How the Key Indicators of Motor Oil Quality Affect the Reliability of Engine Assemblies in Tractors

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Abstract. Diagnostics in place is used for on-the-go monitoring of internal combustion engine condition in tractors. When an engine is running, motor oil is continuously interacting with the engine processes, which is why change in motor oil quality is used as the criterion of such interaction. This research used two diagnostic methods: oil spectrometry to detect the content of wear products in used oil as well as the content of silicon, sodium, and metals from oil additives; and spot check to determine the total contamination of oil, its water content, and dispersancy. Studies found out the characteristic indicators of change in the engine’s technical condition. The authors were able to obtain dependencies that can be used to find out the diameter of additive diffusion spots, the radii of contamination / additive / pure oil zones. The paper establishes how oil quality correlates with the technical condition of the engine. A combined analysis of two oil and ICE assembly diagnosis methods produced the reference values for oil spot checks.

1. Introduction

To date, there are several methods for engine diagnostics in place. One such method uses spectrometric analysis of used oil to detect engines approaching failure, to find which engine assembly is worn out, and to determine what adjustments need to be made or how to repair the engine in the least costly and time-consuming manner [1].

As the engine wears out, motor oil accumulates wear products specific to a friction pair. Repair becomes necessary when the concentration of such products exceeds a certain threshold.

When running in an engine, motor oil is altered. Accumulation of contaminants leads to oil aging. Besides, exposure to high temperatures results in intensive oxidation, polymerization, and carbonization. Oil accumulates the products of these processes, which alters its quality. Besides, such products are deposited on engine parts, increasing the wear of friction pairs.

Thus, motor oil is continuously interacting with the engine processes, which is why change in motor oil quality is used as the criterion of such interaction.

The goal hereof was to find how change in the motor oil parameters correlated with tractor engine indicators of near-failure wear and tear; and to find the impurity concentration thresholds, exceeding which calls for discarding the oil (‘the critical concentrations’).
2. Materials and methods
Test results were processed by mathematical statistics. Standard oil spectrometry and spot check of dispersancy were used to detect and confirm the convergence of critical impurity concentrations as found by spectral and chemical oil analysis. Theoretical analysis was based on a physical model: cross-section of an oil drop on filter paper as produced by the spot check method.

3. Discussion
The following key diagnostic indicators were used:
- content of wear products in used oil;
- content of silicon, sodium, and metals from additives;
- kinematic viscosity of oil;
- total oil contamination;
- water content;
- oil dispersancy.

The wear and tear of friction pairs contributes to 70...80% of engine failure [2]. Piston rings, cylinder liners, crankshaft pins, camshaft cams, push rods, and other parts are exposed to the greatest wear and tear. In normal operation, most run-in parts wear linearly. When oil has been in prolonged use, and the cleaning rate is stable, the rate at which an engine is being worn out can be monitored by the concentration of wear products in oil. In case a friction pair is rendered defective by its progressive wear and tear, the concentration of the metal this pair is made of rises dramatically in oil.

Used oil spectrometry helps quantify the presence of chemical elements from impurities or additives. Thus, the presence and concentration of wear products in oil is a diagnostic parameter that can quantify and quality the wear of specific engine parts or assemblies to determine the required preventive action or part replacement so as to prevent engine failure, ultimately resulting in faster and cheaper engine maintenance or repair [3].

Based on the chemical composition of engine parts, one can list the characteristic elements indicative of the engine’s condition, see Table 1.

**Table 1.** Characteristic indicative elements of D-240 engines.

| Indicative element | Engine condition change                                |
|--------------------|-------------------------------------------------------|
| Iron, Fe           | Cylinder-piston assembly, camshaft, crankshaft, or gear wear |
| Aluminum, Al       | Piston, bearing wear; air filter failure               |
| Tin, Sn; Antimony, Sb | Bearing wear and chipping                            |
| Copper, Cu; Lead, Pb | Connecting rod, camshaft, oil pump enclosure/lid wear |
| Chrome, Cr         | Piston ring and valve wear                            |
| Silicon, Si        | Air filter failure                                    |
| Nickel, Ni         | Piston pin wear                                       |
| Sodium, Na         | Antifreeze leak                                       |

Analysis of the chemicals comprising the engine and summarized in a table like the one below further produces a diagnostic matrix specific to the engine-oil combination. Excess of an element-specific threshold (a critical concentration) points to an out-of-tolerance wear and tear of a specific engine part or assembly.

