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Assessment of the kinetics of changes in selected physicochemical indicators of engine oil in operation

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The article presents the results of operational tests of engine oil, including the observation of changes in the values of selected physicochemical parameters of oil in subsequent operation cycles, in accordance with the service life specified by the vehicle manufacturer. Preliminary analysis of defined indicators characterizing the condition of engine oil were performed in terms of their suitability for the ongoing monitoring of the technical condition of the engine. On the basis of the values of selected indicators of fresh oil recorded in the course of operational tests and during replacement, one indicator was selected, the kinematic viscosity at 100°C, for which an unambiguous trend of changes was observed during the tests. The last stage was to verify the hypothesis about the correlation between the observed changes in the value of the indicator and the mileage of the engine–vehicle.

Key words: *internal combustion engine, cylinder liner, engine oil, kinematic viscosity*

1. Introduction

Lubricating oils used in tribological systems of combustion engines are a mixture of organic compounds and enriching additives, while the physical structure of the oil is not sufficiently explained. Hence, an unambiguous description of their condition and the current assessment of their properties as a lubricant are difficult. Therefore, the characteristics of the oil are not a set of precise quantitative and qualitative data of the chemical composition, chemical structure, or the values of characteristic physical quantities. The characteristics of oil as a lubricant, an element of the tribological system, are expressed using indicators that indicate the possibility of its application in specific kinematic nodes [16].

The description of the lubricant condition cannot be made in isolation from the tribological system. Hence, this concept is understood not only as a description of a state in the physical sense, defined as a set of values of quantities characterizing the macroscopic properties of a system, but also a set of values related to basic functions fulfilled in the system. The condition description must therefore reflect the individual and functional (collective) properties of the lubricant. In practice, these properties are most often assessed by measuring specific parameters – indicators included in the relevant standards for lubricants.

Research is carried out on the behavior of engine oil in operation, however, it concerns only the analysis of the oil itself without taking into account the technical condition of the tribological system in which it worked [1, 3, 5, 8, 9, 14, 15].

Engine oil is a component of the tribological system, the operating conditions of which change over time. It is subjected to variable mechanical and thermal loads resulting from the tasks performed, but it is also subject to variable and usually unfavorable loads due to the wear of the components of the piston-rings-cylinder (PRC) system with time. Among all the elements of the tribological system, engine oil is subject to the most intense physical and chemical changes during operation. This is due to the effect of the system on the oil. The size of the excitations acting on engine oil is related to, inter alia, with the technical condition of the PRC system, expressed by the amount of clearances in this combination [6, 7]. The increase in the amount of blow-by of exhaust gases into the engine crankcase caused by the increasing clearance, as well as the increase in the amount of oil entering the combustion chamber and the amount of unburned fuel entering the oil sump cause the indicators describing the condition of the engine oil to change over time. The kinetics of this process is the result of the occurring tribological phenomena and wear of the PRC system. The analysis of the process of changes taking place in the engine oil in operation and an attempt to describe them mathematically requires to take into account not only the typical forces acting on the oil, but also the changing operating conditions of the system, resulting from the natural wear process of the elements of the PRC tribological system.

The results of the research compliant with the indicated postulate are presented below. Changes in the engine oil were observed and recorded in relation to selected physicochemical indicators at intervals related to its periodic replacement and the progressive wear of the PRC system components. Based on the research results, a mathematical model of the kinetics of changes in selected physicochemical indicators of oil in operation was proposed, correlated with the vehicle mileage.

2. Models of kinetics of changes in oil properties

The aging processes are cumulative and have specific features. During the operation of the oil, partial renewal procedures are performed, regeneration of properties resulting from the need to refill the oil to the volume recommended for a given lubrication system and to use oil filtration in the engine itself [12].

Refreshing by topping up is a discrete process, while regeneration by filtering is a continuous but also random process. In the latter, the randomness is the random trapping of particles that make up the oil contaminants. On the other hand, the purification device itself (filter) operates continuously with varying efficiencies.

