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PROCESSES OF CHANGING THE PHYSICO-CHEMICAL PROPERTIES OF AUTOMOBILE MOTOR OILS DURING OPERATION

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Abstract. Mathematical modeling of the operation processes of automotive engine oils allows to optimize the time of their use during operation. A certain significance for changing the qualitative properties of motor oils is introduced by such an operational indicator as „waste" oil consumption. The article describes the causes and parameters of engine oil consumption, as well as the mathematical model of changes in the physico-chemical properties of engine oil during operation. The one that will allow us to optimize the periodicity of replacing the engine oil, as a result this fact will allow us to increase the distance between the interventions of the corrective maintenance works of the means of transport.

Keywords: *internal combustion engine, cylinder-piston group, cylinder head, fuel and lubricants, automotive engine oils, technical operation of the car, engine lubrication system, consumption of engine oil for waste, refilling („refreshing") engine oil.*

Rezumat. Modelarea matematică a proceselor de funcționare a uleiurilor de motor pentru automobile permite optimizarea timpului de utilizare a acestora în procesul exploatării. O anumită semnificație asupra proceselor de modificare a proprietăților calitative ale uleiurilor de motor este introdusă de un astfel de indicator de explaotare, precum consumul de ulei la „ardere". În articol sunt descrise cauzele și parametrii de consum a uleiului de motor, precum și modelul matematic de modificare a proprietăților fizico-chimice ale uleiului de motor în timpul exploatării.

Cuvinte cheie: *motor cu ardere internă, grupul cilindru-piston, chiulasă, combustibil și lubrifianți, uleiuri de motor pentru automobile, exploatarea tehnică a automobilului, instalația de ungere a motorului; consumul uleiului de motor la ardere; umplerea („împrospătarea") cu ulei de motor.*

1. Introduction

Currently, the main source of obtaining motor oils is crude oil, which is a liquid with a complex chemical composition. It contains 84...87% carbon, 12...14% hydrogen, the rest, 1...5% sulfur, 1...3% oxygen, 0...1% nitrogen [1].

The physico-chemical properties of engine oils largely depend on the type of base oil (petroleum or synthetic elements), the technology used in manufacturing, as well as the type and nature of the additives introduced into the base oil. The oils used in the lubrication systems of thermal engines work in extremely difficult conditions and have a complex composition. All engine oils contain two components (Figure 1) [2]. The main component is the base oil, which represents 80...85% of the final product and the additive package, which constitutes up to 15...20% respectively [1, 3].

Mineral base oils are the purified form of crude oil and have been used as a base for obtaining automotive lubricants since the beginning of their production, and synthetic base oils are chemical products obtained in the laboratory with the specific purpose of lubrication. Synthetic oils are obtained from pure compounds that do not contain contaminating agents.

