Determining threshold values of operating motor oils to diagnose internal combustion engines

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Abstract. Technical fluids (engine oil, antifreeze) have to meet their requirements during the standard operating life to ensure the standard service life of combustion engine systems and mechanisms. The stability of the engine oil during engine operation depends on many factors. Motor oil touches all the processes in the internal combustion engine and can serve as a source of diagnostic information, which will make it possible to carry out maintenance and repair of engine parts as needed, to increase the reliability and durability of the internal combustion engine. The results of the oil sample analysis for each indicator allow us to draw distribution density curves for the serviceable and faulty engine condition. Following the results of the analysis, it is necessary to compare the value of the index with its threshold values, separating the zone of operation condition from the zone of the engine faulty condition. Since the number of serviceable engines under operating conditions is always greater than the number of faulty ones, at the first stage of oil quality control, it is possible to determine the threshold values of indicators separating the zone of normal wear (engine serviceable condition) from the zone of increased wear. The research has resulted in an algorithm for calculating and determining the threshold values of motor oils for tractor engines operated on farms in the Omsk region. The authors selected the values based on two oil indicators: kinematic viscosity at 100°C and flashpoint. The distribution and probability integral of these indicators are better smoothed out by the normal Gauss law. The researchers obtained the maximum and minimum values of indicators corresponding to the 5% boundary of the probability integral.

1. Introduction

Diagnostics is the process of determining the technical condition of a motor using indirect parameters and quality features. Diagnostics as a subsystem of information for production management is simultaneously an element of the maintenance and repair system itself, as well as a subsystem for monitoring the quality of work performed and technical condition of machines [1]. The regular diagnosis provides the possibility to determine the fault without disassembly before the failure to plan its elimination and prevents the progressive wear of parts, reduces the overall cost of maintenance and repair. Diagnostics by operating oil parameters is one of the most effective methods of technical diagnostics of the internal combustion engine (ICE) [2]. Its main advantages include the ability to obtain almost continuous information about the technical condition of the engine without stopping and disassembling, high informativeness, the ability to detect the beginning of increased and accidental
wear of individual components, systematic monitoring of oil quality and the possibility of timely replacement.

2. **Problem Statement**

It is legitimate to consider engine oil as a structural element of an internal combustion engine [3]. Therefore, it is possible to extend the concepts of reliability theory established by GOST 27.002-89 to it, including the concept of operability. The oil must arrive at the consumer in good technical condition, i.e. it must fully comply with the requirements of the normative and technical documentation (NTD) for fresh oil. The oil filled into the lubrication system goes from a serviceable condition to a functional condition at engine start, when it does not necessarily meet the requirements of the NTD for fresh oil, but has not yet reached the limit state specified in the operating documentation [4]. Over time, aging oil can lead to failure and malfunction. Thus, the operating condition differs from the faulty one by values of some indicators, which change directly and obviously negatively affects the engine life, reliability and efficiency [5]. For the same oil brand, failure rates may vary significantly between different engines. The research determined the threshold values of oil indicators at the transition of its parameters to the faulty condition.

3. **Research Questions**

The engine has four main groups of parts exposed to intensive wear: - cylinder-piston; - crankshaft and bushings; gas distribution mechanism; - camshaft and gear bushings [6]. The diagnosis ensures the timely faults detection. The micrometer is the most accurate way to determine the amount of wear on parts, but it requires disassembly of the engine, which is not economically feasible. Currently, there are various methods non-disassembly diagnostics of engines [7]. One main task of diagnosing the technical condition of engine units and assemblies is determining norms of diagnostic parameters [8]. Statistic method determines the diagnostic parameters through the calculation of accumulated analysis results, thus making it possible to determine the actual condition of the engine with the required accuracy, to correct the timing and nomenclature of technical effects during maintenance and repair of internal combustion engines, to improve the reliability and service life of engine components and parts [9]. We have determined the limit values for the engine oil in an internal combustion engine. There are revealed regularities of motor oil parameters influence on the technical condition of the internal combustion engine.

