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On-line Condition Monitoring and Evaluation of Remaining Useful Lifetimes for Mineral Hydraulic and Turbine Oils

VITO TIČ & DARKO LOVREC

Abstract Condition monitoring of hydraulic and turbine oils, and especially their remaining useful life, is becoming an important strategic business advantage for plant owners, which benefits in environment protection and cost reduction.

This monograph discusses the problem of condition monitoring of hydraulic fluids throughout their life-cycles. Particular emphasis is placed on assessing mineral-based oils' conditions and their remaining useful lifetimes quantitatively. Practicality and usefulness are vital when developing and deploying various methods for condition monitoring systems within industrial environments. Therefore, it is important to know the oil degradation mechanisms and influencing factors, commonly used laboratory methods and oil ageing tests, as well as, for on-line condition monitoring system design, the available sensors with all their characteristics and restrictions.

The proposed approach is based on a novel method for testing the durability and oxidation stability of different hydraulic and turbine oils. The developed mathematical model is based on data from previously conducted oil-ageing tests for the assessment of an oil's condition and its remaining useful lifetime. The method can also be used for comparison of different oils and selection of a more adequate oil with high oxidation stability and long service-lifetime.

Keywords: • hydraulic and turbine oils • degradation mechanisms • on-line condition monitoring • test methods • remaining useful lifetime •

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1 INTRODUCTION

1.1 Benefits of oil condition monitoring

Modern production systems require increases in productivity with the lowest possible production costs; which can only be realized by a high degree of automation. The high degree of automation of the production process may also have negative effects, since any systems' shutdowns or even breakdowns, may affect the entire work process.

One of the more common drive systems found within automation and production processes are hydraulic systems, which are expected to operate flawlessly throughout their service-lives. One of the more important components of the hydraulic system is without doubt the hydraulic fluid, since it directly influences the hydraulic system's operation. It has many roles, from transmitting forces and motion, to lubricating all tribological parts, to cooling the hydraulic system and preventing corrosion. Therefore, the hydraulic fluid and the hydraulic system itself must be properly maintained. Thus, the physical and chemical properties of the hydraulic fluid must remain within certain limits. However, because of fluid ageing and the influences of various operating conditions, the fluid properties change throughout its service-life.

Throughout its service-life the hydraulic fluid is subject to many physical-chemical effects which are visible as contamination of the fluid by solid particles, foreign fluids or as fluid degradation because of the chemical reactions of ageing, as shown in Figure 1.1. The hydraulic fluid indirectly represents the condition of the hydraulic system itself therefore its condition is of utmost importance. If the hydraulic fluid condition is continuously monitored, the user's maintenance personnel can plan the maintenance interventions to guarantee the longest possible machine service-life and reliable system operation.

Nowadays the hydraulic fluid's service-life is still usually determined on the basis of the machine maker's recommendations, i.e. specific fixed intervals, time period or number of operating hours. In most cases the time intervals are estimated from experience within a certain safety factor. In this case, neither the actual hydraulic fluid condition (which may still be appropriate), nor the actual operating conditions of the machine (the workload of which may be lower than rated) are considered. Therefore, the hydraulic fluid is often changed, although it still meets the prescribed requirements. In contrast, when the fluid condition is low or the machine is overloaded the premature deterioration of physical-chemical fluid properties cannot be detected.

These days the actual condition of hydraulic fluid is still commonly determined by taking a fluid sample which is then analysed in the laboratory. Failures and system breakdowns can be prevented by eliminating the problems detected by the analysis. Consequently, the maintenance personnel's efforts are spared and, more importantly the repair costs and costs of losses are avoided.

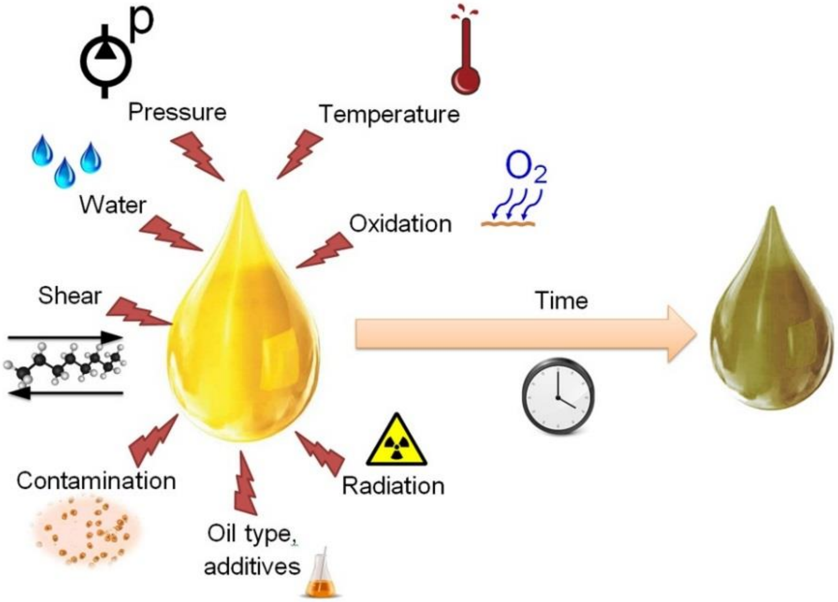


Figure 1.1: Influences on hydraulic fluid throughout its service-life [46]

If economically justified, i.e. on devices with a large quantity of hydraulic fluid or on key production devices (to prevent production shutdown), a periodic condition monitoring is usually set up by periodically taking a fluid sample and analysing it in a laboratory. Such a method allows adaption of hydraulic fluid change intervals to actual conditions, however the reliability of hydraulic fluid condition evaluation depends on the sampling interval, sampling procedure (sampling point, time, sample bottle cleanliness, elapsed time from sampling to analysis), correctly selected parameters for analysis, laboratory equipment and lab personnel's qualifications. Although the method guarantees safety to the machine user, it fails in the cases of sudden changes, e.g. water ingress into the hydraulic system as a consequence of a cooling system fault.

The highest reliability of the machine operation can only be achieved by continuous on-line monitoring of a hydraulic fluid's condition, which can detect problems in real time way before causing major damage. Such modern condition monitoring methods (so-called on-line methods), where the information (signal) is detected by sensors installed in-line on the device, offering continuous monitoring 24 hours a day and thus an insight into the current oil condition and trend analysis over a long period of time. Further on, on the basis of trend analysis, the maintenance works can be strategically planned.

The interest in the on-line condition monitoring methods is rapidly increasing, as the sensor technology is becoming more powerful and easily accessible. Recent researches have dealt with the on-line condition monitoring of oils, which is much more complex than the monitoring of single physical parameters like pressure or temperature. The oil’s 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.

The described on-line methods for the condition monitoring of hydraulic fluids are based on the use of special sensors located on the monitored system. In fact, several sensors are usually needed to measure all the changes in fluid, e.g. temperature, viscosity, relative dielectric constant, electric conductivity, relative humidity, cleanliness level etc. The greatest advantage of on-line methods, in comparison to other methods, is their permanent monitoring, in which sudden condition changes (e.g. water ingress, filling of inadequate hydraulic fluid etc.) can also be detected.

1.2 Development of on-line condition monitoring system for hydraulic fluids

The book demonstrates the development of a system for remote monitoring of mineral hydraulic oils and predictions of their estimated remaining useful lifetimes. Such a system has many advantages over the conventional solutions used nowadays. In addition to continuous monitoring of hydraulic oil and evaluation of its conditions, such a system can also detect sudden changes and unexpected events within the hydraulic system (water ingress, ingress of hard contaminants, temperature increase due to hydraulic component failure etc.) and trigger an alarm to shut down the device before catastrophic consequences appear. The system allows trend analysis of physical-chemical properties and evaluates the current oil condition and the remaining useful lifetime, accordingly.

In comparison to conventional methods (periodic condition monitoring), the implementation of modern on-line condition monitoring system involves certain investment costs. However, on a long-term basis, the use of such a system is a less expensive and more reliable choice which offers several benefits:

- increase in hydraulic system's operational reliability,
- reduction of hydraulic system failures, and thus of the entire machine,
- extension of maintenance intervals and fluid change intervals,
- fluid is changed when it is actually worn out (money savings, eco-friendly),
- reduction in production shutdowns,
- reduction in fluid disposal costs,
- reduction in oil consumption.

Various negative impacts, to which the hydraulic systems are exposed (increased temperature, friction, wear, water ingress etc.), usually result in accelerated oil oxidation and degradation. Effective detection of such physical and chemical changes can only be provided by an on-line condition monitoring system, which is able to detect slow as well as sudden condition changes. In addition to detecting early damage, it also allows easy data recording and history (trend) analysing.

For the development of such a system, all physical-chemical mechanisms causing oil ageing and degradations must be known. Various principles of measuring physical-chemical properties must be researched and studied and then, on basis of those findings, an adequate set of on-line sensors for measuring the changes has to be determined. It must be emphasized that one parameter only is insufficient for gaining reliable results. Therefore, credible oil condition can only be evaluated by measuring several parameters at the same time.

The practicality and usefulness of the proposed system are most important when establishing on-line condition monitoring within an industrial environment. Thus, the research work focused on creating a universal, robust and autonomous system for the remote condition monitoring of mineral hydraulic oils that would be able to automatically evaluate the physical-chemical properties of hydraulic oil without the help of an experienced expert. Such a system should display information on oil condition in a very simple straightforward way. In this manner, the creating and developing of two new virtual parameters for hydraulic oils have been proposed:

- **C – oil condition**, expressed as percentage, and
- **RUL – remaining useful lifetime**, expressed as time format.

Determination and evaluation of the presented parameters would be extremely useful for the on-line condition monitoring of hydraulic oils since it could be used and understood by any of the maintenance personnel or machine users. Further, the system could be connected to central machine controls in order to prevent major damage, since the machine could stop automatically when the system detects inadequate physical–chemical properties within the hydraulic fluid. For example, detected water ingress into the hydraulic system would first cause an alarm and then complete shutdown of the system so that the expensive hydraulic system components are protected (pumps, servo-hydraulic components etc.).

The system would consist of the following elements:

- detecting the physical-chemical properties of oils (sensors),
- detecting and evaluating signal values,
- transmitting data into the central data base,
- storing data from a remote system into the central data base,
- converting certain parameters to a reference set point (as certain measured parameters would depend strongly on other parameters, e.g. viscosity would strongly depend on the oil temperature, therefore viscosity would be converted to reference viscosity at 40°C),
- calculating/evaluating the current oil condition,
- calculating/evaluating the remaining useful lifetime of the oil,
- displaying of data by using a simple, transparent and user-friendly user on-line interface.

2 CONDITION MONITORING OF HYDRAULIC FLUIDS

2.1 About condition and system monitoring in general

Increasing prices of machines and stricter users' requirements relating to the mean time between failures has compelled producers to incorporate condition monitoring systems into the control systems of the machines. This applies particularly to those machines and devices that have to operate continuously and reliably at remote places far away from the maintenance personnel, or when the owner or operator of the machine wants to have complete supervision over the machine's condition. Nowadays the systems for condition monitoring of machines have become an irreplaceable part of any production process and play an important role in the implementation of predictive maintenance. For easier understanding of the importance of machine condition monitoring, a typical machine service cycle [17] is shown in Figure 2.1.

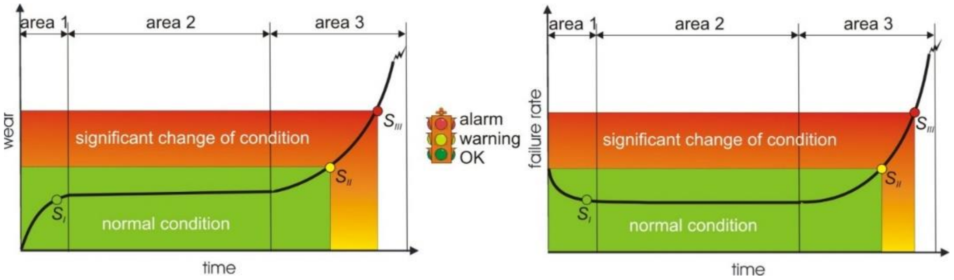


Figure 2.1: Wear of components and level of damages throughout a machine's service cycle [17]

Area 1 represents the machine running-in phase, when initial wear occurs due to irregularities of materials, tolerances, inaccuracies during installation, dirt accumulation etc. This is followed by the actual machine service life with minimum wear of components and no breakdowns (area 2). After lengthy operation the consequences of component wear appear (area 3), when the extent of wear and damage starts to increase exponentially. The role of the condition monitoring system would be early detection of this exponential build-up of damage within the machine (point S_{II} in Figure 2.1).

The condition monitoring methods would be divided into two main groups, the off-line methods where analyses would be done at intervals either periodically, or for special events. Analysis could be performed either on-site where the machine is installed, by connecting the measuring instrument to the machine, or by taking a representative sample which would then be sent to a specialized laboratory for analysis. As off-line analyses would be performed at intervals, there would be a risk of machine failure between two intervals. On the other hand, higher reliability of the machine operation would be ensured by on-line methods, where the condition monitoring system would be located on the machine itself and would continuously monitor and record the conditions of the selected machine parameters. Details on off-line and on-line methods for condition monitoring of hydraulic fluid are given in Chapter 2.2.

Over the years a great number of various machine condition monitoring methods have been developed, which can help improve maintenance work and prevent major damage. The more common and widespread machine condition monitoring methods are the temperature measurements, oil condition monitoring, endoscopy, thermography, acoustic emission and vibration analysis [40]. Whereas for some of the methods special sensors are necessary, other methods use much simpler and visible indicators which may be noticed by an experienced machine operator, e.g. leakage, increased temperature or unusual noise.

Each of the condition monitoring methods can also be evaluated according to certain criteria like price, usefulness, reliability etc. One of the important criteria is also the pre-warning time, i.e. the time from the first fault indication to complete machine failure, as shown in Figure 2.2.

