Researches concerning the hydraulic oil degradation process in gear pumps

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Abstract. The paper investigates the degradation and contamination level of the hydraulic oil used on an endurance stand for testing two different types of gear pumps. Experimental results have been obtained using a Brookfield CAP2000+ viscometer, for determining the oil rheological parameters. Also, the paper presents the Parker CM Laser Particle Analyser used for measuring the size and density of the oil wear particles. The results focused on lubricant analysis represent practical ways to apply predictive and proactive maintenance for hydraulic gear pumps, but also for other hydrostatic equipment.

Keywords: *gear pumps, oil, degradation*

1. Introduction

Oil analysis has always been considered as one of the basic procedures of preventive maintenance, with focuses, in particular, on determining the optimum time needed to replace oils and lubricants. It should be noted that modern tools used in industrial maintenance can perform measurements and analyses in real time, in situ and online, but the analysis of oil and lubricant samples is based on laboratory services [1], [2]. The analysis of hydraulic oils can be successfully included in testing procedures, specific to predictive maintenance that examine the safety of machines and equipment in various fields of activity [3].

The maintenance of lubrication systems in machines relies on periodic inspection and lubricant change [4], [5]. Hard contaminants or soft particles appear in the hydraulic oil of the machines, but also air, water, heat or various substances can influence its properties. Researches in the direction of establishing the link between oil contamination with particles and the occurrence of failures in hydraulic drive systems are now more and more numerous [6].

In this respect, we can mention the research carried out by Stamatios S. Kalligeros [7] on used oils of hydraulic lifts, or by Polychronis S. Dellis [8], on the automatic spectrometry of hydraulic oils used in aircraft in order to prevent engine failures. Alabi and the collaborators predict the failure of an equipment, with the help of a real-time lubricating oil analysis [9]. Amin Almasi described particle analysis methods and an online oil monitoring and highlights that substantial savings can be achievable through an effective oil analysis program [10]. Tatiana Minav and the collaborators made an evaluation of an electro-hydraulic system and a discussion on the usage of hydraulic oil by non-road mobile working machines in sub-zero conditions [11].

In many situations, hydraulic gear pumps are contaminated with various solid particles. These produce fine, abrasive traces of wear, normally observable only under a microscope. Particles with a diameter of less than 5 μm are very abrasive and as they change to a muddy appearance over time, they can endanger pumps and their components. The uncontrolled presence of such particles must be avoided in hydraulic installations, because they act as a grinding medium. At INOE 2000-IHP Bucharest,

researches in this direction was conducted by A. D. Marinescu and collaborators first with the help of the infrared thermography method [12], and then with the help of the vibration method, [13].

2. Experimental stand and methodology

This article follows the two predictive maintenance methods shown above, used in the monitoring of hydraulic gear pumps, through joint researches initiated by specialists and professors from INOE 2000 Bucharest and University POLITEHNICA of Bucharest concerning oil analysis.

In the year 2020, at the Romanian company SC Hesper SA Bucharest, two types of hydraulic gear pumps, in endurance tests were monitored, by the paper authors. According to the manufacturer's coding, these pumps, of 05 series are the following:

- HP0505-0,5+1,5-1-0,2-6-C-06-2, 11 UA (P1 pump), Fig. 1.
- BHP 05-05-010 UB, 01 TC (P2 pump), Fig. 2.

Figure 1. P1 Pump [14]

Figure 2. P2 Pump [14]

The endurance stands of the pumps (Fig. 3 and Fig. 4) are equipped with three hydraulic filters to ensure the quality of the working fluid, more precisely a H46 EP oil.

Figure 3. P1 pump stand endurance

Figure 4. P2 pump stand endurance

The H46 EP mineral oil, is an additive hydraulic oil for extreme pressure, and meets the requirements of the specifications: DIN 51524/ Part 2 HLP, AFNOR NF E 48-603 HM, Sperry Vickers I-286-S, Denison Filterability TP 02100, US Steel 127, STAS 12023-82 [15].

In order to monitorise the hydraulic gear pumps, two different ultramodern working instruments were used, namely: the Parker CM laser particle analyser (Fig. 5) and the Brookfield CAP2000+ viscometer (Fig. 6).

