Wear of brass-steel friction pairs in axial-piston pumps and motors under the influence of polydispersional contamination

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The experience of exploitation of hydraulic drives shows that fluid contamination causes 69% of the breakdowns. The reason of good half of the failures is from abrasive wear [1]. Such failures lead to the shortage of components' longevity (chart 1) and significant decrease in drives energy efficiency. Here it would be appropriate to mention that real operational loads on the drive are much less than nominal ones (fig. 1). That gives even bigger opportunities for amplifying the lifespan of hydraulic components by decreasing the intensity of abrasive wear.

Chart 1. Real and nominal lifespan of hydraulic components of mobile machines

Hydraulic component	Lifespan, moto-hours				Mean shortage of the longevity, %
	mean	maximal	minimal	nominal	
Valve	4021	6112	1930	12000	66.49
Pump	5965	8707	3698	7500	20.46
Cylinder	4626	6754	2868	10000	53.74
Motor	7823	12517	4068	20000*	60.88

*) with regards to the use of motors in the working cycle of the equipment

Quantitatively, deterioration of the output parameters of a component caused by fluid contamination can be defined by the term "contamination sensitivity" (CS) [3]. To describe the CS for a particular hydraulic component means to find the relationship between the wear intensity of the friction pairs and geometric (for instance, dimension) and physical (for instance, hardness) parameters of the contaminant. Change in geometry of the wearing surfaces circumscribes the deterioration of the critical parameter of the component (pump or motor). Needless to say, CS also depends on design specifics of pump/motor parts. In this case, the nature and hardness of sliding surfaces' materials as well as the geometry of corresponding clearances are most important.

Most of recent hydraulic power drives are based on axial piston pumps and motors. These components, as a rule, contain brass-steel friction pairs, which form several precision clearances from 3 to 40 microns. Sliding surfaces have the roughness of 0.12-0.16 microns.

There are different opinions about dangerous coarseness of fluid contaminations. For example, in the book [4] authors recommend removing all the particles for which $d_c/\delta_{aa} > 1$. Here, d_c is the largest size of the particle and δ_{aa} is the dimension of the clearance. Dr. Finkelstein [5] suggests this ratio to be 50% ; in the article [6] – 5%. Many authors consider all particles larger than 1 micron to be dangerous from the point of view of abrasive wear. In general one may say that there is no common opinion about the largest allowable particle size in hydraulic fluid contaminations.

Theoretical appraisal of the dangerous coarseness of contaminants can be made from the analysis of the kinematics of particle passage through the clearance. Because the flow is laminar, the longitudinal (cruise) constituent of particle velocity can be calculated as:

$$\upsilon_{axl} = p/(4*\mu_f*L)*(\varepsilon^2/4-y^2)$$

Here L, ε are length and height of the clearance, y is the distance between the flow (clearance) axle and the center of the particle. So, the difference of linear velocities occurs on the particle and it leads to the particle rotation with the angular velocity

$$\omega = \upsilon_{axl}\{y\} - \upsilon_{axl}\{y+d_c\} = p*d_c*y/(2*\mu_f*L)$$

Then, using the equations of Zhukovsky and Stokes, it is possible to find the transverse velocity as:

$$\upsilon_{crs} = -\pi*\rho_f*p^2*d_c^2/(96*\mu_f^3*L^2)*y*(\varepsilon^2/4-y^2) \qquad (3.2)$$

The relationship between the cruise and transverse velocities is illustrated by fig. 2.a.

Consequently, the condition of the wear of the surface by the particle can be formulated as:

$$L / \upsilon_{axl} > \varepsilon / (2*\upsilon_{crs})$$

If this inequality is not fulfilled, the particle will exit from the clearance without hitting the surface and no wear will be caused. Substituting the expressions for υ_{crs} and υ_{axl} into previous disparity, one can define the dangerous size of the wearing particle as:

$$d_c > ((12* \mu_f^2)/(\pi*\rho_f*p)*y/\varepsilon)^{1/2} \qquad (3.3)$$

Based on the inequality it can be calculated that, for clearances typical for hydraulic components with pressure level of 32 MPa, particles less than 1.5-2.0 microns (with regards to out-of-roundness less than 2.5-3.0 microns) are safe (fig. 2.b). Also, one can note that minimal dangerous size of wearing particle depends not only on the size of the clearance, but also on the distance between the center of the particle and the axle of the clearance. Hence, with the clearance growth due to wear, many particles traveling along the axle will not be able to hit the surface and, consequently, will not cause any wear. This statement, with regards to immutability of contaminations parameters, gives a good explanation for monotonous decrease in wear intensity of hydraulic units with time, which has been noted by many researchers [2,8] and proven by the laboratory tests of transmissions (fig. 3a). Simultaneously, because minimal dangerous size of the wearing particle is less than 25% of the clearance (fig. 3b), and because:

- some clearances in friction pairs of axial-piston pumps and motors decrease under the load up to the thickness of hydrostatic bearing film (the couple “cylinder block – valve plate” can serve as an example);
- due to dynamic oscillations, elements often form V-shaped clearances (for instance, in the conjugation “piston – swashplate”),

the removal of all dangerous particle seems impossible.

