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Influence of Solid Particles as a Contaminants on Degradation Processes in Hydraulic Components or Systems

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Abstract

Authors of numerous papers in the field of testing and maintenance of hydraulic equipment, show that solid particles have the most destructive influence than other contaminants. Their biggest influence are on wearing processes of components with smallest gaps (1-10 um) such as pumps with or without flow regulation, proportional and servo-valves. Except wearing processes, depending on size and concentration, solid particles can cause flow blockage trough small size flow passages (orifices, flow regulators) but also physical and chemical degradation processes of hydraulic oil. This paper presents some of degradation processes which are direct consequence of inapropriate solid particle presence, and results of tests conducted under different working conditions to evaluate influence of particles on a degradation of contacting valve surfaces.

Key words: *Contamination, Hydraulics, Solid Particles, Wear*

1. INTRODUCTION

In order to achieve the most rational utilisation of the potential of modern hydraulic devices, which would also result in the increase in their total utilisation degree, one of the possible solutions could be the increase in working pressure. However, the increased working pressure will cause the proportional increase in energy losses within the system, especially the volume losses.Volume losses have multiple adverse effects on operation of the system, such as:

- decrease in the performing actuator speed,
- decreased possibility of accurate and precise positioning (operation of the system with increased oscillation),
- increased quantity of thermal energy in the system,
- increased pump operation costs caused by compensation of the lost quantity of hydraulic oil,
- decrease in total volume of working fluid in the system, and consequently frequent addition of the working fluid in the tank, etc.

Taking into account the importance of effects of losses on the operation of the system, the increase in efficiency has required some changes in the construction of components, chemical formulation of working fluids and the concept of maintenance of hydraulic systems.

The problem of volume losses is primarily solved using one of the sealing mechanisms:

- contact sealing (with sealing elements) and
- non-contact sealing.

Contact sealing is performed by insertion of a seal element made of suitable material, where the service life and construction of sealing elements will be different for dynamic (dynamic sealing elements) and static (static sealing elements) joints. Systems with non-contact seals are characteristic for internal sealing (i.e. separation of zones of different pressures) of dynamic surfaces. The mechanism of this type of sealing is based on the principle of partial energy expenditure contained in the fluid flowing through the clearance. Regarding the fact the fluid has energy (P) which is the function of the flow (Q) and nominal working pressure (p), the portion of the fluid flowing (with decreased quantity of the flowQ_i) through the clearance from the higher pressure zone toward the lower pressure zone, also has some quantity of energy (P_i). This energy (P_i) is opposed by the flow resistance energy (P_o), which is the function of the working fluid viscosity (η), and the size of axial (h_a) and radial (h_0) clearance. If the relation of the values (P_i) and (P_o) is:

- $P_i<P_o$ – the sealing is complete without any leakage flow, or

- $P_i > P_o$ – the sealing is partial, and the leakage flow is proportional to the relation of the values.

Calculation of the leakage flow through the clearance, for cylindrical contact pair (figure 1), can be performed using the following formula [4]:

$$q_l = \pm\pi \cdot v \cdot r \cdot h_0 + \frac{\pi \cdot r \cdot h_0^3 \cdot \Delta p}{6 \cdot \eta \cdot l} \cdot \left(1 + 1{,}5 \cdot \left(\frac{e}{h_0}\right)^2\right), \qquad (1)$$

where:

v – is speed of piston motion,

r – is piston radius,

h_0 – is nominal clearance *((D-d)/2)*, where *D* is – diameter of the cylinder hole, and *d* is – diameter of the piston,

Δp= p1 - p0 – pressure difference,

η – is dynamic viscosity of working fluid,

l – is the length of clearance (axial clearance - folding), and

e – is excentre.

