To the study of 10D100 diesel engines of operating diesel locomotives by the fuel supply advance angle

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Abstract. The results of the justification for the distribution of diesel engines 10D100 are presented, taking into account the value of the actual advance angle of fuel supply at the nominal operating mode of the diesel generator set of operating diesel locomotives. A methodology for studying the dynamics of changes in the empirical and theoretical distribution of quantities is proposed, lean on the basic principles of probability theory and mathematical statistics, taking into account the criteria of agreement of Pearson and A. N. Kolmogorov's. It has been proven that the distribution of the studied diesel locomotive diesel engines according to the actual fuel supply advance angle corresponds to the law of normal distribution. It is recommended to continue these studies for partial load conditions, covering a larger number of operating diesel locomotives on railway sections of different complexity.

1 Introduction

Currently, about thirty percent locomotive fleet of the diesel traction of «Uzbekistan Railways» JSC is made up of mainline diesel locomotives of the TE10M series in various sectional designs, which carry out railway transportation of goods on sections of the Uzbek railways of varying difficulty, including on electrified sections.

The efficiency of using these diesel locomotives directly depends on the operating process of the diesel engine, taking into account the degree of perfection of the fuel system and the technical condition of its equipment in operation. The system (process) of fuel injection into the cylinders plays a significant role in the performance of a diesel engine, its reliability and durability along the route of rolling stock, as well as operational characteristics, the purpose of which is to ensure normal diesel fuel supply under various operating modes of the diesel locomotive diesel generator set.

One of the ways to improve the performance of a diesel engine is to systematically improve each of the elementary processes that make up its "full" operating cycle. The working process of a diesel engine occurring in the cylinders determines its main operational indicators, namely: indicator and effective power and specific fuel consumption, maximum loads and temperature conditions occurring in the details of the cylinder-piston group and many others.

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The main tasks in studying the working process of a diesel engine are to establish the dependencies of its main indicators on various design, including geometric and technological parameters, as well as on the choice of such a combination of them that achieves the best indicators of the working process.

Numerous theoretical and experimental studies by scientists from various countries have been devoted to solving this problem for diesel locomotive [1, 2, 7, 9-15] and auto-tractor [8] diesel engines, aviation [3-6] engines with spark ignition of fuel, the analysis of the results of which has shown that and how important (and necessary) it is to achieve optimal (rational) and high-quality combustion of diesel or other types of alternative fuel.

In this regard, the relatively high quality of the fuel combustion process should ensure the necessary efficiency of the operating cycle and reliable operation of the diesel engine, which are characterized by high temperatures and pressures of the cycle, minimal fuel and air consumption, not exceeding the permissible values of temperatures and pressures and the intensity of their increase for each cycle.

The results of these studies have a certain scientific interest and practical significance, however, they do not have local components of the quality of the fuel combustion process associated with substantiating the influence of the parameters of charge air and atmospheric air, as well as of the fuel supply advance angle on the parameters of the working process of a locomotive diesel engine at nominal and intermediate load modes of its operation.

Attempts to implement the above were made in studies [16, 17] and were indirectly obtained in the monograph [18], in which the author recommends that when rationing fuel consumption for train traction and choosing the optimal train traffic control mode, rely on one of the indicators for optimizing the transportation operation of locomotives - this maximum efficiency of the power circuit of a diesel locomotive, characterizing indirectly the high level of the working process of a locomotive diesel engine.

2 Objects and methods of research

The quality of the diesel operating process is assessed by energy-economic indicators and the dynamics of fuel combustion in the cylinder. The fuel supply advance angle largely determines these indicators. As experiments have shown [17], a change in the fuel supply advance angle $\varphi_{s.a.a}$ from 8 to 14 degrees of rotation of the diesel crankshaft led to a decrease in the specific effective fuel consumption g_e by 8 - 9 percent, an increase of the maximum combustion pressure p_z^{max} of the fuel by 0.018 - 0.020 MPa/m^2 and the maximum rate of pressure rise $(^{dp}/_{d\varphi})_{\max}$ by 1.5 - 1.6 kPa/deg.

Studies by other authors [2, 7, 8, 11] also indicate a significant influence of the fuel supply advance angle $\varphi_{s.a.a}$ on the performance of the diesel operating cycle. Therefore, it is necessary to impose fundamentally hard and very strict restrictions on adjusting and setting the fuel supply advance angle.

In this regard, the purpose of this research is to study of question the influence of operational factors on the value of the actual advance angle $\varphi_{s.a.a}^{ac}$ of fuel supply to the diesel cylinders of mainline diesel locomotives.

