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DETECTING AND ANALYSING CONDITION OF HYDRAULIC OILS WITH ON-LINE SENSORS*

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Abstract. *On-line condition monitoring of the entire system or individual components can be used for detection of impending system break-down. The on-line monitoring of the state of hydraulic system and fluid plays a decisive role in general on-line condition monitoring. Friction, wear, leakage and excessive temperatures all have impact on lubricating properties of the oil. Apart from this, the oil its self is prone to aging and deterioration processes, which can also result in corrosion and equipment failures. The oil condition can be understood as a fingerprint of the condition of the complete system. Due to a widespread availability of robust and cost-effective on-line sensors for measuring various fluid properties, latest developments deal with on-line oil condition monitoring to determine the condition of hydraulic system and fluid. This allows for maintenance work to be carried out based on the detected system condition.*

Key words: *Oil Ageing, Condition Monitoring, Physical and Chemical Properties*

1. INTRODUCTION

The use of on-line oil condition sensors together with appropriate knowledge of physicochemical changes in oil allows the user to have constant overview of the oil quality and its properties. This information can sometimes be crucial for preventing damage and ensuring reliable system operation.

However, measurement of the oil condition is much more complex than that of e.g. pressure or temperature. The oil condition cannot be determined with only one single parameter. Several parameters must be observed at the same time. For the best understanding and interpretation of the results we also have to track trends of these parameters.

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2. Physical and Chemical Changes in Hydraulic Oil

Physical and chemical properties of hydraulic oil are changing during its use as a function of many influencing factors, such as increased temperature, friction, wear, water contamination, etc…, which results in accelerated oil oxidation, thermal decomposition of the oil and the increased level of oil contamination – Fig. 1. To determine oil condition, the paper presents various physical and chemical changes in hydraulic oil, which can be detected using robust and cost-effective on-line sensors. Understanding the mechanisms of oil ageing and deterioration is crucial, and it is not only necessary for proper interpretation of measured results and taking consequent actions, but it is also important for proper selection of individual sensors or entire condition monitoring system design.

The term oil ageing commonly refers to chemical and physical changes in oil properties. Hydrocarbon ageing processes have been intensively studied since the early 20th century. In these studies a number of theories regarding the principle of chemical reactions are developed. Due to the diversity of the base oils, the diversity of additives and the resulting number of components present in the oil, it is impossible to give a precise and unique statement about the general mechanisms of oil ageing and ongoing chemical processes – we can only imagine many possible chemical reactions. The great diversity of structures can even be seen in base oils.

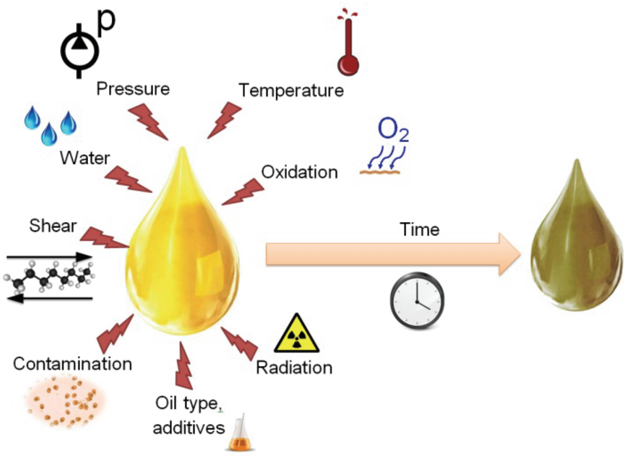

Fig. 1. The key factors that influence hydraulic mineral oil ageing

Additives, even in very low quantities, can have different effects on physicochemical properties of the oil, especially on the ageing process.

Another point, which prevents the prognosis of the individual chemical reaction of oil ageing, is that the chemical reactions depend on the present operating conditions of the machine. The most important influence quantities are temperature and presence of oxygen, water or metal catalysts, which all have a determining influence on the ageing mechanisms. In the past, empirical studies have further explored these influence quantities on hydraulic fluids. Several other parameters also have influence on oil ageing, such as pressure, system volume, shear-rate of long chain molecules, radiation – especially light, etc.

Some of the most important physical and chemical changes in hydraulic oil, which can be detected using robust and cost-effective on-line sensors, are presented below.