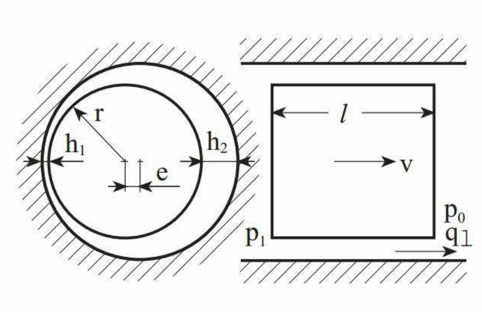


Figure 1. Geometrical parameters of non-contact sealing mechanism

This type of sealing mechanism is successfully used with assemblies with rotary, translatory or combined motions of components. We can single out the following examples:

- distributing valves – contact between piston and cylinder,
- piston pumps – contact between piston and cylinder, contact between drum and collector plate,
- gear pumps – contact between front surface of teeth and stator, contact between front surface of gear and side plates,
- vane pumps – contact between side plate and side of stator, etc.

It is right with these assemblies that the clearance size has great importance. Its values can vary depending on overall dimensions, construction (classical, proportional or servo component), type of the contact and working pressures. With the increase in working pressure, losses caused by leakage flow through clearances can be considerably increased for which reason, quite logically, the increase (axial) and decrease (radial) in clearances is introduced as a countermeasure. We should point out here that with older types of hydraulic components the sizes of radial clearances are bigger and consequently the leakage flow through clearances higher, which required operation under lower pressures. For the sake of higher efficiency, modern hydraulic systems operate at considerably higher working pressures with considerably decreased radial clearances, resulting in minimum leakage flow through clearances, or minimum volume losses [8].

However, right due to the decrease in clearance size in assemblies of hydraulic components (table 1), the impact of solid particles, as contaminants in fluid, on their operation and operation of the system as a whole, will be felt. Frequent occurrence of mechanical blockages or uneven operation of the components or the system, represent only a few of consequences caused by contamination and inadequate maintenance of oil filling. Research has confirmed that solid particles are contaminants showing the most destructive effects and that in a large number of cases where solid particles have been found in the fluid, they have been the main cause of the failure of hydraulic equipment and devices [1], [5].

Table 1. Plan of the experiment

Component		Gap size (μm)
Control valve	Servo	0,5 – 4
	Proportional	1 – 6
	Clasic	2 – 8
Piston pump	Between the piston and the cylinder	5 – 40
	Between control plate and cylinder barrel	0,5 – 5
Vane pump	Between vane tip and stator	0,5 – 1
	Between side surface of rotor and side plate of stator	5 – 13
Gear pump	Between front surface of gear tooth and stator	0,5 – 5
	Between side surface of gear and side plate of stator	0,5 – 5

2. SOLID PARTICLES AS CONTAMINANTS

Solid particles and other contaminants in the hydraulic system, can appear in different ways:

- penetration into the system from the surroundings (through damaged seals, joints),
- generation inside the system (due to wear and tear of parts),
- inadequate maintenance (inadequate filtering or delayed replacement of filter inserts),
- filling already contaminated oil into the system (oil that has been stored in a place with dirty atmosphere for a long period of time, or in a place with temperature oscillations),

- assembling the components that have not been cleaned enough of residues from their manufacturing (particles, chips, pieces of cotton rags) or
- improper assembling.

Presence of solid particles in large concentrations will intensify the wear process, especially with abrasion effects, so that nominal values of the clearances between elements with non-contact sealing, will become higher with time, as well as the volume losses according to the formula (1). In addition to the abrasive effect, solid particles will cause erosion mechanism of wear, which also may contribute to the failure of hydraulic components, however with considerably lower degree comparing to the abrasive mechanism of wear.

In addition to increased wear and tear of contact surfaces, solid particles may cause following:

- blockage of flaw surfaces of small cross-section (throttles, nozzles),
- improper operation of components (piston motion with twitches, increased friction between contact surfaces, incomplete sealing in non-return valves, etc.)
- catalytic process of degradation of physical and chemical properties of working fluid.

Considering the highly adverse effects of solid particles, manufacturers of hydraulic equipment recommend the required cleanliness level for smooth and trouble free operation of the components. The recommendations should be observed in order to extend the service life of the equipment and working fluid, which will result in considerably lower maintenance costs. Table 2 shows the recommendations of Eaton Vickers, as an example.