Thus, even with highly efficient filtration system, sugnificant deterioration of pump/motor output parameters will take place. This deterioration, considering the immutability of gravimetric parameters of fluid contaminations in course of the operation of the machine, can be described as a sequence of 3 main phases:

- Phase of intensive wear (from 5 to 40% of the lifespan). During this phase the clearances increase from their initial values defined by the precision of manufacturing to the magnitude comparable with the prevailing size of the contaminant. According to author’s experience, this magnitude can be defined as 1 ...1.75 d_{cmax} ;
- Phase of normal wear (from 40 to 90% of the lifespan). During this phase the clearances monotonously increase up to 3 ...4 d_{cmax} ;
- Phase of terminal wear (up to 20% of the lifespan), which occurs if the surface-strengthened layer of the elements had been ruined and, hence, the tribological properties of the pair had been changed during the previous phase.

The phase of intensive wear should not be mixed up with the “running in” period. In course of this phase, the wear intensity grows with the number of small particles which can penetrate into the initial (designed) clearances $\delta_{aa}(T=0)$. This effect is clearly visible from the laboratory tests of diesel engines and fuel pumps affected by the contaminations of nearly uniform sizes [8, 9]. From the point of view of the lifespan forecast, the longevity of the particular phase is negligible if the minimal allowable magnitude of the critical output parameter is reached before the phase of terminal wear occurs.

As a critical output parameter for hydraulic pumps and motors, one can use the volumetric efficiency ratio defended as:

$$EER = 1 - Q_{agr} / (q * n)$$

Here Q_{agr} is real volumetric output, m^3/s; q is characteristic volume, m^3/rev, and n is rotation speed, rev/s.

The current value of Q_{agr} depends on the fluid leakage through the clearances and obviously decreases in course of abrasive wear. Thus, change in the volumetric output can be calculated as a sum of partial leakages:

$$\Delta Q = \Sigma(\Delta Q_i)|_{i=1\ldots N}$$

Here ΔQ_i is leakage through the clearance in “i” pair, N is quantity of the friction pairs in the pump. From [10], it is possible to demonstrate that:

$$\Delta Q_i = \varepsilon_{pi}^3 * b_{pi} / l_{pi} * [\, p / (12* \mu_f)] \qquad (3.4)$$

Where ε_{pi}, b_{pi}, l_{pi} are, consequently, height, width and length of "i" aperture (clearance), p is load parameter (here – working pressure).

The amplification of the aperture height can take place due to scratching if particle size is comparable to the clearance and due to hydroabrasive wear if particle size is much smaller than the clearance. In the first case, the depth of particle penetration into the sliding surface will be directly proportional to its size [11]:

$$\varepsilon_{pi} = \theta_{wd} * d_c ,$$

where θ_{wd} is particle-surface penetration ratio, which depends primarily on particle shape and the particle/surface hardness. So, for scratching, the unitary wear can be calculated as:

$$\Delta W_{dM} = \theta_{wd} * \pi/6*d_c^4$$

In case of hydroabrasive wear the depth of particle penetration depends on it size and velocity. From the energy point of view, one can define the unitary wear for this case as:

$$\Delta W_{dA} = \Omega_{wd} * m_c * \upsilon_{crs}^{\ 2} / 2$$

Here Ω_{wd} is penetration ratio, analogous to θ_{wd} .

With regards to (3.2) and counting $y = (\varepsilon/2 - d_c/2)$ at hitting moment:

$$\Delta W_{dA} = 1.727 * 10^{-5} * \Omega_{wd} * \rho_c * \rho_f^2 * p^4 * d_c^9 * \varepsilon^4 / (\mu_f^6 * l^4) * (1 - d_c/\varepsilon)^2 * (1 - d_c/(2*\varepsilon))^2$$

According to the linear summation of damages hypothesis, total wear of the surface due to the impact of "N" particles can be calculated as:

$$\Delta W = \Delta W_d * N$$

Because

$$N = C / (\rho_c * \pi/6 * d_c^3) * \Delta Q * T_c ,$$

where C is particle concentration, kg/m^3, ρ_c is particle density, kg/m^3, T_c is time of the impact of concentration "C" on the hydraulic component, s.

