Wear Particles in the Hydraulic System and Their Impact on the Gear Pump Efficiency

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Wear particles in hydraulics accelerate the wear of elements in a gear pump. The contact between the gear and the pump housing is particularly exposed to wear. With an increase in the amount of particles in the oil, the volumetric efficiency of the pump deteriorates rapidly in the aforementioned contact and the useful life of the pump is thus reduced. The paper shows the calculation of the concentration of wear particles in the oil according to the ISO 4406 standard using the example of 20/19/18. Adding wear particles and sustainable testing at different concentrations affect the rate of decrease in the volumetric efficiency of gear pumps when increasing the concentration of particles in the oil.

Keywords:
wear particles,
gear pumps,
calculation of concentration,
test procedure,
volumetric efficiency

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1 Introduction

Particles in hydraulic fluid are causing up to 70 % of failures of hydraulic component therefore cleanliness of oil is an important parameter [1]. Esteves et al. [2] described general influence of particle size distribution regarding wear mechanism factors.

The degradation of the pump is reflected in the increase of micro-particles in the liquid, leading to a decrease in the quality of the liquid, which is a class that does not meet prescribed standards. Solid particles bring specific wear mechanisms to the contact surfaces (abrasion, erosion, material fatigue, etc.) [3], [4]. Karanovič et al. [3] describe the influence of solid particle impurities in the radial gap between the control piston and the housing of the valve: due to three-body abrasion, they wear away material and increase the gap. As the gap increases, so does the flow through the gap (internal leakage), which causes even more particles to travel through the gap. This further increases friction and accelerates the wear process. Pressure losses in the gaps and the friction of particles cause local heating. To reduce wear intensity, optimal cleanliness is required. Jung-Hun et al. [5] studied the influence of particle composition and quantity. Three different types of particles in oil were used and gear pumps were tested with an output of 14.5 cm^3/rev. at a pressure of 1.6 MPa, rotational speed of 7000 rpm, and temperature of 120 °C. Type 2 particles contain over 97 % of SiO_2 with an average particle size of 27 µm to 31 µm. Type 7 particles contain 34 % to 40 % particles of the same size of SiO_2. A comparison of the achieved flow rates of the pumps before and after the addition of 25 g of powder particles at different shaft rotational speeds shows that particles with a higher content of SiO_2 wear down the elements more. The researchers imply that adding of particles reduce the performance of gear pumps.

The analysis of particle size distribution is an established procedure and clearly presented in standard ISO 4406 [6]. But there is also volume- and mass-based distribution that are in practical use and described in literature [7] according to standard ISO 9276.

The purpose of this paper is to present the transformation of cleanliness ISO 4406 code to adding appropriate mass for achieving the desired cleanliness in hydraulic oil, demonstrate the degree of decrease in volumetric efficiency in gear pumps and to predict the failure of the gear pump due to oil cleanliness.

2 Materials and methods

2.1 Adding particle mass to achieve appropriate concentrations

The mass of particle addition to achieve the appropriate fluid cleanliness classes was estimated based on the calculation of particle volume and particle density. It was assumed that the particles were in the form of a ball with a nominal diameter, made of two materials, namely steel with a density of 7874 kg/m^3 and quartz sand (SiO_2) with a density of 2650 kg/m^3.

The calculation of the mass of steel particles is presented using the example of two cleanliness classes. Transition from cleanliness 16/15/14 to cleanliness 20/19/18 according to ISO 4406 in a system with 13 L of hydraulic fluid. Initially, it is necessary to determine how many particles need to be added to move from class 16 to class 20. ISO 4406 shows that in class 16 there are 480 particles (mean particle number) larger than 4 μm, while in class 20 there are 7500 particles larger than 4 μm in 1 mL of liquid. Therefore, it is necessary to determine the difference in particle number for the move from class 16 to class 20 using equation (1).

$$\Delta x_{4\,\mu\mathrm{m}} = x_{\mathrm{H}\,4\,\mu\mathrm{m}} - x_{\mathrm{L}\,4\,\mu\mathrm{m}} = 7500\,\frac{\mathrm{particles}}{\mathrm{mL}} - 480\,\frac{\mathrm{particles}}{\mathrm{mL}} = = 7020\,\frac{\mathrm{particles}}{\mathrm{mL}} \tag{1}$$

Where:

- $\Delta x_{4\mu\mathrm{m}}$ [/]… the difference between the number of particles between two classes greater than 4 μm,
- $x_{\mathrm{H}\,4\mu\mathrm{m}}$ [/]… the number of particles in the higher class (in this case 20. class),
- $x_{\mathrm{L}\,4\mu\mathrm{m}}$ [/]… the number of particles in the lower class (in this case 16. class).