When analyzing the kinetics of changes in oil properties, the following issues should generally be considered:

1. All the physical and chemical processes that take place during its use (aging).
2. The process of regeneration (refreshing) by adding fresh oil.

Physico-chemical processes take place under all conditions of oil use, but their intensity depends both on the type and type of oil, as well as on the physical parameters determined by the conditions of using the oil in a given system (temperature, pressure, volume). On the other hand, the refreshing process is a natural consequence of the loss of oil as a result of its combustion, as well as possible leaks from the system.

Taking into account that in reality not only oil quality changes over time due to the refreshing process, but also physical and chemical processes occurring in the oil volume, it seems that the most appropriate image of the kinetics of changes may be exponential curves. Such a situation is presented in Fig. 1. However, it is also a certain approximation of an averaging nature, but having the advantage of reflecting relatively well the general tendency of changes, which is an expression of the influence of both considered.

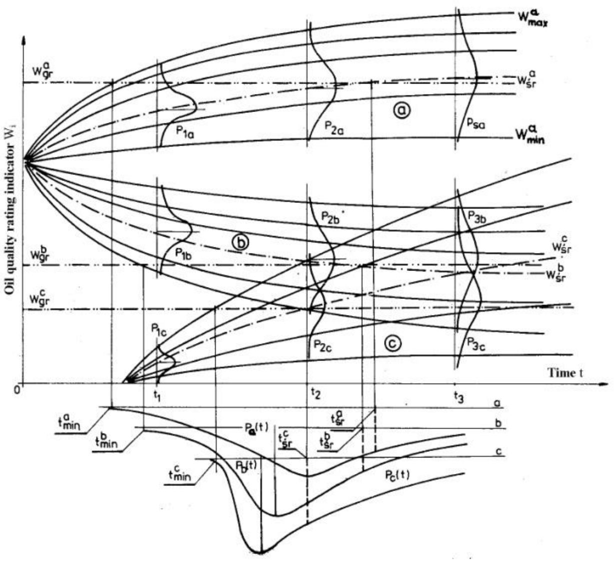

Fig. 1. Kinetics of changes in oil quality assessment indicators [11]

Thus, for research and comparative purposes, it is necessary to propose a mathematical model describing the changes taking place in the used engine oil. This model, with high probability, should take into account the kinetics of changes in relation to selected physicochemical parameters of oil essential for the proper functioning of the tribological system. Such research has been conducted for a long time.

For example, in the work [13] it was assumed that the absolute difference in the values of fresh oil and oil properties after a specified operation time allows the assessment of changes in the properties of the aged oil in comparison with the properties of fresh oil. The course of these changes has a specific character of an exponential sequence with the limit (1) and (2):

$$\lim_{n\to\infty}|P_0 - P_i|_{\,P} = \alpha \cdot \Delta t \tag{1}$$

and

$$\lim_{n\to\infty}\sum_1^n k^n = \alpha \cdot \Delta t \cdot \frac{k}{1-k} \tag{2}$$

where: α – the slope of the straight line, Δt – continuous operation time between successive additions of mechanical, n – the number of cycles of the fluid and the number of further additions, k – the unit volume of fresh oil to the lubrication while each additions, P – analyzing the property of the lubricating oil , which for fresh oil takes the value of P_0 and during aging, without taking into account refreshing, changes rectilinearly as a function of working time to the final value of P_i in the next working cycle.

The presented model allowed the authors to state that the analyzed lubricating oil aging process does not have a limit state as a function of time.

The problem remains open and research on the kinetics of changes in selected properties of engine oil in operation is still carried out. The results of tests of engine oils in service presented in [17] allowed for the development of a statistical model using the basic mathematical model – a linear function. The obtained model based on changes in the kinematic viscosity at 100ºC of engine oils under operating conditions can be used to predict the behavior of engine oil during operation. It should be noted, however, that in order to obtain a complete picture of changes taking place in the oil, it is advisable to interpret the kinematic viscosity in addition to the dynamic viscosity (HTHS), the degree of oxidation and the acid number. These properties can affect the reliability of the entire engine, and it is therefore important to continue observing the degradation state of the engine oil. Moreover, the research, as the authors point out, mainly covered vehicles operated in conditions that can be described as "difficult", i.e. frequent engine start, short distances, prolonged idling. Hence, the proposed model of the kinetics of changes in kinematic viscosity at 100ºC of engine oils does not necessarily reflect the changes taking place in the engine operated under statistically average load conditions.