Then, with regards to (3.4):

- for scratching

$$\Delta W_{dM} = \theta_{wd} * p/(12* \mu_f) * \varepsilon_{pi}^3 * b_{pi} / (l_{pi} * \rho_c) *d_c *C * T_c$$

- for hydroabrasive wear

$$\Delta W_{dA} = 2.74 * 10^{-4} * \Omega_{wd} * b_{pi} * \rho_f^2 * p^5 * d_c^6 * \varepsilon^7 * \\ * (1 - d_c/ \varepsilon)^2 * (1 - d_c/(2*\varepsilon))^2 / (\mu_f^7 * l^5) * C * T_c$$

Taking the derivative and considering:

$$\Delta W_d = d(W_d) = d(\varepsilon)*b*l ,$$

and also, from (3.4):

$$d(\varepsilon) = d(\Delta Q)*[4* \mu_f * l_{pi} / (\varepsilon_{pi}^3 * b_{pi} * p)]$$

it is possible to derive the equation for calculation of deterioration of the critical parameter of the hydraulic component, affected by the contaminations of concentration C an size d_c :

- for scratching

$$\Delta Q = \Phi_{hM}' * d_c * C * T_c$$

- for hydroabrasive wear

$$\Delta Q = \Phi_{hA}' * [(1 - d_c/\varepsilon)^2 * (1 - d_c/(2*\varepsilon))^2] * d_c^6 * C * T_c$$

Here:

$$\Phi_{hM}' = \theta_{wd} * p^2 * b_{pi} / (\mu_f^2 * l_{pi}^3) * \rho_f / \rho_c * \varepsilon^3$$

$$\Phi_{hA}' = 6.9 * 10^{-3} * \Omega_{wd} / (\mu_f^{8} * l^{7}) * p^{6} * \rho_f^{2} * b_{pi} * \varepsilon^{9}$$

So far, there is no analytical equations for Ω_{wd} and θ_{wd} which could be adequately applied to the matter and which could serve as a base for corresponding calculation. Nevertheless, the magnitudes of the ratios mentioned above certainly depend only on:

- hardness, size and shape of the particles;
- loads and velocities;
- fluid (lubrication) properties;
- properties of materials of sliding surfaces.

All abovementioned parameters remain constant during the lifespan of the pump/motor. Therefore the established equations can be used for the CS – calculation. Because any real contaminant is polydispersional, magnitude of d_c should be calculated as a sum:

$$d_{c\Sigma} = \{ \Sigma [d_{ci}^{\psi} * M_{ci}] / M_{ci} \}^{1/\psi}$$

Here M_{ci} is quantity of the particles of "$d_{ci.}$" size.

Taking into account that during the lifespan the "d_c/ε" ratio, with the change of ε, takes on all values in the domain, the expression in the brackets can be equated with a certain constant $\alpha_{\varepsilon d}$. Then the relationship between the deterioration of the flow output and the parameters of the contaminant can be written as:

$$\Delta Q = \Phi_h * \alpha_{\varepsilon d} * d_{c\Sigma}^{\psi} * C * T_c \ , \tag{3.5}$$

where $\psi = 6$, $\Phi_h = \Phi_{hA} * \alpha_{\varepsilon d}$, $\alpha_{\varepsilon d} = 0.193$ if $d_c < \delta_{aa}$, and $\psi = 1$, $\Phi_h = \Phi_{hM}$ if $d_c > \delta_{aa}$, because the last ratio applies to scratching.

The equation (3.5) corresponds well to the results of laboratory and field tests for axial-piston pumps. For example, the laboratory test results published in the book [3] can be analyzed (fig. 4). It is visible from the figure 5, that calculation of the specific output loss per unit of the contaminations concentration ($\Delta Q/C$ – ratio) yields similar results for all magnitudes of the concentrations (from 25 to 300 g/m^3). Thus, one may consider it experimentally proven that deterioration of the critical parameter of the component is a linear function of the contaminant concentration, as follows from the equations (3.5), and not a power function as many researchers believe (for instance, [12, 13]).

It is interesting to note that root-mean-square deviation of experimentally determined magnitudes of $\Delta Q/C$ decrease with the amplification of particle sizes. This effect seems to be connected with the necessity of the measurement of small values of ΔQ (from 0.1% to 0.5%) while working with the contaminations of "0-5 microns" and "0-10 microns" types. For such precise measurement the conditions of the test should be extremely stable, which is hard to achieve.

To verify the expression (3.5) from the point of view of quantitative influence of particle sizes on CS-parameters it is necessary to take into account the specifics of the testing procedure, where ACFTD (Air Cleaner Fine Test Dust) is used [3]. In course of testing, the component is exposed to the action of all types of contaminants in sequence. In each type various particles less than certain size are represented (the number of ACFTD type is equal to the largest size in microns). According to the equation (3.5), specific output loss due to the sequential influence of the ACFTD contaminant of all types, from the 1st (5 microns) до N_j (j microns), can be calculated as:

$$\Delta Q_{Nj}' = \Delta Q_{Nj} / C = \Phi_h * \Sigma \{ [\Sigma (M_{ci} * d_{ci}^{\psi})]|_{i=1\ldots Nj} \}|_{j=1\ldots j}$$

Here M_{ci} is quantity of the particles of d_{ci} size in the contaminant of N_j type. Fig. 6 demonstrates the magnitudes of specific output loss calculated for different types of ACFTD. Specific output loss for ACFTD j=20 microns counted as 100%. Calculation had been done with the assumption that for particles with $d_c < 40$ hydroabrasive wear prevails. It is visible from the figure that miscalculation is reasonable (less than 15%).

