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[1,2.] Vito TIC, [2.] Darko LOVREC, [3.] Jörg EDLER

OPERATION AND ACCURACY OF PARTICLE COUNTERS FOR ON-LINE CONDITION MONITORING OF HYDRAULIC OILS

[1.] OLMA d.d., Poljska pot 2, Ljubljana, SLOVENIA
[2.] University of Maribor, Faculty of Mechanical Engineering, Smetanova 17, Maribor, SLOVENIA
[3.] Technical University of Graz, Institute of Production Engineering, Kopernikusgasse 24, Graz, AUSTRIA

Abstract: *Real-time monitoring of oil contamination in hydraulic system is one of the most effective measures of prevention and early diagnosis for system failures. Contaminants such as particles, moisture, soot, fuel, and process fluids are commonly found in industrial lubricants and hydraulic fluids. However, particle contamination is typically recognized as the most destructive to the oil and machine. Paper presents operation principle of today's on-line particle counters and reports about their accuracy levels. Report is based on experimental research where 4 different cost-effective on-line particle counters were compared to a sophisticated laboratory-based particle counter.*

Keywords: *hydraulic oil, on-line condition monitoring, particle counters*

INTRODUCTION

The research area of condition monitoring of hydraulic oils has been very intense in recent years [1-6], where mechanical contaminants are often mentioned as the main reason for the failure of hydraulic and lubricating systems. Particle contamination leads to machine breakdown, downtime, and maintenance costs. It has been shown that 70-85% of hydraulic component failures are due to particulate contamination with up to 90% of these failures due to abrasive wear. On-line measurement of particle contamination levels provides easy analysis of a machine's condition. Detecting failure mechanisms such as early detection of oil contaminants allows maintenance personnel to increase machine life and reliability.

The most widely deployed method today for determining fluid cleanliness is to use an automatic optical particle counter. There are a variety of instruments commercially available to optically count particles; from low-cost online optical particle counters (on which we are focusing in this experiment), portable units for onsite use, to large, sophisticated lab-based instruments. However, all instruments, whether they be a hand-held unit or a full lab instrument use one of two methods, either a white light source, or more commonly today, a laser.

While measuring the particle contamination levels the credibility of the measurements it is indeed very important. We have therefore decided to conduct a comparative test of 4 various low-cost on-line particle counters compared with high-precision instrument Internormen CCS 2 used in laboratories. At the same time we have made some additional experiments to explore known problems with on-line particle counters in events such as the effect of temperature and the impact of air bubbles.

OPERATION PRINCIPLE OF ON-LINE PARTICLE COUNTERS

Automated light blockage particle counting technology was first introduced in the 1960s. The basic function of a light blockage automated particle counters is simple; a beam of light is projected through the sample fluid, if a particle blocks the light, it results in a measurable energy drop that is roughly proportional to the size of the particle. [7]

More modern types of automated particle counter are based on the light scattering method. As with the light blockage method, particles produce a measurable interference in the transmission of light through the sample in the light scattering cell. However, instead of simple white light, this method employs a laser. The highly focused light emitted is interrupted by a particle, producing a scattering effect. The increase in energy across the sampling area is measured with this type of particle counter, just the opposite of the light blockage method. [7]

A sample of oil may contain a multitude of problems, which may interfere with the goal of accurately counting and sizing the solid particles. The most common problem is entrained air bubbles and water droplets, which scatter and block light, and are erroneously counted as particles by the optical automated particle counters. Without special sample preparation, an optical particle counter does not work well with fluid that is dark or fluids that are heavily contaminated with silt or soot. These conditions can produce so-called coincidence error, or in extreme cases may completely prevent the transmission of light.

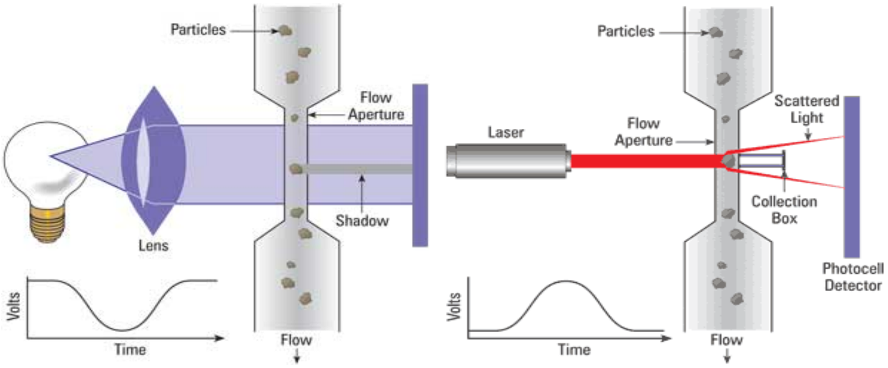

Figure 1 – Light blockage (left) and light scattering particle counter [7]