According to the author, the mathematical models proposed so far do not fully reflect the actual changes taking place in the engine oil. Due to the limitations occurring during the operational tests or the adopted boundary conditions, the proposed model does not fully reflect the actual changes taking place in the engine oil between its changes, especially with the increase of the engine mileage. Therefore, it is important to observe and analyze the changes taking place in the oil in subsequent cycles of its replacement, taking into account the actual mileage of the engine and the mutual correlation of these parameters.

3. Research method

Among the physicochemical and functional indicators characterizing the condition of the lubricating oil, in operational tests the most frequently used (apart from the contamination content) is kinematic viscosity. The conditions of cooperation of the elements: piston, piston rings, cylinder liner are primarily determined by the viscosity of the lubricant between them. It determines the nature of friction, both in a cold and warm engine [10]. It is also important during engine start-up [2]. Moreover, the viscosity of engine oil changes significantly during its service life. It is related to, inter alia, with the leakage of unburned fuel to the engine oil pan, which in turn is largely conditioned by the tightness (wear) of the PRC connection. The increase in clearance between the piston and the cylinder liner, observed along with the mileage of the vehicle–engine, favors the penetration of more and more fuel and faster dilution of the engine oil. The simultaneous processes causing the increase in oil viscosity do not neutralize the above tendency, and moreover, their intensity is not closely correlated with the progressive wear of the PRC system. Their occurrence is mainly related to the aging processes of the oil taking place in the high-temperature zone of the engine, i.e. the lubricating layer on the cylinder liner surface. Thus, the process of diluting engine oil during operation is observed [4], and it intensifies with the mileage of the vehicle. The kinetics of changes in oil viscosity is thus reflected in the decreasing function with absolute increases with the vehicle mileage.

However, the changes taking place in the exploited oil include not only its degradation, as a result of the system's impact, but also the refreshing phenomenon through "refills". The image of the physicochemical state of the used oil just after topping up is strongly distorted. A portion of fresh oil improves the properties of the lubricant, bringing them closer to the initial values. Hence, the moment of the analysis is an important issue.

The actual condition of the used oil is observed at the time of its replacement. Observations of users' behavior indicate that they do not make any top-ups of oil before its soon planned oil change. Thus, the condition of engine oil at the time of its replacement well reflects the resultant of the forces acting on the engine oil in the next, full cycle of its operation.

The model of the kinetics of changes in the properties of engine oil in operation, proposed by the author, also takes into account the correlation between the phenomenon of cylinder liner wear, which is a continuous process observed for the same kinematic pair, and the oil degradation process taking place for subsequent, new portions of oil after each oil change. Moreover, the actual oil service life may be different for subsequent changes, although statistically, with high service culture, its expected value will be close to the recommended by manufacturer.

The above requirements take into account the proposed index of the intensity of changes in C_W oil properties. It is characterized by the relationship (3):

$$C_W = \frac{W_p - W_k}{t_{ol}} \quad \text{for } t > 0 \tag{3}$$

where: W_p – value of the measured index of oil condition assessment for fresh oil, W_k – value of the measured oil condition assessment index for used oil (at the time of replacement), t_{ol} – engine oil operation time to be changed, C_w – index of intensity of changes in oil properties.

This indicator provides average information about the intensity of the engine's impact on the oil. It does not take into account periodic changes in the measured value of the oil parameter, but reflects the long-term tendency of the observed changes.

The operational tests have shown that the best indicator of the intensity of changes in kinematic viscosity at 100°C – C_{V100} for the purposes of the presented method.