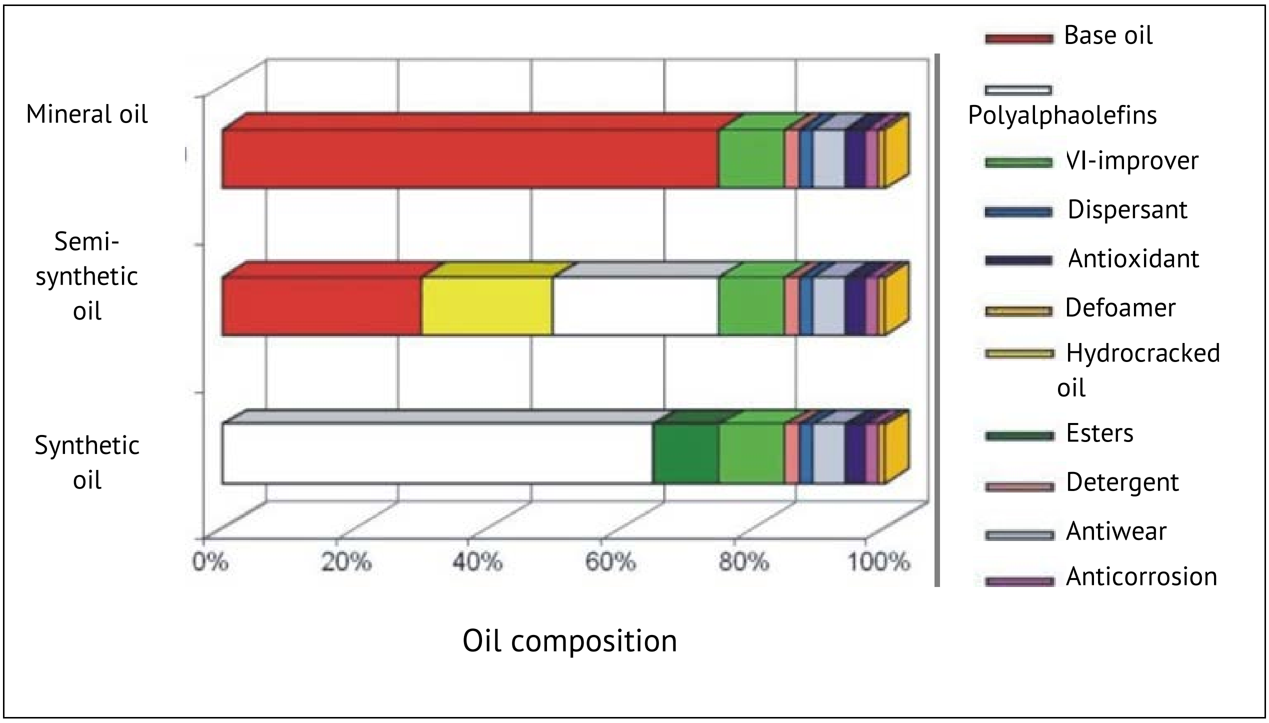

Figure 1. The composition of motor oils [2].

Additives are chemical substances (organic compounds, based on metals or polymers), which, by combining with the base oil, have the role of improving certain characteristics of the oils used in the lubrication systems of thermal engines[4].

Depending on the origin of the base, the oils can be: vegetable, mineral, synthetic and semi-synthetic. Vegetable oils were widely used in technology, starting from the Bronze Age until the 60s of the 20th century. Mineral oils are obtained from crude oil by different methods. Synthetic oils are organic compounds or organic elements, obtained from different types of raw material – crude oil, coal, gas, esters etc. Dozens of types of synthetic oils are known, of which the most widespread are synthetic hydrocarbons (polyalphaolefins, olefin oligomers), dialkylbenzenes (alkylated aromatics, alkylbenzenes), neopentyls (polyol esters), diesters, polyalkylene glycols (polyglycols, polyesters), fluorocarbons, organophosphorus (esters of phosphoric acid), silicones (siloxanes, polysiloxanes, polyorganosiloxanes) [1].

Mineral oils are themselves natural oils mixed with additives. Base oil is a refined oil. Semi-synthetic oils are based on refined oil, but it is an oil that has gone through a hydrogenated refining process. After this process, the oil is obtained, which has the qualities of a synthetic oil.

Synthetic oils represent oils obtained in laboratories from synthesized base oils. Due to the stable and well-calculated molecular structure, it presents a higher quality. It presents an advance over natural oils, because they are designed from the beginning for lubrication, so the manufacturer can focus better on the finished product than on natural oil products.

2. Working conditions and functions of engine oils

Permanent engine oils are subject to quite high thermal and mechanical loads due to the multiple couplings, which have different lubrication conditions. For example, the pressure in the oil film between the surface of the cylinder and the working surface of the segment varies sharply within the limits of 0.15...0.30 MPa, in the area of the compression segment and within the limits of 0.5...1.3 MPa, in the lubrication segment area, and the piston speed varies from 0 to about 15 m/s. In some circumstances the pressure in the oil film can reach the value of 2.0 MPa. The temperature of the lubricant film varies within the limits of 270...280 ^{o}C, in the channel of the upper compression segment, and during supercharging this temperature can reach 300...350 ^{o}C. If the „cylinder-piston segment" coupling is worn, gas leaks are greater and, then, the temperature can reach 450 ^{o}C for SIE (spark ignition engines) and 500...700 ^{o}C for CIE (compression ignition engines). Crank shaft spindles and bearings work under heavy conditions at oil film temperatures of 150...160 ^{o}C and very high specific pressures. The temperature of the oil in the oil bath, under such operating conditions, does not drop below 80...100 ^{o}C [1,5,6].