Figure 5. Parker Laser CM particles analyzer

Figure 6. Brookfield CAP2000+ viscometer

The Parker CM laser particle analyser (fig. 5) allows a 2-minute contamination test procedure. It's made of a particle monitor designed to be used in the field. Multi-standard ISO,NAS, AS4059E and GOST 17216 cleanliness reporting, data entry, data graphing and integral printing are all standard on this world proven contamination monitor.

The main product features are indicated according to the technical sheet of the manufacturer [16]:

- Special 'diagnostics' are incorporated into the icountLaserCM microprocessor control to ensure effective testing.
- Routine contamination monitoring of oil systems with icountLaserCM saves time and saves money.
- Contamination monitoring is possible during application operation - icountLaserCM saves on production downtime.
- Data entry allows individual equipment test log details to be recorded.
- Data retrieval of test results from memory via hand set display.
- Automatic test cycle logging of up to 300 tests can be selected via hand set display.
- Totally portable, can be used as easily in the field as in the laboratory.
- Automatic calibration reminder.
- Instant, accurate results achieved with a 2 minute test cycle.
- Data entry allows individual equipment footprint record.
- Data graphing selectable via the integral printer.
- Auto 300-test cycle logging via LCD handset input.
- RS232 to USB computer interface.
- Limit level output to control peripheral equipment such as off-line filtration via internal relay limit switches.
- Auto-testing allows for the conducting of automatic sequencing tests on flushing systems for example.
- Memory access gives test search facility

The Brookfield CAP2000+ viscometer (Fig. 6) is a compact analysis laboratory instrument that can be used to test products over a wide range of temperatures and viscosities, and which has the following characteristics:

- • viscosity range: 0.2....15 Poise;
- • shear rate: 10...13 s⁻¹;
- • temperature 5-75 °C, or 50- 235 °C;
- • rotation speed 5-1000 rpm;
- • small sample <1 ml;
- • integral temperature control;
- • an optional software CAPCALC 32, for complete control and data analysis.

3. Results

3.1. Analysis of contaminant particles

With Parker CM laser particle analyser, experiments were performed separately for the oil samples taken from the endurance stands of P1 and P2 pumps. The analyzer printer provided for each performed analysis a special receipt indicating the number of solid contaminant particles in the oil samples, having a diameter d in the range of (4 ... 70) μm . All the obtained results from the analysis of the oil samples of the two pumps P1 and P2 were listed separately in the Table 1 and Table 2.

Table 1. Monitoring of P1 pump.

Test Number	Date	Number of solid contaminants, in 100 ml oil samples					
		$d = (4 \dots 6) \mu\text{m}$	$d = (6 \dots 14) \mu\text{m}$	$d = (14 \dots 21) \mu\text{m}$	$d = (21 \dots 38) \mu\text{m}$	$d = (38 \dots 70) \mu\text{m}$	$d > 70 \mu\text{m}$
1	05/02/2020	1403664	974014	259064	116878	18192	1125
2	07/02/2020	1366371	887264	96842	16578	4192	259
3	17/02/2020	1400614	905721	143964	45907	5521	341
4	24/02/2020	1327150	759992	52257	12528	1600	98
5	06/03/2020	1606700	926778	65307	13828	1664	102
6	13/03/2020	1585857	821485	23807	3535	700	43
7	20/03/2020	1630407	868892	26871	4335	607	37
8	15/07/2020	2039592	775442	12742	2671	485	30
9	17/07/2020	2611414	1455735	76507	10264	857	53

Table 2. Monitoring of P2 pump

Test Number	Date	Number of solid contaminants, in 100 ml oil samples					
		$d = (4 \dots 6) \mu\text{m}$	$d = (6 \dots 14) \mu\text{m}$	$d = (14 \dots 21) \mu\text{m}$	$d = (21 \dots 38) \mu\text{m}$	$d = (38 \dots 70) \mu\text{m}$	$d > 70 \mu\text{m}$
1	04/06/2019	1308178	400542	9085	3185	1121	69
2	10/06/2019	1430071	1094278	457542	210392	59314	3669
3	10/06/2019	1363457	1024407	422328	189150	52414	3242
4	10/06/2019	1559421	487650	13921	4357	1007	62
5	10/06/2019	1561271	487835	12350	3542	764	47
6	24/06/2019	1349300	383728	32428	12764	3292	203
7	24/06/2019	1307342	345814	34164	13735	3835	237
8	02/07/2019	1346250	408171	45650	17007	5600	346
9	02/07/2019	1336057	408578	47250	16864	5357	331
10	11/07/2019	1236678	291721	7678	2814	642	39
11	23/07/2019	1248728	334685	9764	3192	585	36
12	22/08/2019	1243300	314607	12557	4557	864	53
13	05/09/2019	1152842	319300	27464	11514	2278	140
14	10/09/2019	1154557	290657	13500	4957	914	56
15	19/09/2019	2453142	1339885	65164	13992	2121	131
16	27/09/2019	893692	216971	10657	4064	850	52
17	18/10/2019	1062800	389142	31521	11871	2635	163
18	01/11/2019	737407	236314	19035	7935	2107	130