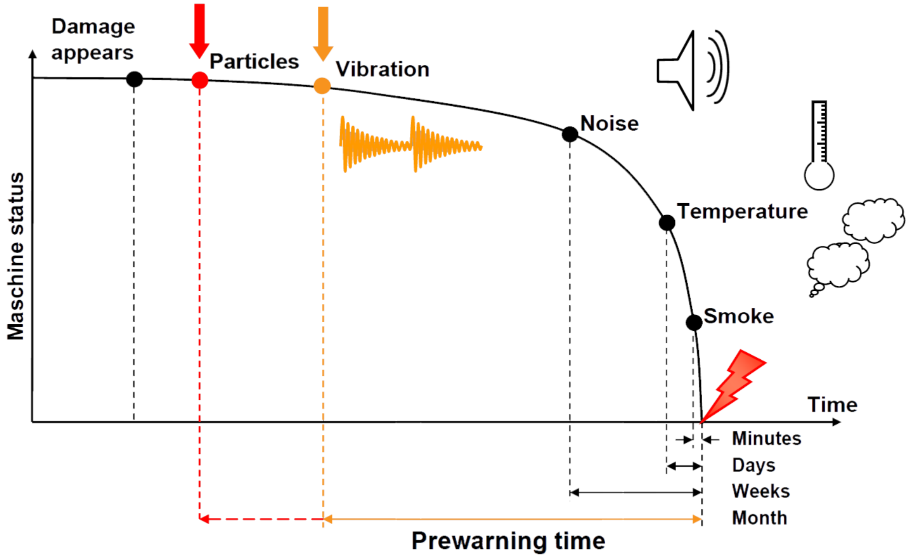


Figure 2.2: Pre-warning time prior to damage occurring using different types of condition monitoring methods [40]

Early warning about a machine fault is very valuable, since it allows the maintenance personnel to plan the repairs and maintenance work necessary for safe and trouble-free operation of the machine and production process, in advance. Figure 2.2 shows that some fault occurrence indicators like increased temperature or smoke do not guarantee enough early warning to prevent failure of the machine or its components.

Figure 2.2 emphasizes the importance of oil condition monitoring (when hydraulic power systems are used) that monitors the conditions of individual hydraulic components or also the condition of the in-service hydraulic fluid. Modern on-line condition monitoring systems and off-line hydraulic fluid analyses allow early detection of damage occurrence within the observed machine so that the fault can be removed before complete machine breakdown.

2.2 Condition monitoring of hydraulic fluids

Hydraulic fluid condition monitoring offers many advantages like continuous determination of actual machine condition and detection of slow as well as sudden oil condition changes. In addition to early fault detection and prevention of heavy machine damage, it also allows continuous acquisition of operating data so that the maintenance intervals and machine shutdowns can be planned.

The condition monitoring methods have already been divided into off-line and on-line methods in the previous chapter. When hydraulic fluid condition is monitored by off-line methods, the fluid samples are periodically taken from the hydraulic system and further off-line analysed in a distant laboratory, where measurements of physical-chemical parameters are performed for determining the fluid condition. The measuring methods of physical-chemical parameters in a laboratory are presented in detail in Chapter 2.3.

Figure 2.3:Various oil condition monitoring methods – from left: periodic laboratory analyses, periodic analyses on-site, continuous on-line condition monitoring

Continuous detection of changes of physical-chemical properties of hydraulic fluid is only possible with on-line methods, when proper sensors for measuring certain parameters are installed on the monitored machine. These parameters usually differ from the parameters determined in a laboratory. The parameters and values detected by on-line sensors are presented in Chapter 2.4.

There is also a middle way, i.e. the on-site methods, where the fluid sample is taken from the hydraulic device and quickly and simply analysed on the spot. These methods are less precise than the laboratory methods, although they are sufficient for quick evaluation of the hydraulic fluid condition.

The advantages and disadvantages of individual methods are indicated in Table 2.1, where it can be seen that the off-line analyses (analyses in distant chemical laboratories) provide a more detailed picture of the oil condition and are more precise than the on-line analyses.

Table 2.1: Advantages and disadvantages of various condition monitoring methods for hydraulic fluids [39]

Method	**Advantages**	**Disadvantages**
Periodical oil analysis in external laboratory	• Highly precise devices give credible data in accordance with standards • Detailed picture of oil condition • Measurements are evaluated and commented on by an experienced professional	• Sampling procedure affects the analysis results • Time between sampling and laboratory analysis (influences on sample) • Detailed analyses report single condition in contrast to continuous measurements • Expert evaluating the fluid condition has no direct access to hydraulic device
Periodical on-site analysis	• No time delay between sampling and analysis • If analysis results coincide with analysis results of outside laboratory, identical limit values can be established • Direct access to device and maintenance personnel is possible	• For some analyses handling of chemicals and solvents is necessary • Faults and events not anticipated are not detected • Sampling procedure affects the analysis results • Analysis results can be evaluated only by experienced person • Limited number of analyses (complete picture of hydraulic fluid condition is not guaranteed)
Remote on-line condition monitoring	• Continuous measurement (24 hours a day) reliably detects sudden and not anticipated events • Fault is detected in real time • Historical recording and trends analysis of individual values are possible • Automatic alarming system can be created • Data can be mathematically or statistically processed	• Sensor values are considerably different from values measured in laboratory analyses • Sensor calibration is frequently complicated and valid only for a particular hydraulic fluid type • Experiences are required for evaluation of hydraulic fluid condition • Interpretation of a single parameter may be misleading • Limited number of sensors and parameters that can be monitored

However, they also have disadvantages, e.g. laboratory analysis shows only (single) current hydraulic fluid condition, the sampling process can considerably affect the analysis results; besides, laboratory analyses are relatively expensive.

In contrast to off-line analyses, on-line analyses allow continuous monitoring of hydraulic fluid condition and thus, protect the machine against sudden events, since the fault is detected in real time. In that way, a system for automatically alarming the user or even a system for automatic machine shutdown in case of sudden fluid condition deterioration could be created. One of the major advantages of on-line methods is also historical recording and trends analysing. On the other hand, the greatest disadvantage of on-line systems is the limited number of sensors and sensor values that can be monitored. In most cases, these parameters also differ from the parameters monitored by conventional laboratory analyses. Therefore, direct comparison between parameters is impossible.

2.3 Conventional laboratory analyses

Conventional laboratory analyses are conducted on the basis of periodically taken samples that are analysed in a distant chemical laboratory. The proper sampling procedure, as presented in Chapter 2.3.1, is very important for accurate analyses and successful implementation of hydraulic fluid condition monitoring program.

2.3.1 Proper oil sampling

If the fluid sample does not represent the actual condition of the hydraulic oil in use, all further diagnostic procedures and analyses are meaningless. Proper sampling procedures are a basis for efficient and accurate laboratory analyses. Inadequate sampling, improper sampling, incorrect handling of samples and postponing of analysis may lead to inaccurate and misleading results [41], [26].

Before the first oil sample is taken from the monitored device, it is necessary to determine the proper sampling point, which must remain unchanged during the entire condition monitoring program. The sample should always be taken at the same spot and under identical machine operating conditions. This is the only way to ensure comparability between individual analyses. The sampling process for an individual device should be properly recorded so anyone can repeat it in the same way. It is recommended to keep records on sample taking together with information about the time of taking, machine working hours and intermediate observations. This information needs to be sent together with the sample to the laboratory that will, based on these records, conclude more easily about the origin of the fluid deterioration and origin of the machine fault.

The sample should always be taken during the machine's operation, i.e. during a typical work cycle, when the hydraulic fluid is in circulation and the machine, as well as the hydraulic fluid, is at its working temperature. These issues are discussed in detail in Chapter 4.3.

The hydraulic fluid on the return line in front of the filter contains most of the information about machine operation and wear of hydraulic components, since it has just covered the path throughout all the hydraulic components and the filter has not yet isolated the possible solid particles generated within the hydraulic system as a consequence of wear.

Taking a sample from the tank should be avoided as a representative and comparable sample is hard to obtain. The hydraulic fluid in the tank is very non-homogeneous, therefore the analysis results may be misleading when the sample is taken from tank. In addition, the sampling device that is dipped into the fluid may be full of dirt.

The sampling bottle, as well as all sampling devices used in the process, must be completely clean. Used sampling bottles must never be re-used. Further on, the same sampling devices must never be used for sampling several fluids consecutively but should be properly cleaned between individual samplings.

Properly taken samples should be sent to the laboratory for analysis at once, as the sample and hydraulic fluid properties start to change immediately after the sample has been taken.

2.3.2 List of conventional laboratory analyses

The parameters which are usually determined during laboratory analysis for mineral oils and on the basis of which the condition of oil is evaluated, are collated in Table 2.2 and described in detail below. For reliable evaluation of oil condition, in addition to the parameters presented, data are also needed on the initial oil condition and results of possible previous analyses. Trend Analysis is much more convenient than a single analysis result and consists of several analyses and which can also predict the condition of oil in the near future.

The choice of laboratory analyses and the methods used in our research, as presented in Table 2.2 was made according to the used hydraulic oil, i.e. mineral hydraulic oil VG 46 and according to the available laboratory equipment. There are, of course, other hydraulic fluid condition monitoring methods available, but they are not usually used for monitoring the conditions of mineral hydraulic oils. A comprehensive list of tests for various hydraulic fluids can be found in the literature, e.g. [25] or in catalogues of individual laboratories, e.g. [56], [59].

Table 2.2: List of the more frequent laboratory analyses of mineral hydraulic oils

Test method	Standard	Unit
Colour	ASTM D 1500	[L]
Flash point	SIST EN ISO 2719	[°C]
Density	ISO 12185	[g/cm^3]
Viscosity at 40 and 100 °C	ASTM D 445	[mm^2/s]
Viscosity index	ASTM D 2270	[-]
Neutralization number	ASTM D 974	[mg KOH/ g]
Water content (Karl Fischer)	SIST EN ISO 12937	[ppm]
FT-IR spectrum (oxidation level)	ASTM E 2412	[-]
Four ball – Welding point	IP 239-85	[kg]
Four ball – Wear test	IP 239-85	[mm]
Cleanliness level	ISO 4406	[-]
X-Ray elementary analysis	ASTM D-6481	[wt. %] or [mg/kg]
Foaming – I., II. and III. sequence	ASTM D 892	[ml/ml]

2.3.3 Colour

Fresh mineral hydraulic oils have their characteristic colours. Usually, they are of light, clear, brown-yellow colours. In the course of their service lives, they tend to lose their brightness and become dark and mat. These optical changes may be a consequence of the common oil-ageing process but frequently they may be important visible symptoms of accelerated mineral oil degradation requiring further analyses and proper actions [27].

The colour depends on the presence of oil impurities absorbing a certain spectrum of light. Completely clean fresh oil is of clear brown-yellow colour, almost transparent (little or almost no light is absorbed). Impurities formed by oil ageing and degradation absorb the lights of selected frequencies and produce specific oil colours and shades. The colour could be determined in an automated way by a spectrophotometer or visually by means of comparing colour scales like ASTM D 1500 [2], [27].

If the method ASTM D 1500 is performed visually, the result can be determined in L 0.5 steps, while with the use of automated spectrophotometers it could be determined with L 0.1 precision [2].

During our research, the oil sample colour was determined visually by the ASTM D 1500 method [2]. The usual colour of the discussed HLP ISO VG 46 hydraulic oil is L 1.5 or L 2.0.

2.3.4 Flash point

The fluid flash point provides an important piece of information about mineral oils. Flash point is the temperature at which, under certain test conditions [66], the mixture of oil vapours and air inflames when approached by an open flame. The flash point temperature differs from the burning point (DIN 51584, DIN ISO 2592) and its values for mineral oils are usually between 150 and 200 °C (even up to 245 °C). The fluid temperature within the hydraulic system should not exceed 60 °C, therefore the hazard of self-inflammation is relatively low [41].

The flash point measurements were performed using the SIST EN ISO 2719 method [66] on the equipment shown in Figure 2.4. The usual flash point of the discussed HLP ISO VG 46 hydraulic oil is around 240 °C.

Figure 2.4: Apparatus for determining the flash point within open and closed vessels

2.3.5 Density

The fluid density is provided by the producer for each hydraulic fluid produced. Although the density measurement includes the most frequent laboratory analyses of hydraulic mineral oils, its value rarely changes with fluid ageing. Any density change is mostly a consequence of the ingress of foreign fluids into the hydraulic fluid.

The density measurement was performed by the Mettler Toledo DE40 automatic density meter as shown in Figure 2.5, using the ISO 12185 method [36]. The density of the discussed HLP ISO VG 46 hydraulic oil at 15 °C is usually around 0.87 g/cm^3.

Figure 2.5: Mettler Toledo DE40 automatic density meter

2.3.6 Viscosity

Viscosity is one of the more significant properties of lubricating oils since it affects their capacities for creating lubricating film and reducing friction and component wear. It is the most important hydraulic fluid parameter since by selecting correct viscosity gradation and maintaining it guarantees the longest possible service-life of a component within the hydraulic system [21]. Therefore, hereinafter viscosity will be discussed in detail.