At the same time, the oil is chemically reacted with the oxygen in contact with the air, it is contaminated by the combustion gases, other gases and the fuel infiltrated into the oil bath, due to the pumping of the segments. In such „uncomfortable" conditions, the oil must perform, over a long period of operation, the following functions [1,3,7]:

- the formation of a stable unctuous film (a film) on the surfaces of the contacted parts, excluding a metal contact at the micro-aspirator level (surface adhesion) and ensuring the reduction of surface wear;
- efficient sealing of the combustion chamber, excluding or reducing to a minimum gas leaks to the oil bath;
- heat removal, released from fuel combustion and friction between parts, cooling of parts surfaces;
- prevention of calamine deposits and lake formations;
- prevention of the corrosion process of the parts;
- prevention of decanting, maintaining deposits from aging and wear in the form of a stable emulsion, evacuation of these deposits from the friction zone;
- neutralization of acids, formed during oil oxidation and fuel combustion.

The lubrication function consists in creating a film of lubricant between the parts in relative motion in order to reduce frictional forces, wear and prevent seizure.

The cooling function consists in evacuating, with the help of the lubricant, a quantity of heat from the friction area of the parts' surfaces.

The function of removing (cleaning) the wear products of the parts, mechanical impurities that may come from the environment.

The chemical protection function is manifested by the property of lubricants to form on the surface of the parts, with which they come into contact, an adherent and persistent film, which also has the role of protecting the metal surfaces from the corrosive action of external and internal factors.

The sealing function that manifests itself on the one hand by protecting the bearings against abrasive particles, and on the other hand by sealing the combustion chamber more firmly due to the oil film between the segments and the cylinder.

The function of engine oil additives [8-10]:

1. To protect metal surfaces:
   - ✓ anti-wear and anti-seize additives – adhere to metal surfaces, forming a protective film between the components;
   - ✓ anti-rust and anti-corrosive additives – additives that protect metal surfaces from corrosion from the chemical attack of water or other contamination agents. When the components have ferrous metals in their structure, this corrosion is called rust;
   - ✓ friction modifiers – to reduce the friction coefficient;
   - ✓ oxidation and corrosion inhibitors;
   - ✓ detergents – form the oil's ability to prevent impurities from sticking to the surface of the parts;
   - ✓ dispersants – form the ability of the oil to maintain in suspension the products of oil degradation and fuel oxidation with the action against the formation of any deposits in the engine, with the exception of calamine.
2. To protect the gaskets – they prevent the gaskets and semi-rings from being attacked.
3. To protect the oil:
   - ✓ antifoams – contain silicone to prevent the formation of air bubbles;
   - ✓ antioxidants - limit the effect of high temperatures, which lead to burning (oxidation) of the oil.
4. To expand the field of use:
   - ✓ depressants (antifreezes) – protect the oil at low temperatures, preventing its solidification;
   - ✓ viscosity modifiers (thickeners) – to increase the viscosity index.
5. Multifunctional additives for the simulant improvement of several properties.

3. Oil consumption by burning

It is known that any engine consumes oil. To understand how much the engine should consume, engine oil consumption rates will help us. They are different for various engines and are almost always determined by construction [11,12].

Usually, in terms of fuel consumption, for gasoline engines of cars, the norm can be taken as 0.005...0.025 L of oil per hundred liters of fuel. For V6 or V8 engines, the flow rate will be higher – up to 0.030...0.040 L per hundred liters of fuel. In engines with significant mileage, engine oil consumption increases steadily and reaches one liter per 1000 km or more. For gasoline turbine engines, the minimum engine oil consumption is 0.8 L per change interval of 6...7 thousand km [13,14].

Truck engines use more oil, usually 0.7...1.2 liters per 1000 kilometers. A high-mileage diesel engine can burn up to 0.8% oil per 100 liters of fuel (0.2...0.250 L per 1000 km). At the same time, oil consumption in engines after a major overhaul, as a rule, increases. Light diesel engines consume less oil. The norm will be within the limit of

0.5 liters per 10.000 km. The amount of oil consumption when the alarm should be sounded is the same – 2 liters per 100 liters of diesel [14]. During the operation of the engine, the oil undergoes several physico-chemical transformations due to various phenomena that occur in it. These transformations lead to the loss of the qualities of performing the necessary functions and subsequently to its degradation. One of the main causes is oil burning.