Using equation (3.5) for exploitation forecasts, it is necessary to make adjustments for chemical difference between real contaminations and ACFTD (fig. 7). Laboratory and field tests [14], including ones applied to hydraulic axial-piston pumps and motors [15], show that the relationship between wear intensity and particle hardness can be assumed to be linear with acceptable accuracy. Accordingly, it is possible to adjust the equation (3.5) using the hardness ratio:

$$k_h = H_{hc(ecs)} / H_{hc(rcs)} \tag{3.6}$$

The geometry of the particle is independent from its size but is defined only by the particle's physical nature [14]. So, it is practical enough to use the concept of the "equivalent hardness", which can be calculated based on the experimental data on the physical and chemical composition of the contamination in the particular hydraulic drives (fig. 8). Hence, from (3.5) and (3.6), it is possible to forecast the lifespan of the hydraulic component as:

$$T_{c(rcs)} = T_{c(ecs)} * [\, d_{c\Sigma(ecs)}^{\psi} / d_{c\Sigma(rcs)}^{\psi} * C_{(ecs)} / C_{(rcs)} * H_{hc(ecs)} / H_{hc(rcs)}] \qquad (3.7)$$

Here the indexes (ecs) and (rcs) apply to the standard and real operational regimes consequently.

Thus, the following limitations of the use of the equation appear:

- the duration of the standard regime has to be sufficient for the decrease of the critical parameter of the component to the magnitude comparable with the one minimally allowable for the real operational regime;
- the contamination concentration in standard regime has to be small enough to prevent progressive wear. In other words, the acceleration ratio should not be too large. Author is of the opinion that concentration should be less than 160 g/m^3 and maximal particle size should not exceed 40 microns.

It is obvious from the equation (3.7) than the larger maximal particle size, the less is allowable concentration of contamination. In reality the relationship is inverse: the fluid with minor contamination concentration contains smaller particles. Fig. 9 illustrates the specific lifespan of the components as a function of the concentration of the contaminant of different granulometric. The function calculated for axial-piston pump applicably to the collinear (concentration from 250 to 3915 p/ml, fig 9a) and fan-shaped (concentration 250 p/ml, crumbling ratio from 2 to 64, fig 3b) distribution.

From fig. 9 one can see an enormous difference in the calculated magnitudes of the lifespan. Field tests (see black rhombs on the graph) show less amplification of pumps durability. That can be explained by the following circumstances:

- real contamination contains particles of different nature. Sometimes, the increase of concentration happens because of penetration of particles of lesser abrasivity, even is their size is large;
- abrasive wear is not the only type of wear revealed in the exploitation of hydraulic components. It prevails when fluid contamination is rather high (for the recent drives – higher than 15/13 level according to ISO 4406). However, when purity of liquid is further improved adhesive wear and fatigue play the greater role in diminishing longevity.

The author believes that the equations (3.5) – (3.7) yield numbers applicable to real life only if the calculated changes in the lifespan due to increase of purification levels do not exceed 3-5 times.

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Figures

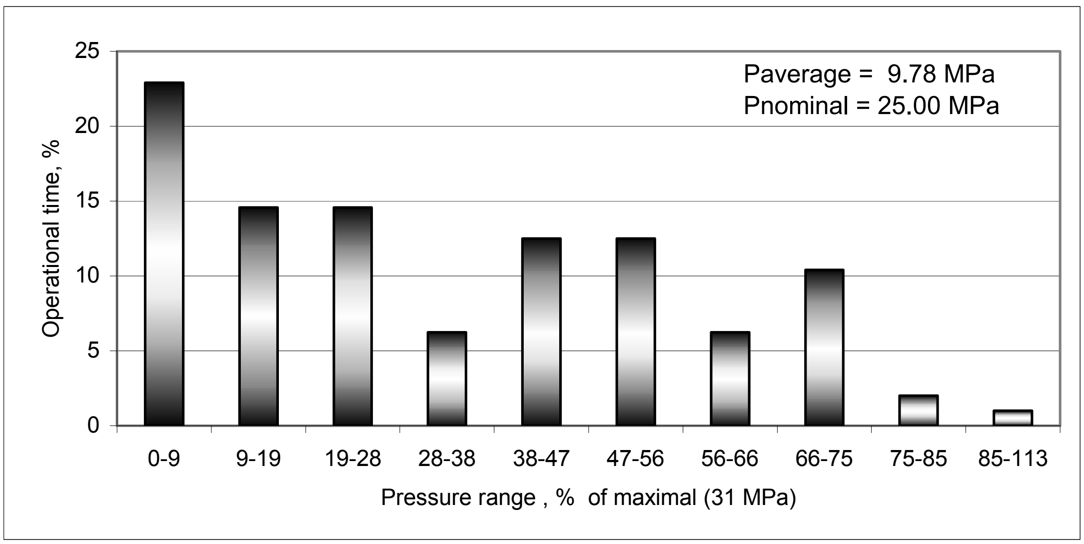

Fig. 1. Real loads on the hydraulic drive of a mining shovel (experimental data for 102 hours of operation).