Dynamic viscosity is determined by a rotating viscometer or a falling ball viscometer. It can be described on the basis of two surfaces separated by a fluid layer of h thickness as shown in Figure 2.6. The force required to move the top surface is proportional to surface A and velocity v [65]:

$$F \propto A \cdot v \tag{2.1}$$

It can be assumed that the fluid film, separating the two surfaces, consists of many infinitely thin layers. If two fluid films of different thicknesses consisting of smaller layers, are compared, the surface velocity in both cases is identical. The individual fluid layer in the thicker fluid film is subject to minor sliding. The velocity gradient for two fluid films of different thicknesses h and identical velocities v will be different. As the thicker film contains several single layers, the force required to move one layer is smaller. The viscous resistance changes in inverse ratio to the film thickness *l/h*. The force required to move the top surface is, thus, proportional:

It can be assumed that the fluid film, separating the two surfaces, consists of many infinitely thin layers. If two fluid films of different thicknesses consisting of smaller layers, are compared, the surface velocity in both cases is identical. The individual fluid layer in the thicker fluid film is subject to minor sliding. The velocity gradient for two fluid films of different thicknesses h and identical velocities v will be different. As the thicker film contains several single layers, the force required to move one layer is smaller. The viscous resistance changes in inverse ratio to the film thickness *l/h*. The force required to move the top surface is, thus, proportional:

$$F \propto \frac{A \cdot v}{h} \tag{2.2}$$

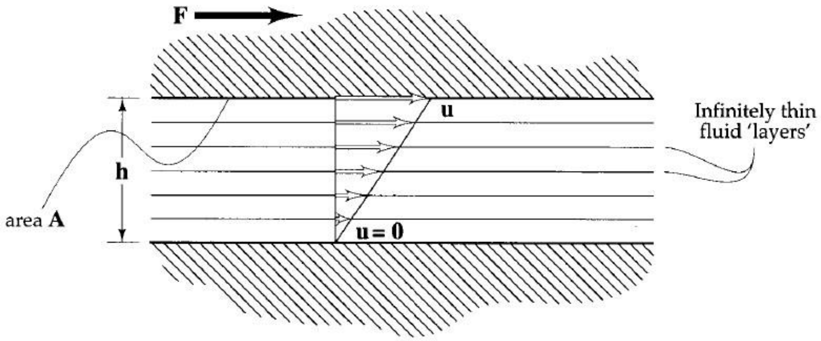


Figure 2.6: Schematic representation of fluid between two moving surfaces [65]

That ratio applies to most fluids. Different fluids have different dynamic viscosities representing the constant of ratio η:

$$F = \eta \, \frac{A \cdot v}{h} \tag{2.3}$$

The dynamic viscosity η can be derived at from Equation 2.3:

$$\eta = \frac{F}{A} \cdot \frac{h}{v} \tag{2.4}$$

or

$$\eta = \frac{\tau}{\frac{v}{h}} \tag{2.5}$$

η [Pas] – dynamic viscosity,
τ [Pa] – shear stress acting on fluid,
v/h [s^{-1}] – velocity gradient, which is perpendicular to shear stress.

Kinematic viscosity is determined by the use of a viscometer on the basis of fluid flowing out and is defined as the ratio between the dynamic viscosity of the fluid and its density [65]:

ν [m^2/s] – kinematic viscosity,
η [Pas] – dynamic viscosity,
ρ [kg/m^3] – fluid density.

According to their viscosity the mineral hydraulic oils are divided into viscosity grades (VG) relating to the reference fluid temperature 40 °C at ambient pressure. The viscosity grades are defined in the DIN E 51524 standard, which is also adopted by the international ISO standard. The actual value of the oil viscosity can deviate from the rated value by ±10 %. Table 2.3 indicates the viscosity grades more often used in hydraulic systems and their minimum and maximum values, i.e. permissible deviation.

Table 2.3: Viscosity grades according to ISO VG classification [42]

ISO viscosity grade	Kinematic viscosity at 40 °C	
	Min.	**Max.**
22	19.8	24.2
32	28.8	35.2
46	41.4	50.6
68	61.2	74.8
100	90	110
150	135	165
220	198	242

The hydraulic fluid viscosity is not constant but changes depending on the temperature, pressure and shear stresses [41]. When monitoring the hydraulic fluid condition, the viscosity is always determined at air pressure, i.e. ambient pressure, which is assumed to be constant. The shear stresses are also constant, therefore the viscosity dependence on pressure and shear stresses can be neglected and attention focused only on the dependence of viscosity on temperature. More information about the dependence of viscosity on pressure and shear stresses can be found in various literature e.g. [63], [41], [65].

In general, the viscosities of all hydraulic fluids decrease with temperature increase. The viscosity value at a specific working temperature is a very important piece of information, as it defines the lubricating film thickness separating two contact surfaces. The oil viscosity at a certain temperature can be calculated from viscosity-temperature equations determined according to the ASTM viscosity-temperature chart.

Several equations describing viscosity temperature dependency are known. Some of them are quite empirical, while the others are based on theoretic models. The equations indicated in Table 2.4 are the more frequently used. The most accurate is the Vogel equation for which three measurements of viscosity at different temperatures are required for determining its constants.

Table 2.4: Equations describing viscosity – temperature dependency [65]

Name	Equation	Description
Reynolds	$\eta = b \cdot e^{-aT}$	One of the first equations; accurate only for limited temperature range
Slotte	$\eta = \frac{a}{(b+T)^c}$	Sensible; useful in numerical analyses
Walther	$(\nu + a) = b \cdot d^{1/T^c}$	Basis for ASTM viscosity-temperature chart
Vogel	$\eta = a \cdot e^{b/(T-c)}$	Most accurate; very useful in engineering

a, b, c, d		– constants,
v	[m^2/s]	– kinematic viscosity,
T	[K]	– absolute temperature.

The ASTM diagram (ASTM D 341), which is empirically based completely on the Walther equation from Table 2.4, is frequently used for determining viscosity at certain operating temperatures.

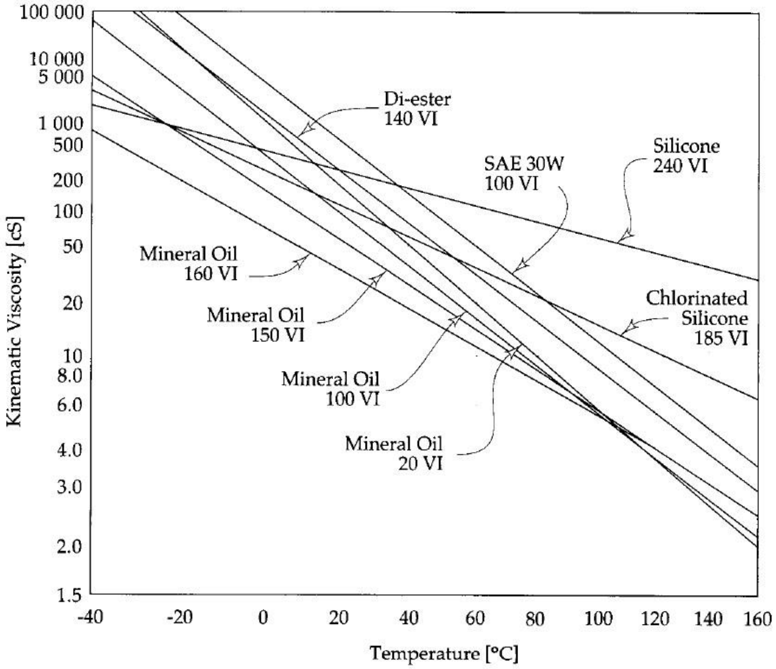


Figure 2.7: ASTM diagram: viscosity-temperature dependence for different oils [65]

Although the diagram is based on the Walther equation, it presupposes and simplifies certain parameters in it. Nevertheless, the ASTM diagram is rather accurate and describes very well the mineral and synthetic oil viscosity under normal operating conditions.

Usually, the hydraulic fluid viscosity is measured at the reference temperatures 40 °C and 100 °C. The two data for kinematic viscosity at both temperatures are also a basis for determination of the viscosity index. More frequently, the capillary and rotational viscometers are used for measuring viscosity. In general, the capillary viscometers are suitable for fluids with negligible non-Newtonian effect, while rotational viscometers are more suitable for fluids with strong non-Newtonian effect. Some viscometers incorporate a special heating chamber for the control and measuring of temperature, responsible for stabilization of the temperature – viscosity characteristic.

Capillary viscometers are based on the flow of a certain volume of fluid through a capillary tube within in a specific time. The time necessary for the flow of specific fluid quantity gives the kinematic viscosity, while the flow through capillary tubes must remain laminar. The measurement and calculation of kinematic viscosity is based on the Poiseuille’s law of stationary viscous flow in the tube [65].

Figure 2.8: Apparatus for determining kinematic viscosity at specific temperatures

The measurement of mineral hydraulic oil viscosity was performed by a capillary viscometer within a tempering bath according to ASTM D 445 procedure [6], as shown in Figure 2.8.

2.3.7 Viscosity index

As already shown in Figure 2.7, different oils also have different straight-line inclinations within the ASTM diagram. Already in the 1920s, it was well-known that Pennsylvanian base oils were better than Texan base oils. Pennsylvanian base oils had the best viscosity-temperature characteristics, while the Texan ones had the worst ones since their viscosity was very temperature dependent [65].

From technology point of view, the need for a parameter appeared which would accurately describe the viscosity-temperature dependency and thus in 1929 the viscosity index was introduced. The viscosity index is a completely empirical parameter comparing specific oils with two reference oils, the viscosities of which change very differently with temperature. The two reference oils were selected in a way that one of them had a viscosity index equal to 0 and the other had a viscosity index equal to 100 at 100 °F (37.8 °C), However, at 210 °F (98.89 °C) they both had identical viscosity as the oil viscosity index is determined as shown in Figure 2.9.

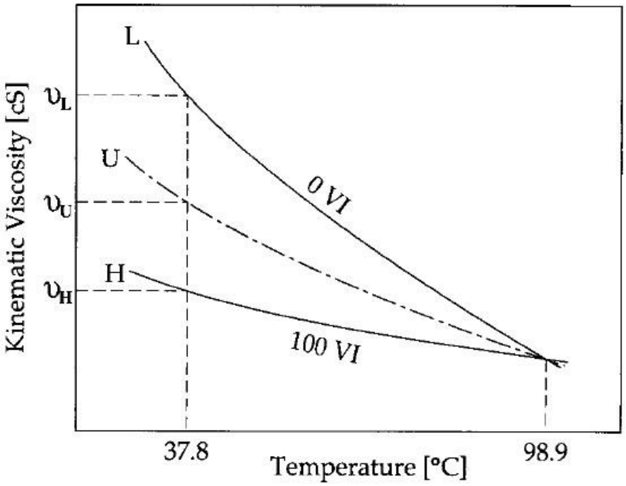


Figure 2.9: Evaluation of viscosity index [65]

As the Pennsylvanian and Texan oils had identical viscosity at 210 °F (98.9 °C), they were selected as reference oils. Viscosity index 100 was assigned to the base oil from Pennsylvania, while viscosity index 0 was assigned to the Texan base oil. The viscosity index can be calculated according to equation (2.7) [65]:

$$I = \frac{(L-U)}{(L-H)} \cdot 100 \tag{2.7}$$

The kinematic viscosity of the observed oil is first measured at 40 °C (parameter U) and 100 °C. Then from the ASTM D 2270 [3] table the parameters L and H are determined with respect to the viscosity of the oil observed at 100 °C. When the data had been inserted into the above equation, the latter gave the viscosity index of the studied oil.

The viscosity index is a measure of viscosity stability on the oil temperature changes. High viscosity index implies that the oil has better viscosity stability on temperature changes. The viscosity index of most refined mineral oils on the market is around 100, while multi-grade and synthetic oils have a higher viscosity index, i.e. about 150.

2.3.8 Neutralization number

Fresh and used oils contain base and acid ingredients present as additives or as oxidation products of decomposition occurring during usage. The relative quantity of acid ingredients is determined by titration with the base and is indicated as added potassium hydroxide - KOH in mg KOH/g of oil. When testing fresh oils, the neutralization number is determined as one of the control parameters for verification of composition constancy. When monitoring the hydraulic fluid condition, the trend of the neutralization number is one of the criteria for estimating the hydraulic fluid degradation extent and its further usability [13].

The neutralization number tells how much KOH must be added to 1 g of oil to neutralize the acids present in the oil. In the fresh oil the neutralization number value depends on the base oil itself and the additive package contained in the oil. In mineral hydraulic oils, the neutralization number varies from 0.2 to 1.5 mg KOH/g but usually equals from 0.4 to 0.6 mg KOH/g. The permissible values for in-service oils are defined by the producer, but detailed oil analysis is usually required when the neutralization number increases from 0.3 to 0.4 mg KOH/g in relation to fresh oil value [41].

The results of neutralization number measurements in this book were obtained according to the standardized procedure ASTM D 974 [13], i.e. by titration with the KOH base.

2.3.9 Water content measured by Karl Fischer titration

Hydraulic oil sample analyses often confirm the presence of small or greater quantities of water. Even a small amount of water content influences the oil chemical properties and reacts with the metal surfaces of hydraulic components. The damage level on the oil and machine depends on the quantity and time of water presence in the oil and device. Therefore, our aim must not be to keep the water content below the permissible limit but rather to operate without or with minimum possible water content [41].

The water content measured by Karl Fischer titration is one of the more widespread methods for the determination of water content in oil. It allows determination of water content with good repeatability over a short time interval of 1 to 2 minutes over an area of some ppm to 100 % [37]. During the measurement, water reacts with iodine and the reactive component formed during the reaction between sulphur dioxide and alcohol (usually methanol) in the presence of the base (imidazole) [37].

Measurement of water content was performed, in our case, by Karl Fischer titration according to the standardized procedure ISO 12937 using a Mettler DL 35 Karl Fischer titrator, as shown in Figure 2.10.

Figure 2.10: Mettler DL 35 Karl Fischer titrator

2.3.10 FT-IR spectrum

Infrared analysis of used lubricants has proved to be an excellent method for monitoring the trend of hydraulic fluid changes and is used for investigating the molecular changes in lubricant. All covalent chemical bonds as in organic molecules (CH_4 or methane) absorb the infrared radiation causing the bonds to vibrate by expanding and shrinking. The strength of the bond between atoms, depending on the atomic structure, determines which part of the IR spectrum is absorbed by molecules.

This phenomenon can be illustrated and compared with Hooke’s law of the spring, where the amount of energy triggering the spring oscillation depends on the hardness of the spring and mass fixed at the spring’s end. In case of FT-IR spectrum this relates to the absorbed IR energy and nature of the bond between carbon (C) and hydrogen (H) atoms. The amount of energy in the IR beam is proportional to its wavelength – the smaller the wavelength the greater the energy. Although in this case only as much energy is absorbed as is necessary to cause vibration. All other energies, either smaller or greater, have no effect [60].

Therefore, in molecules containing several different types of bonds (e.g. C-H and C=O) at least two different absorption bands would be expected. Certain chemical bonds in the molecule show different IR absorptions. This property is properly utilized in analytical chemistry. Chemists refer to the mentioned absorption with the wave number [cm^{-1}], which represents a more practical manner of illustrating the absorbed radiation frequency and simply represents the number of waves per cm. The final part of the equation is the amount of absorbed radiation. It is indicated using the simple Beel-Lambert’s law implying that the amount of absorbed IR radiation is proportional to the concentration of absorbed lines and distance to be covered by IR radiation [60].