Some authors [4,5,6] and international companies provide recommended concentrations of indicative elements in used oil, see Table 2; nevertheless, critical concentrations need to be adjusted because engine parts may vary in chemical elements they are made of, engines operate in a variety of climates and other conditions, etc. For this research, the authors used guidelines from Komatsu and T.S. Motozova, which were adjusted for the conditions of Omsk Oblast.
Table 2. Critical concentrations per guidelines.

| Element | T.S. Motozova | Komatsu |
|---------|---------------|---------|
| Normal concentration of the element, g/t | alerting concentration, g/t | near-failure concentration, g/t | normal concentration, g/t | alerting concentration, g/t | near-failure concentration, g/t |
| Cr | Up to: 5 | 5-10 | > 10 | 5 | 5-25 | 25 |
| Fe | 100 | 100-200 | 200 | 45 | 49-95 | 95 |
| Pb | 10 | 10-30 | 30 | 25 | 25-80 | 80 |
| Si | 40 | 40-80 | 80 | 20 | 20-40 | 40 |
| Sn | 5 | 5-15 | 15 | - | - | - |
| Cu | 40 | 40-80 | 80 | 15 | 15-45 | 45 |
| Al | 30 | 30-70 | 70 | 8 | 8-16 | 16 |

Research has shown that spectrometry is not enough to address all the issues of engine diagnostics. Therefore, finding out the optimal oil lifespan necessitates comprehensive sample testing, e.g. spectrometry should be complemented with physical and chemical tests of used oil.

As oil is running in the engine, it accumulates the products of oil oxidation and thermooxidative destruction; it also contains traces of soot and other products of incomplete oil combustion [7].

When an engine is operating under inappropriate conditions, e.g. at lower temperatures, particles are deposited on engine parts as sludge or carbon deposits. Piston rings are carbonized, drainage hopes of oil channels are clogged, and the filters are contaminated. As a result, oil supply to friction pairs is diminished, more gas reaches the engine carter, and other accident-inducing processes occur [8].

It has been found out that crankshaft bearing insert slippage occurs due to sludge clogging the mesh of the oil receiver, oil channels, and filtering elements, which in turn drastically reduces the supply of oil to bearings.

Thus, the quantity and quality of impurities in oil is a parameter that indicates the technical condition of the engine and the functionality of its systems. The suitability of oil itself in terms of mechanical impurity presence can be determined by the express diagnosis of total oil contamination.

This express method consists in finding the percentage of mechanical impurities in oil by the so-called spot check that uses filter paper. The researchers prepared reference oil samples containing a preliminarily known amount of a contaminant; centrifuging returned percentage values of mechanical impurities in the references. This produced a scale of spot references, see Figure 5.

Engine performance is affected not only by the total quantity of particles accumulated in oil but also by their size, particle size distribution, and the ability of deposit on engine parts, depending on the dispersancy of oil. Oil dispersancy is controlled by adding special additives to oil. As insoluble impurities accumulate in oil, some part of the additives is spent to neutralize the acidic products, to disperse the contamination / oil oxidation particles with additive metals, and to convert them into a colloidal solution. Thus, more intensive oil oxidation and faster accumulation of impurities result in faster consumption and ‘triggering’ of the additives [9].

Oil dispersancy is tested by finding the concentration of additive elements by spectrometry coupled with spot check of the mechanical impurity content.

Figure 1 shows a physical spot-check model that was used to mathematically describe the production of a chromatogram. The model is the cross-section of an oil drop spreading over the filter; it has two zones:

1. surface layer 1, 10-9 m thick, which is the boundary of the oil sample. Oil and impurity particles in the surface layer interact with oil and air molecules.
(2) inner volume of the oil spot, which contains the oil itself and the components of additives and mechanical impurities, as well as the elements of oil destruction.

