on diesel crankshaft speed *n* in the idle mode (*a*) and comparison of average values of fuel consumption during the tests (*b*): *1*, commercial connecting rod; *2*, modernized connecting rod.

The complex (on the layout unit and a full-size diesel engine) tribometric testing has revealed the efficiency of the modernization of a commercial connecting rod, which improves the quality of oil supply to the CPG parts. Moreover, the hypothesis has been confirmed that matching the oil quantity supplied to the moving contact area of the parts with the level of their dynamic loading reduces friction losses significantly.

CONCLUSIONS

1. The new experimental methods developed and applied for determining the contribution of individual sources of oil supply to the total oil supply to the cylinder of a high-speed piston engine have revealed that the greatest contribution to the oil supply to both sides of the cylinder wall loaded and unloaded by the action of the piston lateral force is made by a specially organized jet oil supply from the connecting rod hole (from 52 to 97%). Although the inertial oil ejection from the rotating connecting rod bearing clearances plays a comparable but smaller role (up to 40% on the unloaded side of the cylinder wall), this source does not participate in the oil supply to the loaded side of the cylinder, for which lubrication is much more important.

2. The uneven oil distribution on the unfolded inner surface of the cylinder (the degree of unevenness varies from 3.6 to 4.1) has been experimentally proved. In addition, the character of this distribution indicates violating the matching of the oil quantity in the friction area of parts to the level of their dynamic loading.

3. Based on the mathematical modeling of the CPG jet oil supply, the modernization of the commercial connecting rod of the power unit of a diesel-electric generator set has given grounds for predicting the improvement of the cylinder lubrication process due to the controlled improvement of oil supply to the loaded side of the internal rubbing surface of this part, which is experiencing a deficit of lubricant.

4. Experimental evaluation of cylinder oil supply on the layout installation has shown that the modernized connecting rod can significantly (by 13%) reduce the unevenness of oil distribution along the cylinder circumference and partially eliminate the discrepancy between the amount of oil in the friction area between cylinder and piston and the level of dynamic loading of these parts.

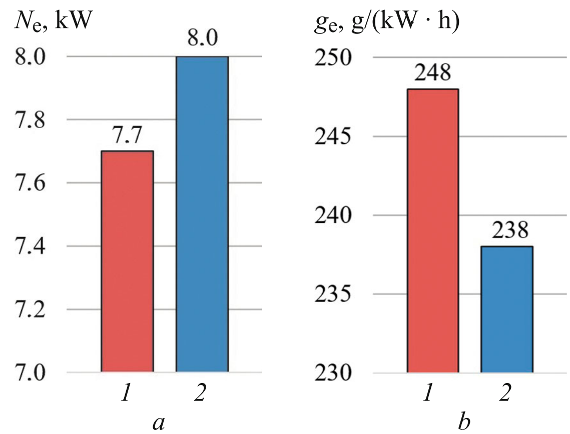

Fig. 10. The forecast values of effective power N_e (*a*) and specific effective fuel consumption g_e (*b*) of diesel engine 1 × 8.5/8.0 when operating with commercial (*1*) and modernized (*2*) connecting rods under load at crankshaft speed 3000 rpm.

5. Comparative complex (layout unit and engine stand) tests of the commercial and modernized connecting rods have proved the validity of the previously accepted hypothetical idea that matching the amount of oil supplied to the level of dynamic loading of lubricated parts can lead to a reduction in friction losses. Thus, as a result of replacement of a commercial connecting rod with a modernized one, which meets the conditions of the hypothesis, a significant (guaranteed to exceed the measurement error) relative reduction of friction losses in the CPG and CM by 10% was obtained in layout tests; whereas in tests on a full-size diesel engine 1 × 8.5/8.0, a similar replacement of the connecting rod was accompanied by a significant reduction in fuel consumption in the mode of taking the idling characteristic (method of estimating friction losses) by an average of 12%.

TABLE 2. Input Data for Predicting the Energy and Economic Performance of a Diesel Engine 1 × 8.5/8.0 When Operating under Load

Test operation mode	Control value of the object		Relative difference between the control values of commercial and modernized objects, %
	commercial	modernized	
Antifriction additives			
Characteristic of the idling mode ($N_e = 0$) G_t, kg/h	0.51	0.49	4
External speed characteristic ($N_e > 0$):			
N_e, kW	8.0	8.1	1
g_e, g/(kW · h)	246	243	1
Connecting rods			
Characteristic of the idling mode ($N_e = 0$) G_t, kg/h	0.58	0.51	12
External speed characteristic ($N_e > 0$):			
N_e, kW	7.7	8.0	4
g_e, g/(kW · h)	248	238	4

6. Methods for computational modeling and experimental monitoring of the process of CPG oil supply, design methods and results, as well as the application of efficient connecting rod construction in terms of friction loss reduction can have both scientific and practical value in the engineering, development, and operation of power units of diesel-electric generator sets.