The FT-IR analysis results are usually given in the form of a chart, where on the abscissa axis the wave numbers from 4000 to 500 cm^{-1} can be indicated, while on the ordinate axis either IR absorbance or transmittance can be indicated. The absorbance A [-] is a measure of the light or energy amount not transmitted (not reflected) by the sample and proportional to the matter concentration in the solution. The sample transmittance T [-] is the ratio between the intensity of IR light which passed through the sample and the intensity of IR light at the entry into the sample [75]. Absorbance A and transmittance T are mathematically related in equation (2.8) [75]:

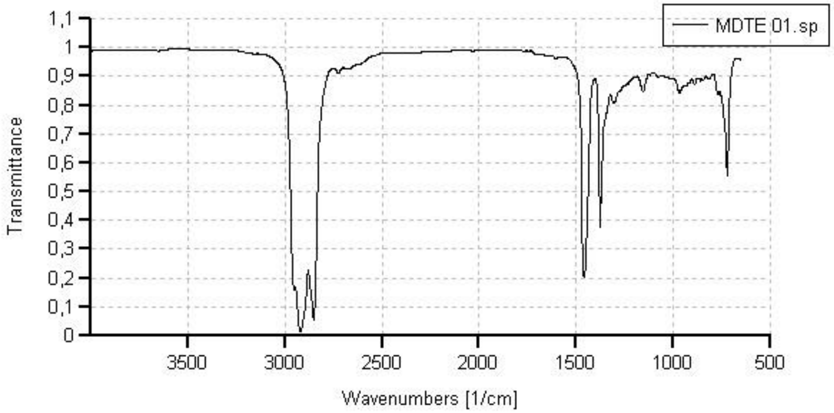
$$A = log_{10}(1/T) \tag{2.8}$$

In FT-IR analysis of used oils also the spectral subtraction can also be made, i.e. from the recorded IR spectrum of used oil the spectrum of fresh oil is subtracted. As a result the difference between both spectra is obtained from which it is possible to see the molecular changes between fresh and used oil, i.e. to detect the oxidation, nitration, sulfation etc. products [14], [60].

An example of the FT-IR spectrum of a mineral oil sample and its transmittance and absorbance is shown in Figure 2.11, while Figure 2.12 shows the result of subtracting absorbance between two samples.

At high temperatures and pressures, the organic compounds partly oxidize in the presence of oxygen (they chemically react with oxygen). This results in many different products the layouts and structures of which are very complicated. Some compounds dissolve in oil while the others remain insoluble due to the presence of dispersive matters and additives in oil. Carboxylic acids contribute to oil acidity while during the oil neutralization they use up their basic reserve. When oil is subject to longstanding oxidation it becomes chemically acidic and likely to cause corrosion while viscosity, as an oil chemical property, is increased [60].

The FT-IR method determines the oxidation extent as a general response to carbonyl band (C=O) between wave numbers 1800 and 1670 cm^{-1}. Within that band, the IR energy is absorbed due to the bond between oxygen and carbon in the oxidized oil. Modern lubricants contain very little compounds having considerable absorption within that band, therefore monitoring of that band of the IR spectrum in fact represents direct measuring of the oxidation level (compared with secondary techniques like the neutralization number for considering all types of acids in oil) [14], [60].



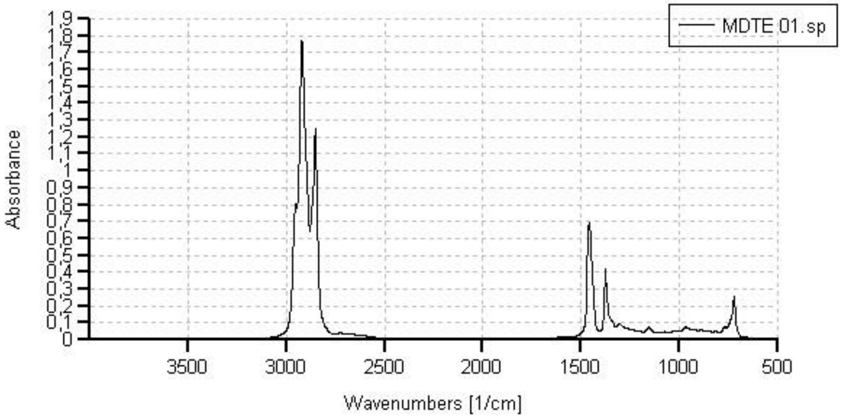


Figure 2.11: Example of FT-IR spectrum of mineral oil sample: transmittance (top) and absorbance (bottom)

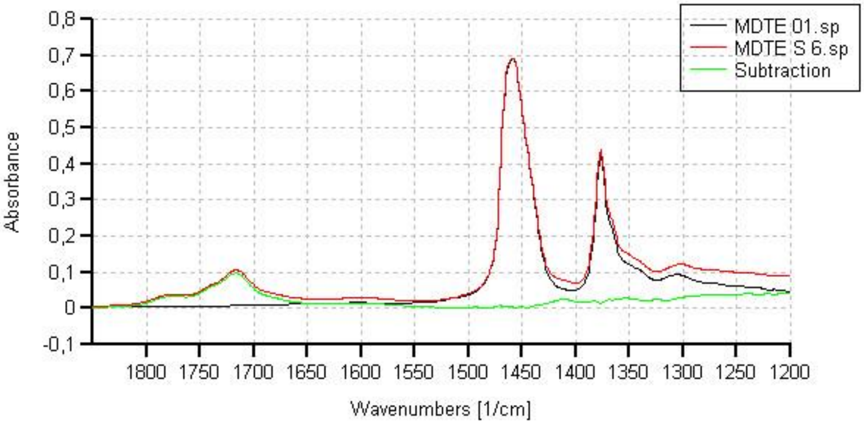


Figure 2.12: Subtraction of absorbance between two samples

In organic compounds that are subject to high temperatures and pressures, in addition to oxidation products, also the nitration products are also formed in the presence of nitrogen and oxygen. They mostly appear in the forms of nitrogen oxides like NO, NO_2 and N_2O_4. These products cause oil thickening and viscosity increase. Some products also have acid nature. In addition, the nitration products are the principal cause of forming of insoluble resin products – varnish [14], [60].

The nitration products can be detected by FT-IR analysis, since their bonds have characteristic absorbance between wave number 1650 and 1600 cm^{-1}, i.e. the band on the FT-IR spectrum immediately behind the oxidation products [14], [60].

Sulphuric compounds are not usually found in base oils but they are also used as additives to lubricants for reaching specifically desired properties. Sulphate side products like SO_2 and SO_3 are formed by oxidation of the mentioned sulphur-containing compounds. Those compounds accelerate the formations of varnish deposits and in general decompose oil. Sulfates are measured by the FT-IR method in the same way as oxidation and nitration, i.e. by monitoring increases in their characteristic IR absorbance between wave numbers 1180 and 1120 cm^{-1} [14], [60].

FT-IR analysis of soot products is an exception and differs from the general approach, when the surface below the curve in certain band of the wave number is estimated. Soot has no specific IR absorption bands. Instead, soot products cause general dispersion of IR radiation which is more intense with higher wave numbers. Therefore, the soot content is simply measured by reading the absorption using wave number 2000 cm^{-1}. Analysis of soot products is usually used for analysing fuel properties and less for fluids that primarily serve as lubricants [14], [60].

Table 2.5 shows the more common absorption wave numbers with possible interferences during measurements.

The FT-IR analyses were performed according to the standardized ASTM E 2412 [14] procedure by the device Perkin Elmer Spectrum 100, shown in Figure 2.13 in combination with ZnSe HATR window.

Table 2.5: Characteristic absorption wave numbers in FT-IR analysis [60]

Parameter	Wave number (cm^{-1})	Accuracy	Interferences
Oxidation	Mineral oil – 1750 Organic ester – 3540 Phosphate ester – 815	25 %	VI improvers, dispersants, heavy moisture contamination
Sulfation	1150	25 %	Sulphurous additives (ZnDDP, sulphur/phosphorus EP, some rust inhibitors)
Nitration	1630	25 %	VI improvers, dispersants
Soot	2000	10 %	Particle size/density
Water	Mineral oil – 3400 Organic ester – 3625	25 %	Excessive soot, detergent additives, glycol, antioxidant, ester base-stocks, severe oxidation, free vs. dissolved water
Glycol	880, 3400, 1040, 1080	50 %	Water, antioxidants, oxidation by-products
Fuel	Diesel – 800 Gasoline – 750 Jet fuel – 795-815	50 %	Varying fuel aromaticity, fuel evaporation
Phenol inhibitors	3650	50 %	Moisture, glycol
ZnDDP	980	35 %	Aromatic impurities, fuel, silica (dirt)

Figure 2.13: FT-IR analyser Perkin Elmer Spectrum 100

2.3.11 Four ball welding point and -wear test

Hydraulic fluid lubricating properties can be determined by measuring the welding point and by the wear test according to standardized procedure (e.g. IP 239-85). This method is based on applying the load to four standardized steel balls of 12.7 mm diameter. The top rotating ball slides on top of three fixed balls at constant loading and constant rotating speed of 1440 min^{-1} (Figure 2.14 left). Measurement of the welding point and the wear test of lubricating oil, emulsion and grease can be performed on the same apparatus.

The welding point is measured at specific load and by exerting pressure on the top ball during the 10 s test. The top steel ball rotates and presses with the test load against the bottom three immovable balls dipped in the analysed fluid. The measurement result is given in kg (or in N) and is represented by two numbers, e.g. 140/160 (or 1400/1600). The first number indicates the maximum load at which ball welding did not occur during the test (10 s). The other number indicates the least loading at which complete welding and sintering of steel balls occurred during the test [35].

The wear test lasts much longer, i.e. 60 ±1 min, at constant temperature and load. The ball wear depends on the load, velocity, test duration and properties of the lubricant tested. As all parameters, except the lubricant properties are constant, the result (the ball wear) only depends only on the lubricating properties of the fluid tested. After completion of the test, the result is reached by measuring the wear on the bottom three steel balls under the microscope, where the radiuses of wear depressions on the three immovable balls are measured. The wear extent is defined as the mean diameter of ball wear under known conditions [35].

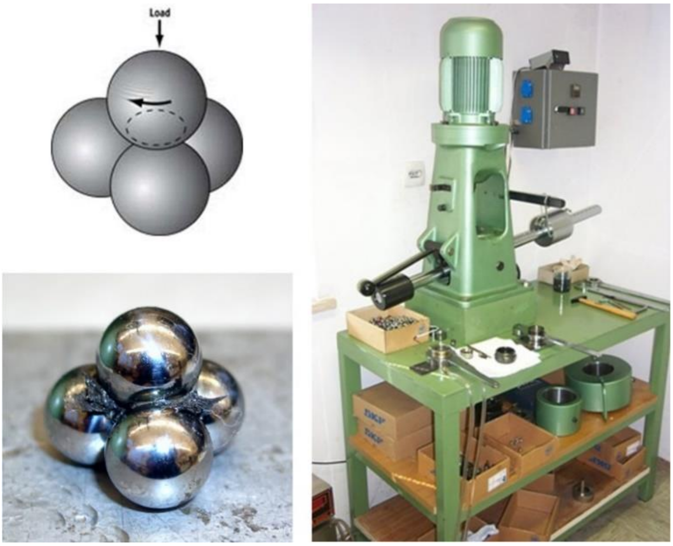


Figure 2.14: Measurement principle of welding point and wear test (left), four-ball apparatus Hansa Press (right)

The analyses, determination of welding point and wear test, were performed according to the standardized procedure IP 239 [35] using the four-ball apparatus Hansa Press, as shown in Figure 2.14 right.

2.3.12 Oil cleanliness level

Mechanical contaminants are considered to be the main reason for hydraulic and lubricating systems' failures. By proper control of the hydraulic fluid cleanliness level, the service-lives of hydraulic components can be prolonged [18].

The hydraulic fluid cleanliness level is determined on the basis of the number of particles of specific size within a specific fluid volume. The measurements are usually performed by automatic particle counters, measuring the cleanliness level according to the selected standard. Each particle in the fluid causes reduction of light intensity, which is detected by the photodiode in the device and converted into an electrical signal. The change of voltage, which is directly proportional to the particle size, is converted by the microcomputer into proper information about the particle size.

The cleanliness level can be indicated in accordance with different standards, the more widespread being [41]:

- ISO 4406 (old standard) defines the number of particles larger than 5 and 15 μm, or 2.5 and 15 μm in 100 ml fluid sample.
- ISO 4406: 1999 (new standard) defines the number of particles larger than 4, 6 and 14 μm in 1 ml fluid sample.
- NAS 1638 defines the number of particles of sizes 5 to 15, 15 to 25, 25 to 50, 50 to 100 and over 100 μm in 100 ml fluid sample.
- SAE AS 4059 defines the number of particles larger than 4, 6, 14, 21, 38 and 70 μm in 100 ml fluid sample.

We have used ISO 4406:1999 standard, which consists of a sequence of three numbers, e.g. 17/14/10. The first number indicates the concentration and cleanliness level of particles larger than 4 μm, the second number larger than 6 μm, and the third number larger than 14 μm. Cleanliness levels according to ISO 4406:1999 indicating the permissible particle number in 1 ml of hydraulic fluid are shown in Table 2.6.

The required hydraulic fluid cleanliness level in specific hydraulic systems is prescribed by the fluid producer in relation to hydraulic components and anticipated machine service-life. If those data are not available, the general recommendations that can be considered as orientation are indicated in Table 2.7. It must be emphasized that the most sensitive component is determinant, i.e. at least such a cleanliness level must be reached and maintained as required by that component [41].