The object of the study is a two-section mainline freight diesel locomotive of the 2TE10M series, the diesel generator set of which consists of a two-stroke locomotive diesel engine 10D100 with counter-moving pistons and a GP-311B generator, and the working of process of this diesel engine regarding the supply of fuel to the cylinders.

The subject of the study is the parameters of individual elements of the working process of diesel of diesel locomotives in operation, related to the advance angle of fuel supply to the

cylinders, fuel combustion pressure at the top dead center of the piston position in the cylinder, taking into account the fuel combustion temperature.

To achieve the stated goal of the research, the main basic methods of probability theory and mathematical statistics were used.

The characteristics of the empirical distribution were calculated using the properties of theoretical and empirical distributions outlined in [20].

A preliminary assessment of the distribution was carried out numerically, based on the following characteristics:

– arithmetic mean of the distribution x, which characterizes the center of grouping of random variable values

$$\bar{X} = \overline{h_1} \cdot \Delta x + C \tag{1}$$

where $\bar{h}$ - first beginning (initial) moment;
C - "false zero";
Δx - increment in interval;

– dispersion of the empirical distribution, characterizing the degree of dispersion of values relative to the center

$$S^2 = m_2 = (\Delta x)^2 \cdot (\overline{h_2} - \overline{h_1}) \tag{2}$$

where m_2 - second central moment;
$\overline{h_2}$ - second beginning (initial) moment;

– distribution asymmetry

$$S_k = \frac{m_3}{S^3} \tag{3}$$

where m_3 - third central moment,

If the value S_k = 0, then the curve is symmetrical; if $S_k > 0$ - the curve has a positive asymmetry, and if $S_k < 0$ - then the asymmetry is negative.

– kurtosis of distribution

$$E_k = \frac{m_4}{S^k} - 3 \tag{4}$$

where m_4 - fourth central moment.

The value of E_k characterizes the steepness of the curve in relation to the normal distribution curve, for which E_k = 0. When the value of E_k > 0, then the top of the curve is above the normal distribution curve and if the value of E_k < 0, then the location of the specified curve will be lower.

The correspondence of the empirical and theoretical distributions was justified using the Pearson goodness-of-fit test χ^2, which is the most accurate verification method, as it provides a minimal error in accepting an incorrect hypothesis compared to other methods [20] and allows one to assess the statistical significance of differences between two or more relative indicators (frequencies, shares):

$$\chi^2 = \sum_{i=1}^{i=n} \frac{(n_i - m_i \cdot \widetilde{p_i}) \cdot (n_i - m_i \cdot \widetilde{p_i})}{m_i \cdot \widetilde{p_i}}$$

where n_i - frequency in interval;
m_i - number of samples;
$\widetilde{p_i}$ - estimation of the probability of falling into the interval for each group.

And finally, the final testing of the hypothesis was carried out according to the agreement criterion of A.N. Kolmogorov [21, 22]. This criterion takes into account the

discrepancy between the statistical and theoretical distribution functions, and a value equal to

$$D_{max} \cdot \sqrt{N \geq \lambda}$$

where N - total number of measurements, $N = \sum_{i=1}^{i=8} n_i$;
λ - agreement criterion of A. N. Kolmogorov.

When λ = 0, the probability that the distributions correspond to the chosen one will be equal to P(λ) = 1; at λ = 1; - P(λ) = 0.

3 Results and discussion

To identify the nature of the distribution of diesel locomotive diesel engines 10D100 along the specified angle $\varphi_{s.a.a}^{ac}$, 36 diesel locomotive engines in operation were examined at a number of depots of the Kazakh Railway. In order to fix the value of $\varphi_{s.a.a}^{ac}$ on a running diesel engine, a special device [19] was used to analyze the operation of fuel equipment, which makes it possible to measure the value of the fuel supply advance angle with an accuracy of ± 0.1 degrees of rotation of the diesel crankshaft. Since the actual angle $\varphi_{s.a.a}^{ac}$ of fuel supply advance was measured on 20 fuel pumps of each diesel engine, therefore 720 measurements were made. This allowed us to establish the nature of the dynamics of the distribution of diesel engines by the magnitude of the mentioned angle $\varphi_{s.a.a}^{ac}$ and group them into certain intervals in accordance with the provisions of probability theory [20]. The results of grouping diesel engines according to the actual angle $\varphi_{s.a.a}^{ac}$ of fuel supply advance are given in table. 1.

Table 1. Distribution parameters of diesel locomotive diesel engines 10D100 based on the actual fuel supply advance angle

Options and designation	Sum	Interval numbers			
		1	2	3	4
1	2	3	4	5	6
Intervals boundary	-	13-15	15-17	17-19	19-21
Middle of the interval, X	-	14	16	18	20
Interval frequency, n_i	720	80	110	200	180
Frequency periodicity, $W(x_i)$	1.0	0.111	0.153	0.378	0.250
Relative frequency periodicity, $W(x_i)/_{\Delta X}$	0.5	0.056	0/576	0.140	0.124

Continuation of table No. 1.