The most common unit of reporting particle contamination (fluid cleanliness) is the ISO Code System, typically the ISO Standard 4406:1999. In this standard, the number of particles in three different size categories, >4 μm, >6 μm and >14 μm are determined in one milliliter of sample. ISO 4406:1999 states that the number of particles in each size category should be counted with the absolute count converted to an ISO code, using the ISO range code chart [8] presented in Figure 2.

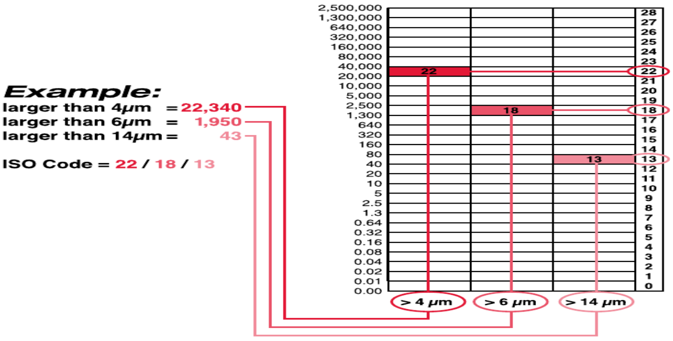

Figure 2 – ISO range code chart [9]

Figure 3 – Internormen contamination control system, CCS 2

EXPERIMENT

The goal of our experiment was to test the accuracy of low-cost on-line particle counters that are commonly used for monitoring hydraulic systems and also to evaluate known problems with on-line particle counters in specific operating conditions.

PARTICLE COUNTERS

The operation of 4 different low-cost automated on-line particle counters was compared to high-precision laboratory instrument Internormen CCS 2, presented in Figure3, which can be used in mobile or stationary applications in systems with high-pressure or high-viscosity ranges. The counting is performed in eight different counting channels at >4 μm, >4.6 μm, >6 μm, >6.4 μm, >10 μm, >14 μm, >21 μm and >37 μm.

Figure 4 – Cost effective on-line particle counters used in our experiment

The four low-cost on-line particle counters are not specifically named in results (section 3.4) due to privacy reasons and are only marked with numbers from 1 to 4. Nevertheless, they are presented in Figure 4, from left to right:

- ☐ Argo-Hytos Opcom
- ☐ Hydac CS1000
- ☐ RMF CMS
- ☐ Parker MCM20

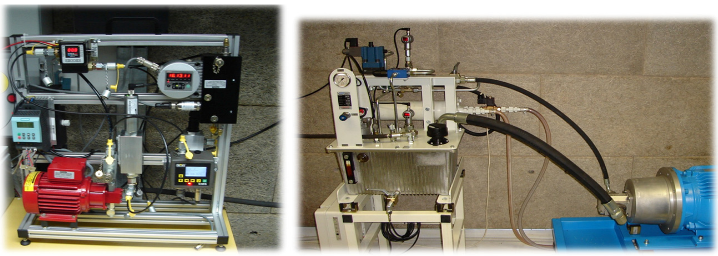

Figure 5 – Setup of by-pass pump and on-line particle counters (left) and operating hydraulic unit used in test 4 (right)

SETUP OF THE MEASURING SYSTEM

The measuring system included 1 high-precision laboratory particle counter CCS2 and 4 low-cost on-line particle counters which were all connected in series, so that the same sample of oil was passing through each of the counters. At the end of the test line a flow-check valve was placed to provide proper back-pressure of around 30 bar and to ensure constant oil flow through the sensors. The oil flow was provided by a special bypass pump producing around 120 ml/min of flow, presented on Figure 5.