The last stage is to verify the hypothesis on the correlation between the observed changes in the kinematic viscosity of the used engine oil, expressed with the C_{V100} kinematic viscosity change intensity index, and the engine–vehicle mileage.

4. Operational research

4.1. Research object and methodology

The object of the operational tests were five 110 kW diesel engines installed in medium-duty trucks. The tests were carried out under supervised operational test conditions. The tests were carried out after factory-new engines were installed in the vehicles, and their initial technical condition was known (cylinder liners micrometers were carried out to the extent possible after the cylinder head had been disassembled, the compression pressure, crankcase exhaust gas blow – by and exhaust smoke were measured). The vehicles were part of the fleet. The average load of the load box was 5000 kg and never exceeded the permissible load capacity of the vehicle. The daily mileage of the cars was from 240 to 350 km. The cars were operated in urban and non-urban driving conditions. The engine lubrication system uses engine oil of API CE/SF quality class and SAE 15W/40 viscosity class. This oil was used throughout the research period and came from one production batch. All technical maintenance of engines was performed in accordance with the manufacturer's recommendations.

The method of evaluation of the physicochemical and functional parameters of the oil was used to assess changes in oil properties. The chemical analysis of fresh oil as well as used oil samples, collected at the time of replacement, and used oil were carried out in one laboratory with the use of a commissioned system. This allowed to maintain the repeatability of the measurement methods used, and thus increase the reliability of the obtained test results. Selected physicochemical properties of fresh oil are presented in Table 1.

Table 1. Physical and chemical properties of 15W40 oil

The parameter under study		Unit	Value
Kinematic viscosity at 40°C		mm^2/s	99.52
Kinematic viscosity at 100°C		mm^2/s	14.21
Base number		mg KOH/g	10.84
Carbon residue according to Conradson		%	1.38
Sulphated ash		%	1.10
Flash point in a closed cup		°C	190
The content of elements derived from improvers	calcium – Ca	%	0.33
	zinc – Zn	%	0.13
	phosphorus – P	%	0.12

The actual mileage between exchanges did not differ by more than 10%. During the exchange, a sample of used oil was taken (about 1 dm^3). Additionally, the content of elements derived from the engine's structural elements was determined for the used oil (iron – Fe, copper – Cu, lead – Pb).

4.2. Results and analysis

The analysis of changes in the condition of oil in operation was carried out as an assessment of the kinetics of changes in the selected oil index. The basis was information on:

- the value of the selected condition assessment indicator for fresh oil,
- values of the selected condition assessment indicator for used oil (at the time of replacement),
- oil service time (car mileage between oil changes).

This information is related to the indicator of the intensity of changes in C_W oil properties (3). The following oil condition indicators were assessed in terms of changes occurring during operation.

Among the physicochemical indicators:

- kinematic viscosity at temperature 40°C – ν_{40},
- kinematic viscosity at temperature 100°C – ν_{100},
- base number – LZ,
- carbon residue according to Conradson,
- sulphated ash,
- flash point in a closed cup,
- the content of elements derived from improvers: Ca, Zn, P. of the functional indicators:
- the content of metallic elements originating from the engine's structural elements: Cu, Fe, Pb.

The analysis of changes in engine oil was carried out for the mileage above 10,000 km. This allowed to eliminate errors related to the running-in process of kinematic pairs in the engine. Only the period of stabilized wear was included in the analysis (Lorentz curve).

The calculated values of the intensity index of oil properties changes C_{Wi} (i = 1, 2, ..., n, where n – the number of the next oil change) for each of the above-mentioned oil condition indicators were related to the vehicle mileage corresponding to the time of measurement (vehicle mileage in when the oil is changed). Using the STATISTICA® program, the correlations between the C_{wi} index for each of the observed oil condition indexes and the vehicle mileage were determined. Initially, the data was fitted with a linear regression model estimated using the maximum likelihood method under the socalled generalized least squares method. The application of the above-mentioned method made it possible to include in the estimation process a theoretically justified assumption about the correlation of successive measurements of oil parameters. This assumption was introduced by assuming that the random term in the regression model is subject to a continuous first-order autoregressive process. However, in the course of further analyzes and as a result of the sensitivity analysis, it was shown that the use of the above-described advanced statistical apparatus changed the results of the analysis to a minimal degree in relation to the classical model of normal linear regression. As a result, in order to simplify the presentation of results and facilitate interpretation, the linear regression models were estimated using the classical method of least squares. The second type of regression lines were used to initially estimate the dependencies sought. The results of the calculations are summarized in Table 2 (the determined correlations are significant at the confidence level of $1-\alpha = 0.95$ assumed as the border value of the acceptable error level [18]).