4. **Purpose of the Study**

The purpose of the study is to improve the methods of diagnosing the internal combustion engine on the parameters of running engine oil. This includes the theoretical definition of the threshold values of the parameters of operating engine oil and check them with practical research.

5. **Research Methods**

The definition of diagnostic parameters used the statistical method and mathematical processing of the accumulated results of analyses.

6. **Results**

After refueling the engine and putting it into operation, the engine oil goes through two stages of work before replacement [10]. At the first stage, there is a significant change in all the indicators characterizing the quality of operating oil [11]. There is an increase in the content of mechanical impurities, oil viscosity, the content of wear products in the oil, and vice versa, a decrease in the flashpoint of the oil, alkaline number, and value of hydrogen index, the content of additive elements. The first stage of oil operation (zone A, Figure 1), which lasts 45-55 hours for a diesel engine, ends with relative stabilization of the indicator value and followed by the second stage of oil operation (zone B) which is the longest. If any system or unit is faulty in the engine, then the indicator also stabilizes, but at a higher level. For example, a centrifuge fault increases the total oil contamination
value compared to the total contamination value of a serviceable oil cleaning system. If at that moment the fault is not eliminated, heavy oil pollution will cause increased engine wear, which will go into emergency under the influence of a further increase in oil pollution [12]. There comes the third stage of oil operation, which is unacceptable. But in case of restoring the functionality of the centrifuge, the value of total oil contamination will decrease to its original value after a certain period of operation.

While determining the threshold values of operating oil parameters it is necessary to consider the analysis results of oil samples with stabilized values of indicators, i.e. oils operating in the zone B [13].

Based on the results of oil sample analysis for each indicator, we can construct distribution density curves for serviceable (I) and faulty (II) engine conditions. The faulty condition must be confirmed by a control inspection performed during engine maintenance or repair [14].

Following the results of the analysis, it is necessary to compare the value of the index with its threshold values, separating the zone of operation condition from the zone of the engine faulty condition [15]. We can record this task as a following condition:

\[ x_i < x_I \quad x_i \in D_1, \]
\[ x_i < x_{II} \quad x_i \in D_2, \]  \hspace{1cm} (1)

where \( x_i \) is the measured value of the indicator; \( x_I \) and \( x_{II} \) are indicator threshold values; \( D_1 \) is serviceable engine condition; \( D_2 \) is faulty engine condition; \( C - x_i \) belongs to the \( D_1 \) or \( D_2 \) condition.

The whole area of the indicator values usually has three zones:

I - zone of normal wear, corresponding to the serviceable engine condition;

II - zone of increased wear, corresponding to the transition from the serviceable to the faulty engine condition;

III - zone of emergency wear corresponding to the faulty engine condition;

These zones are separated by threshold boundaries \( x_I \) and \( x_{II} \).

Since the values of the indicator scatter for the serviceable and faulty conditions of the motor can take more or less values characterized by the standard deviation, there are two options for the location of the density curves of the indicator distribution. Case A (Figure 02) shows when the curves do not intersect and case B when the curves intersect. There are two cases of different threshold positions.

For the first case, the boundary of the engine serviceable condition of \( x_I \) is set at 95% probability integral boundary for the distribution of the index corresponding to the serviceable condition of the engine, and the boundary of the engine faulty condition is set at 5% probability integral boundary for the distribution of the index corresponding to the faulty condition of the engine.

In the second case, where there is an intersection of the distribution density curves for serviceable and faulty engine conditions, the approach to boundary definition is slightly different. The boundary of a serviceable condition of engine \( x_I \) specifies not on the curve of the density distribution of the index corresponding to a serviceable condition of the engine (I) but corresponds to 5% boundary of probability integral for the curve of the density distribution of the index corresponding to a serviceable condition of the engine (II), i.e. it corresponds to the beginning of the curve (II). In the second case, if the value of the indicator lies in the zone of increased wear II, it is necessary to decide about attributing the motor to a serviceable or faulty condition. Thus, there may be one of two mistakes. The first type error \( \alpha \) (false fault) is characteristic of the left side of zone II and means that a serviceable engine will be classified as faulty. The second type error \( \beta \) (omission of the fault) is characteristic for the right side of zone II and consists in the faulty motor being classified as serviceable.