Test Number	Date	Number of solid contaminants, in 100 ml oil samples					
		d = (4 ... 6) μm	d = (6 ... 14) μm	d = (14 ... 21) μm	d = (21 ... 38) μm	d = (38 ... 70) μm	d > 70 μm
19	22/11/2019	591578	164757	6792	2485	550	34
20	13/12/2019	1420257	1049650	350835	149642	11092	686
21	18/12/2019	1124900	623764	54964	15871	3242	200
22	10/01/2020	1016107	578250	52542	23178	10135	626
23	05/02/2020	1151692	550957	21528	7157	2542	157
24	07/02/2020	1188914	690671	61157	14485	2942	181
25	17/02/2020	1144214	637850	40507	7107	2300	142
26	24/02/2020	957750	444607	20521	7214	2414	149
27	06/03/2020	1335950	681400	40657	10650	2314	143
28	13/03/2020	1353321	691785	48628	23014	15814	978
29	20/01/2020	1279535	640528	53292	23300	9357	578
30	15/07/2020	1558407	589071	67414	28078	4207	260
31	08/09/2020	1080121	324278	28700	12335	2442	151

The overtime evolution of oil contaminants particles number function of their diameters is graphically presented, using an unique coordinate system. Thus, the diagrams corresponding to the P1 and P2 pump monitoring were drawn in Fig. 7, respectively in Fig. 8. The construction of the pump P2 diagrams was done taking into account only nine representative tests for its monitoring, registered in Table 2.

Figure 7. P1 pump over time oil contaminants evolution

Figure 8. P2 pump over time oil contaminants evolution

3.2. Rheological tests for fresh and used oil samples

Monitoring of the oil state in a drive unit can be useful for assessment of its damage and defects. One of the most important parameters of lubricating oil is its viscosity. Excessive changes in the oil viscosity value can indicate damage of the drive unit and/or its defects [17], [18]. Significantly lower viscosity can indicate the presence of fuel or coolant in it [19].

The use of the Brookfield rotational viscometer with cone-disk working geometry, allowed the determination of the analyzed oil samples rheological properties. Fig. 9 shows the principle on which the viscometer is designed and made. The main parts of the viscometer are the cone and the disk, between which the oil sample is inserted. A rotational motion with angular velocity ω is imprinted on the cone; the disk is fixed. The viscometer is provided with transducers necessary for oil flow measurement: shear rate, shear stress and temperature.

Figure 9. Rotational viscometer principle

Regarding the rheological experiments, three types of tests were performed:

- Test for homogenization;
- Test for determining the parameters of the rheological model;
- Test for variation of the oil apparent viscosity with temperature.

The test for homogenization was performed for a H46 EP fresh oil sample (Fig. 10). The homogenization test is a time test, done at different speeds of the viscometer, in order to establish the necessary time for measurement stabilization. This time is necessary for designing the rheological experiment. The following results were obtained (Table 3):

Table 3. Time for homogenization

Rotation speed, rpm	Time, s
100	25
200	20
500	25

Figure 10. Homogenization time for fresh oil sample, at different rotation speeds

To determine the lubricant rheological model for fresh oil and used oil on P1 and P2 pumps, it was used an “imposed velocity gradient” test, with the variation limits $200 \dots 2000 \text{ s}^{-1}$, at a constant temperature of 20°C and a homogenization time given by Table 3. The tests were carried out with a load up to 2000 s^{-1} and unloading up to 200 s^{-1} , in order to highlight the effects of lubricant thixotropy. The obtained rheograms are presented in Figure 11.