EXPERIMENTS CONDUCTED

To test the accuracy of low-cost on-line particle counters and to investigate the credibility of measurements at various operating conditions four different experiments were made:

- ☐ *Test 1: Fresh oil sample (ISO VG46 grade) at 20°C was measured to test the accuracy of sensors*
- ☐ *Test 2: Fresh oil sample (ISO VG46 grade) at 60°C was measured to test the impact of temperature*
- ☐ *Test 3: The sensors were connected to a smaller hydraulic tank in a bypass line to test the impact of air bubbles entrained in oil. Special setup of the suction line and the air valve before the main pump enabled us to introduce many air bubbles in the oil – see Figure 6.*
- ☐ *Test 4: The sensors were connected to an operating hydraulic unit in a bypass line to test the impact of temperature, air bubbles and unsteady flow conditions of oil sample – see Figure 5, right.*

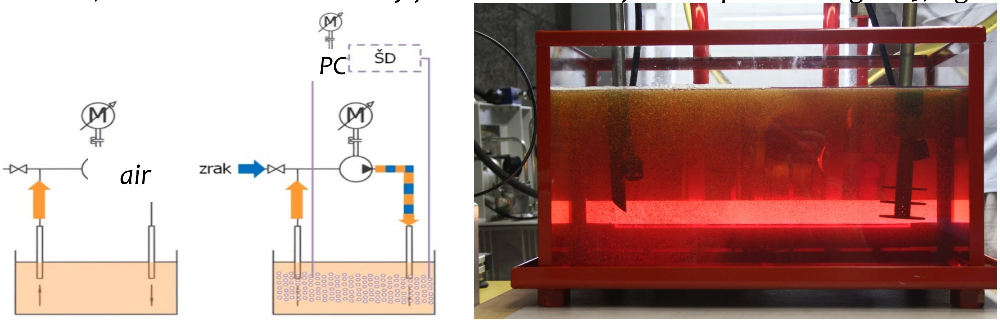

Figure 6 – Setup of test 3: investigation on the impact of air bubbles entrained in oil

RESULTS

To obtain the most accurate information four measurements were made in sequence for each test. The results presented in tables 1-4 represent averaged values of these four measurements, although the ISO 4406 class code can only be reported as a whole number.

Experimental results of test 1 in table 1 shows that only two on-line particle counters are within declared measuring accuracy, which is ± ½ ISO class for all of the listed on-line counters.

Results of test 2 which are presented in table 2 shows, that the on-line particle counters are slightly more accurate at hydraulic oil's working temperature of 60 °C.

Table 1 – Experimental results of test 1, average of 4 measurements connected to an operating hydraulic unit in bypass line

Particle counter	Class according to ISO 4406		
	> 4 µm	> 6 µm	> 14 µm
Internormen CCS 2 (reference)	*20*	*17*	*12*
On-line particle counter 1	*20*	*17*	*12*
difference	*0*	*0*	*0*
On-line particle counter 2	*19*	*16*	*11*
difference	*-1*	*-1*	*-1*
On-line particle counter 3	*18,75*	*16*	*11,75*
difference	*-1,25*	*-1*	*-0,25*
On-line particle counter 4	*18*	*16*	*10*
difference	*-2*	*-1*	*-2*

Table 2 – Experimental results of test 2, average of 4 measurements. Fresh oil at 60 °C

Particle counter	Class according to ISO 4406		
	> 4 µm	> 6 µm	> 14 µm
Internormen CCS 2 (reference)	*20*	*18*	*13*
On-line particle counter 1	*21*	*19*	*14*
difference	*1*	*1*	*1*
On-line particle counter 2	*20*	*17*	*12,5*
difference	*0*	*-1*	*-0,5*
On-line particle counter 3	*20*	*18*	*13*
difference	*0*	*0*	*0*
On-line particle counter 4	*19*	*17*	*12,5*
difference	*-1*	*-1*	*-0,5*

In test 3, the impact of air bubbles entrained in oil was evaluated. The results of this experiment are presented in table 3, while the step response of one of the on-line particle counters is shown in figure 7. It can be seen from the figure, that the measurements become inaccurate at the same moment the air is present in oil. The table shows that air bubbles most affect measurements of ISO > 14 µm class and according to the results it is believed that the air bubbles generally have size greater than 20 µm.