The procedure is repeated for the next two classes (particles larger than 6 μm and 14 μm). The volume of the sphere is given by the particle diameter and the average particle volume between the two particle diameters can be calculated. Equation (2) gives the mean value of the volume of the spheres between 4 μm and 6 μm.

$$V_{\text{avg 4 µm}-6\text{ µm}} = \frac{V_{4\text{ µm}} + V_{6\text{ µm}}}{2} = \frac{\left(\frac{4 \cdot \pi \cdot r_{4\text{ µm}}^3}{3} + \frac{4 \cdot \pi \cdot r_{6\text{ µm}}^3}{3}\right)}{2} = \tag{2}$$

$$= 7.33 \cdot 10^{-17}\ \text{m}^3$$

Where:

- $V_{\text{avg 4 µm}-6\text{ µm}}$ [m³]…the mean value of the volume of the balls between 4 µm and 6 µm,
- $V_{4\text{ µm}}$ [m³]… volume of a sphere with radius 4 µm,
- $V_{6\text{ µm}}$ [m³]… volume of a sphere with radius 6 µm,
- $r_{4\text{ µm}}$ [m]… radius 4 µm particle ($2\text{x}10^{-6}$ m),
- $r_{6\text{ µm}}$ [m]… radius 6 µm particle ($3\text{x}10^{-6}$ m).

For each particle class, it is necessary to determine the mean volume value. For example, between 4 µm and 6 µm, the volume value of the spheres is $7.33\text{x}10^{-17}$ m³, and the weight is expressed by considering the density of the material, in our case steel. If we additionally multiply the mean weight of the spheres by the number of calculated particles, we obtain the concentration of particles (c) occurring in the size range from 4 µm to 6 µm (Equation (3)).

$$c_{\text{particles 4 µm}-6\text{ µm}} = V_{\text{avg 4 µm}-6\text{ µm}} \cdot \rho_{\text{Fe}} \cdot \Delta x_{4\text{ µm}} = 0.026\ \frac{\text{g}}{\text{L}} \tag{3}$$

If we assume an exponential distribution and divide the particles into groups from 4 µm to 6 µm, from 6 µm to 14 µm, from 14 µm to 21 µm, from 21 µm to 26 µm, and so on up to 100 µm, and add the values and divide by the volume of the liquid in which the particles are located, we obtain the mass of particles that needs to be added to the system to ensure adequate cleanliness (equation (4)).

$$m_{\text{particels}} = \frac{c_{\text{particles 4µm−6 µm}} + c_{\text{particles 6 µm−14 µm}} + \cdots + c_{particles\ \text{91 µm−100 µm}}}{V_{\text{fluid}}} = \frac{c_{\text{particles 4µm−100 µm}}}{V_{\text{fluid}}} = \frac{0{,}146\,\frac{\text{g}}{\text{L}}}{13\ \text{L}} = 1.89\ \text{g} \quad (4)$$

We determined that 1.89 g of particles were required to be added to a 13 L hydraulic fluid system to go from a fluid cleanliness of 16/15/14 to a fluid cleanliness of 20/19/18. We assumed that the particles were steel and that the size distribution of the added particles matched the calculated differences in the particles to be added.

2.2 Testing procedure and test rig for gear pumps

The durability testing of gear pumps was done with the control adding of wear particles to the hydraulic system. Table 1 shows concentration of wear particles in 13 L of hydraulic oil ISO VG 46, used to carry out the tests.

Table 1: Concentration of wear particles in oil used for durability tests of gear pumps.

	Test 1	Test 2	Test 3	Test 4	Equivalent to cleanliness 20/19/18
Added mass of wear particles [g]	8.00	5.04	3.51	2.08	1.89
Wear particles concentration [g/L]	0.615	0.387	0.270	0.160	0.146

The rig (Figure 1) for testing gear pumps is consisting of conical reservoir. The design of reservoir is restricting particles to settle and therefore even distribution of particles in the fluid is present in the oil. Gear pump (the specimen) sucks the oil from reservoir and pushes it to 4/3 directional valve with solenoids and hydraulic aluminium block. Valve redirects flow to two pressure relief valves that are loading the pump at 22 MPa. The flow goes onwards to priority valve where oil has two paths. It can return directly back to reservoir, or it goes through the filter back to reservoir. This priority valve is there to remain cleanliness at desired level.