Table 2.6: ISO 4406 Cleanliness class codes [41]

Number of particles in 1 ml of fluid		ISO 4406	Number of particles in 1 ml of fluid		ISO 4406
more than	**up to and including**	**code**	**more than**	**up to and including**	**code**
1,300,000	2,500,000	**28**	40	80	**13**
640,000	1,300,000	**27**	20	40	**12**
320,000	640,000	**26**	10	20	**11**
160,000	320,000	**25**	5	10	**10**
80,000	160,000	**24**	2.5	5	**9**
40,000	80,000	**23**	1.3	2.5	**8**
20,000	40,000	**22**	0.64	1.3	**7**
10,000	20,000	**21**	0.32	0.64	**6**
5,000	10,000	**20**	0.16	0.32	**5**
2,500	5,000	**19**	0.08	0.16	**4**
1,300	2,500	**18**	0.04	0.08	**3**
640	1,300	**17**	0.02	0.04	**2**
320	640	**16**	0.01	0.02	**1**
160	320	**15**	0.00	0.01	**0**
80	160	**14**			

Table2.7: Recommended cleanliness levels of hydraulic fluid [34]

	Pressure in hydraulic system		
	< 140 bar	**< 210 bar**	**> 210 bar**
Pumps			
Gear or vane pumps (fixed displacement)	20/18/15	19/17/14	18/16/13
Piston pumps (fixed displacement)	19/17/14	18/16/13	17/15/12
Vane pumps (adjustable displacement)	18/16/13	17/15/12	-
Piston pumps (adjustable displacement)	18/16/13	17/15/12	16/14/11
Valves			
Check valves	20/18/15	20/18/15	19/17/14
Directional valves	20/18/15	19/17/14	18/16/13
Flow control valves	20/18/15	19/17/14	18/16/13
Slip-in cartridge valves	19/17/14	18/16/13	17/15/12
Proportional valves	17/15/12	17/15/12	16/14/11
Servo valves	16/14/11	16/14/11	15/13/10
Actuators			
Hydraulic cylinder, vane or gear motors	20/18/15	19/17/14	18/16/13
Piston motors, motors with swash plate	19/17/14	18/16/13	17/15/12
Hydrostatic transmissions	16/15/12	16/14/11	15/13/10
Testbeds	15/13/10	15/13/10	15/13/10

The service-life of the hydraulic machine and its components may be prolonged by the use of hydraulic fluid with better cleanliness level. Table 2.8 shows the predicted life extension factor of the hydraulic system's service-life when using fluid of better cleanliness. For example, if for a specific hydraulic system the rated cleanliness level of the hydraulic fluid is 21/19/16, while in the system the constantly maintained cleanliness level is 18/16/13, it can be predicted that the hydraulic system's service-life will be extended by the factor 2. This is illustrated in Figure 2.15 showing that the control and maintenance of a proper hydraulic system's cleanliness level is of key importance for trouble-free long-term operation and service-life extension of the machine.

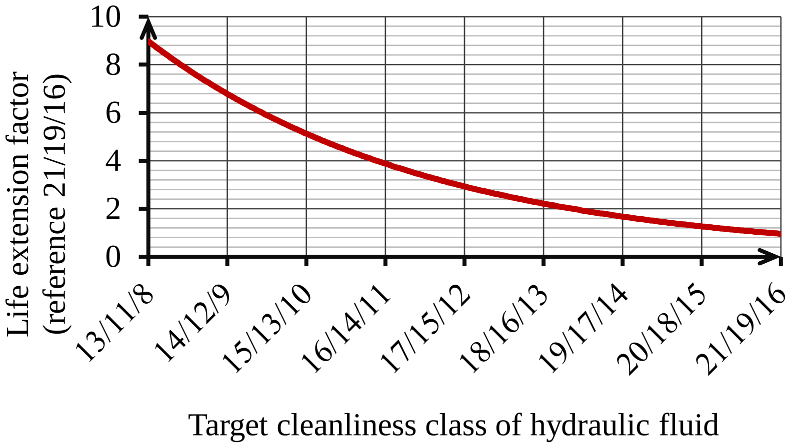


Figure 2.15: Predicted life extension factor for a hydraulic system when using improved hydraulic fluid cleanliness level than the reference one (21/19/16)

Table 2.8:Life extension table for cleanliness level [20]

Ref. cleanliness level	Predicted life extension factor for hydraulic system when using improved hydraulic fluid cleanliness level then the reference one								
	21/19/16	20/18/15	19/17/14	18/16/13	17/15/12	16/14/11	15/13/10	14/12/9	13/11/8
24/22/19	2	3	4	6	7	8	>10	>10	>10
23/21/18	1.5	2	3	4	5	7	9	>10	>10
22/20/17	1.3	1.6	2	3	4	5	7	9	>10
21/19/16		1.3	1.6	**2**	3	4	5	7	9
20/18/15			1.3	1.6	2	3	4	5	7
19/17/14				1.3	1.6	2	3	4	6
18/16/13					1.3	1.6	2	3	4
17/15/12						1.3	1.6	2	3
16/14/11							1.3	1.6	2
15/13/10								1.3	1.6

Laboratory analyses of hydraulic fluid cleanliness levels were carried out by eight-channel automatic particle counter Internormen CCS 2, as shown in Figure 2.16 and were evaluated according to the standardized procedure ISO 4406:1999 [38].

Figure 2.16: Automatic particle counter Internormen CCS 2

2.3.13 X-Ray elementary analysis

Hydraulic fluids contain many chemical elements which are normally divided into three groups: wear metals, contaminants and additives. Their presence can be determined by the use of X-rays. Operation of the X-ray device is based on the principle of uniform energy of an individual chemical element. When the sample is lightened by X-rays, interaction of rays with chemical element atoms in the sample is triggered. As a result of exposure to rays, the ejection of electrons from the orbital element starts in the atom, which leads to jumping of electrons from higher orbitals into lower ones and the energy stability of the atom is reached. During the jump, the electrons of the individual chemical element emit precisely determined energy detected by the detector in the device as radiation of specific wavelength and converted into a spectrum by the use of computer equipment. By the use of standard solutions, the calibration curve can also be prepared and the concentration of chemical elements calculated on the basis of the result [8].

X-ray elementary analyses were performed according to the standardized ASTM D 6481 [8] procedure by the device Oxford Instruments XRF analyser X-Supreme 8000 shown in Figure 2.17.

Figure 2.17: Oxford Instruments XRF Analyser X-Supreme8000

2.3.14 Foaming test

Air in hydraulic fluid is usually present in the form of dispersed air bubbles. At low pressures (e.g. ambient air pressure), the mineral oil can absorb around 10 volume per cent of air and at higher pressures even more. Oil containing a higher share of air at pressure relieving evolves air bubbles and oil foams causing trouble in hydraulic system operation and cavitation in hydraulic components. In the presence of air bubbles and oil foams accelerated oil oxidation takes place since the contact surface between air and oil is larger (larger surface, where chemical oxidation reactions take place). When the air bubble is subject to sudden pressure increase and that pressure takes place with simultaneous temperature increase of air in bubble (thermodynamics), uncontrolled self-ignition of the mixture of compressed air and oil (mini explosion) can occur. This phenomenon is called diesel-effect and destroys the surrounding metal surfaces as well as softer seals and, with increased temperature, contributes to faster oil degradation [45].

The standardized method for determining the oil foaming characteristic is prescribed by the ASTM D 892 standard. The measurement process takes place in three consecutive sequences (I, II and III). In the first sequence, the oil sample (190 ml) is tested in 1000 ml measuring cylinder dipped in a tempering bath at controlled temperature of 24 °C. The prescribed quantity of air is pumped into the oil sample. After five minutes of air inducing, the pump is disconnected and the volume of foam above oil is measured. The sample is then left still for 10 minutes and afterwards the volume of foam above oil is measured again. The result is indicated in the form of two numbers, i.e. volume of foams above oil (in ml) immediately after disconnection of pump and volume of foams above oil after 10 minutes of resting of the sample, e.g. 20/0.

The procedure in the second sequence is similar to the procedure in the first sequence, except that measurement is performed at 93.5 °C. The second sequence represents the tendency of oil towards foaming at high temperatures.

The procedure in the third sequence is the same as in the first sequence, except that for measurement the sample from the second sequence is used. Its foams are shattered by mixing and it is cooled to 24 °C temperature at which the measurement is performed. The result of III sequence is different from the result of I sequence since some lubricating oils with modern additives have different foaming characteristics when mixed (when the additive against foaming has been dispersed into small particles) but that result cannot be repeated after several weeks' resting (e.g. in the warehouse) [10].

The foaming tests were executed according to ASTM D 892 [10] procedure by standardized Petrotest equipment, as shown in Figure 2.18.

Figure 2.18: Foaming test apparatus

2.4 On-line analyses

The greatest advantage of on-line analyses compared to conventional laboratory analyses is their continuous measuring and reliable detection of sudden unexpected events, when the fault is detected so to speak in real time. Another advantage is the trend analysis, since automated systems also record the histories of measurements.

A disadvantage of on-line condition monitoring is particularly the limited number of sensors and values that can be monitored. Parameters measured by on-line sensors usually differ from parameters determined by laboratory analyses therefore direct comparison between them is not possible. For interpreting the measurements it is usually necessary to conduct sensor calibration which is valid only for an individual hydraulic fluid.

In contrast to pressure or temperature measurements, the on-line condition monitoring of hydraulic fluid is much more complex. The oil condition does not depend on an individual parameter only but on several parameters. The oil condition changes depending on load, oil type and other boundary values.

In the frame of on-line hydraulic fluid condition monitoring today it is possible to measure by on-line sensors the temperature, viscosity, dielectric constant, electric conductivity, relative humidity, cleanliness level, light transmittance, odour (maybe vapour products of oxidation) etc. The more frequent and more widespread methods are discussed hereinafter.

2.4.1 Temperature

Temperature is one of the basic and more outstanding physical values to be continuously monitored. At high temperatures, the hydraulic fluid ages much faster. This is caused by accelerated oil oxidation resulting in a reduction of the oil’s service-life by about one half for every 10 °C above 60 °C [3].

The values of some physical-chemical parameters detected by on-line sensors depend strongly on the hydraulic fluid temperature. The temperature may affect the change of viscosity, relative humidity, dielectric constant and electric conductivity of the hydraulic fluid. Frequently the temperature compensation and calculation of a specific parameter to the reference value at 40 °C must be performed.

2.4.2 Relative humidity

In practice, water is one of greatest hazards to the hydraulic and lubricating oil. It reduces the carrying capacity of the lubricating film and acts as a catalyser in the processes of oil ageing and degradation. Reduction of water content in oil considerably extends its service-life as shown in Table 2.9 and in Figure 2.19.

Table 2.9: Life extension factor for water content [20]

Reference water con [ppm]	Expected life extension factor for hydraulic system when using oil with less water content then the reference one								
	2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
50.000	12.500	6.500	4.500	3.125	2.500	2.000	1.500	1.000	782
25.000	6.250	3.250	2.250	1.563	1.250	1.000	750	500	391
10.000	2.500	1.300	900	625	500	400	300	200	156
5.000	1.250	650	450	313	250	200	150	100	78
2.500	625	325	225	156	125	100	75	50	39
1.000	250	**130**	90	63	50	40	30	20	16
500	125	65	45	31	25	20	15	10	8
250	63	33	23	16	13	10	8	5	4
100	25	13	9	6	5	4	3	2	2

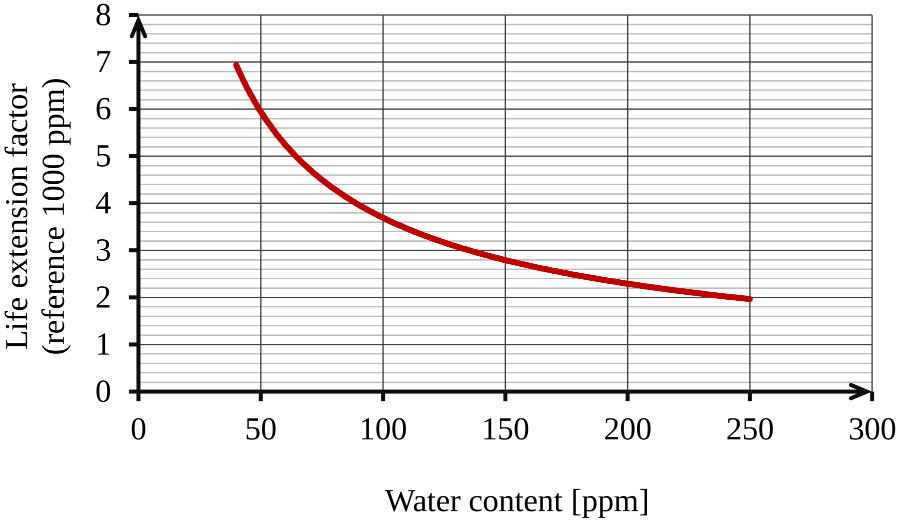


Figure 2.19: Expected life extension factor for a hydraulic system when using oil with less water content than the reference one (1000 ppm) [20]

The service-life of our hydraulic system will be 3 times longer, if constant water content of 130 instead of 1000 ppm is maintained. Therefore, the control and maintenance of properly low water content in the hydraulic system is of utmost importance for its flawless operation and extension of service-life.

Water may be present in hydraulic oils in three forms:

- dissolved, invisible to the naked eye (single-phase fluid),
- emulsified, visible in the form of finely dispersed water droplets in oil,
- free, clearly visible as a separate phase.

The water content in hydraulic oil can also be measured by on-line sensors, by measuring oil capacitance. Capacitive sensor elements are not expensive and are robust so that they are usable over a wide range of oil types and system conditions. The capacitive sensors detect the relative humidity changes within the near environment. They translate that into the per cent of saturation in hydraulic or lubricating oil. An example of the on-line oil relative humidity sensor and its structure is illustrated in Figure 2.20.

In equation (2.9) the relative humidity ϕ is defined as the ratio between the quantity of currently present water in oil e_w and the maximum quantity of dissolved water $e_{w,max}$ oil can receive at a specific measuring temperature, expressed as percentage [1]:

$$\phi = \frac{e_w}{e_{w,max}} \cdot 100\% \tag{2.9}$$

Figure 2.20: Oil relative humidity sensor [32]

The oil is 100 % saturated, when it contains maximum dissolved water quantity at specific temperature and pressure, i.e. when the first free water particles start to appear.

