PROPER INSTALLATION AND CALIBRATION OF ON-LINE CONDITION MONITORING SYSTEMS FOR MINERAL OILS

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ABSRACT
Today many users still change lubricants at fixed intervals but do not take into account their actual conditions. Thus, on several occasions lubricants are often changed when they are still in good condition. On the other hand, the condition of a lubricant over a fixed interval, can suddenly deteriorate, which may lead to major damage to the machine. Therefore, lubricants should be monitored periodically (in a chemical laboratory), thus allowing for adjustment regarding their actual conditions.
Due to the increasing availability of on-line sensors for oil condition monitoring, our latest research and development activities have focused on on-line condition monitoring and also indirectly the machinery to which they are fitted. Remote on-line condition monitoring systems have many advantages over conventional monitoring systems and chemical analyses. Thanks to constant monitoring of lubricants in real-time, the system can also detect sudden deteriorations of lubricants' conditions and trigger alarm notification, before catastrophic consequences might occur. Fitting a modern on-line condition monitoring system provides the user with the highest level of operational reliability and allows him/her to reduce machines' down-times and extend lubricant maintenance intervals.
However, the measurement of oil condition is much more complex than, for example, measurement of oil temperature or pressure. In order to obtain reliable and accurate operations of on-line sensors, we have to pay special attention to the correct installations and calibrations of the sensors.

Keywords: on-line sensors, condition monitoring, mineral oils

1. INTRODUCTION

As already mentioned, the greatest advantage when on-line condition monitoring of lubricants, in comparison with conventional laboratory analyses, is their continuous measuring and reliable detection of sudden and unforeseeable events, when the fault is detected, so to speak, in real-time. Another advantage is the trend recording, considering the data from on-line sensors are usually acquired by automated systems that can store the history of the measurement results [1].

On the other hand, on-line monitoring has its own limitations. The most significant of them is the limited number of sensors and parameters that can be monitored. Also the parameters, measured by on-line sensors, tend to differ from the parameters, as determined by laboratory analysis. Thus, a direct comparison between them is impossible. Last but not least, calibration of the sensors is complicated and often valid for only one fluid type [1].

Due to these specific features, the on-line monitoring of lubricants is much more complex than the monitoring of single physical parameters, such as pressure or temperature. The oil condition cannot be determined by a single parameter but rather by several parameters measured at the same time. Additionally, the properties of oil change depending on the system load, type of oil, and other boundary conditions [2].

In order to achieve adequate quality of results from an on-line monitoring system, there are several key factors to consider whilst designing and implementing the system:

- selection of suitable on-line sensors,
- proper installations of the sensors,
- determination of appropriate mounting locations for the sensors (representation of the sample must be ensured),
- adequate data acquisition unit for gathering and processing data from the sensors,
- additional measures and procedures for improving the accuracy and credibility of the measurements.

With regard to the points given above, this paper presents some of the concepts and measures that can be used to enhance accuracy and quality of on-line sensors' measurements.

2. ON-LINE SENSORS

Most of the common parameters measured by today's on-line monitoring systems for lubricants are:

- temperature,
- relative humidity,
- viscosity,
- dielectric constant,
- electrical conductivity,

lubricant cleanliness class.

We have already presented these methods and sensors in detail in various literature [3-5]. The sensors can be divided into two main groups: sensors that detect the physical-chemical properties of the lubricant and sensors that measure the cleanliness class of the lubricant – particle counters.

Before taking actions for improving sensor measurements, special attention should be paid to the installations and locations of the sensors, as the sensors' locations alone (the locations where the lubricants are measured) can have significant influences on the measurements' results.

3. MOUNTING LOCATIONS OF ON-LINE SENSOR SYSTEMS

On-line sensors for oil condition monitoring can be mounted at four main locations:

- on a hydraulic tank,
- on the main hydraulic return line,
- on the main hydraulic pressurised line and

- on a hydraulic bypass line.

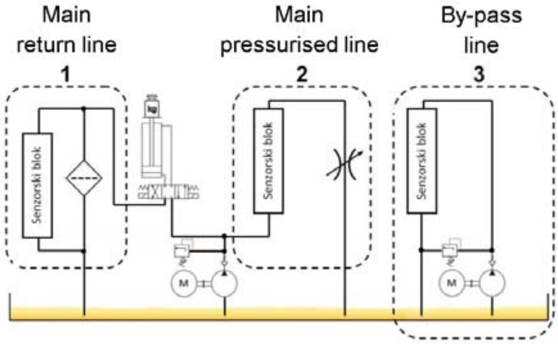

Figure 1. Different mounting locations for on-line sensors' systems

3.1. Mounting sensor system in a hydraulic tank

When it comes to the mounting locations of the sensors, the biggest difference between sensors of physical-chemical properties of oil and particle counters is that the particle counters need a certain oil flow through the sensor element that usually stands between 30 and 300 ml/min. Therefore, particle counters cannot be used if the sensor system is mounted in the tank because the sensors are only immersed in oil.