Table 3 – Experimental results of test 3, average of 4 measurements connected to a smaller hydraulic tank in a bypass line to test the impact of air bubbles entrained in oil

Particle counter	Class according to ISO 4406		
	> 4 µm	> 6 µm	> 14 µm
Internormen CCS 2 (reference)	*20*	*17*	*13*
On-line particle counter 1	*20,25*	*18,5*	*14,25*
difference	*0,25*	*1,5*	*1,25*
On-line particle counter 2	*19*	*17*	*13,5*
difference	*-1*	*0*	*0,5*
On-line particle counter 3	*19,5*	*18*	*16*
difference	*-0,5*	*1*	*3*
On-line particle counter 4	*19*	*17*	*13*
difference	*-1*	*0*	*0*

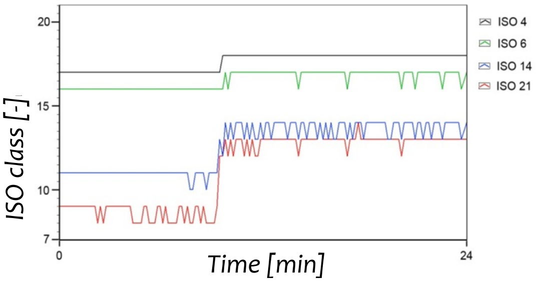

Figure 7 – Experimental results of test 3: step response at the impact of air bubbles entrained in oil

The most concerning results have been recorded in test 4 when on-line particle counters were connected to an actual operating hydraulic unit. The worst position of sampling point was intentionally *selected to prove the impact of proper oil sampling point. The temperature, air bubbles and unsteady flow conditions had a great negative impact on the counters accuracy, as seen from table 4.*

Table 4 – Experimental results of test 4, average of 4 measurements connected to an operating hydraulic unit in a bypass line to test the impact of temperature, air bubbles and unsteady flow conditions of oil sample

Particle counter	Class according to ISO 4406		
	> 4 µm	> 6 µm	> 14 µm
Internormen CCS 2 (reference)	18	15	11
On-line particle counter 1	18,25	15	7,75
difference	0,25	0	-3,25
On-line particle counter 2	15,25	11,5	7,75
difference	-2,75	-3,5	-3,25
On-line particle counter 3	15,25	12	8,25
difference	-2,75	-3	-2,75
On-line particle counter 4	16	12,5	7
difference	-2	-2,5	-4

CONCLUSIONS

Today automatic particle counters are widely used in filter testing and fluid contamination analysis laboratories and in industrial facilities to monitor filters and cleaning processes and machines. They cannot be considered as true particle counters, but rather as fluid contamination monitors. The light blocking and light scattering method have their own drawbacks which result in poor sensor accuracy if not installed and used correctly. That is why special attention is needed while selecting the position of on-line sampling point and designing the hydraulic bypass system.

To obtain most accurate and realistic results the on-line particle counters should operate in their optimal operating condition, or as near as possible to them:

- *Although they operate at the fluid flow from 30 to 300 ml/min, we must ensure maximal flow rate as possible. Lower fluid flows (less than 100 ml) were tested to be less accurate.*
- *The fluid flow through the particle counter should be as stable as possible. For this manner it is advisable to use special bypass pump that provides stable oil flow independent of temperature and viscosity of oil.*
- *Although the operating conditions allow working pressure from 1 to 300 bar it was tested that their accuracy improves at higher pressures where pressure is sufficient to eliminate interference from air bubbles.*
- *Water levels in oil should also be kept to minimum as the on-line particles count water droplets as solids due to light blockage.*
- *When selecting on-line sampling point to be used in a bypass system for on-line particle counting we should choose an area with steady flow conditions and minimal air entrainment.*

In summary particle counters are a must for the user to properly maintain its hydraulic system, reduce breakdowns and schedule maintenance. They also enable wear surveillance and early recognition of damage, which is essential for large gears and lubrication systems. One small low-cost on-line particle counter can save great deal of expenses and trouble if used correctly. The paper only focuses on the application of on-line particle counters and their accuracy in specific operating conditions. However, since the on-line particle counters cannot indicate all important fluid conditions (for example viscosity, water level, etc.), the proper on-line condition monitoring system should also include other sensors for evaluation of physical and chemical properties of hydraulic fluid and its condition. And it is also important to point out, that the most on-line sensors for condition monitoring of hydraulic fluids are basically only indicators for early detection of impending system damage. In order to obtain the most detailed, accurate and reliable information on hydraulic fluid state the on-line measurements should be updated with the periodical laboratory testing of the proper fluid sample.

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