In addition to temperature (Figure 2.21) and pressure, the water solubility also depends on the chemical compatibility between water and oil. Consequently, the saturation degree can considerably vary in relation to different base oils and different formulations of additive packages. Therefore the relative humidity is not directly associated with water quantity in weight per cent or ppm usually measured by off-line laboratory analyses, e.g. Karl Fischer method [22], [44].

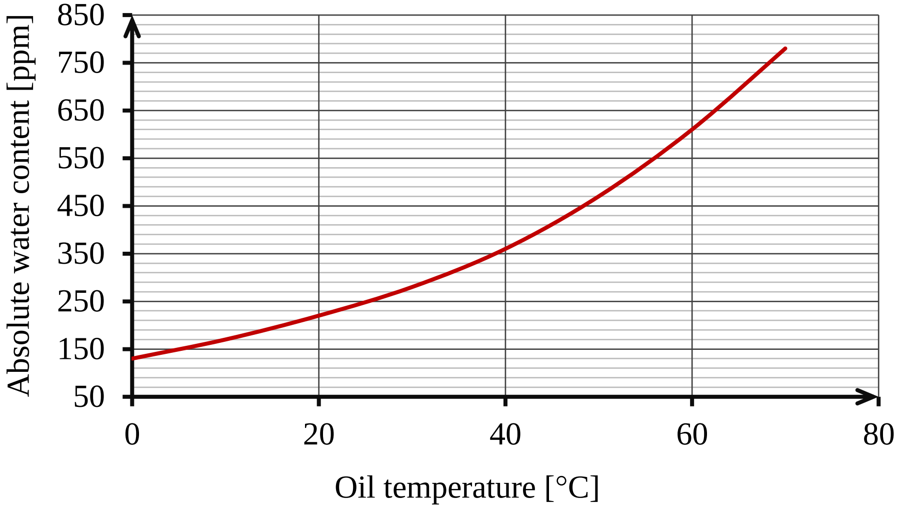


Figure 2.21: Example of a water-in-oil saturation limit curve [52]

Relative humidity and hydraulic fluid saturation limit depend on the fluid type; therefore sensors must be additionally calibrated for different fluid types, if the information about the water content should be expressed in weight per cent. The sensor, giving such information about the percentage of saturation as the weight water content, becomes a powerful diagnostic tool as on the one side it gives the information about possible formation of free water and phase separation and on the other side it signals the absolute change of water quantity as a consequence of its entering due to leakage or its reduction due to processes such as dehydration.

2.4.3 Viscosity

Today, most on-line viscosity measuring sensors appropriate for hydraulic fluid condition monitoring are based on quartz micro balance (QMB) and surface acoustic sensors (SAW) [24] [15]. The operating principle of both type sensors is similar.

In the QMB principle, the quartz crystal is integrated within the oscillating circle, oscillating non-damped with the characteristic frequency of some MHz. When the quartz crystal is wetted with fluid, a part of oscillation is absorbed causing change in the resonance frequency. The influencing factors are the surface structure of the quartz crystal, number of wetting phases, quartz crystal material and its basic frequency. The two principal influencing parameters on the side of the fluid are viscosity and density. The square root of their product depends on the frequency change. If the density is known, the viscosity can be calculated.

The SAW principle contains two inter-digital transducers (IDT) located at the top of the piezoelectric base. The first IDT transducer is driven by the oscillating electric voltage exciting formation of mechanical waves on its surface. The waves propagate on the fluid towards the other IDT transducer. The result is the characteristic SAW transfer function with characteristic resonance frequency and damping.

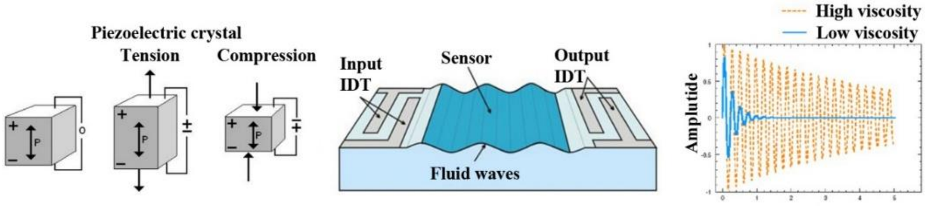


Figure 2.22: Operating principle of an on-line viscosity sensor (SAW)

With the fluid viscosity change also the transfer function damping also changes. However, damping *a* is not influenced only by the fluid viscosity η, but also by its density ρ (equation 2.10):

$$a \approx \sqrt{\eta \cdot \rho} \tag{2.10}$$

$$a \approx \sqrt{\eta \cdot \rho} \tag{2.10}$$

2.4.4 Dielectric constant and electric conductivity

The hydraulic fluid ageing and degradation is usually associated with changes in the chemical molecular structure usually expressed as changes of the electric properties of the fluid (like its ability to polarize). Therefore, the dielectric constant and the electric conductivity are two parameters able to illustrate quite well the changes of hydraulic fluid condition.

Fresh mineral oils have their characteristic dielectric constant and electric conductivity usually having low values. As the two parameters are a specific fluid property, they allow detection of:

- **oil change**: ingress of other oil types or oil of another producer can be detected (different additive packages),
- **ageing mechanisms**: due to oil ageing processes (oxidation and additive decomposition) acid products changing the base oil conductivity are formed in the oil. Dielectric constant and electric conductivity monitoring allows observation of the oil ageing trends and conclusions about its degradation,
- **oil refreshing**: with the value decrease the fluid or filling refreshing is detected,
- **contamination**: contaminants frequently met in hydraulic oils have much higher dielectric constant and electric conductivity than the hydraulic oil, as shown in Table 2.10. Therefore, any slight increase in concentration of a certain contaminant could be interpreted as a considerable change of the fluid electric properties.

Table 2.10: Electric conductivity σ and dielectric constant εr of oil and various contaminants

Medium	σ [S/m]	ε_r
Air	$0.3 \text{ to } 0.8 \cdot 10^{-14}$	1.0006
HM and HLP oils	$3 \text{ to } 10 \cdot 10^{-10}$	2.0 to 2.2
Water	0.005 to 0.05	80
Copper	$5.7 \cdot 10^{7}$	6.0 – 6.2

Inter-digital transducers and micro-sensors are usually used for measuring the constant. Some micro-sensors pose a problem because of limited depth of dipping due to their relatively small construction, where the individual elements are usually distant between 10 to 50 µm. Therefore, they can only reach the thin surface layers of the fluid. Besides, they are very sensitive to surface contamination and deposits' formation [44].

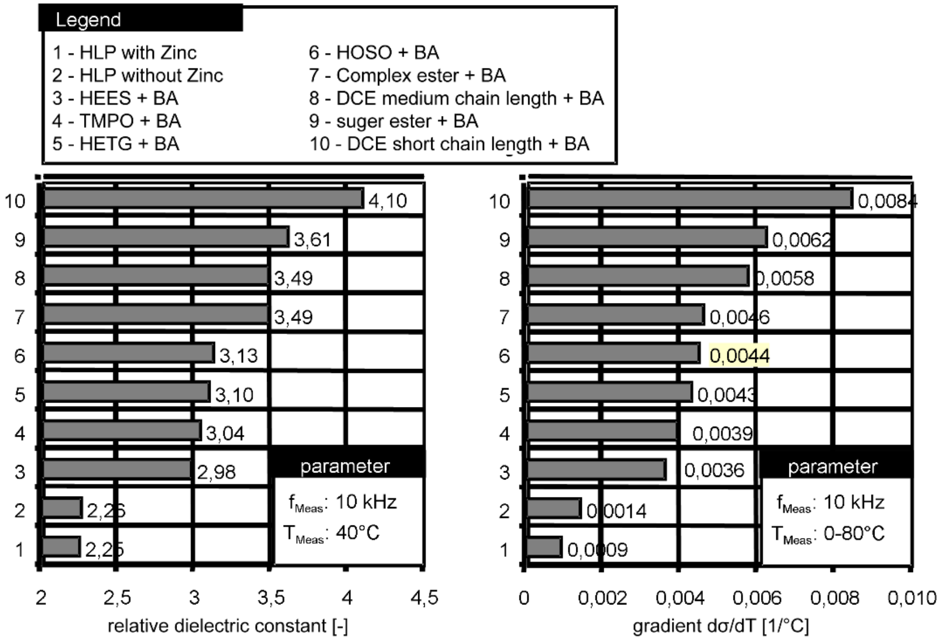


Figure 2.23: Dielectric constants of various hydraulic fluids and temperature gradients [48]

Dielectric constant and electric conductivity of mineral oils are also two temperature-dependent parameters; therefore, calculation to the reference temperature 40 °C must be made. The dielectric constants of some frequently used hydraulic fluids and their temperature gradients are shown in Figure 2.23.

2.4.5 Oil cleanliness level

Technological development within the sphere of optical particle counters have progressed from portable types to be used as servicing tools over sensors for stationary application, e.g. on test desks, to small robust and budget priced sensors for installation in almost any lubricating or hydraulic system. Modern on-line particle counters function on the principle of light scatter, as shown in Figure 2.24. The particle number and size are determined on the basis of the scattered light detected by a photo-detector.

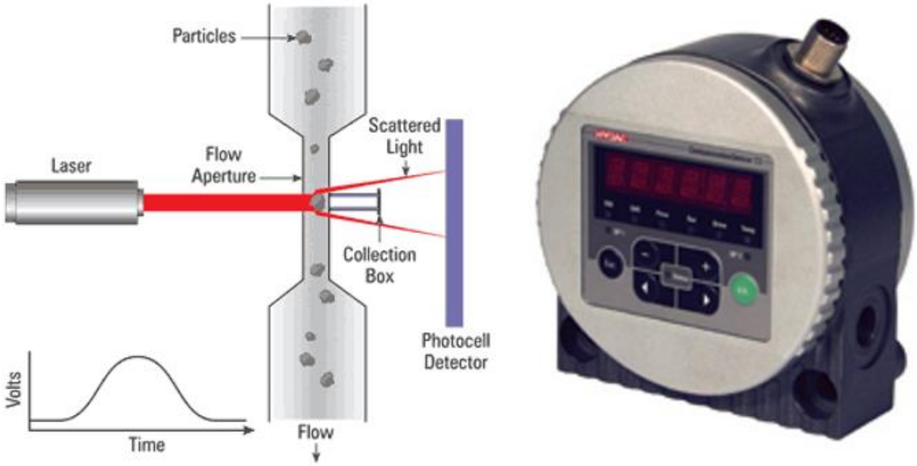


Figure 2.24: Operating principle of a light scattering on-line particle counter [55] (left) and an example of an on-line particle counter [33] (right)

2.4.6 Measurement of oxidative volatile products

Everyone dealing with hydraulic device maintenance knows that the odour of used hydraulic fluid differs from the original fresh oil odour. Scientifically, the odour corresponds to (half) quantitative analysis of volatile ageing components. Concentrations of individual volatile components above the lubricant depend on the condition of equilibrium on the component quantity in oil in accordance with the specific component vapour pressure. The detected concentration changes during the vapour phase are directly related to oil condition changes. However, the dependence is not trivial, as it is affected by various internal and external parameters. Already in the gas space above the fresh hydraulic oil the characteristic structure of volatile components can be detected. It consists, for example, of hydrocarbons with short chains, alcohols or sulphuric compounds with low molecular weight, originating in the production process. Because of the usual fluid ageing during operation that oil finger print gradually changes. Consequently, the gas chromatographs between fresh and used oil can be compared [64].

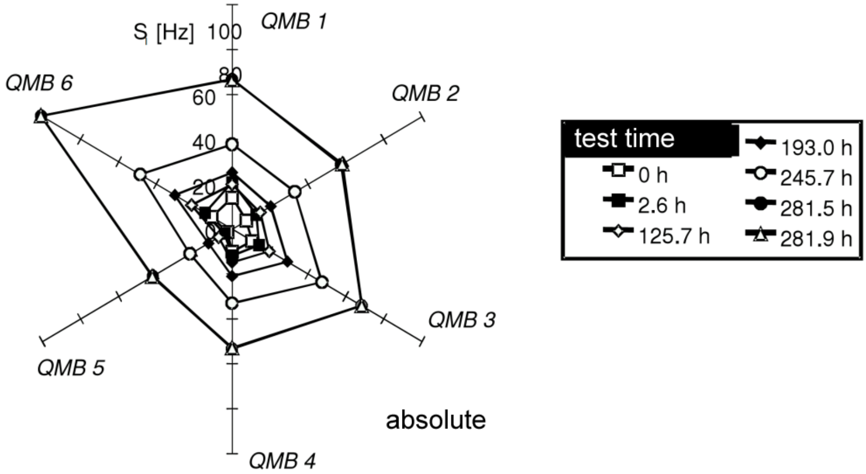


Figure 2.25: Results of measurements by a QMB sensor [50]

Usually the gas phase composition is rather complex, as more than 30 volatile components can be determined. The formations of new ingredients and the deteriorations of others can be established. The characteristic composition strongly depends on the selected lubricant and hydraulic system operating conditions. As the gas chromatography is not suitable for on-line condition monitoring of hydraulic fluids (price, time), a possible alternative is the gas sensor (so-called electronic nose) detecting the ingredients' groups reflecting the oil ageing. So far, the sensor QMB-6 has already been used for such measurements [64]. The number 6 means six micro weights with different coatings, located in the sensor cell. The coated micro weights are proper for determining small vapour molecule quantities with selective adsorption on the coating. Adsorption increases the coating weight, which is detected by the change of the quartz crystal resonance frequency. The frequency change is proportional to the difference in weight. As the six coatings absorb different molecule types, the frequency offset of the six quartz crystals creates a "signature" characteristic of the vapour phase composition, as shown in Figure 2.25.