In those cases where there are no particle counter predictions during the monitoring system, it is recommended that the sensors are installed near the pump intake lines. The oil flow in this region of the tank is usually the calmest and more stable with the least amount of contaminants (e.g. air, soiled-contaminants), that might distort the measurements' results [6].

If the sensor system includes particle counters, it is necessary for them to be mounted on hydraulic piping and in this case, there are three main options, as presented in the continuation.

3.2. Mounting sensor system on main return line

Mounting the sensor system on the main hydraulic return line seems more appropriate, as the fluid is measured before the filter element. Thus, the fluid is measured that has just passed the whole hydraulic system and contains the most contaminants (information about the condition of the hydraulic system). This method of mounting usually takes advantage of pressure difference on the filter element (2 – 5 bar), which is used to power the fluid flow through the sensor system. If a particle counter is being used, this small pressure difference almost satisfies the flow needs of a counter. Moreover, this flow is low-pressurised and is also variable, as it depends on the fluid's viscosity and temperature. As our tests have revealed that the accuracies of on-line particle counters are much better at higher flows and pressures, we do not recommend the installations of a particle counter in such way.

3.3. Mounting sensor system on main pressurised line

When mounting a sensor system on the main hydraulic pressurised line, an additional flow valve is needed, which regulates the oil flow rate through the sensor system, regardless of oil pressure, viscosity, and temperature. The particle counter is usually installed at the front of the valve, so that oil flowing through the counter is under high pressure, which then compresses any air bubbles (if present) and thus improves the accuracy and stability of the cleanliness class measurement. As the sensors regarding the physical-chemical properties of oil must not usually be exposed to high pressures, they are placed after the valve, where only low pressure is present (return line to the tank).

3.4. Mounting sensor system on bypass line

By using an additional (small) pump, which powers the fluid through the sensor system, a bypass hydraulic system can be designed for condition monitoring. Although such a design is the more expensive one, it provides the best and most constant flow conditions for on-line sensors, which is especially important when an on-line particle counter is being used.

Suction and return line locations within the hydraulic tank must be placed carefully when designing a condition monitoring bypass system. Pumping and measuring oil from "dead-zones" of a hydraulic tank (where fluid does not circulate) could lead to substantial errors during condition monitoring [7].

4. MEASURES TO IMPROVE THE ACCURACIES AND CREDIBILITIES OF MEASUREMENTS

In order to obtain high quality results with on-line monitoring systems, knowing well the flow conditions in the system is insufficient, it is also crucial to understand the operating principles of the on-line sensors and how their data is evaluated. Aimed at investigating sensors' operations and improving their measurement accuracies, we conducted several small studies, presented further in the continuation.

4.1. Measurement of relative humidity

On-line sensors detect relative water content in the oil and express it as a percentage. The oil is 100 % saturated if it contains a maximum amount of water at a certain temperature and pressure (saturation limit). Whilst as, in conventional chemical laboratory analysis, the absolute water content is measured by the Karl-Fischer method, which reports the volume of water in weight percent or ppm.

The saturation limit can vary significantly, depending on the type of hydraulic oil (different base oils and various additive packages used). Therefore it is sensible to determine the saturation limit of a particular oil, as it represents the threshold above which water becomes extremely harmful to a hydraulic system (free water is present).

The saturation limit was determined using two on-line sensors and the Karl-Fischer method according to the following procedure. Various amounts of water were added to one litre of hydraulic oil. Then each sample was measured using on-line relative humidity sensors over a temperature range. The temperature was recorded when the sensor had reached 100 % relative humidity (saturation limit). The same samples were then passed for comparative laboratory analysis of the absolute water content using Karl Fischer procedure. The measurement results are shown in Table 1 and in Figure 2.

Based on the data in Table 1 we then determined a plot of the saturation limit for the mineral hydraulic oil (ISO VG 46). Figure 2 clearly shows that the saturation limits at operating temperatures of 40 – 60°C lay at between 90 and 180 ppm, which is much lower than the permissible limits provided by lubricant producers (500 ppm).