2.1. Temperature

Temperature is certainly one of the basic and most important physical quantities, which requires continuous monitoring. A well-known fact is that the hydraulic fluids age much faster at high operating temperatures because of the accelerated rate of oxidation. It is believed that life expectancy of hydraulic mineral oil is halved for every 10 °C above 60 °C. Moreover, most of the other physical and chemical parameters of hydraulic fluid are highly dependent on the temperature. The temperature also influences viscosity, relative humidity, dielectric constant and electrical conductivity of the hydraulic fluid. Change of each parameter with temperature will be briefly explained below.

2.2. Viscosity

Also, viscosity is very important physical property of mineral hydraulic oils because it affects the lubrication film and thus the friction and wear. The viscosity value is typically specified in a narrow band for a certain type of oil. However from oil to oil the viscosity might differ. From system and component view certain upper and lower threshold values for the operating viscosity are specified. Changes of the viscosity throughout the operation might result from oil deterioration and contamination with other oils respectively fluids. Thermal oxidation very often leads to an increase of the viscosity, whereas shear-stress especially of long chain VI-improver-oils leads to a decrease of viscosity.

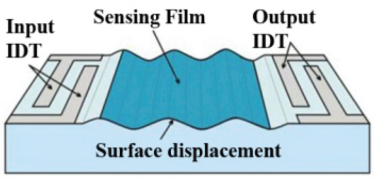

Fig. 2. Quartz crystal wave resonator for on-line viscosity measurement

Fig. 2 presents the on-line viscosity measurement that can be made by placing the quartz crystal wave resonator in contact with liquid. As the acoustic wave resonator supports a standing wave through its thickness the wave pattern interacts with electrodes on the lower surface (hermetically sealed from the liquid) and interacts with the fluid on the upper surface. Described measurement principle is very sensitive to surface contamination and formation of deposits, which is a common problem of most modern on-line sensors.

Hydraulic oil viscosity varies with pressure and temperature. Since the measurements take place at a relatively low and constant pressure, the effect of pressure can be neglected. However, we should not ignore the impact of temperature. With increasing temperature the viscosity is sharply declining. In order to accurately determine the change of viscosity of hydraulic oil through its lifetime it is therefore appropriate to take a baseline - the calibration curve, which shows the relationship between temperature and viscosity.

In our test, the viscosity-temperature calibration curve is recorded for hydraulic mineral oil between 10 °C and 90 °C. Acquired data points are mathematically and statistically evaluated.

Fig. 3 shows calibration curve obtained experimentally to determine the coefficients *a*, *b* and *c* of Vogel equation:

$$\eta = a \cdot e^{b/(T-c)} \quad (1)$$

where:
a, b, c, d – constants,
η – dynamic viscosity [Pas],
T – absolute temperature [K].

The quality of obtained calibration curve (function) is given by the coefficient of determination R^2.

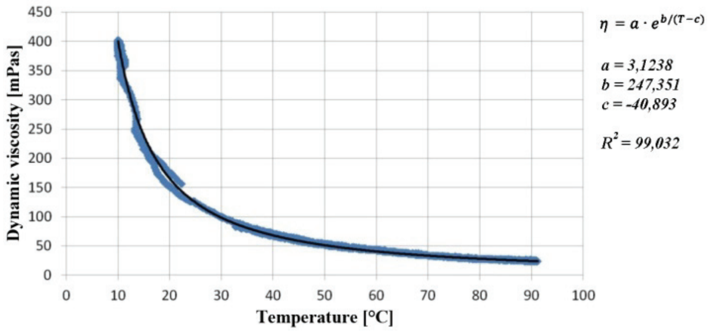

Fig. 3. Experimental viscosity-temperature calibration curve

Unlike the conventional laboratory methods, which report oil kinematic viscosity *ν* at 40 °C in cSt, on-line sensors usually report dynamic viscosity *η* measured at system temperature (*T*).

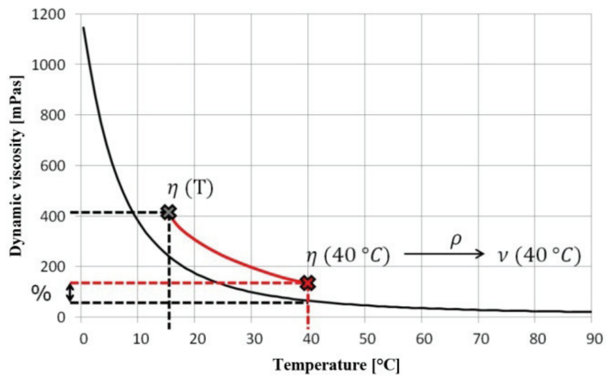

Fig. 4. Assessment of viscosity increase

To be able to compare these two methods, firstly, we need to normalize measured dynamic viscosity *η* at system temperature to dynamic viscosity at 40 °C *η(40)*. The calculation is done on the basis of experimentally obtained viscosity-temperature calibration curve. After knowing *η(40)* we have two options, either to estimate the increase in dynamic viscosity at 40 °C in percentage, or to calculate the kinematic viscosity where we assume that the density of the oil is constant. The process is shown in Fig. 4.