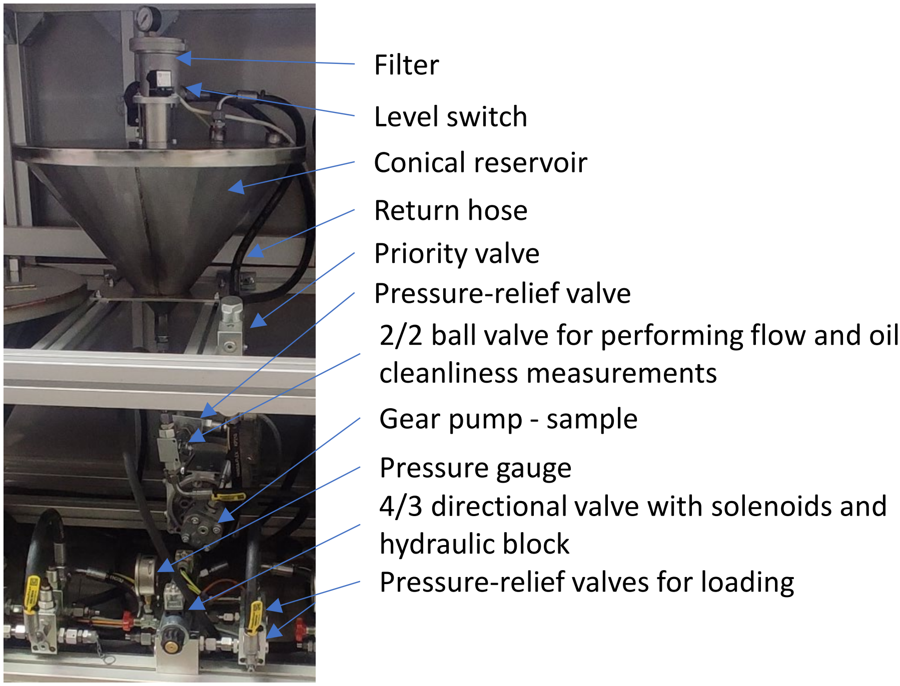

Figure 1: Test rig for durability testing of hydraulic gear pumps with wear particles.

3 Results

The pump tested at a concentration of 0.387 g/L (Figure 2) experienced the first major drop in volumetric efficiency at 50 h of operation, when at 0 MPa pressure the pump achieved an efficiency of 0.97, at 5 MPa it achieved an efficiency of 0.90, at 10 MPa it achieved an efficiency of 0.81, at 15 MPa it achieved an efficiency of 0.77, at 20 MPa it achieved an efficiency of 0.71 and at 25 MPa the efficiency dropped to 0.48. After 429 h of operation the efficiency dropped to 0 at 25 MPa pressure, while the efficiencies at lower pressures did not change significantly. After 546 h of operation the efficiencies dropped to 0 also at 150 MPa and 200 MPa. The oil temperature in the tank during the test was 60 ±4 °C.

Figure 3 compares volumetric efficiencies at different concentrations of wear particles in the oil at different pressures. It is important to note that the pump service lives and thus the operating times are different. Figure 3 shows that with increasing pressure, the efficiency decreases at the same pressure.

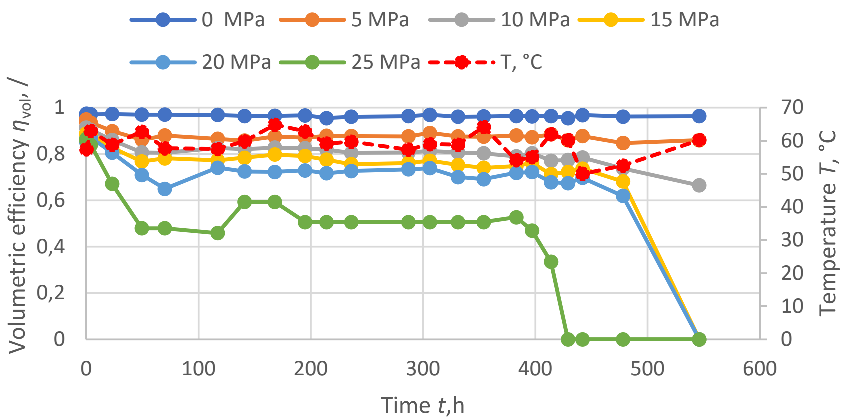

Figure 2: Measured volumetric efficiency of a pump tested with wear particles at a concentration of 0.387 g/L at a durability test site.