Options and designation	Sum	Interval numbers			
		5	6	7	8
1	2	7	8	9	10
Intervals boundary	-	21-23	23-25	25-27	27-29
Middle of the interval, X	-	22	24	26	28
Interval frequency, n_i	720	80	40	20	10
Frequency periodicity, $W(x_i)$	1.0	0.111	0.050	0.030	0.010

Relative frequency periodicity, $W(x_i)/_{\Delta X}$	0.5	0.056	0.030	0.010	0.008

Source: «Compiled by the author».

The number of intervals was chosen from the condition of preserving the characteristic features of the distribution and excluding sharp frequency deviations. For convenience of calculations, the unit of measurement of the actual angle $\varphi_{s.a.a}^{ac}$ was taken to be $1 \cdot 10^{-4}$ s, that is, the amount of fuel supply advance relative to the top dead center of the diesel crankshaft position was determined by time. An empirical graph of the above distribution is shown in fig. 1. The abscissa axis shows the actual fuel supply advance angle, further denoted by the letter *X*, and the ordinate axis shows the approximate probability of falling into a given interval, that is, the relative frequency repeatability. The initial data for constructing the histogram are given in table. 1.

As a result of the numerical calculations, the following values of the distribution parameters were obtained: $\bar{x} = 18.89 \cdot 10^{-4}$ s; $S^2 = 9.5$; $S_k = 0.48$ and $E_k = 0.14$.

Thus, it could be assumed that the resulting distribution is close to the normal distribution, since S_k and E_k are only slightly greater than zero.

The normal distribution law (Gauss's law) is written as follows [21, 22]

$$n(x, a, \sigma) = \frac{1}{\sigma \cdot \sqrt{2\pi}} \cdot exp\left[-\frac{(x-a)^2}{2\sigma^2}\right] \tag{5}$$

where n - normal probability density;
a, σ - distribution parameters.

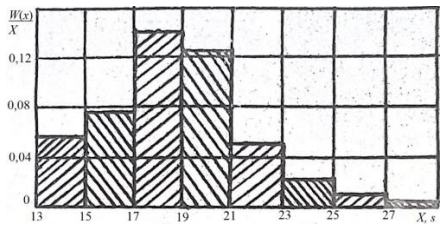

Fig. 1. Diagram of distribution parameters of diesel engines 10D100 depending on the actual fuel supply advance angle. Source: «Compiled by the author».

The differential curve of the normal distribution law is shown in fig. 2, where on the ordinate axis the letter *N* denotes - $n(x, a, \sigma)$, and the number 1 is curve of the graphical dependence $n = \frac{1}{\sigma \cdot \sqrt{2\pi}} \cdot e^{\frac{-(x-a)^2}{2\sigma^2}}$.

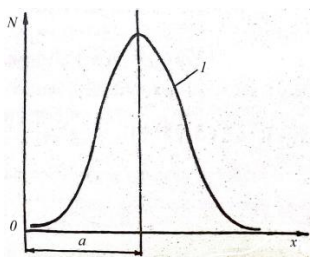

Fig. 2. Graph of the distribution of parameters of diesel engines 10D100 from the actual fuel supply advance angle. Source: «Compiled by the author».

In this case, we equate the value of a to the average value of arithmetic deviations, namely:

$$a = \bar{x} = 18{,}89 \cdot 10^{-4}, s \tag{6}$$

and the parameter σ - to the standard deviation of the empirical distribution, namely:

$$\sigma = \sqrt{S^2} = 3.08 \cdot 10^{-4}, s \tag{7}$$

Thus, we obtained the normal density in the following form

$$n(x; 18.89; 3.08) = 0.13 \cdot exp\left[-\frac{(18.89-x)^2}{19.0}\right] \tag{8}$$

For the convenience of analysis, the resulting distribution was normalized, with the values of the abscissa and ordinate expressed in fractions of σ. The histogram and distribution curve are presented in fig. 3. It can be assumed that the distribution is really close to the normal distribution, since from fig. 3 it can be seen that only small parts of the histogram extend beyond the curve. It should be noted that this comparison is very approximate, and a more accurate comparison is made using special criteria.