Recommendationsabout the cleanliness level, on the market of hydraulic components, differ from manufacturer to manufacturer, which leads to a conclusion that each manufacturer has his own method of determination of recommended cleanliness level. In some cases, the recommendations are non optimum. It can represent a problem for users, especially those who use components of different manufacturers. They have to maintain their systems in accordance with the requirements of their respective manufacturers. The non-existence of universal method of appropriate cleanliness level determination represents an important issue on global level [2], which could be solved with introduction of ISO 12669 standard (Hydraulic fluid power - Method for determining the required cleanliness level (RCL) for a system). Writing of the standard began in 2013 [7].

Table 2. Cleanliness classes according to ISO 4406/99 [6]

Eaton Vickers		
Component	Sistemi radnog pritiska do 210 bara	Sistemi radnog pritiska preko 210 bara
Constant displacement pumps and motors		
With gears	20/18/15 (Motor) 19/17/15 (Pump)	19/17/14 (Motor) 18/16/13 (Pump)
With vanes	19/17/14	18/16/13
With pistons	19/17/15 (Radial motor) 18/16/13 (Axial motor) 18/16/14 (Pumpa)	18/16/13 (Radial motor) 17/15/12 (Axial motor) 17/15/13 (Pump)
Variable pumps i motors		
With vanes	18/16/14	17/15/13
With pistons	17/15/13	16/14/12
Valves		
Electro-hydraulic	20/18/15	19/17/14
Cartrige	20/18/15	19/17/14
Proportional	18/16/13	17/15/12
Servo	16/14/11	15/13/10

To understand the effects of solid particles (i.e. cleanliness level of working fluid) on the decrease in working performances of hydraulic components, an experiment has been performed. The test component was directional control valve 4/2, mechanically activated.

3. SETUP OF EXPERIMENT

Figure 2. shows the scheme of experimental installation. The concept of installation is based on the principle of open hydraulic circuit with circulating oil with pre-defined cleanliness level. The hydraulic device consists of a tank of $V = 90\ l$ capacity, a gear pump with internal teeth of specific capacity $q = 6{,}5\ cm^3$, pressure filter of absolute filter fineness with factor $\beta_5 = 200$, and a heat exchanger for maintenance of required working temperature in the system. In addition to the above mentioned components, the hydraulic system also contains:

- throttle valve, to adjust working pressure in the system,

- safety valve, to limit the maximum value of
- working pressure,
- prevent oscillations of working pressure in the system,
- the test model was mechanically activated directional control valve 4/2.

The experiment has been performed with mineral based hydraulic oil of ISO VG 46 viscosity and HM quality level.

Plan of the experiment, i.e. the settings of working parameters of the experimental installation to test the effects of solid particles in working fluid on directional control valves, is shown in table 3.

Each of the three valves from table 3, with the same working properties (nominal diameter of the opening NO6, flow capacity *Q = 11÷20 l/min,* maximum working pressure *p = 320 bar*), is installed individually into the system to test the effect of impurities.

Table 3. Plan of experiment

Control Valve →	RV1	RV2	RV3
Working pressure (bar)	150		
Working temperature (°C)	45		
Number of cycles (-)	1 100 000		
Valve activation frequency (Hz)	1		
Oil cleanliness class for 4 μm particles	ISO 22	ISO 21	ISO 20

4. EXPERIMENTAL RESULTS AND DISCUSSION

Considering the fact that during the experiment very large number of data has been gathered, we will present only those data which reflect the effects of solid particles on the tested directional control valve in the best manner.

Results (regarding the change in clearance size) presented in table 4 have been obtained under constant maintenance of cleanliness level of working fluid required for 4 μm particles and constant working parameters such as, pressure, temperature and leakage flow (according to table 3), after 1 100 000 work cycles of thevalve.