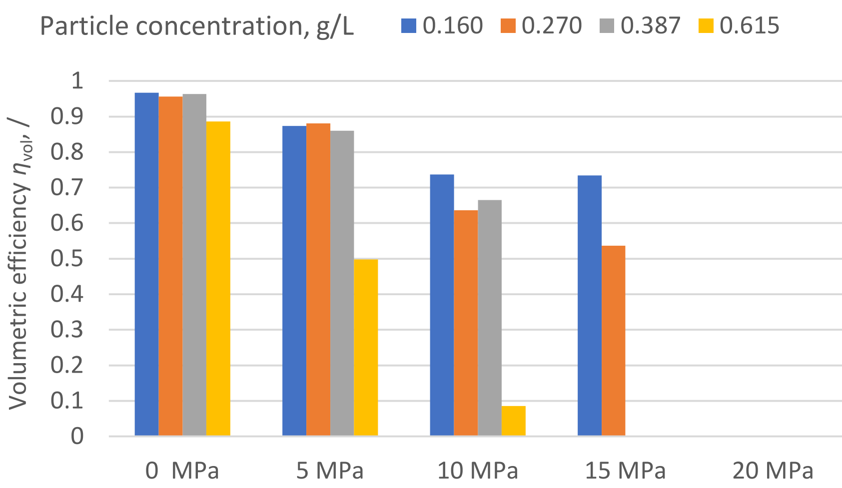

Figure 3: Measured volumetric efficiency of pumps tested with wear particles at the end of the test at different concentrations on a durability test rig.

The cleanliness of the oil according to ISO 4406 was monitored during each pump test with wear particles. A deterioration in cleanliness means that more particles have entered the oil and therefore, according to ISO 4406, the particle counter shows higher classes according to which cleanliness is defined. In the case of an improvement in cleanliness, this means that there are fewer particles in the oil (and consequently lower classes) than at the beginning of the test due to appropriate filtration of the hydraulic oil in the system. The clean oil measurements taken before each pump test were 16/15/12 and 15/14/12, respectively (Figure 4). The oil cleanliness classes after 20 minutes of testing the pump with wear particles at a concentration of 0.387 g/L increase sharply from the initial values of 16/15/12 to the value of 22/22/21. After 70 hours of pump operation, the second class, which records the number of particles larger than 6 μm, and the third class, which records the number of particles larger than 14 μm, are reduced by one class so that the cleanliness stabilizes at 22/21/20. At the end of the test, the cleanliness is 22/21/19 after 546 hours of operation.

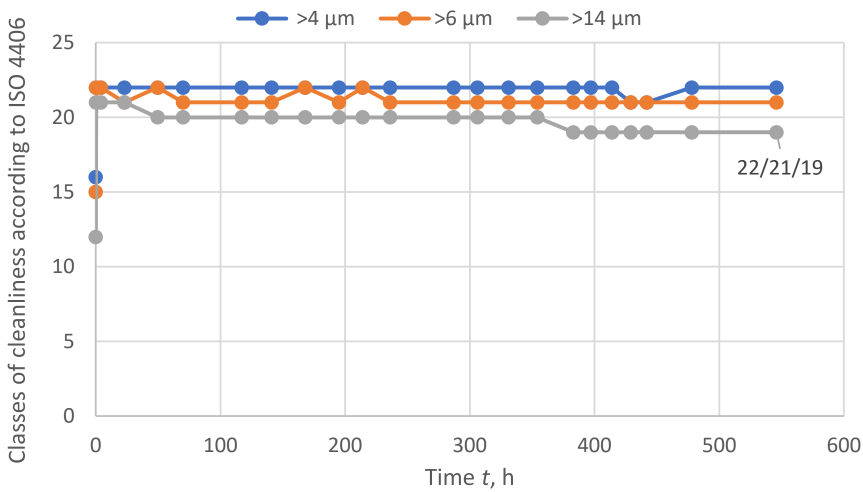

Figure 4: Measured oil cleanliness of a pump tested with wear particles at a concentration of 0.387 g/L.

4 The effect of particles on reducing volumetric efficiency

The consequence of the gradual decrease in the volumetric efficiency of the pump is a gradual increase in internal leakage due to wear. By adding particles to the system, we accelerate the wear processes in the pump. This was proven by durability tests that were carried out without adding particles at constant filtration, with the addition of wear particles.

In the durability test without adding particles and with constant filtration, the pump operated flawlessly for 7079 h, which is 295 days at 24-hour continuous operation. After the test, the volumetric efficiency was 0.84 at a pressure of 20 MPa.