2.4.7 Measurement of optical properties

Hydraulic system users know well that during operation the hydraulic fluid colour changes. In the laboratory applications the optical property change is detected by infrared (IR) or ultraviolet (UV) spectroscopy. However, the wave lengths used for that purpose are not yet reachable on budget priced and simple sensors. The colour changes in oils can also be observed in the visible and near infrared light spectrum UV/VIS-NIR. Today, that spectrum is covered by the optical semiconductor technology accessible on the market and applicable for on-line optical oil property change monitoring [50]. Figure 2.26 shows the light transmittance changes with oil ageing [48].

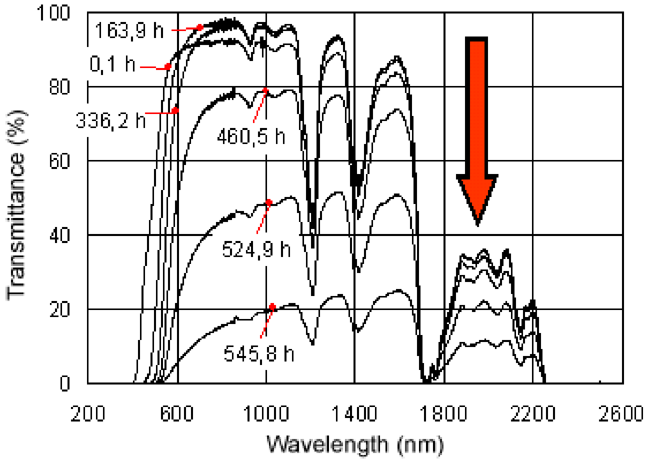


Figure 2.26: Oil spectral changes at different stages of ageing [48]

2.4.8 Multi-sensors

As the name indicates, the multi-sensors are able to measure several parameters at the same time. Most frequently, in addition to temperature also the viscosity, dielectric constant, humidity and electric conductivity are measured by their use. They function on the basis of the previously mentioned principles of measurements of individual parameters. An example of such a multi-sensor is shown in Figure 2.27.

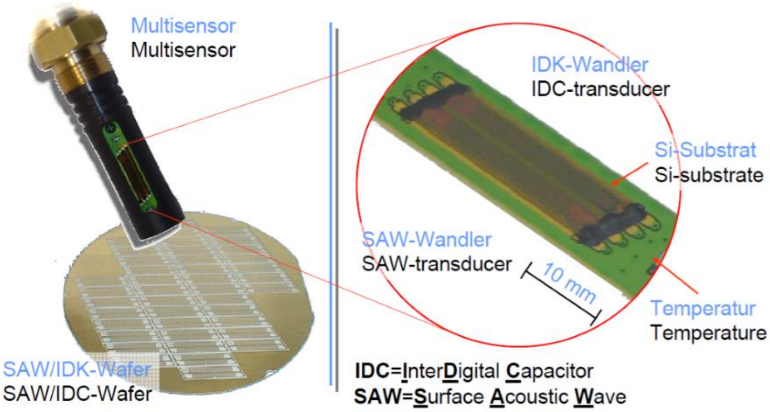


Figure 2.27: Multi-sensor structure [50]

3 COMPOSITION AND DEGRADATION MECHANISMS OF MINERAL HYDRAULIC OILS

For better understanding of degradation mechanism of mineral oils, it is necessary to know their composition, manufacturing process and post-processing oil treatment. Although all these aspects are described in detail in various literature, in this chapter we just summarize only the key information needed for understanding oil deterioration processes.

In general, oils may have two origins – biological and non-biological, which offer a high number of hydrocarbon compounds. Those compounds are usually present as complex mixtures and can be used for many other purposes in addition to lubrication (i.e. control of wear and friction). The required lubricant properties in modern industry are increasingly high and versatile, therefore selection and formation of proper hydrocarbon mixture for lubrication is a technically complicated process. Most natural oils contain compounds likely to impede the lubricating properties but also compounds essential for the lubricating process. Lubricants made of natural or mineral oils are partly refined and partly impure. The balance between the impure and refined portions is of key importance for the oil oxidation stability and depends on the lubricant application. Chemicals added on purpose to oil in order to improve its properties are called additives. Additives may drastically change the lubricants' properties and are essential for their effectiveness. They also determine the specific lubricant properties like oxidation stability, protection against wear and friction, corrosion tendency, foaming, hardening and other properties [65].

Lubricants must meet two basic requirements: they must reduce friction and wear and maintain these properties in spite of permanent lubricant decomposition. Chemical reactions of lubricants with the atmosphere (oxygen) and water are unavoidable, as the lubricants are hydrocarbons. Also additives present in oil decompose over the course of time and operation, since they react with the environment and machine metal parts. Lubricant decomposition is unavoidable and must not exceed a specific limit during the lubricant's service-life [65].

Typical lubricating oil comprises 95 % of base oil and 5 % of additives. The physical-chemical oil properties depend on additives as well as on the base oil itself. The base oils are classified into three basic groups: biological, mineral and synthetic. Oils of the mentioned different origins have their characteristic properties and are fit for the following purposes [65]:

- Biological oils are suitable for application where the infection hazard must be minimized, e.g.: food stuff or pharmaceutical industry. Biological oils may be of vegetable or animal origins.

- Mineral oils are the more frequently used lubricants in industry. They are made of crude oil and are used in applications with moderate temperature requirements. Typical uses of mineral oils are e.g. lubrication of shafts, bearings, engines, turbines etc.
- Synthetic oils are artificially developed substitutes for mineral oils. They are specifically developed and have "better" qualities than mineral oils. For example, temperature-resistant synthetic oils used in machines of high capacities and operating at high temperatures. Synthetic oils are available for very low temperatures too.

As this work related to mineral hydraulic oils, their compositions and degradation mechanisms, only the information that is relevant for further understanding of the problem is summarized based on literature [65], [43], [62], [63], and [48], and in concise form given in the following chapters.

3.1 Origins and compositions of mineral oils

Mineral oils are the more often used lubricants. They are made of crude oil exploited in different parts of the world. The use of mineral oils has its advantages and disadvantages which must be carefully weighed during lubricant selection and formation of the lubricating system. The mineral oil price is (relatively) low and, in spite of the fast development of synthetic oils, hard lubricants and wear-resistant polymers, their further use in many industrial branches is still always guaranteed [65].

Crude oil has a complicated chemical structure divided into several fractions by the distillation process called fractional distillation. This distillation process starts by the heating of crude oil so that it is transformed into vapour which then travels through a high vertical tower (fractional tower) containing several separation plants at different levels.
The vapour passes through three stages, the temperature decreases and drops are formed. The fraction, the boiling point of which corresponds to the temperature of the stage, will condense. In that way, the most volatile compound will condense at the highest stage in the tower, while the compounds with the highest boiling point will condense at lower stages.

In the production of mineral based oils (and crude oil fuels), the distillation takes place at atmospheric pressure as well as at considerably reduced pressures. At the atmospheric pressure the following fractions are produced in growing order in relation to the boiling point temperature: gas, petrol, kerosene, gas oil, diesel fuel, lubricating oils and the rest. Non-boiled fraction deposit at the tower bottom is reheated and continues its way to the vacuum tower, where at lower temperatures and at lower pressure the decomposition of the internal structure is prevented. The vapours are condensed at higher stages, where the distillation fractions are obtained by vacuum pumps. From the remaining fraction from the atmospheric tower the following fractions are produced by this method in growing order in relation to boiling point temperature: gas oil, lubricating oil and a small rest.
All types of crude oil do not need to be processed over two phases. Depending on the origin some types of crude oil are light enough so that only heating under atmospheric

pressure suffices for their complete distillation. After distillation, the distilled fractions of the lubricating oils are subject to various phases of refining and processing in order to obtain various medicinal, cosmetic, industrial and automotive oils and lubricants. Refining includes further distilling of impure lubricating oils and mixing with organic solvents for washing-out impurities. The purpose of refining is to remove waxes with high molar mass, aromatic hydrocarbons and compounds containing sulphur and nitrogen. Waxes cause oil hardening at higher temperatures. Aromatic compounds influence the viscosity reduction at higher temperatures, while the compounds containing sulphur and nitrogen cause accelerated surface corrosion causing faster wear. They also may influence faster wear of the seals [65].

In the further refining stages, the oil travels through absorbing filters and is exposed to hydrogenation ($+H_2$) in the presence of a catalyser. The lubricant may also be mixed with concentrated sulphuric acid to effectively remove the complex organic compounds, e.g. sulphuric acid esters. Such processing, however, causes great difficulties when removing waste products. Therefore, processing with sulphuric acid is applied only to oils of particularly high purities, e.g. pharmaceutical oils [65].

As already emphasized, the main feature of refining is that crude oil is a very changeable and complex mixture of hydrocarbons and that it’s refining only approximately imposes the final product quality. The target of the process is not to create a pure compound but a product with certain prescribed properties as desired for a specific application [65].

The mineral oil’s structure is very complex, e.g., a detailed analysis confirm that crude oil consists of around 125 different ingredients out of which only 45 have been researched in detail. A major part of oils consists of hydrocarbons with around 30 carbon atoms in each molecule. Each molecule comprises several linked aliphatic (straight) chains and cyclical carbon chains. Almost any possible form of the structure of cyclical and aliphatic chains can appear, therefore the number of possible complex molecule forms in each individual oil sample is considerable [65].

Mineral oils also contain certain portions of impurities, which result in useful or harmful properties, e.g. they improve the anti-oxidation properties, cause formation of deposits reducing the lubricating properties etc. There are also many other ingredients present in mineral oils like waxes, which are practically unusable resp. unwanted when used as hydraulic oil, as they easily oxidize into harmful organic acids. Special additives are necessary for neutralizing those waxes and related compounds [65].

Mineral oils differ in relation to crude oil origin and refining process. Principal differences between mineral oils are based on:

- chemical structures,
- sulphur content, and
- viscosity.

Three basic mineral oil chemical structures are known [63]:

- paraffinic,
- naphthenic, and
- aromatic.

Those structures are due to different crude oil origins and correspond to accurate chemical types. As shown in Figure 3.1 the straight paraffines (s.c. n-paraffines) consist of straight hydrocarbon chains and branched paraffines (isoparaffines) of branched hydrocarbon chains. Naphthenic consist of cyclic hydrocarbons with saturated bonds, while aromatic compounds also contain benzene. The oils differ in relation to relative portions of paraffin, naphthenic and aromatic ingredients [63].

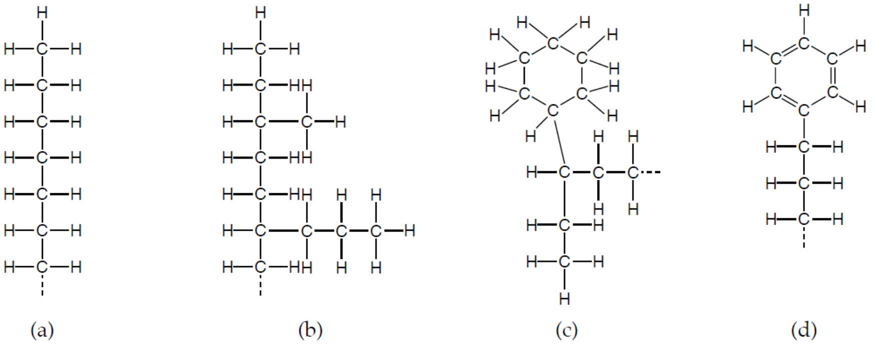

(a) (b) (c) (d)

Figure 3.1: Types of mineral oils: a) straight paraffin, b) branched paraffin, c) naphthenic, d) aromatic [65]

Aromatic oils are present only as a minor portion of naphthenic or paraffin oils. The oil is named with respect to the chemical composition representing the majority portion. For example, paraffin oil implies that the majority of hydrogen and carbon atoms are linked in the form of paraffin chains. Those paraffin chains are further cyclically linked with carbon atoms and form complicated molecules.

Naphthenic oils contain much smaller paraffin hydrocarbon chains and the majority of carbon is present in cyclical molecules. Also a limited amount (around 20 %) of simple paraffin (alkanes) is present in oil. The presence of one or the other types of molecules determines some physical lubricant properties, e.g. pour point, viscosity index, dependence of viscosity on the pressure etc. Considerable differences between paraffinic and naphthenic oils exist in the viscosity dependence on temperature and pressure, therefore correct selection of the base oil is very important in general. Paraffin oils are also more expensive as they require more refining phases than naphthenic oils [65].

Mineral oils also differ according to the sulphur content, crude oil origin and refining process. Low sulphur amounts guaranteeing good lubrication and oxidation lubricant properties are desirable in oil. For example, 0.1 to 1 % of natural sulphur content ensures lower wear. [65]. On the other hand, too much sulphur negatively affects the machine's operation, e.g. it accelerates the seal corrosion.

3.2 Additives

Base mineral oils cannot meet the requirements of high-quality lubricants without the use of additives [43]. Additives are usually of organic or metallic-organic origins. A certain percent of additives are added to improve the oil lubricating properties and service-life.

Specific purposes of additives are:

- reduction of friction and wear by assuring adsorption and good lubricating properties at extreme pressures (EP),
- improvement of oil oxidation resistance,
- corrosion control,
- contamination control (reaction products, wear particles and other impurities),
- reduction of temperature influence on oil viscosity change,
- reduction of lubricating properties by decreasing the pour point and preventing foam formation.

Carefully selected additives are very effective for the improvement of oil properties. Therefore, most suppliers hide the details about the composition of their products. This may also imply that the oil supplier and user only have available information about the additive package and not about individual additives in the oil. This may cause difficulties in analysing used oils. The secrets behind the additives imply that their formulation is partly an art and not only scientific and technical work.

The more frequent additive packets used in the preparation and blending of oils contain the following additive types [62]:

- for wear prevention (anti-wear),
- to increase resistance to pressure (EP – extreme pressure),
- to increase ageing stability (oxidation inhibitors – antioxidants),
- to increase corrosion protection (corrosion inhibitors – corrosion preventive additives),
- detergents,
- dispersants,
- viscosity-temperature dependency improvers – VI improvers,
- pour-point depressants,
- anti-foam additives.