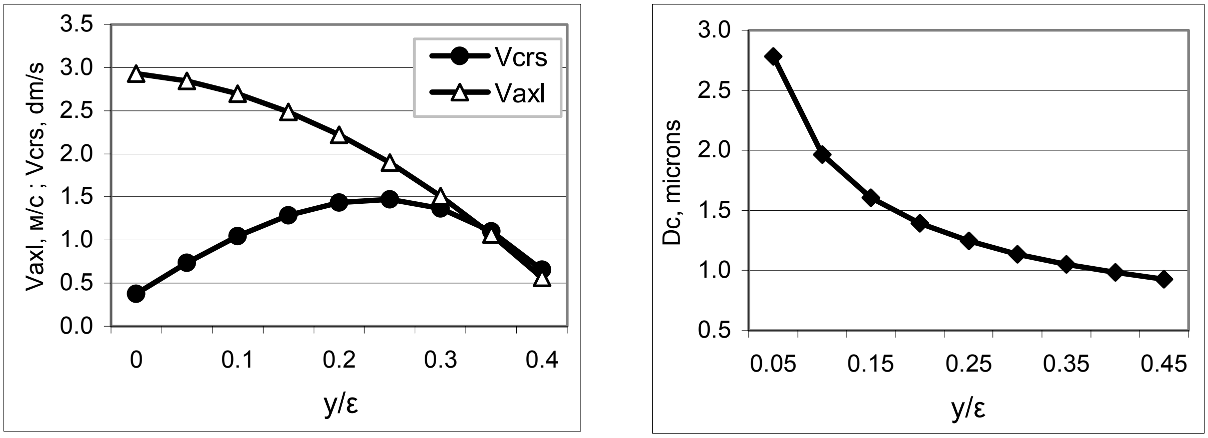

Fig. 2. Kinematics of particle passage through the clearance

a) The relationship between the longitudinal and transverse velocities (p=32MPa, $d_c/\varepsilon=0.25$)

b) The size of the "safe" particle as a function of the distance from the axle of the clearance (when $y/\varepsilon=0$ the particle traveling along the axle of the clearance)

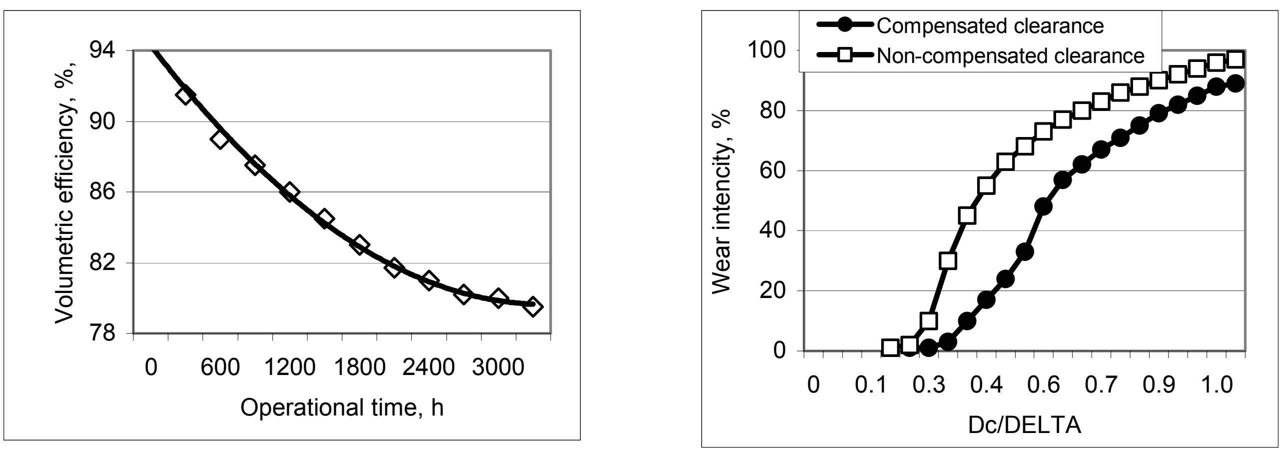

Fig. 3. Abrasive wear of axial-piston pumps and motors

a) Critical output parameter (volumetric efficiency) of the transmission (swashplate) working with the fluid of 16/14 contamination level according to ISO 4406, p=25MPa, n=25 rev/s.