The deposition of impurities in the surface layer and inside the spot were analyzed separately due to different force interaction.

Figure 1. Physical model of oil spot spreading over the filter surface: (1) surface layer; (2) oil drop; (3) impurity particles; (4) filter; (5) filter pores.

The formation of the additive zone can be analyzed as the process of additive particles diffusing from an instantaneous point source, the concentration of the additive in which equals the mass fraction of the additive $\rho$ multiplied by the drop volume $Q$. The diffusion process is determined by the effective diffusion coefficient; given that the spot is spreading in the plane $x$-$y$, find the impurity concentration by the formula:

$$u(x, y, z, t) = \rho Q \left(\frac{1}{2\sqrt{\pi Dt}}\right)^3 e^{-\frac{x^2+y^2+z^2}{4Dt}}.$$  

When making the equation (1), it was assumed that the coordinate onset was in the center of the drop. The boundary of the visible additive distribution area depends on the additive diffusion coefficient in the drop, the spreading time, the additive concentration, and the sensitivity of the eye.

A luminous flux incident upon the oil spot (chromatogram) surface is partly absorbed by the filter paper in the additive material and partly reflected. Assuming that the additive layer and the filter paper do not let the light pass through, write the reflected flux as the equation:

$$I = I_0 - \Delta I_{\text{loss}},$$

where $\Delta I_{\text{loss}}$ is the loss of the luminous flux in the material and in the additive in the filter paper; $I_0$ is the incident luminous flux.

Luminous flux loss can be found by the formula:

$$\Delta I_{\text{loss}} = I_0 e^{-\alpha l},$$

where $\alpha = \alpha_0 u$ is the absorption coefficient proportional to the additive concentration; $\alpha_0$ is a constant coefficient; $l$ is the layer thickness.

Given the formulas (2) and (3), the reflected light can be written as follows:

$$I = I_0 \left(1 - e^{-\alpha l}\right).$$

After substituting the value $\alpha = \alpha_0 u$ and running the transform, the equation is written as:

$$e^{-\alpha_0 ul} = \frac{I_0 - I}{I_0}.$$  

For two layers of the oil drop that have thickness values $l_1$ and $l_2$ while differing in the concentrations of impurities, write the equality:
\[ e^{-\alpha_0 t_1} e^{-\alpha_0 t_2} = e^{-\alpha_0 (t_1 + t_2)} = \frac{I_0 - I}{I_0}. \]  

(6)

Transform the equation (6) into:

\[ e^{-\alpha_0 \int udl} = \frac{I_0 - I}{I_0}. \]  

(7)

Let \( \delta \) be the sensitivity of the observation tool; then rewrite the expression as follows:

\[ \frac{I_0 - I}{I_0} < \delta \]

an oil spot resulting from the additive diffusion will be invisible if:

\[ \frac{I_0 - I}{I_0} > 1 - \delta \]

The visibility and invisibility of the oil spot can be calculated by the formula (5) and will depend on the value of the integral \( \int udl \).

The integral is solved as follows:

\[ \int udl = \rho Q \left( \frac{1}{2\sqrt{\pi}Dt} \right)^2 e^{-\frac{R^2}{4Dt}}. \]  

(8)

The integration is based on an assumption that the observer is in infinity, and the z-axis follows the line of sight.

If the additive concentration is zero, the additive diffusion zone will have a maximum boundary. Given that \( x^2 + y^2 = R \), the equation (8) can be written as:

\[ \rho Q \left( \frac{1}{2\sqrt{\pi}Dt} \right)^2 e^{-\frac{R^2}{4Dt}} = c, \]  

(9)

where \( c \) is the integration constant.

After converting the equation (9) assuming that the diffusion coefficient is constant, the equation for the additive diffusion zone diameter is written as follows:

\[ D_\phi = 4 \sqrt{-Dt \ln \frac{4\delta \pi Dt \delta}{\rho Q}}. \]  

(10)

where \( D \) is the diffusion coefficient;

\( t \) is the observation time;

\( \delta \) is the sensitivity of the instrument used for detecting the additive diffusion zone radius.