Figure 11. Rheograms for tested oils

The lubricant rheological parameters are calculated by using the rheometer software, for power law rheological model (Table 4):

$$\tau = m \left(\frac{du}{dy} \right)^n \quad (1),$$

where:

m - consistency index (which is equivalent to the Newtonian fluid viscosity);

n - flow index (equal to 1 if the fluid is Newtonian).

Table 4. Rheological parameters for fresh and used oil samples

Oil state and type	Newtonian model		Power law model		
	Viscosity, Pa·s	Correlation coefficient, %	Consistency index, Pa·s ⁻ⁿ	Flow index	Correlation coefficient, %
H46 EP fresh oil	0.085	97.8	0.210	0.877	97.9
P1 Pump used H46 EP oil	0.090	97.5	0.250	0.861	98.2
P2 Pump used H46 EP oil	0.095	92.3	0.177	0.915	91.4

To determine the apparent viscosity variation versus temperature for analyzed lubricants, there were made tests for an imposed velocity gradient of 1000 s⁻¹. The obtained rheogram is presented in Figure 12.

Figure 12. Variation of the apparent viscosity versus temperature

4. Discussions

The analysis of the diagrams for pump P1 (Figure 7) shows that the number of oil contaminant particles with diameter d in the range (4 ... 21) μm decreased throughout the endurance cycle, while the number of contaminant particles, having the diameter d in the range (38 ... 70) μm , is relatively constant. The contribution of particles with diameters d in the range (4 ... 21) μm was a major one, while the contribution of particles with diameters d in the range (38 ... 70) μm was negligible.

Concerning the pump P2, the same analysis (Figure 8) establish that the number of oil contaminant particles with $d = (4 \dots 6) \mu\text{m}$, decreased throughout the endurance cycle, while the number of contaminant particles having $d = (14 \dots 70) \mu\text{m}$ is relatively constant. The contribution of particles with diameters $d = (4 \dots 6) \mu\text{m}$ was a major one, while the contribution of particles with diameters $d = (14 \dots 70) \mu\text{m}$ was negligible.

Regarding the rheological tests, it can observe that the characteristic rheological model for fresh oil and used oil on P1 pump is the power law model, while for used oil on and P2 pump is the Newtonian model, with a high correlation coefficient. For the fresh oil and used oil on P1 pump, it hasn't been observed any thixotropy phenomenon. This shows that the structure of both oils is very stable. On the other hand, the thixotropy for P2 used oil pump is very pronounced, which means that its structure is relatively unstable and heterogeneous.

Another important observation which results from rheological test is that the apparent viscosity of the lubricant, in the range of 20 ... 40°C, increases once with the oil wear degree. Once the temperature is rising, the difference between the values of the viscosity for fresh or used oils becomes insignificant.

Conclusions

In this paper the authors studied the influence of solid contaminant particles on the wear of two hydraulic gear pumps on the endurance stands, using two modern laboratory appliances, namely a Parker analyser and a Brookfield viscometer.

- Using the Laser CM Parker analyzer, the researchers established the contribution of contaminant particles to the wear of the P1 and P2 pumps, depending on their diameters:

- For P1 pump, particles with diameters $d > (4, 6, 14, 21) \mu\text{m}$ were more numerous, and thus they used more the pump, while the number of particles with diameters $d > (38, 70) \mu\text{m}$ was negligible, so they used the pump less.

- For P2 pump, the particles with diameters $d > (4, 6) \mu\text{m}$ were more numerous, and thus they used more the pump, while the number of particles with diameters $d > (14, 21, 38, 70) \mu\text{m}$ was negligible, so they used the pump less.

- Using the Brookfield CAP2000 + viscometer, there was an increase in apparent viscosity of the used oil in P1 and P2 pumps, which is explained by the increase of the contaminant particles number, after run-in. The following rheological models were chosen: power law for H46 EP fresh oil sample and P1 pump used oil sample; Newtonian model for the P2 pump used oil sample.

Thus, the interest parameters for evaluation of the P1 pump oil contamination were the consistency index and the flow rate respectively, but for evaluation of the P2 pump oil contamination, the dynamic viscosity was the main indicator of the contaminants appearance.

- The experiments described in this paper support the predictive maintenance activities in the field. Thus, the laboratory performed analysis of the oil allowed the quantification of the impurities number, with a direct effect on the wear of the hydraulic gear pumps, but also the indication of the rheological models to be followed for their good modeling.

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