b) Wear intensity of the elements of axial-piston pumps/motors as a function of the ratio Dc/DELTA. Here "Dc" is particle size and "DELTA" is height of the clearance. Generalized data of the laboratory tests for different types of transmissions (including results given in the report [16])

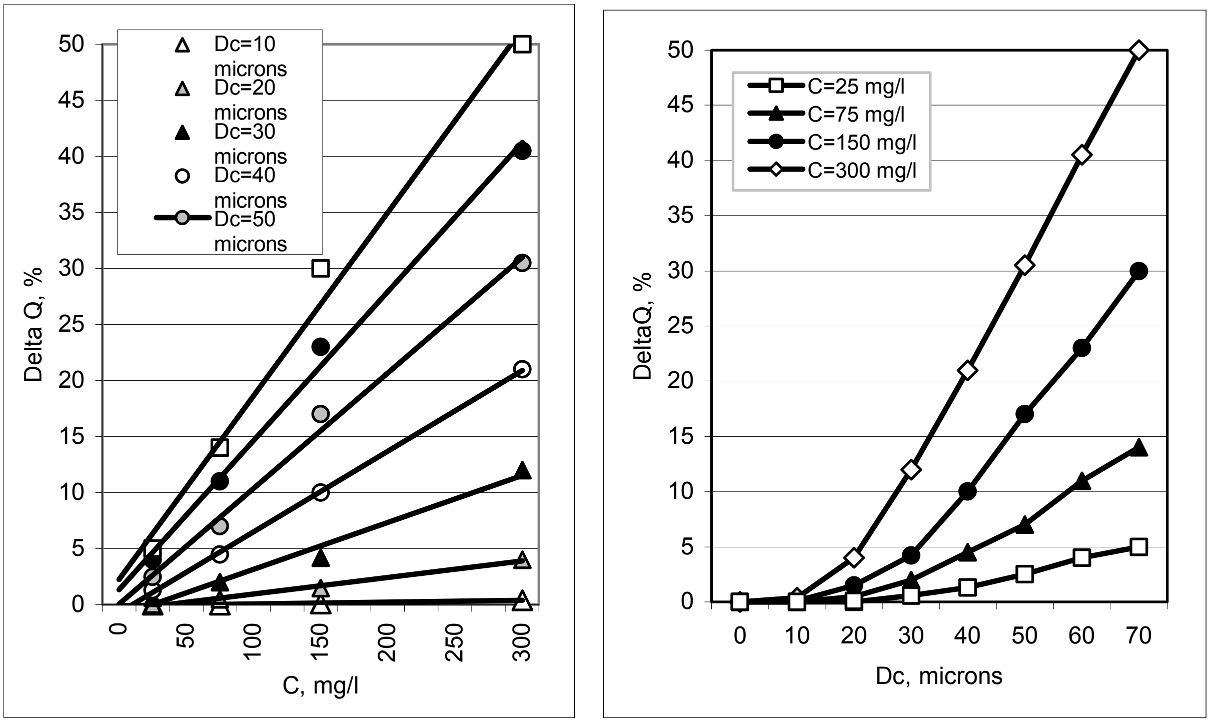

Fig. 4. CS-test results for hydraulic pumps.
a) Output losses as a function of contamination concentration
b) Output losses as a function of maximal particle size

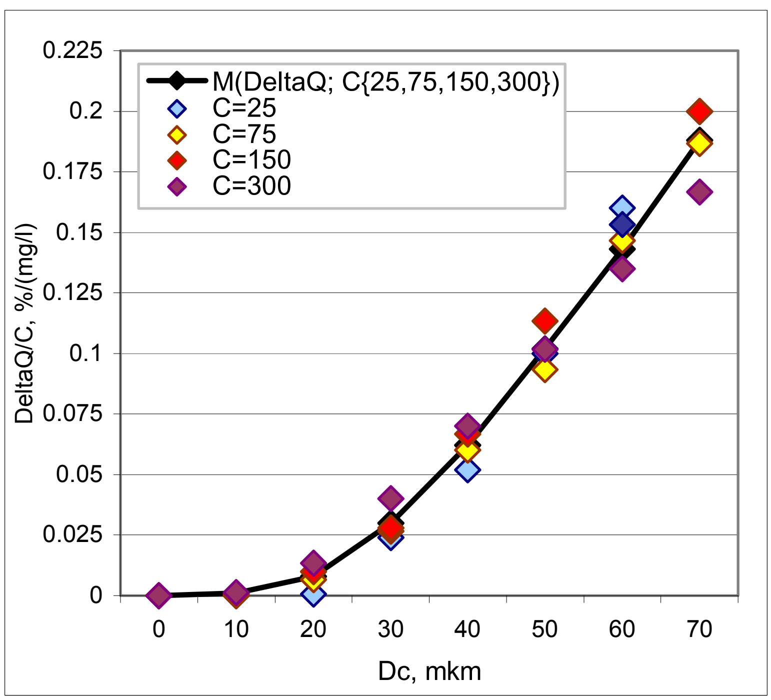

Fig.5. Specific output loss per unit of the contaminations concentration (DeltaQ/C) as a function of contamination concentration "C" and particle size (Dc - maximal size of the particle in the contaminant).