Obviously, the consequences of these errors will differ, so we need to choose the optimal value of the \( x_{II} \) threshold where the total cost of errors of the first and second types was minimal.

To determine the value of \( x_{II} \) it is advisable to use the minimum risk method, which proceeds from the condition of the minimum average risk of errors of the first and second types [4].

Based on the minimum risk condition, we make the following decision on the condition of the node with the measured value of parameter \( x_i \):
where $f(X/D_1)$ is the density of the indicator distribution in serviceable condition; $f(X/D_2)$ is the density of the index distribution in faulty condition; $C_{12}$ is the cost of skipping the fault (error of the second type); $C_{21}$ is COST OF FALSE ALARM (ERROR OF THE SECOND TYPE); $P(D_1)$ is probability of the node serviceable condition; $P(D_2)$ is probability of the node faulty condition.

From a minimum average risk condition

$$
\frac{f(X_1/D_1)}{f(X_1/D_2)} = \frac{C_{12}P(D_2)}{C_{21}P(D_1)},
$$

(4)
Thus, by knowing the laws of distribution for serviceable and faulty conditions, the cost of errors of the first and second types, as well as the probability of the node state from statistical data we can determine the value of the threshold \( X_2 \).

The logarithmic normal distribution is typical for most indicators, oil properties - diagnostic parameters. We have inserted the density expression for this distribution into expression (4) as follows:

\[
\frac{1}{0.4343} \frac{0.4343}{X_2 \sigma_1 \sqrt{2\pi}} \frac{1}{0.4343} \frac{0.4343}{X_2 \sigma_2 \sqrt{2\pi}} \text{ln} \lambda = 1 - \Phi \left( \frac{\lambda}{\sigma} \right),
\]

where \( \lambda = \frac{C_2 P(D_2)}{1 - C_2 P(D_2)} \) is the likelihood ratio

After the transformation we will get the full quadratic equation as follows:

\[
AX^2 + BX + C = 0,
\]

where \( X = \log X_2; A = \log \sigma_1; B = 2(\log \sigma_1 - \log \sigma_2); C = \left( \sigma_1^2 \log \sigma_1 \right)^2 - 2\log \sigma_1 \log \sigma_2 \log \lambda \sigma_1^2 \sigma_2 \).

The positive root of the equation is equal to:

\[
X = -\frac{B - \sqrt{B^2 - 4AC}}{2A},
\]

For the normal distribution, \( \log \sigma_1 \) and \( \log \sigma_2 \) are replaced by \( X_1 \) and \( X_2 \) respectively.

When determining the likelihood ratio \( \lambda \) (6) for the probability of the faulty condition of the object \( P(D_2) \), we take the ratio of the number of samples corresponding to the faulty condition of the object \( m \) to the total number of samples \( n \) taken during the testing period.

\[
P(D_2) = \frac{m}{n},
\]

Probability of the object serviceable condition

\[
P(D_1) = 1 - P(D_2)
\]

Since the number of serviceable engines under operating conditions is always greater than the number of faulty ones, at the first stage of oil quality control it is possible to determine the threshold values of indicators separating the zone of normal wear (serviceable condition of the engine) from the zone of increased wear (boundary \( X_1 \)).

From all values of sample of each indicator we exclude sharply distinguished values, applying the rule of three standard deviations:

\[
X_{ib} \sim X \pm 3\sigma
\]

where \( \sigma \) is mathematical expectation of the indicator value without sharply distinguished values; \( \sigma \) is the standard deviation; \( X_{ib} \) is a sharply distinguished value of the indicator.

Among the remaining sample values, it is possible to determine the minimum and maximum values, the value of the interval to the number of intervals in the variation series.

\[
h = (X_{max} - X_{min}) / (1 + 3.322\log n),
\]

where \( X_{min} \) and \( X_{max} \) are the minimum and maximum values; \( n \) is number of indicator values in the sample; \( h \) is value of the interval.