Table 2. List of linear correlation coefficients for the assessment of oil condition changes in relation to the vehicle mileage

Oil condition change assessment indicators C_{wi}	The value of Pearson's linear correlation coefficient r	Coefficient of determination R^2	Test probability value p
Kinematic viscosity at 40°C	–0.71	0.532	0.00044
Kinematic viscosity at 100°C	–0.81	0.628	0.00006
Base number	correlation irrelevant		
Carbon residue according to Conradson	0.46	0.28	0.00541
Sulphated ash	correlation irrelevant		
Flash point in a closed cup	correlation irrelevant		

Exemplary waveforms are shown in Figs 2–4.

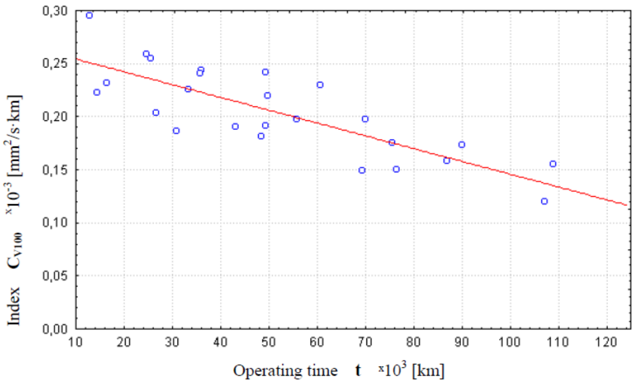

Fig. 2. The course of the kinematic viscosity change intensity index at 100°C C_{V100} as a function of operating time

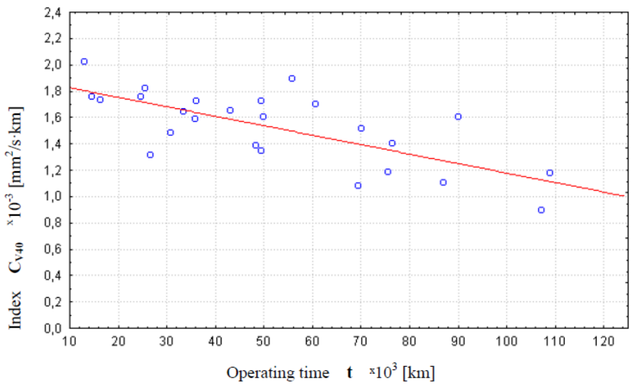

Fig. 3. The course of the kinematic viscosity change intensity index at 40°C C_{V40} as a function of operating time

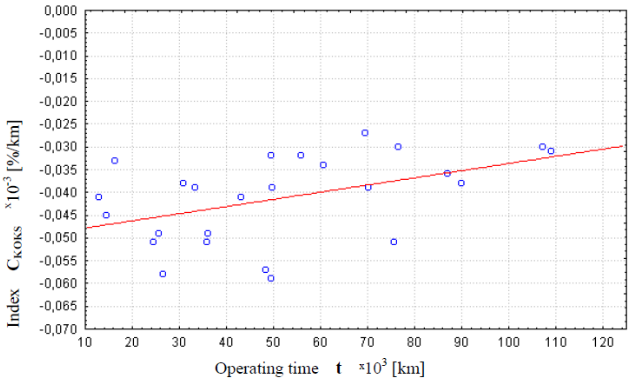

Fig. 4. Course of the change intensity index of coking residues according to Conradson C_{KOKS} as a function of operating time