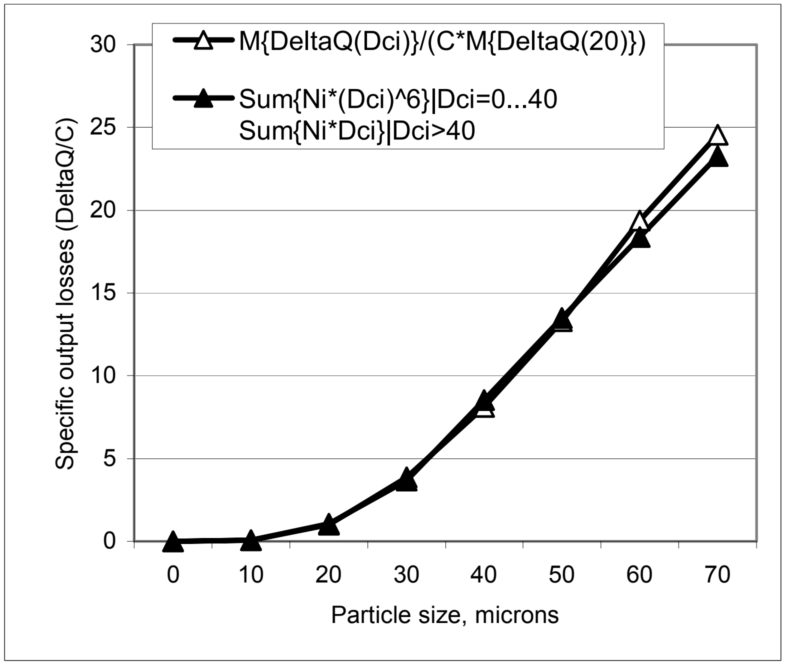

Fig.6. Magnitudes of specific output losses for different types of ACFTD: calculated (black triangle) and experimental data (white triangle.

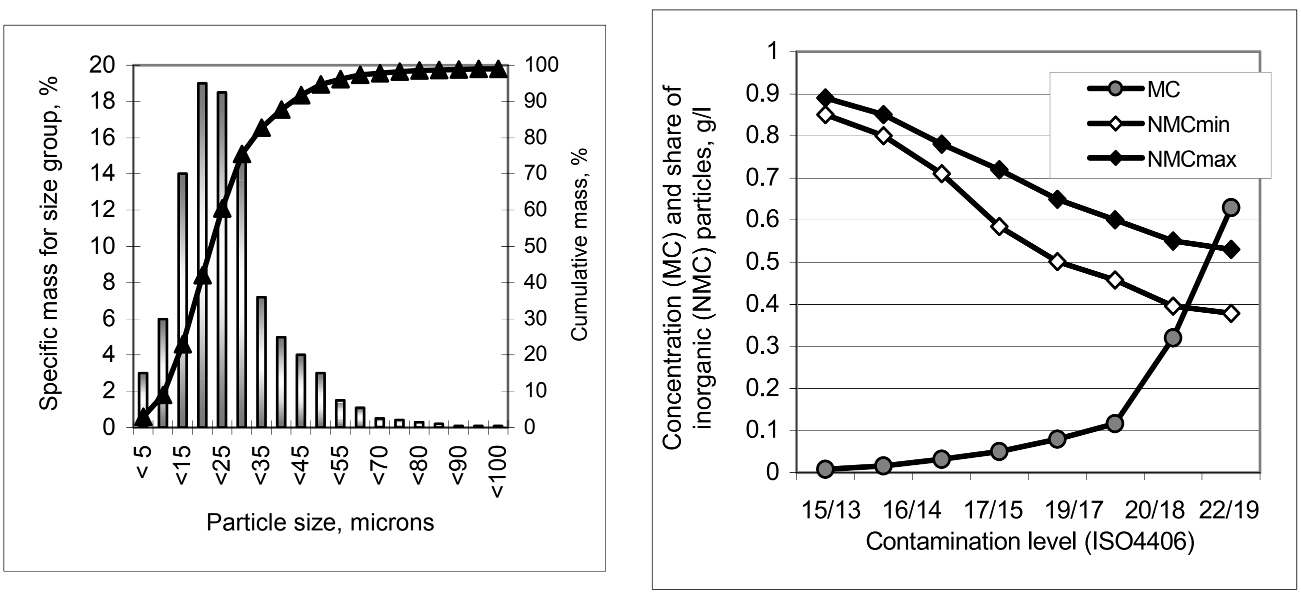

Fig. 7. Parameters of real contaminant (mobile machines hydraulic drives taken as an example)