Compliance with ethical standards

Conflict of interest. The authors have no financial or proprietary interest in any of the material discussed in this article.

REFERENCES

1. B. Tormos, J. Martín, R. Carreño, and L. Ramírez, "A general model to evaluate mechanical losses and auxiliary energy consumption in reciprocating internal combustion engines," *Tribol. Int.*, **123**, 161 – 179 (2018). DOI: 10.1016/j.triboint.2018.03.007
2. V. W. Wong and S. C. Tung, "Overview of automotive engine friction and reduction trends — Effects of surface, material, and lubricant-additive technologies," *Friction*, **4**, 1 – 28 (2016). DOI: 10.1007/s40544-016-0107-9
3. J. B. Heywood, *Internal Combustion Engine Fundamentals*, McGraw-Hill Education, New York (2018).
4. Y. Mansoor and P. Shayler, "The effect of oil feed pressure on the friction torque of plain bearings under light, steady loads," *Tribol. Int.*, **119**, 316 – 328 (2018). DOI: 10.1016/j.triboint.2017.11.013
5. D. E. Sander, H. Allmaier, H. H. Priebsch, M. Witt, and A. Skiadas, "Simulation of journal bearing friction in severe mixed lubrication — Validation and effect of surface smoothing due to running-in," *Tribol. Int.*, **96**, 173 – 183 (2016). DOI: 10.1016/j.triboint.2015.12.024
6. M. Söderfjäll, A. Almqvist, and R. Larsson, "Component test for simulation of piston ring-cylinder liner friction at realistic speeds," *Tribol. Int.*, **104**, 57 – 63 (2016). DOI: 10.1016/j.triboint.2016.08.021
7. I. G. Galiev, K. A. Khafizov, and F. Kh. Khaliullin, "Modernization the system of bearing units lubrication of a turbo compressor of the tractor engine," *Vestn. Kazan. Gos. Agrar. Univ.*, **14**(1), 71 – 76 (2019). DOI: 10.12737/article_5cceddb77ac7e0.09639673
8. S. V. Putintsev, S. A. Anikin, and S. S. Strelnikova, "Fundamentals and some results of numerical modeling the cylinder-piston group jet-oil supply in a high-speed four-stroke internal combustion engine," *J. Mach. Manuf. Reliab.*, **52**(3), 271 – 280 (2023). DOI: 10.3103/S1052618823030159
9. A. Yu. Shabanov, A. B. Zaitsev, A. A. Metelev, and Ya. P. Pystovalov, "Simulation parameters of friction and wear conjugation in the friction cylinder," *Nauch.-Tekhn. Vedom. SPbPU. Estestv. Inzh. Nauki*, No. 3, 15 – 21 (2016). DOI: 10.5862/jest.249.2
10. B. Zhao, X.-D. Dai, Z.-N. Zhang, and Y.-B. Xie, "A new numerical method for piston dynamics and lubrication analysis," *Tribol. Int.*, **94**, 395 – 408 (2016). DOI: 10.1016/j.triboint.2015.09.037
11. C. Kirner, J. Halbhuber, B. Uhlig, A. Oliva, S. Graf, and G. Wachtmeiste, "Experimental and simulative research advances in the piston assembly of an internal combustion engine," *Tribol. Int.*, **99**, 159 – 168 (2016). DOI: 10.1016/j.triboint.2016.03.005
12. J. Schäffer, C. Kirner, M. Härtl, and G. Wachtmeister, "Development of a measuring system for the visualization of the oil film between the piston and cylinder liner of a gasoline engine," *SAE Int. J. Engines*, **13**(2), 175 – 190 (2020). DOI: 10.4271/03-13-02-0013
13. S. G. Ahling, *Elements of Lubricant Transport Critical to Piston Skirt Lubrication and to Leakage into the Piston Ring Pack in Internal Combustion Engines. Doctoral Dissertation*, Massachusetts Institute of Technology (2021). https://hdl.handle.net/1721.1/139871
14. S. V. Putintsev and A. G. Ageev, "Experimental research of conditions of cylinder oil supply in high-speed four-stroke internal-combustion engine," *Trakt. Sel'khozmash.*, No. 10, 45 – 49 (2016).
15. S. V. Putintsev and A. F. Biktashev, "Computer program CRJet for modeling cylinder and piston assembly oil jet supply process," *Gruzovik*, No. 8, 3 – 6 (2018).