All volumetric efficiencies of durability tests of pumps with wear particles were presented, and for an easier and more constructive understanding. A comparison of regression lines was made, which describe the trend of decreasing volumetric efficiency with operating time at different concentrations of wear particles. An example of such lines in tests with wear particles is shown in Figure 5. At a pressure of 20 MPa, the slope of the curve for wear particles with a concentration of 0.270 g/L is much smaller than for a particle concentration of 0.615 g/L, indicating a faster decrease in volumetric efficiency at a higher concentration of wear particles in the oil. For comparison, Figure 5 also shows a measurement without the addition of particles (WITHOUT).

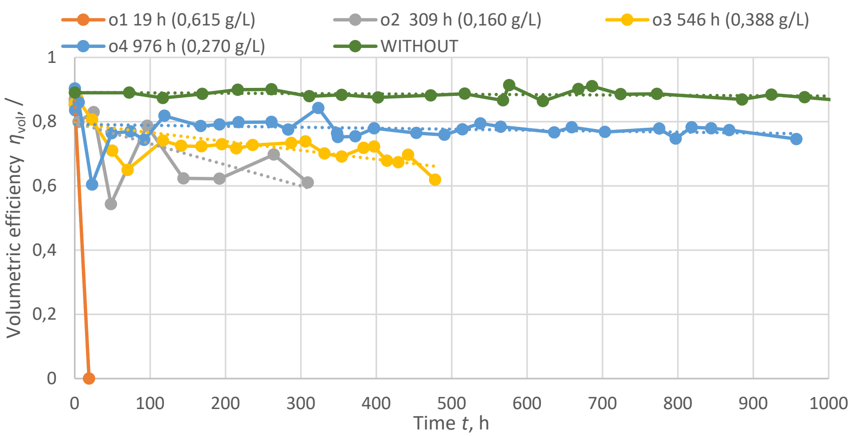

Figure 5: Results of volumetric efficiency measurements for pumps at 20 MPa pressure tested with wear particles at different concentrations and comparison without adding particles (WITHOUT).

Figure 6 shows the slope of the regression lines in pump tests with different concentrations of wear particles. The slope of the lines varies at 0.045 1/h at a concentration of 0.615 g/L, 0.0003 1/h at a concentration of 0.388 g/L, 0.00003 1/h at a concentration of 0.270 g/L and 0.0007 1/h at a concentration of 0.160 g/L. We find that at lower concentrations of wear particles, the volumetric efficiency does not decrease as rapidly, as the particles deform and have a smaller impact on the efficiency and do not significantly affect the pump, and it turns out that they do not have a significant impact on the remaining hydraulic components either. When a sufficient amount of wear particles appears in the system, the volumetric efficiency of the pump begins to decrease more rapidly, as can be seen in Figure 6.

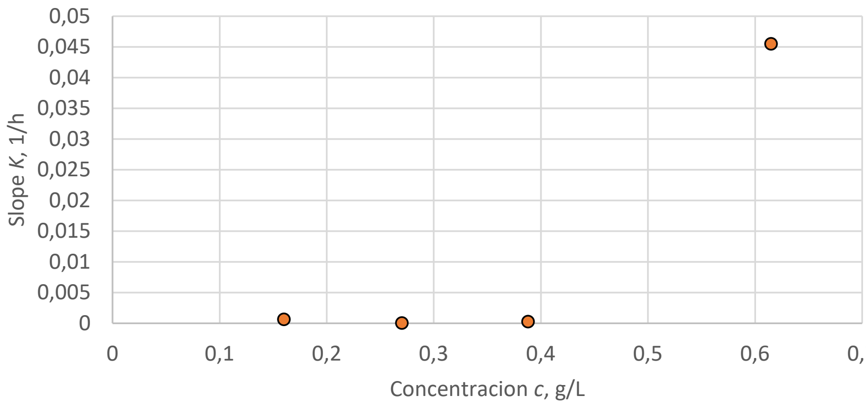

Figure 6: Slope of the lines at a pressure of 20 MPa for pumps tested with wear particles at different concentrations.

5 Conclusion

The calculation of mass of added particles to reach desired cleanliness of ISO code 20/19/18 and thus the concentration was represented. The concentration of particles was 0,146 g/L and the amount of mass added was 1,89 g in 13 L of oil. Research shows that the volumetric efficiency of a gear pump decreases slowly, with a more pronounced acceleration at higher concentrations. The slope of the regression lines describing the decrease in volumetric efficiency varies depending on the particle concentration. A higher concentration of wear particles causes a faster decrease in efficiency, which is consistent with the expected accelerated effect of wear. The results of the research allow the determination of an acceleration factor based on the measured service life of pumps tested at different particle concentrations. The acceleration factor for tests at typical oil cleanliness in the industry is also described.

Acknowledgments

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