a) Pareto diagram for specific mass of particles as a function of particle size

b) Share of inorganic particles in the contamination

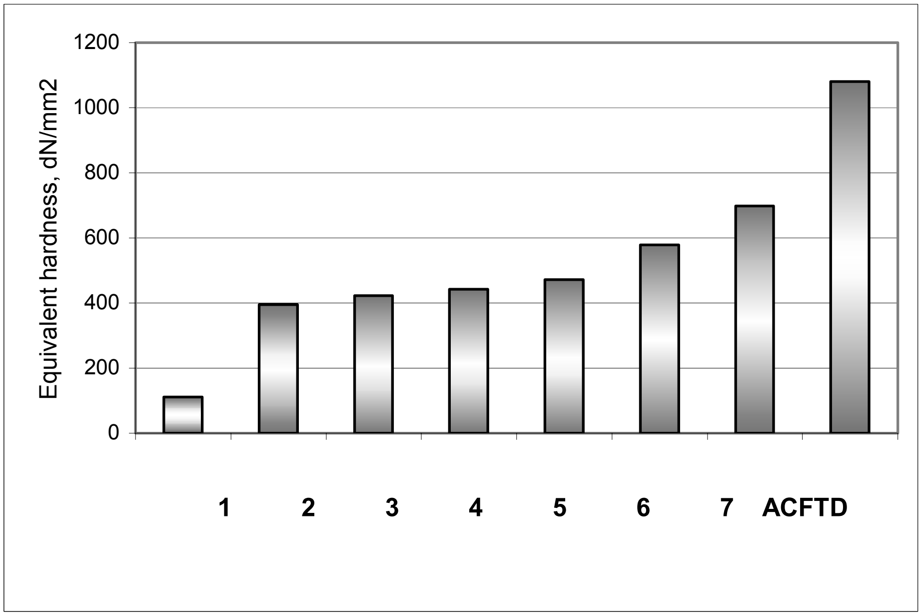

Fig. 8. Magnitudes of equivalent hardness of the contaminations:

1 – coal dust 2 - ground dust

Contamination in different hydraulic systems:

3 – construction machinery 4 – quarry equipment

5 – aircrafts 6 – mining machines

7 – machine tools

ACFTD - Air cleaner fine test dust (road dust)

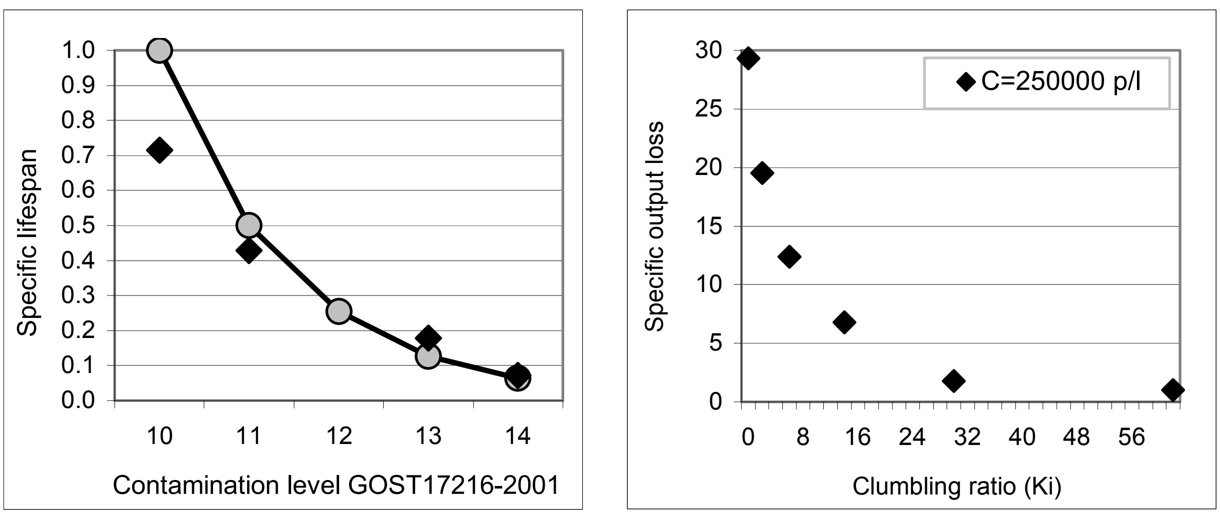

Fig. 9. Specific lifespan and output loss as a function of the parameters of contaminations

a) For contaminations of collinear granulometric (GOST17216-2001).

Gray circles – calculated, black rhombs – experimental data obtained from the field tests.

б) For contaminations of fan-shaped granulometric (10 class, GOST28028-89)