Table 1. Results of saturation limit measurement

Sample	Karl Fischer (ppm)	Saturation temperature(°C)	
		Sensor S1	Sensor S2
1	65,9	29	29
2	76,1	41	36
3	123,7	49	49
4	149,7	53	53

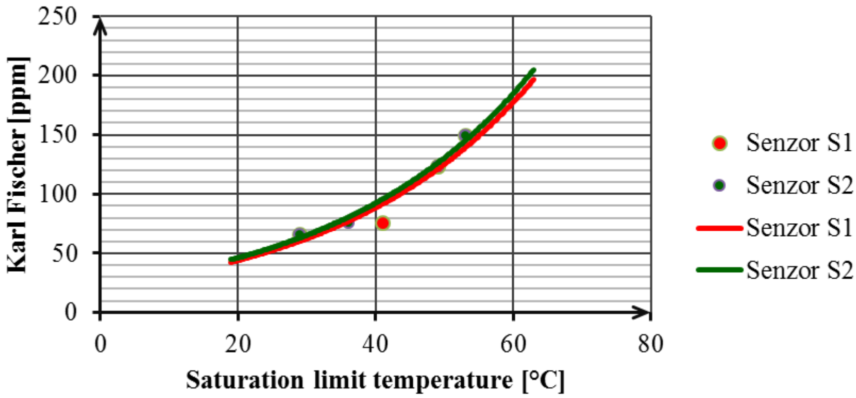

Figure 2. Saturation limit of mineral hydraulic oil (ISO VG 46)

4.2. Measurement of viscosity

The viscosity of a hydraulic fluid is one of its more important properties that must be constantly monitored. The accuracies of two on-line viscosity sensors were tested on mineral hydraulic oil ISO VG 46 within a temperature range from 30 to 80 °C.

The results are presented in Figure 3 (chart above), where the black line represent the “actual viscosity” of the oil, and was determined in a chemical laboratory according to the ASTM D445 at two characteristic temperatures (40 and 100 °C). The kinematic viscosity over the entire temperature range was then calculated using a simplified Walther equation derived at from the ASTM D341 standard [8]. However, the bold lines (red and green) represent the viscosity measurements’ results from two on-line sensors.

The results show a strong deviation of on-line measured viscosity compared to the actual kinematic viscosity. The measuring errors of the on-line viscosity sensors are also presented in the form of relative errors (thinner lines), which reached up to 70 % for both sensors S1 and S2. The presented inaccuracies were definitely too great and monitoring with such sensors would only be a waste of time and money. We assumed that such deviations occurred because the sensors are factory calibrated only by a certain type of fluid. Nevertheless, the accuracy could be greatly improved if a particular sensor were to be additionally calibrated to a specific type of hydraulic fluid.

In comparison to Figure 3 (chart above), Figure 3 (chart below) shows the on-line viscosity measurement results after the sensors had been additionally calibrated. It can be clearly seen from the figure, that calibration of a specific sensor to a specific hydraulic fluid significantly improves the accuracies of on-live viscosity measurements.

After implementation of the calibration curve, the relative errors of sensor S1 were reduced to 5 %, whilst the relative errors of sensor S2 were slightly higher due to very low output signals and the inaccuracy of the used A/D data acquisition card.

In addition to the implementation of a dedicated calibration curve, valid only for a specific oil and sensor combination, the viscosity can only be monitored if the kinematic viscosity at the operating (measuring) temperature is calculated to viscosity at 40 °C. Thus, we have developed a special program based on ASTM D341 and D2270 standards, which transforms the viscosity at a measured temperature to viscosity at 40 °C. In this way, the trend of viscosity change can be monitored over a longer period of time, despite the temperature fluctuations within the hydraulic system.