Experimental studies show that the difference between the diffusion zone radii found by the equation (10) and experimentally is about 30%, as the equation does not take into account the oil viscosity \( \nu \), the additive concentration in oil as described by the pH value, the filter paper density \( \varphi \), and the transfer of impurities in the spreading oil drop.

How these parameters affect the diffusion coefficient was found experimentally in this study.

Oil drop layers adjacent to the paper spread over its surface when affected by the force induced by the difference in gravity and pressure. Such spread is hindered by capillary forces induced in the paper pores.

Considering the forces acting on the spreading drop in Figure 2, the capillary forces fill the pores with oil, which causes the subsequent layers to spread over the filled pore without being hindered by the capillary forces.
If the drop volume equals $V = \frac{4}{3}\pi r^3$, it should fill the pores on the paper surface

$$\pi R^2 \times h \times \phi,$$

where $\phi$ is the material porosity, i.e. $\phi = \frac{V_{\Pi}}{V_{\Pi}}$

Figure 3 shows the physical model of filter pore filling.

This volume should equal that of the drop

$$\pi R^2 h \phi = \frac{4}{3}\pi r^3$$

Thus, the oil drop spread radius can be found by the formula:

$$R = \sqrt[3]{\frac{4}{3} \frac{r^3}{h \phi}}$$  \hspace{1cm} (11)

The equation (11) shows that the diameter of the filter-paper spot resulting from the spread of the drop depends on the initial drop size as well as on the porosity and thickness of the paper.

The research team obtained dependencies for finding the radii of the contamination, additive, and pure oil zones, as well as the dependency (11) which determines the maximum spot radius.

Research data was used to collect reports on engine failures so as to adjust the acceptable limits of the diagnostic parameters, optimize maintenance schedules and therefore to reduce the costs of such
maintenance and ongoing repairs while improving engine reliability, extending mean time to repair and the total lifespan [10, 11, 12].

Failure reporting depends on engine diagnostics [13]. Its data is used to adjust the acceptable limits of the diagnostic parameters which have been set by testing.

This study established the correlation between oil quality and engine condition, see Table 3.

**Table 3.** Oil quality and engine condition correlation.

| Increased Si content | Increased Fe, Al, Cu content | Low alkalinity |
|----------------------|-----------------------------|----------------|
| Near-failure wear of parts | Air cleaner failure | High total oil contamination |
| Fuel injection system failure | Fuel system failure | |
| Low-quality oil | High-sulfur fuel | |
| System leakage | Increased coolant and sodium content | Low flash temperature content |
| Low dispersancy | | |

Theoretical and experimental studies of tractor oil samples produced reference spots of M-10DM and M-10G₂₉ motor oils, see Figure 5. These can be used for express testing of the dispersancy of used oil as well as for on-the-go monitoring of key physical and chemical indicators of oil in use.

1. Fresh oil Dispersancy not determined

2. Shortly used oil Dispersancy DS=0.8-0.9

3. Used oil in good condition Dispersancy DS=0.7-0.8

4. Depleted oil Dispersancy DS=0.6
4. Conclusions
Testing the effect of key motor oil quality indicators on the engine parts reliability produced the following findings:

1. A list of the characteristic elements indicative of the condition of a D-240 engine.
2. The authors found the dependency (10) that can determine the diameter of the additive diffusion zone assuming the diffusion coefficient is constant.
3. Experimental studies showed that the difference between the diffusion zone radii found by the equation (10) and experimentally was about 30%, as the equation did not take into account the oil viscosity $\nu$, the additive concentration in oil as described by the pH value, the filter paper density $\phi$, and the transfer of impurities in the spreading oil drop.
4. The research team obtained dependencies for finding the radii of the contamination, additive, and pure oil zones, as well as the dependency (11) which determines the maximum spot radius.
5. The study established the correlation between oil quality and engine condition, see Figure 4.
6. The researchers were able to make spot-check reference samples of M-10DM, M-10G; k motor oil.

5. References
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