According to table 2, the value of coefficient K_{Zi} expressing the relation of the clearance size at the beginning and at the end of the experiment, shows that the highest wear, considering all three tested cases, has been with Z_2 clearance. Similarly, we notice that with the increase in the cleanliness level of working fluid, the wear of contact surfaces of the piston and cylinder of the control valve has been dramatically decreased. In case of Z_2 clearance, with cleanliness level for RV1 valve according to ISO 22/17/13,

- accumulator of working volume *V = 0,5 litres* and gas pressure up to p_0 = *120 bars*, to

coefficient K_z is 5,03, whereas with the increase in cleanliness level to ISO 21/15/11 for RV2 valve, coefficient K_z has been decreased to 1,96, which represents 2,5 times lower value comparing with RV1 valve. In the third case, cleanliness level for RV3 valve has been increased to ISO 20/15/10, where coefficient K_z has decreased to 1,49 which is, comparing to RV1 valve, 3,4 times lower, and comparing with RV2 valve, 1,3 times lower. The next clearance size measured by wear level is Z_1. Its changes are considerably smaller comparing with Z_2, but not negligible.

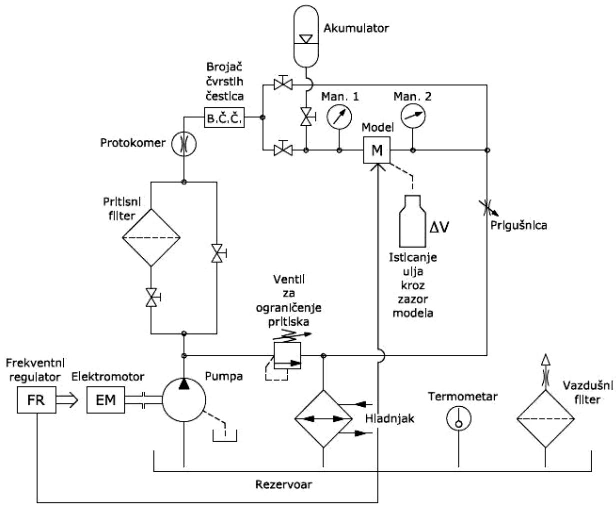


Figure 2. Experimental installation scheme

Table 4. Gap size change for examined valves

Control valve →	RV1	RV2	RV3
K_{Z1}	2,38	1,63	1,23
K_{Z2}	5,03	1,96	1,49
K_{Z3}	1,5	1,29	1,22
K_{Z4}	1,25	1,13	1,11

K_{Zi} - coefficient which express the gap size increase rate

Increase in clearance size, decreases the efficiency because volume losses are consequently higher (the losses are increased according to cubic function of clearance size – formula 1). Consequently, it will make it possible for larger solid particles sizes to enter the clearance, which can trigger a very intensive process of wear or a mechanic blockage of movable elements. In relatively short period, this process can result in the component failure. Generally speaking, the above described issues can shorten the service life of components, and cause the overall decrease in the system performance.

The volume of leakage flow through clearances represents the parameter that determines the volume efficiency rate of the component. Table 5 shows data related to the flow of fluid in static condition of valve operation (when the directional control valve is in neutral position, i.e. when all connections P, A, B and R

are closed) per each 100 000 cycles, at constant values, as shown in table 3.
Figure 3 shows curves describing the function of change of volume losses with the change of the number of working cycles.

Table 5. Change of volume losses

Br. ciklusa	RV1	RV2	RV3
	q_1 (ml/min)	q_2 (ml/min)	q_3 (ml/min)
0	7.1	6.4	6.84
100 000	8.4	7.7	7.95
200 000	9.7	8.1	8.41
300 000	10.5	8.6	8.39
400 000	10.97	8.5	8.84
500 000	10.8	8.7	9.21
600 000	11.1	9.4	9.98
700 000	11.93	9.94	10.32
800 000	12.8	10.5	10.61
900 000	13.2	10.7	11.31
1 000 000	13.96	11.7	12.22
1 100 000	16.5	13.7	13.7