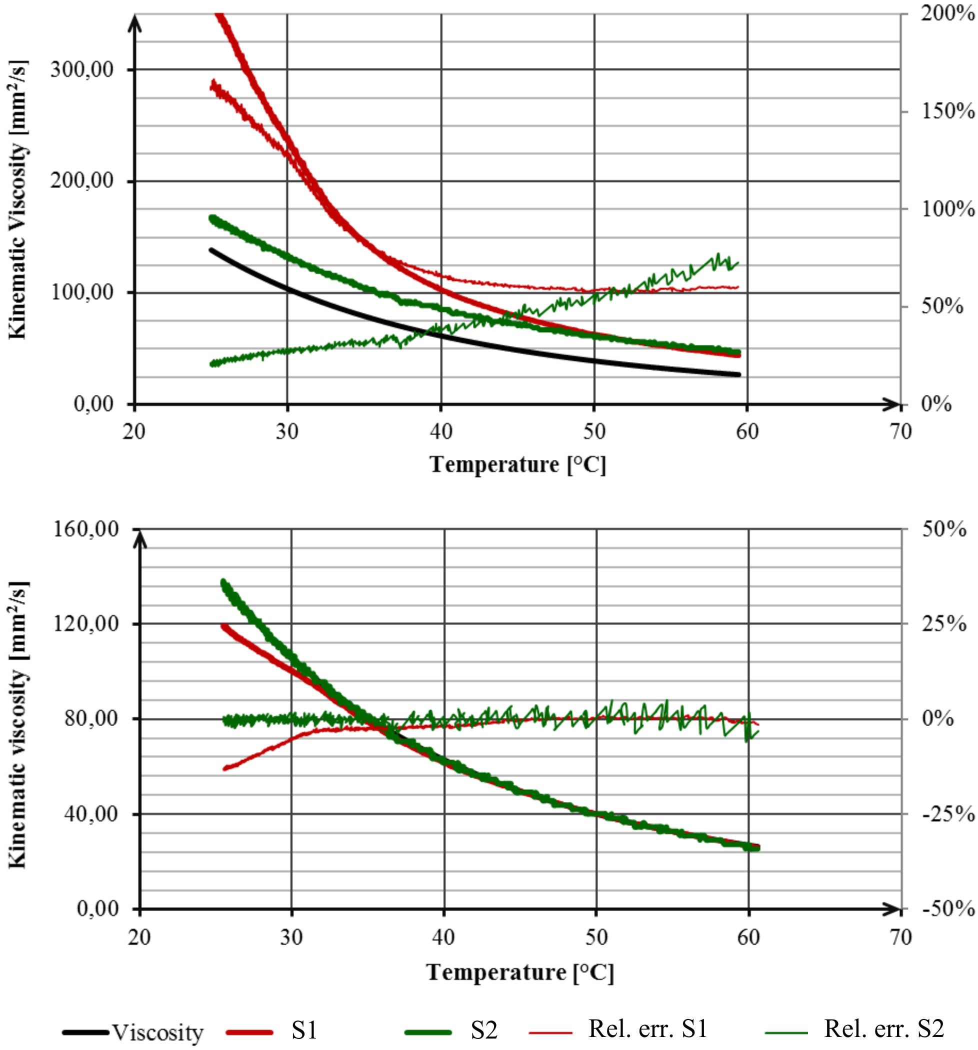

Figure 3. On-line viscosity measurements vs. actual viscosity
above: raw sensors readings; below: after the implementation of calibration curve

4.3. Measurement of dielectric constant

Within our research, the dielectric constant of the mineral hydraulic oil was measured by three different on-line sensors. Figure 4 presents the results, which have been compared to a precise laboratory measurement of the dielectric constant, made by the Biotechnical Faculty of Ljubljana. The figure shows that the dielectric constants measured by on-line sensors significantly differed from the actual values. At this point we could implement a calibration curve, similar to that we did for the viscosity measurement. As this procedure should be done for each combination of oil type and sensor, we decided (due to economic reasons) to ignore the absolute value of the dielectric constant. As we only monitor and track relative changes in the dielectric constant of oil, the accuracy of its actual value is rather unimportant.

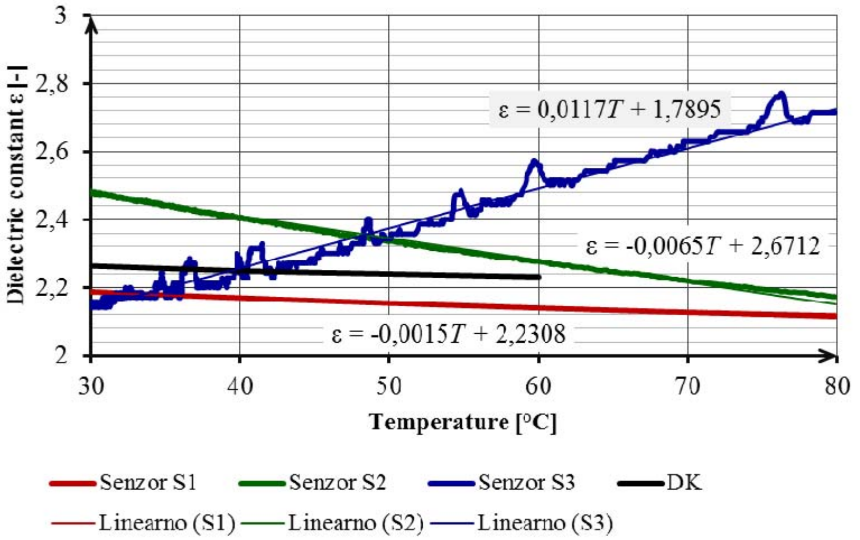

Figure 4. On-line measurements of dielectric constant with three sensors

Figure 4 also shows the temperature dependency of the dielectric constant. As the dielectric constant changes linearly with temperature, we need to find corresponding temperature gradients for each sensor, which then allows us to transform each measuring result (at a given operating temperature) to its reference value at 40 °C – trend tracking.