Oil consumption for waste in an internal combustion engine of a car is a process of reducing the volume of oil in the lubrication system, caused by the features of the power unit, internal malfunctions, defects and other reasons. Internal combustion engines always use engine oil. Engine oil consumption is influenced by a large number of factors. These are engine design features (diesel engines consume more oil) and operational features (high speeds, heavy engine loads), weather and climatic conditions, etc.

Examples include: turbocharged engines Audi, BMW, Subaru, individual models of Mercedes, Porsche, Ford, Mazda, Mitsubishi and Toyota engines, which show excellent appetite for engine oil (Table 1) [11,15].

Table 1

Causes of oil consumption

Car brand	Engine model	Engine oil consumption	Causes of oil consumption
VW	TSI, TFSI, TDI, CAWA, BRZ	up to 1 L/1000 km	Constructive particularities
BMW	Twin Turbo, V8, M54	1 L/1000 km	Engine overheating, crankcase ventilation entanglement, twin turbine
Porsche	3,2 V6	1 L/2000 km	Constructive particularities
Mercedes	OM 606, M112	1 L/10000 km	Engine overheating, water in fuel
Ford	Duratec	1 L/1000 km	Blocked segments. Fuel quality
Mazda	FP 1,8	up to 5 L/1000 km	Wear of lubrication segments
Mitsubishi	4G 64	1 L/1000 km	Constructive particularities
Subaru	EJ20, EJ25, V6R	1 L/1000 km	Constructive particularities
Toyota	4A-FE	2. L/10000 km	Wear of lubrication segments

The problem of increased oil consumption is associated not only with additional costs for the operation of equipment, but is also fraught with the risk of damage and premature failure of the engine. The stability of the oil level in the engine crankcase is the key to its reliable and long-term operation.

Causes of engine oil fumes. Increased oil consumption in the engine can manifest itself for several reasons [16]:

- natural waste, the normative indicators of which are approved by engine manufacturers;
- low quality motor oils;
- use of engine oils not suitable for this type of engine;
- unsatisfactory technical condition of the engine (wear of the cylinder-piston group);
- faulty turbocharged compressor;
- ejection of part of the engine oil through the exhaust system or through the cooling system.

Parameters affecting oil consumption. There is not a single indicator that would show the real rate of oil waste. But two indirect parameters stand out [17]:

1. Evaporation of engine oil.
2. Flash point.

The hardest thing to know is the first indicator, because this information is nowhere to be found. As for the second parameter, it is easy to find the necessary information. These data are found in many reference books and show at what temperature the lubricant of the power unit ignites on contact with an open flame. It depends on the composition of the oil, namely the presence of light fractions in its composition. The higher their number, the lower the temperature required for ignition.

Engine oil volatility is regulated by the API (American Petroleum Institute), ACEA (Association of European Automobile Manufacturers) and OEM (Original Equipment Manufacturers) standards using a special Selby-Noack test. The Selby-Noack test is standardized in the ASTM D5800 method and consists in simulating high-temperature oil volatility in the engine by keeping the oil sample in a special device at a temperature of 250 ^{o}C for 1 hour [15, 16]. The volatility is expressed as a percentage. The lower the percentage of evaporation in the test, the more stable the oil is in terms of oil loss. Knowing the NOACK value, you can predict the intensity of oil consumption in your engine. The most „liberal" – at about 15% – evaporation rate requirements are shown by the API standard. More stringent – about 13% – requirements are imposed by engine manufacturers (OEMs).

On average, mineral lubricating compositions lose about 22...25%, and modern synthetic oils – no more than 8...10% [15].

To compensate for oil consumption for waste, periodic topping up of fresh engine oil (preferably of the same type and brand) is used to maintain the appropriate level in the engine crankcase.

To develop a reasonable frequency of changing the engine oil in engines with a different degree of oil consumption for burnout and, accordingly, the frequency of refilling (freshening), consider the following model of the processes of its operation.

4. Mathematical model of changes in the physical and chemical properties of engine oil during operation

The empirical character of dependence of alkaline number of engine oil (y) on the mileage or operating time (x) suggests that it refers to the type of exponential, monotonically decreasing to a certain limit. This assumption agrees with the equations obtained by a number of authors on the basis of theoretical considerations [6,17,18]. In addition, in favor of such an assumption indicates a simplified representation of the chemical transformations occurring as a result of interaction of oil with air oxygen and exhaust gases[19]. Let's assume that the chemical transformation can be interpreted by the simplest scheme:

$$A_1 \underset{k_2}{\overset{k_1}{\rightleftharpoons}} A_2 \tag{1}$$

where: A_1, A_2 – substance reaction component;

k_j – the rate constant of the j-th stage of a complex reaction.