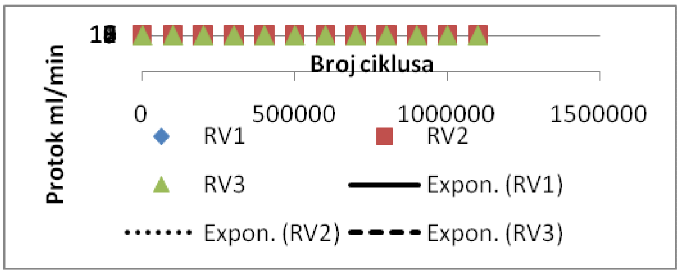
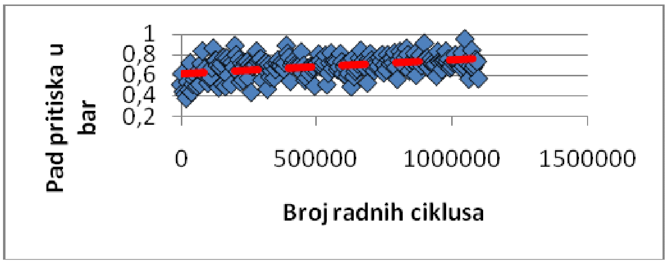
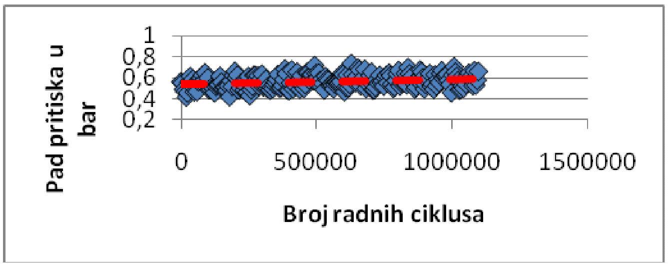


Figure 3. Comparative charts of volume loss for all three valves

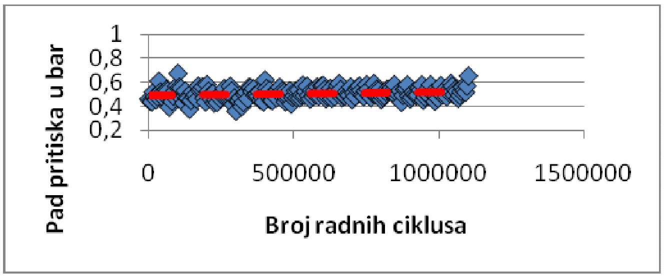
As you can see in table 5 and figure 3, the highest volume losses have been obtained in operation of RV1 valve with oil according to ISO 22/17/13. The main reason for this is worn contact surfaces of working elements of the directional control valve. Unlike RV1, with RV2 (ISO 21/15/11) and RV3 (20/15/10) valves, volume losses are considerably lower, because of oil cleanliness and considerably lower wear and tear of contact surfaces.
Volume losses represent the main reason for decrease in the system response speed, decrease in preciseness and accuracy of positioning of working elements, impossibility to reach the designed speed of working elements, etc.
Pressure drop in the components represents the local loss of hydraulic energy that is automatically transformed in thermal energy, due to the overcoming of obstacles present on the surface along which the fluid flows.
Considering the fact that during the experiment very large number of data has been gathered, we have presented only a graph showing the pressure drop values during the flow of fluid through the directional control valve in operating position, in figure 4.



a) Pressure loss for RV1



b) Pressure loss for RV2



c) Pressure loss for RV3

Figure 4. Comparative charts of pressure loss for all three valves

Increase in pressure drop will be caused also by the increase in clearance size, i.e. by the leakage of fluid through clearances, which means that higher fluid leakage will cause higher pressure drop. Another important point that we can see on comparative charts is that cleanliness level of working fluid influences the measuring of pressure drop values, i.e. the dissipation of results around the average value is higher when the cleanliness level of working fluid is lower. Figure 5 shows the interpretation of the measuring results through normal distribution with the aim of showing more clearly differences in terms of dissipation of results around the average value.
In the case of RV1 valve, using oil of the lowest cleanliness level, standard deviation σ is the highest, and with the increase of oil cleanliness level, cases RV2 and RV3, the deviation decreases.