We should round up the value of the interval to a whole number or a simple fraction.

The beginning of the first interval

\[
a_1 = X_{min} - \frac{h}{2},
\]

for the variation series of the concentration of wear products and general contamination, the left border is equal to zero \((a_1 = 0)\).

The total number of row intervals is determined from the following condition.
\[
\frac{X_{\max}}{n} \geq \frac{h}{N},
\]

(15)

Each variation series requires the determination of empirical frequencies by intervals and standard deviation.

\[
p_i = \frac{m_i}{n},
\]

(16)

where \(m_i\) is the number of hits of the indicator values in the interval; \(P_i\) is frequency in the interval.

\[
\sigma = \sqrt{\frac{\sum (X_j - \mu)^2}{n-1}},
\]

(17)

where \(X_j\) is the current value of the indicator; \(\sigma\) is the standard deviation; \(\mu\) - mathematical expectation of the indicator.

Mathematical expectation of the indicator.

\[
\mu = \frac{\sum X_j}{n}.
\]

(18)

The obtained values \(\mu\) and \(\sigma\) allow us to determine the theoretical frequencies and the probability integral for the alignment curve

\[
p_i^I = \exp\left(\frac{(X_j - \mu)^2}{2\sigma^2}\right),
\]

(19)

where \(X_j\) is the value of the midpoint of the interval; \(p_i^I\) - theoretical frequency in the \(i\) interval.

We calculate for two laws of distribution: normal and logarithmic normal.

Verification of the empirical distribution to the normal and logarithmic normal law is done on the basis of Pearson's consent.

\[
\chi^2 = \sum_{j=1}^{N} \frac{(p_j - p_j^I)^2}{p_j^I},
\]

(20)

The results of determination of threshold values of D-240 serviceable engine indicators.

The sample included values of oil samples taken from engines of tractors operated in farms of Omsk region.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|}
\hline
\textbf{Indicator} & \textbf{Oil brand} & \textbf{Value of indicator by period} \\
\hline
Kinematic viscosity at 100°C & M-10-B_2 & 10.7, 10.5, 10.3, 10.5, 10.3, 9.7, 12.6, 12.8, 10.7, 11.5, 12.6, 12.6, 12.6, 10.2, 12.4, 8.4, 12.6, 12.0 \\
Flashpoint & M-10-B_2 & 202, 213, 205, 190, 204, 215, 195, 200, 200, 200, 200, 200, 200, 175, 166, 170, 205, 210, 204, 212, 205, 198, 197, 198, 170, 205, 195, 190 \\
\hline
\end{tabular}
\end{table}

Figure 3 shows the distribution density curves and the probability integral of oil viscosity. Figure 4 shows the distribution density and integral probability curves of the oil flashpoint temperature.
Figure 3. Distribution density and probability integral of kinematic viscosity at 100°C of oil M - 10 - B₂

Figure 4. Density of distribution and probability integral of oil flashpoint

7. Conclusion
As a result of the research we can draw the following conclusions:

1. When determining the threshold values of the operating oil parameters it is necessary to consider the analysis results of the samples with stabilized values.

2. To ensure fault-free operation of the machines, it is necessary to determine the maintenance level of the machines sufficient to prevent sudden failures and perform the necessary maintenance and repair work on the machines based on the diagnosis of engine oil parameters.

3. The distribution and probability integral of oil viscosity is better smoothed out by the normal Gauss law. The mathematical expectation of viscosity is $11.23 \pm 0.48 \text{ mm}^2/\text{s}$. The maximum permissible viscosity of M-10-B₂ oil, corresponding to the 95% boundary of the probability integral, is $13.32 \text{ mm}^2/\text{s}$. The minimum permissible viscosity corresponding to the 5% boundary of the probability integral is $9.12 \text{ mm}^2/\text{s}$. 
4. The distribution and probability integral of oil flashpoint is better smoothed out by the normal Gauss law. The mathematical expectation of the flashpoint is $197.6 \pm 4.2^\circ S$. The minimum allowable flashpoint for serviceable engines corresponding to the 5% probability integral limit is $177.5^\circ C$.

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