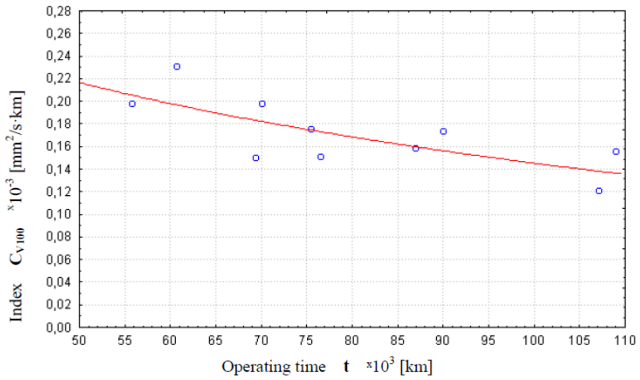

Fig. 5. Power regression model of the C_{V100} index in relation to the vehicle mileage

Thus, among the oil condition indicators observed in operation, the highest value of the linear correlation coefficient with respect to the vehicle mileage was obtained for the kinematic viscosity change intensity index at 100°C C_{V100}. This result confirms the correctness of the theoretical analysis carried out. By limiting ourselves to this parameter of engine oil, the C_{V100} index curves were determined in relation to the operating time. The highest value of the curvilinear correlation coefficient, at the level of R = 0.741, was obtained for the regression line described by the power function (the panel of the STATISTICA program was used). Thus, the course of changes of the C_{V100} index in relation to the operating time can be described by the relationship (4):

$$C_{V100} = (3.277) - (2.142) \cdot t^{(0.033)} \left[\frac{mm^2}{s \cdot km}\right] \quad (4)$$

where: t – engine operation time (mileage) [km].

The course of the determined dependence is shown in Fig. 5.

This dependence, apart from the highest value of the correlation coefficient, well reflects the physical interpretation of the observed phenomenon. Changes in the properties of engine oil tend to a certain limit but do not reach it, which perfectly correlates with the course of the power function. The results of the analysis, verified in operational tests, confirm the relationship between the changes taking place in the used engine oil in terms of kinematic viscosity at 100°C, and the mileage of the vehicle–engine.

5. Conclusions

Based on the analysis of the factors influencing the phenomenon of engine oil degradation in operation, it can be concluded that:

1. The changes in selected physicochemical properties recorded in the engine oil tests confirm the thesis about the correlation between the value of the observed parameter and the vehicle mileage.
2. The conducted operational tests confirm the correctness of the theoretical analysis performed and indicate that the changes taking place in the used engine oil are, among others, as a result of wear of the PRC system components. In this approach, among the physicochemical and functional indicators characterizing the condition of the used lubricating oil, only the kinematic viscosity at 100°C sufficiently reflects the degradation processes occurring in this combination. It has also been shown that there is a close relationship between changes in the kinematic viscosity of the used engine oil, expressed by the intensity index of changes in kinematic viscosity at 100°C C_{V100}, and the mileage of the vehicle–engine.
3. As a result of the tests, no relationship was found between the vehicle mileage and the content of elements derived from engine components in the tested engine oil. It can therefore be concluded that the methods of spectroscopic analysis of the content of metallic elements in engine oil can only be an auxiliary means in assessing the condition of the engine. They can be of key importance in estimating the acceptable wear of lubricated kinematic pairs.

Nomenclature

API	American Petroleum Institute
C_w	index of intensity of changes in oil properties
C_{V100}	kinematic viscosity change intensity index at 100°C
HTHS	High Temperature High Shear rate
p	test probability value
PRC	Piston-Rings-Cylinder
r	the value of Pearson's linear correlation coefficient
R^2	coefficient of determination
R	curvilinear correlation coefficient
SAE	Society of Automotive Engineers
t_{ol}	engine oil operation time to be changed
W_k	value of the measured oil condition assessment index for used oil (at the time of replacement)
W_p	value of the measured index of oil condition assessment for fresh oil

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