Then, denoting the current concentration of the initial substance expressed in moles by the letter C, the initial letter C_0 and, considering the conditions of the material balance, from which it follows that the concentration $A_2 = C_0 - C$, we can obtain a differential kinetic equation in the form:

$$\frac{dC}{dt} + (k_1 + k_{-1}) \cdot C = k_{-1} \cdot C_0 \tag{2}$$

where: t – the current time with initial conditions:

$$C(0) = C(t) \Big|_{t=0} = C_0 \tag{3}$$

The solution of equation (2) under condition (3) can be represented as:

$$C = C_0 - \alpha \cdot (1 - e^{-bx}) \tag{4}$$

where:

$$a = \frac{k_1 \cdot C_0}{k_1 + k_{-1}} \tag{5}$$

$$b = k_1 + k_{-1} \tag{6}$$

By analogy with (4), the dependence of the base number of engine oil (y) on the mileage (x) can be postulated as:

$$y = y_0 - \alpha(1 - e^{-bx}) \tag{7}$$

This equation corresponds to the differential equation:

$$\frac{dy}{dx} + by = b(y_0 - \alpha) = c \tag{8}$$

with initial conditions:

$$y(0) = y_0 \tag{9}$$

The general solution of the inhomogeneous linear ordinary differential equation (LODE) (8) is:

$$y(x) = y_0 \cdot a^{-bx} + \frac{c}{b}(1 - e^{-bx}) = y_0 \cdot e^{-bx} + (y_0 - a) \cdot (1 - e^{-bx}) = y_0 - a \cdot (1 - e^{-bx}) \tag{10}$$

Equations (7) and (8) can only be used if there is no oil in the considered mileage interval, adding fresh engine oil to compensate for its waste during operation.

If we mean the mode with topping up („refreshing") oil at some point in time, then this situation requires special consideration.

Let: m_0 – the initial volume of oil in the engine crankcase, expressed in liters;

Δm – oil waste in liters per car mileage in thousand km;

y_0 – base number of fresh engine oil, expressed in mg KOH/g;

$y(x)$ – base number of oil in the crankcase before topping up, expressed in mg KOH/g;

Δy – increase in the base number of oil as a result of topping up, mg KOH/g.

Based on the condition of the need to maintain the volume of oil in the crankcase at a constant level, we will compose an equation for calculating the increase in base number:

$$\frac{m_0 - \Delta m}{m_0} \cdot y(x) + \frac{\Delta m}{m_0} \cdot y_0 = y(x) + \Delta y \tag{11}$$

From this expression we have:

$$\frac{\Delta m}{m_0}(y_0 - y) = \Delta y \tag{12}$$

An analysis of experimental data allows us to judge that oil waste is linearly expressed in terms of vehicle mileage, i.e.:

$$\Delta m = \gamma \cdot \Delta x \tag{13}$$

where: γ – the rate of oil burning, related to the unit of the mileage scale, l/ths. km.

Substitution of expression (13) into (12) will lead to the relation:

$$\Delta y = \frac{\gamma \cdot \Delta x}{m_0}\left(y_0 - y\right) \tag{14}$$

This expression allows the increase in base number due to topping up (refreshing) engine oil. It is appropriate to note that the interval Δx is calculated either from the start of engine operation (if we are talking about the first topping up), or from the moment of the previous topping up.

Let us now return to the differential equation (8), bearing in mind the need to correct it if the oil is topped up once and instantly at $\Delta x = x_1 - x_0$, when the base number (before topping up) is determined by equation (7).

It is known from the theory of linear differential equations that in such a case the right side of equation (8) must be supplemented by a „control" in the form:

$$\begin{cases} \dfrac{dy}{dx} + by = b(y_0 - a) + \Delta y_1 \cdot \delta(x - x_1) \\ y(0) = y_0 \end{cases} \tag{15}$$

This equation describes the change in base number, taking into account the fact that at the moment $x = x_1$ oil is added, leading to an instantaneous jump in base number Δy_1.