4.4. Measurement of cleanliness class

As during any measurement procedure, the credibility of the measured values for the cleanliness class is the key factor. The practical accuracies of on-line particle counters were determined by a comparative test, in which several on-line particle counters were compared to a precise and calibrated laboratory instrument – particle counter Internormen CCS2. Four on-line sensors were connected in series to guarantee the same flow conditions throughout each one, followed by the precise laboratory particle counter.

Table 2 shows the deviations of each particle counter in the ISO 4406 class with respect to precise instrument calibration to ± 0.1 ISO class. During the test, at least 4 readings were taken for each test point and the results report the average of these readings.

Table 2. Results of comparative test on the accuracy of on-line particle counters

Average deviation	**ISO 4**	**ISO 6**	**ISO 14**
Particle counter PC-1	0,3	0,7	-0,15
Particle counter PC-2	-1,15	-1,2	-0,85
Particle counter PC-3	-1,1	-0,55	0,25
Particle counter PC-4	-1,4	-0,85	-1,25

The accuracy of on-line particle counters is provided by the producers and is usually ± 0.5 ISO class for measurements within the range from 13/11/10 to 23/21/18. The conducted tests revealed that on-line particle counters did not achieve this accuracy, but rather they operated within an accuracy of ± 1 ISO class. There were also differences amongst the sensors.

However, we can sum up that particle counters typically measure 1 ISO class less (1 ISO class cleaner fluid), which represent dangerous results for the user.
We also noticed that the particle counters experienced some difficulties whilst measuring the cleanliness of the oil whilst the hydraulic system was operating. Therefore, we performed several tests to investigate the responses of the particle counters to certain interferences, such as the presence of air bubbles. As air bubbles (and also water droplets) in oil also deflect the light passing through the oil, they are also detected as particles.
Oil with air bubbles and without them was measured and the results are summarised in Table 3, which indicates that air bubbles mostly affect the measurements of the ISO 14 and ISO 21 classes. Thus, it can be assumed that the majority of air bubbles have diameters of 21 μm or more.

Table 3. Results of test on air bubbles' presence in hydraulic oil that affect particle counters

	Without air bubbles			**With air bubbles**			**Average error**
	PC-1	**PC-2**	**PC-3**	**PC-1**	**PC-2**	**PC-3**	
ISO 4	17,9	17,0	17,4	18,9	18	18,5	1,0
ISO 6	16,0	16,0	16,1	17,6	16,9	17,1	1,2
ISO 14	11,9	11,0	11,2	16,2	13,7	14,7	3,5
ISO 21	10,2	8,7	9,1	16,5	12,9	13,8	5,1

Therefore, we must ensure that any air bubbles and water droplets are removed from the oil prior to entering the particle counters otherwise the measurements will lead to false results. Another option is to minimise the impact of the presented air bubbles by raising the pressure of the hydraulic fluid passing the measuring cell in the particle counter to at least 30 bar or more, whereby the air bubbles are squeezed to a minimum and thus do not cause distortions of the measurements.

5. CONCLUSION

On-line monitoring systems for lubricants offer us the highest level of protection for our systems because the lubricants (and the systems) are monitored constantly 24 hours a day. In this paper we have tried to focus on the proper installations of on-line sensors and tried to provide insights into some measures and procedures that can help us achieve maximum accuracy and credibility of the results. In fact, we spotted several on-line sensors in the field that only serve the purposes of beauty instead of performing their primary tasks.
In addition to these installation procedures and additional measures for improving the qualities of the measurements, it is also essential to establish an adequate system to record and display the results. Thus, we have developed a special user-interface that is accessible on-line with a common internet browser. In this way, the technical service, as well as an individual user, has access to information on oil condition at anytime from anywhere. Besides displaying current measuring values, the web interface also provides data history in the forms of flexible multi-axis charts. The system also includes an alarm function that notifies the user in case the minimum or maximum value has been reached.
Our system has already been proved in the field. One of our partners has managed to extend the lubricant change interval four-fold, whilst another partner noticed a sudden ingress of water into the hydraulic system, which allowed him to stop the system immediately and prevent major damage to his system.

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