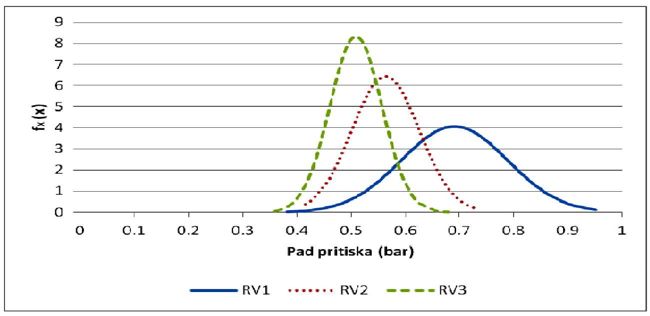


Figure 5. Normal distribution of pressure loss data

Table 6. Values of standard deviation for all three valves

	RV1	RV2	RV3
$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2}$	**0,09811**	**0,06187**	**0,04790**

It is supposed that the deviation, in addition to the measuring uncertainty of sensors, occurs also as a result of high quantity of impurities that, with theirchaotic movement in case of the change of fluid flow direction, represent additional resistance (barriers) which the fluid has to overcome losing in this way part of its energy. It is also supposed that decrease in deviation as a result of the increase in cleanliness level has its limits, i.e. the increase of oil cleanliness level can to a certain extent enable more precise reading of results by means of measuring instruments. However, in order to be able to determine the limit, experiments focused only on observation of that phenomenon for different cases, should be performed additionally.

Pressure drop and volume losses cause the decrease in efficiency of hydraulic systems and accordingly in their competitiveness in relation to other driving devices. For this reason, in modern, sophisticated hydraulic systems, considerable attention is paid to the conditioning of working fluid, which represents a component of multifunctional importance.

4. CONCLUSION

The experimental work has shown that cleanliness level plays an important role in the extending or shortening of the service life not only of directional control valves, but also of all other components in a hydraulic system. Improper maintenance of cleanliness of working fluid has the most adverse effects on control devices (control groups, pumps, proportional and servo valves), which have very small clearance values. It decreases operation performances of the system and shortens its service life, and consequently increases maintenance and operation costs.

Due to difference in recommendations among manufacturers of hydraulic components, an optimal service life of a component has not been clearly defined yet. For this reason, in 2013 the developing an ISO standard that would solve the problem was initiated. The standard should impose unique regulations for the maintenance, i.e. conditioning of the working fluid and in this respect, of the entire system as a whole.

Maintaining of the required cleanliness level of working fluid, considerably contributes to the optimization of the service life of fluid and the system as a whole. Aside from optimization, from environmental aspect, additional costs related to transport and disposal of used oil and components will be reduced.

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Uticaj čvrstih čestica kao zagađivača na procese degradacije u hidrauličkim komponentama ili sistemima

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Primljen (16.06.2014.); Recenziran (16.01.2015.); Prihvaćen (02.03.2015.)

Rezime

Autori brojnih radova na polju testiranja i održavanja hidrauličke opreme pokazuju da čvrste čestice imaju najdestruktivniji uticaj u odnosu na ostale zagađivače. Njihov najveći uticaj jeste na procese habanja komponenti sa najmanjim pukotinama (1-10 um), kao što su pumpe sa ili bez regulacije protoka, proporcionalni i servo ventili. Osim kod procesa habanja koji zavise od veličine i koncentracije, čvrste čestice mogu da izazovu blokadu protoka kroz otvore male veličine i protoka (prigušnice, regulatori protoka), ali i na fizičke i hemijske procese degradacije hidrauličkog ulja. Ovaj rad predstavlja neke od procesa degradacije koji su direktna posledica neadekvatnog prisustva čvrstih čestica, kao i rezultate testova koji su izvršeni u različitim radnim uslovima kako bi se procenio uticaj čestica na degradaciju kontaktnih ventilskih površina.

Ključne reči: *kontaminacija, hidraulika, čvrste čestice, habanje*