Equation (15) is a typical equation of a linear dynamic system with a perturbing function in the form of an instantaneous impulse $\delta(x - x_1)$ - an impulse function ($\delta(\cdot)$ is the Dirac delta function [9]) that has the following properties:

$$\delta(x - x_1) = 0 \quad npu \quad -\infty < x < \infty, \quad x \neq x_1$$

$$\int_{-\infty}^{\infty} \delta(x - x_1)dx = 1$$

To obtain the general solution of equation (15), it suffices to add to solution (10) of equation (8) a particular solution of the equation:

$$\begin{aligned} &\frac{dy}{dx} + by = \Delta y_1 \cdot \delta(x - x_1) \\ &y(0) = y_0 \end{aligned} \tag{16}$$

The general solution of equation (10 and 15) can be written as a composite function:

$$y(x) = y_0 - \alpha(1 - e^{-bx})\Big|_{x \geq 0} + \Delta y_1 \cdot e^{-b(x-x_1)}\Big|_{x \geq x_1} \tag{17}$$

Note also that the second and third terms on the right side of the equation are not equivalent. The second term $\left[-\alpha(1-e^{-bx})\right]$ „acts" on the entire interval of existence of the argument (x), i.e. from (0) to (∞) (theoretically). The third term „acts" only for $x \geq x_1$, and besides $x \geq x_1$, for it gives a jump on a curve different from Δy_1. In other words, it is a composite function. Figure 2 shows a dependency graph for a function of the form (17), where: $y_1 = y(x_1) = y_0 - \alpha(1-e^{-bx_1})$, and the jump Δy_1 is calculated by the equation:

$$\Delta y_1 = \frac{\gamma x_1}{m_0}\left[y_0 - y(x_1)\right] \tag{18}$$

The graft section at is $x > x_1$ described by a composite function:

$$y = y_0 - \alpha(1 - e^{-bx})\Big|_{x \geq 0} + \Delta y_1 \cdot e^{-b(x-x_1)}\Big|_{x \geq x_1} \tag{19}$$

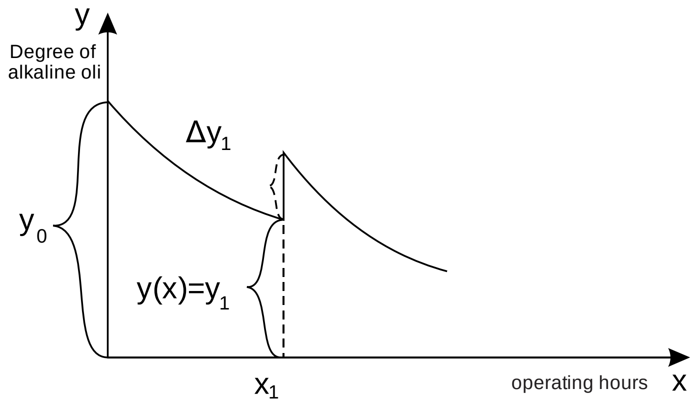

Figure 2. Diagram of the change in the alkaline number of the engine oil as a function of the operating hours in the presence of an instantaneous pulse refill oil [9].

Now let's consider a more complicated case, when oil is topped up many times in portions at different mileage values $x_1, x_2, ..., x_k$. Obviously, in this case, the „jumps" of the base number, due to the addition of oil at will $x = x_1; x = x_2; .....x = x_k;$ be expressed by equations of the form:

$$\begin{cases} \Delta y_1 = \dfrac{\gamma \cdot x_1}{m_0}\left[y_0 - y(x_1)\right] \\ \Delta y_2 = \dfrac{\gamma \cdot (x_2 - x_1)}{m_0}\left[y_0 - y(x_2)\right] \\ ----------------- \\ \Delta y_k = \dfrac{\gamma \cdot (x_k - x_{k-1})}{m_0}\left[y_0 - y(x_k)\right] \end{cases} \tag{20}$$

It should be borne in mind that the values $y(x_2), y(x_3), ..., y(x_k)$ must be calculated taking into account previous jumps.