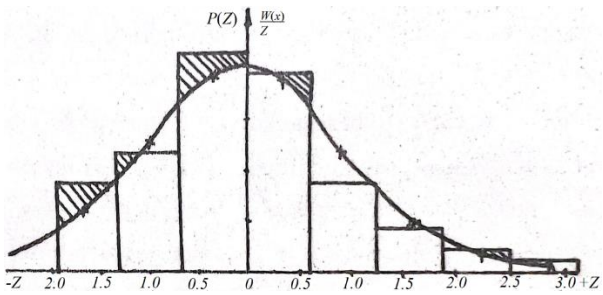

Fig. 3. The histogram and of the distribution curve of parameters of diesel engines 10D100 from the actual fuel supply advance angle. Source: «Compiled by the author».

As a result of the calculations, the value of Pearson's goodness-of-fit criterion was obtained: χ^2 = 2,389. After finding the indicated value χ^2, the number of degrees of freedom should be determined using this analytical dependence

$$K = L' - \mathrm{C} - 1 \tag{9}$$

where L' - number of intervals;

C - number of parameters of the theoretical distribution function ($C = 2$, since the normal distribution law).

Thus, we have

$$K = 7 - 2 - 1 - 4$$

According to the table IV appendix [3] we find that the obtained value $\chi^2 = 2.389 < \chi_q^2 = 3.36$ corresponds to a 50 percent significance level, which confirms the hypothesis of a normal distribution law.

Interim calculation data to determine the mentioned agreement criterion λ A.N. Kolmogorov are summarized in table 2, according to which the maximum value of the difference $[n_i' - (m_i \cdot p_i)']$ is equal to the number 5.

Table 2. Initial data for determining the criterion of agreement by A.N. Kolmogorov's

Interval number	Frequency in interval, n_i	Estimation of mathematical expectation, $m_i \cdot \tilde{p}_i$	Cumulative frequency, n_i'	Cumulative mathematical expectation, $(m_i \cdot p_i)'$	Difference, $[n_i' - (m_i \cdot p_i)']$
1	2	3	4	5	6
1	80	78	80	78	2
2	110	116	190	194	-4
3	200	201	390	395	-5
4	180	171	570	566	-4
5	80	86	650	652	-2
6	40	43	690	695	-5
7	20	17	710	712	-2
8	10	8	720	720	0
Sum	720	720	-	-	-

Source: «Compiled by the author».

That's why

$$D_{max} = \frac{5.0}{N} = 0.0063$$

Therefore, the value λ = 0.0063 $\sqrt{720}$ = 0.534.

Using Appendix XI [3] for a given value of λ we find the probability that the function is chosen correctly. Indeed, for λ = 0.534 the value $P(\lambda) = 0.95$, that is, the agreement is quite good.

Thus, the distribution of diesel locomotive diesel engines 10D100 in terms of the actual advance angle of fuel supply in the nominal mode corresponds to the distribution along the Gaussian curve (normal distribution law).

The most significant factor listed is the last one. It is known [23] that compliance of the actual values of fuel combustion pressure p_z with the established standards is achieved by selecting the thickness of the gaskets between the fuel pump body and its seat (installation location), that is, by changing the advance angle of the fuel supply to the cylinder. The reasons for the increased or decreased combustion pressure p_z of fuel can be defects in the fuel equipment (poor atomization, uneven cyclic fuel supply, uneven fuel injection into the cylinder, and others), defects in the gas-air path, non-compliance with the normal volume of the compression chamber, and others.

4 Conclusion

The research results allow us to draw the following general conclusions.

1. The statistical analysis carried out indicates a significant spread in the actual angle $\varphi_{s.a.a}^{ac}$ of fuel supply advance for diesel engines of operating diesel locomotives.
2. It has been established that the nature of the dynamics of the distribution of diesel engines of operating diesel locomotives in terms of the actual angle $\varphi_{s.a.a}^{ac}$ of fuel supply advance corresponds to the Gauss curve, that is, by the normal law distribution, which indicates significant shortcomings in the quality of repairs and operating conditions of diesel locomotives.
3. When releasing diesel locomotives from repair, in the event of a discrepancy between the combustion pressure p_z of the fuel and the established standards, it is advisable to

find out the true causes of this defect, and not to eliminate it by changing of the angle $\varphi_{s.a.a}$ of fuel supply advance.

4. For two-stroke diesel locomotive diesel engines with an angle $\varphi^{n}_{s.a.a}$ of fuel supply advance not exceeding 16 degrees of rotation of the diesel crankshaft ($\varphi^{n}_{s.a.a} \leq 16°$), it is advisable to regulate the value of the specified angle when setting up a diesel generator set during rheostat tests $\varphi^{n}_{s.a.a}$ only with a plus tolerance.

In addition, these studies should be continued and, in this regard, further studied and substantiated the dynamics of changes in the empirical and theoretical distribution of the studied two-stroke diesel engines according to the actual advance angle of fuel supply to their cylinders, with taking account partial load conditions on railway sections of varying complexity, in including Uzbek ones.

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