2.3. Relative humidity

Water is in practice one of the greatest threats to the hydraulic and lubricating oil. Lubricant film reduces the load and act as a catalyst in the processes of aging and degradation of oil. Water may be present in a dissolved, emulsified or free form.

Relative humidity Φ is defined as the ratio of the absolute humidity e_a and saturation humidity e_n (the highest possible absolute humidity) at a given temperature, expressed as a percentage:

$$\Phi = \frac{e_a}{e_n} \cdot 100\% \tag{2}$$

Changes in relative humidity capacitive sensors detect and show the percentage of saturation of the hydraulic oil. Oil is 100 % saturated if it contains the maximum amount of bound water at a certain temperature and pressure. In addition to a function of temperature and pressure, water solubility also depends on the chemical compatibility of the water and oil. Consequently, the level of saturation can significantly vary depending on the different base oils and various packages of additives [1].

For hydraulic systems is important to know the relative humidity, because it allows us to monitor the point of condensation from the moist when oil starts separating water droplets. This leads to the formation of mild emulsion, and, consequently, accelerated corrosion of components.

2.4. Conductivity

The conductivity of a solution is a measure of its ability to conduct electricity. The electrical conductivity of a solution of an electrolyte is measured by determining the resistance of the solution between two flat or cylindrical electrodes separated by a fixed distance. An alternating voltage is used in order to avoid electrolysis. Typical frequencies used are in the range 1 to 3 kHz. The dependence on the frequency is usually small.

Electrical conductivity of solution G is inversely proportional to resistance R: $G = 1/R$. Since the resistance is expressed in ohms Ω, the electrical conductivity is expressed in Ω^{-1}. Electrical conductivity of the sample increases with cross section and decreases with distance:

$$G = \frac{\kappa A}{l} \tag{3}$$

where:
G – electrical conductivity,
κ – specific electrical conductivity,
A – cross section area,
l – length between the electrodes.

Specific fresh oil has its own characteristic conductivity, which is typically of lower value. Because conductivity is oil specific it is a criterion for differentiating oils. Also the entry of foreign substances (solid/liquid) can be detected if such entry causes a change in conductivity. Thus oil changes, oil mixtures, and contamination can be detected.

In addition conductivity changes due to aging processes so that the course of aging can also be tracked based on conductivity.

2.5. Relative permittivity

Relative permittivity ε_r of the fluid is a measure of its polarity. Basic oils and additive packages with different chemistry and from different manufacturers can differ in polarity. Thus polarity of the fluid is a quality factor through which oil changes, oil mixtures and refreshing can be detected.

Moreover, oils change their polarity during the aging process. It is also possible to monitor the trend of aging. Measurement of relative permittivity ε_r is based on a capacitive measurement transformer moistened with oil.

When there are two electrical charges q_1 and q_2 placed in vacuum and are separated with distance r, the potential energy of their interaction equals:

$$V = \frac{q_1 q_2}{4\pi\varepsilon_0 r} \tag{4}$$

When these two same charges are placed into media (air, liquid), potential energy of their interaction equals:

$$V = \frac{q_1 q_2}{4\pi\varepsilon r} \tag{5}$$

where:
V – potential energy of electrical charges at distance r,
q_1, q_2 – electrical charges,
ε – permittivity in media,
ε_0 – permittivity in vacuum,
r – distance between charges.

Permittivity is usually given as relative static permittivity or dielectric constant, which is dimensionless parameter:

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} \tag{6}$$

where ε_r is relative static permittivity or dielectric constant. Dielectric constant of the media is high, if its molecules are polar or highly polarized.

Fig. 5 presents temperature dependency of electrical conductivity and dielectric constant for mineral hydraulic oil. Data shown in the figure were obtained experimentally and are further used to normalize temperature dependency of electrical conductivity and dielectric constant.

Like viscosity, the electrical conductivity and dielectric constant are also monitored at 40 °C to neglect the temperature effect on these two parameters. Since they cannot be always measured at 40 °C, they are normalized to 40 °C with post-calculation.