If multiple impulse actions are performed on the system (multiple impulse oil topping up), then the differential equation can be written in the form:

$$\begin{cases} \frac{dy}{dx} + by = C + \sum_{i=1}^{k} \Delta y_i \cdot \delta(x - x_i) \\ y(0) = y_0 \end{cases} \quad (21)$$

The solution of such an equation (provided that $x_{i+1} > x_i$) is constructed similarly to the previous case and is expressed as a function:

$$y(x) = y_0 - \alpha(1 - e^{-bx})\Bigg|_{x \ge 0} + \Delta y_1 \cdot e^{-b(x - x_1)}\Bigg|_{x \ge x_1} + \Delta y_2 \cdot e^{-b(x - x_2)}\Bigg|_{x \ge x_2} + ... + \Delta y_k \cdot e^{-b(x - x_k)}\Bigg|_{x \ge x_k} \quad (22)$$

The dependency graph for such a composite function is shown in figure 3.

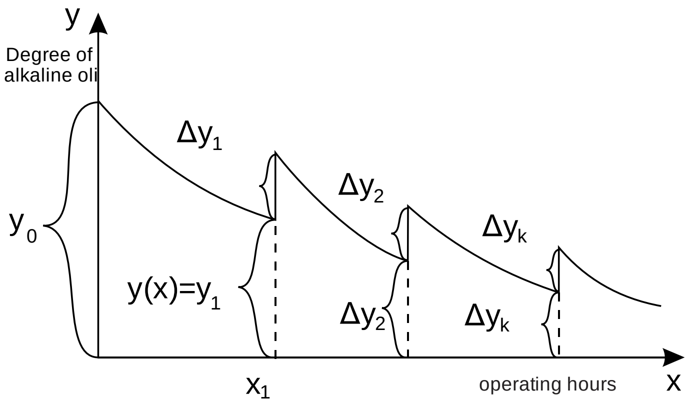

Figure 3. Diagram of the relationship between the alkaline number of the engine oil and the operating hous in the presence of multiple pulse refills during operation motor vehicle[9].

It is appropriate to note that the jumps, even with the same intervals between topping up, $x_1 - 0 = x_2 - x_1 = ... = x_k - x_{k-1} = \Delta x$ will not be equal to each other.

To describe the process of changing the physical, chemical and operational properties of the engine oil depending on the mileage, technical condition of the engine and the degree of "freshening" of the oil, you can use a mathematical model of the form:

$$y = y_0 \pm a(1 - e^{-bx}) \pm \sum_{i=1}^{k} \Delta y_i \cdot e^{-b(x - x_i)}$$

where: y_0 – the initial value of the quality indicator of fresh (commercial) motor oil;

x – the current value of the car's mileage;

$x - x_i$ – the mileage interval between the moment of topping up engine oil, which compensates for oil consumption for waste;

k – the number of top-ups made during the period of operation of the oil in the engine.

Parameters „*a*” and „*b*” in the mathematical model can be described depending on the technical state of the engine using the formulas:

$$\begin{cases} a = \alpha_0 + \alpha_1 Q + \alpha_2 Q^2 \\ b = \delta_0 + \delta_1 Q + \delta_2 Q^2 \end{cases}$$

where: Q – oil pumpability through the engine lubrication system, l/min;

$\begin{cases} \alpha_0, \alpha_1, \alpha_2 \\ \delta_0, \delta_1, \delta_2 \end{cases}$ – the coefficients of the system of equations.

In operating conditions, the process of „refreshing" the engine oil can be regarded as a repeated pulse refill and described by the equation of the form:

$$\Delta y_i = \frac{\gamma(x - x_i)}{m_0}\left[\pm y_0 \mp y(x_i)\right]$$

where: m_0 – the amount of engine oil in the engine crankcase, set by the manufacturer;

$y(x_i)$ – the current value of the oil quality index at the time of the next oil top-up;

γ – engine oil burn rate.

The rate of engine oil burnout during operation is described by an equation of the form:

$$\gamma = \gamma_0 + k\bar{x}$$

where: γ_0 – oil burn rate corresponding to the technical condition of the new engine;

$\bar{x}$ – vehicle mileage since the start of operation;

k – an empirical coefficient that takes into account the wear of engine parts.

5. Conclusions

In the given article the peculiarities of engine oil combustion are analyzed, taking into consideration the renewal of engine oil due to the addition of oil up to the necessary limits of engine operation, the physical-chemical properties of engine oil are maintained at an optimal level necessary for the proper functioning of internal combustion engines. This allows us to increase the time between corrective maintenance interventions. One of the main parameters of the maintenance work is the oil change, which increases the vehicle ride periodicity.

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