3. APPLICATION OF ON-LINE CONDITION MONITORING OF HYDRAULIC OIL

The practicality and usefulness of on-line condition monitoring (OCM) methods for hydraulic fluids can be clearly shown in its real industrial application. Fig. 6 presents data from OCM of industrial hydraulic system, which is ideal for OCM, since its poor construction design puts high stress on mineral hydraulic oil, which is prone to accelerated oil oxidation and deterioration.

It is very difficult to show the large amount of data in such small picture. That is why only three major parameters are presented:

- temperature (red),
- relative humidity (blue),
- dielectric constant (green).

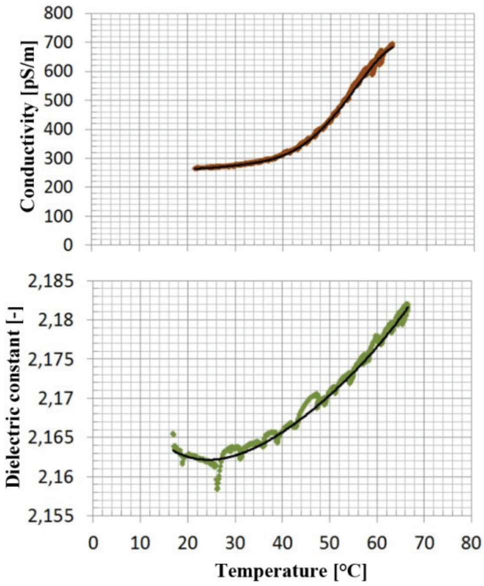

Fig. 5. Temperature dependency of electrical conductivity and dielectric constant for mineral hydraulic oil

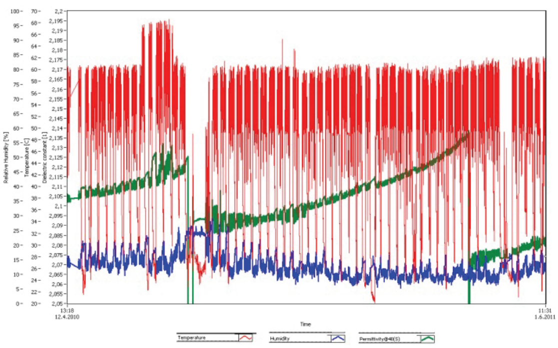

Fig. 6. Industrial application of on-line oil condition monitoring system

It can be clearly seen that the dielectric constant (green) is rapidly increasing due to the accelerated oxidation and deterioration of oil and then suddenly drops when the oil replacement has taken place.

It is assumed that dielectric constant is increasing due to the thermal decomposition of oil because there were no other contaminants detected during this time - relative humidity is low and constant. Also, there were no increased oil contamination levels detected (ISO 4406).

Our assumptions were confirmed by parallel chemical laboratory analysis which reported high neutralization number of mineral hydraulic oil and suggested immediate oil change.

4. CONCLUSION

The use of on-line oil condition sensors together with appropriate knowledge of physico-chemical changes in oil allows the user to have constant overview of the oil quality and its properties. This information can sometimes be crucial for preventing damage and ensuring reliable operation of the system.

Long term predictions in the field of condition monitoring certainly include smaller, more sophisticated OCM systems with multiple condition monitoring analysis capabilities, artificial intelligence (expert rules, fuzzy logic, neural network algorithms,…) that will be eventually massed produced.

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DETEKCIJA I ANALIZA STANJA HIDRAULIČNIH MAZIVA SA ON-LAJN SENZORIMA

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On-lajn nadgledanje stanja celokupnog sistema ili pojedinačnih komponenti može se iskoristiti za otkrivanje nastupajućih otkaza sistema. On-lajn nadgledanje stanja hidrauličnog sistema i fluida igra odlučujuću ulogu u opštem on-lajn nadgledanju stanja. Trenje, habanje, curenje i preterane temperature – sve to ima uticaj na podmazivna svojstva maziva. Pored toga, i samo mazivo je podložno procesima starenja i kvarenja što može, sa svoje strane, dovesti do korozije i otkaza opreme. Stanje maziva se može smatrati za pokazatelj stanja celokupnog sistema. Zbog sveprisutne raspoloživosti rogobatnih i skupih on-lajn senzora za merenje različitih svojstva fluida, najnovija istraživanja se bave on-lain nadgledanjem stanja maziva radi određenja stanja hidrauličnog sistema i fluida. Time se omogućava rad na održavanju na osnovu detektovanog stanja sistema.

Ključne reči: *starenje maziva, nadgledanje stanja, fizička i hemijska svojstva*