Additives reducing friction and wear are probably the more important additives used in oil formulations. More precisely, these are adsorption and extreme pressure (EP) additives improving the oil lubricating properties. Improved oil properties reached by the mentioned additives are very important, since the base oil alone does not ensure enough good lubricating properties protecting the machine against increased friction and wear [65]. Those additives are divided into the following groups [63]:

- adsorption additives and boundary layer additives,
- anti-friction and anti-wear additives,
- additives for increasing pressure stability (EP – extreme pressure).

3.2.1 Adsorption additives

The polar and adsorption additives improve the lubricating properties and are often used to prevent the occurrence of gluing. Fatty acids, esters and amines of the same fatty acids are mostly used as additives of this type [63]. Usually, at one end of the molecule they have a polar group (–OH) and in contact with the surface they react on the basis of the adsorption mechanism. The surface film created according to that mechanism is efficient at relatively low temperatures and loadings. Molecules adhere with the polar group to the surface and form a carpet of molecules reducing friction and wear (Figure 3.2). An important feature of these additives is the branched carbon atom chain, which must be long enough to ensure a stable and lasting film [65].

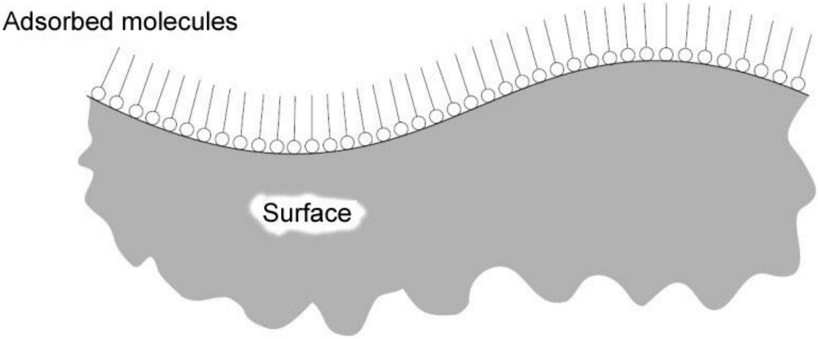


Figure 3.2: Adsorption lubricating mechanism [65]

Adsorption additives are very sensitive to temperature [63]. They lose their effectiveness at temperatures between 80 and 150 °C depending on the additive type used [65]. At increased temperature enough energy is collected on the surface that the additive desorbs (decomposes). The critical temperature at which the additive must be “disabled” can be changed by increasing the concentration – higher additive concentration implies higher critical temperature.

3.2.2 Anti-wear additives

At increased temperature and loading the adsorption additives cannot assure a proper protective layer. Anti-friction and anti-wear additives have been developed to protect surfaces at increased loadings and temperatures [63]. There are several types of anti-wear additives currently used in oil formulations. For example, in engine oils zinc-dialkyl-dithio-phosphate (ZnDDP) is used and in turbine oils tricresilphosphate and other phosphate esters. Where relatively low improvement in oil anti-wear properties is required, phosphorus additives are mostly used [65].

The anti-wear additives react with the surface on the basis of chemisorption (during the reaction a chemical compound is formed) forming a protective layer which is much more durable than the layer created by adsorption [63].

Zinc-dialkyl-dithiophosphate (ZnDDP) is an important additive often used in engine oil formulations. Originally, it was developed as an antioxidant and detergent but later on it was discovered that the compound also acted as an anti-wear and EP additive. The term anti-wear relates to improvement of oil lubricating properties at moderate temperatures and loading, while the term EP (extreme pressure) additive is used for additives improving the lubricating properties at very high loadings and temperatures. Though some authors recognize ZnDDP as a mild EP additive, it is mostly classified as an anti-wear additive in literature. The chemical structure of ZnDDP is shown in Figure 3.3.

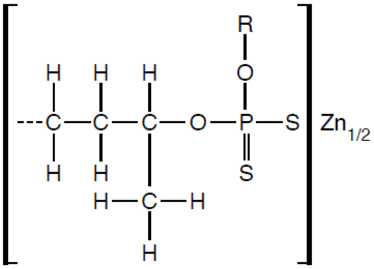


Figure 3.3: Chemical structure of ZnDDP – zinc-dialkyl-dithio-phosphate [65]

By changing the side group, it is possible to obtain a series of related compounds, e.g. zinc-diphenyl-dithiophosphate. However, those compounds are not as effective in reducing friction and wear as ZnDDP. The presence of ZnDDP has an important role. If it is replaced by another metal, the lubricating properties are lost. It was found out, that the wear extent increased with different metals in the following order: cadmium, zinc, nickel, iron, silver, lead, tin, antimony and bismuth. Cadmium assures the lowest wear extent but is too toxic for practical use.

Like many other additives, ZnDDP is usually not available in pure form and contains many impurities affecting the lubricating properties to different extents. The surface of the protective film created as a result of ZnDDP action, acts as a lubricant and reduces friction and wear during the interaction of two surfaces. The lubricating mechanism of ZnDDP is rather complicated as the additive has three active elements – zinc, phosphorus and sulphur. Water and oxygen are also active elements and their presence increases the complication of the lubricating mechanisms. All these elements and compounds contribute to the forming of a protective film and our current understanding regarding the formation of such a surface film is that it consists of a matrix of zinc-polyphosphates including iron oxide and iron sulphide. The film thickness is of magnitude order 10 nm. It is also sometimes conditioned that the surface film could be formed by spontaneous additive decomposition on the worn surface, as in the surface film only a little iron is found. Even the film thickness assuring the additive efficiency in accordance with operating conditions is a matter of discussion.

ZnDDP is more appropriate for moderate loads. In applications with high loads and under the influence of higher temperatures the ZnDDP can increase the wear to the level exceeding solely the base oil. This phenomenon is shown in Figure 3.4 showing that with the use of ZnDDP at low loadings the wear is reduced with temperature, while at higher temperatures it is increased.

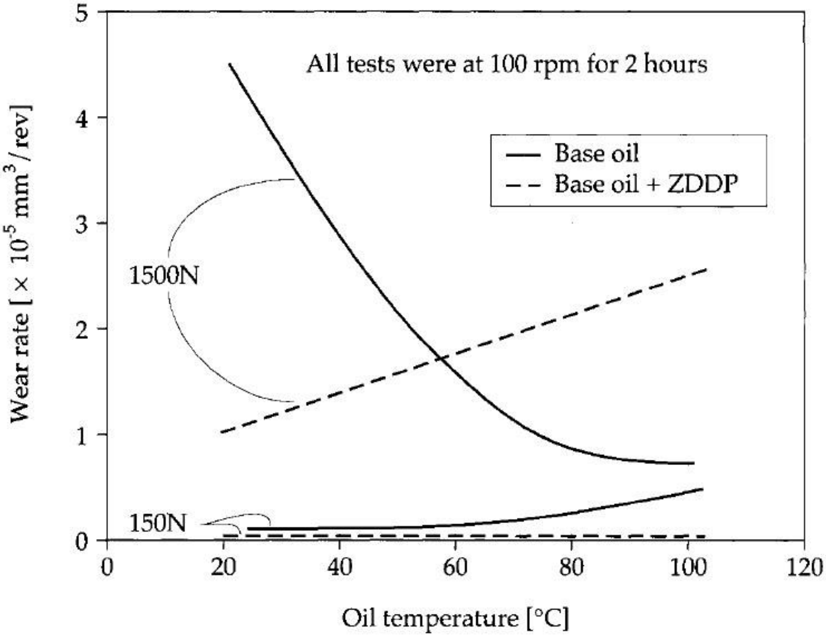


Figure 3.4: Influence of load and temperature regarding the effectiveness of ZnDDP on wear rate [65]

ZnDDP is a characteristic example of the empirical nature of additive development and lubricant science. The problem of valve wear and engine oil degradation was already solved many years ago by the use of ZnDDP while scientific understanding and interpretation of the process have been available only recently [65].

In addition to ZnDDP tricresyl phosphate (TCP) has been used for more than 50 years as an anti-wear additive acting similarly to ZnDDP, on the basis of the chemisorption mechanisms on the operating surfaces.

It is very effective in reducing friction and wear at temperatures up to approx. 200 °C. At that temperature, enough energy is available on the surface that the chemisorbed film is decomposed. At the same time, the compound forms a less efficient phosphate surface film, which is considerably weaker than ZnDDP and has a limited carrying capacity [65].

In the formulations other anti-wear additives are also used like dilavril- phosphates, dibutyl-phosphate, diethyl- phosphate, tributyl-phosphate and triparacresyl-phosphate. They work in the same way as ZnDDP or TCP creating a surface film by chemisorptions. Some of these additives, e.g. dietyl-phosphate can also behave as a moderate EP additive [65].

3.2.3 Additives for increasing pressure stability – EP additives

Pressure stability increasing additives or EP-additives are so conceived that they react with metal surfaces under the influence of extreme loadings, e.g. on heavily loaded gear pairs. Under such operating conditions, very high temperatures occur locally. EP additives usually contain at least one aggressive non-metal like sulphur, antimony, iodine or chlorine. The latter, when reacting with an exposed metal surface creates a protective film with low shear strength reducing friction and wear. The reaction with metal surface is a mild form of corrosion therefore the additive concentration is critical. If the EP additive concentration is too high, it may lead to excessive corrosion. If the concentration is too low, it may happen that the surface is not completely protected, which may lead to its damage. If the EP additives contain sulphur and phosphorus they may slow down the oil oxidation. Degradation and/or decomposition of those additives may already occur at moderate temperatures. EP additives are not usually used for the oil service-life prolongation at higher temperature.

3.2.4 Oxidation inhibitors – Antioxidants

During the service-lives of mineral oils, the oxidation process is unavoidable. During the oxidation process, the friction and wear negatively affecting the machine operation are considerably increased. The principal oxidation effect is a gradual increase of oil viscosity and acidity. That effect is visible in Figure 3.5 showing the changing of mineral oil viscosity and neutralisation number (or TAN – Total acid number) as a function of oxidation time [65].

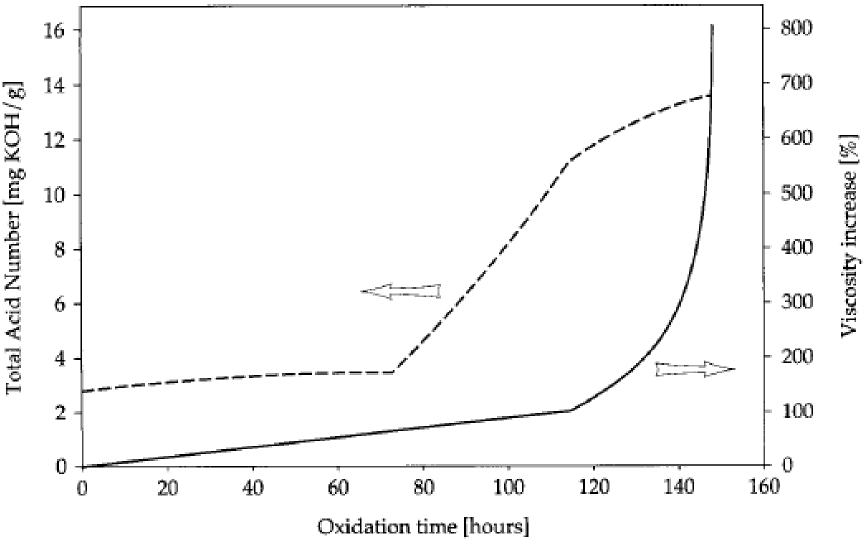


Figure 3.5: Oxidation effect on mineral oil viscosity and acidity [65]

Figure 3.5 shows that oxidation lasting over 120 hours causes sudden viscosity increase. Between 120 and 150 hours the viscosity increases by as much as 8 times. A similar trend can be noticed in the oil neutralization number (TAN). Heavily oxidized oil has no longer has the appropriate physical-chemical properties and must be replaced, as due to increased viscosity it causes power losses and difficulties during pump suction. However, oxidation is not the only cause of oil viscosity increase.

The other reason is varnish formation due to the diesel effect. Increased oil acidity may also cause concentrated corrosion of some components like seals and bearings. As indicated in Figure 3.6, the oil must be changed when the neutralization number has risen by about 0.5 mg KOH/g in relation to the initial value. The period before any drastically change of oil lubricating properties represents the oil usable service-life [65].

The free radical chain reaction is understood as the general oil oxidation mechanism. However, identification of the precise mechanism is hindered due to the complex and changeable mineral oil structure. It is interpreted as the initial phase of the oxidation process and takes place as follows [63]:

$$\text{R–H} \rightarrow \text{R}^\circ + {}^\circ\text{H} \qquad \text{(radical formation)} \qquad (3.1)$$

$$\text{R}^\circ + \text{O}_2 \rightarrow \text{R–O–O}^\circ \qquad \text{(peroxide formation)} \qquad (3.2)$$

$$\text{R–O–O}^\circ + \text{R–H} \rightarrow \text{R–O–O–H} + \text{R}^\circ \qquad \text{(propagation)} \qquad (3.3)$$

with:
R–H – hydrocarbon,
R – radical,
R° – free radical,
H° – hydrogen ion,
R–O–O° – peroxide radical,
R–O–O–H – organic acid.

Formation of radicals, i.e. thermally activated decomposition of hydrocarbon molecules is understood as the initial reaction. In the second reaction, the peroxides are formed, representing the first oxidation phase, namely direct reaction between the hydrocarbon and dissolved oxygen. The process of further chain reaction is shown in the third reaction showing how the oxidized hydrocarbons can have a catalytic (accelerating) effect and strongly accelerate the oxidation process. The peroxide radical R-O-O° is very reactive and its presence controls the reactive velocity. Reaction with hydrogen ions produces carboxylic acids R-O-O-H which are a basis for accelerated oxidation. Therefore, each oxidation phase consequentially leads to several products which are capable of oxidizing themselves until already a major part of oil is already in the strong oxidation process.

Contrary to the minor amount of the mentioned products (only traces) in fresh oil the oxidation can continue very quickly after the critical point has been reached. Therefore, the oxidation process is self-accelerating. The final oxidation result is conversion of the original hydrocarbons into a series of carboxylic acids, ketones and alcohols able to form compounds with greater molecular mass during condensation (Figure 3.6). These compounds with greater molecular mass form varnish and deposits blocking the oil paths [65].

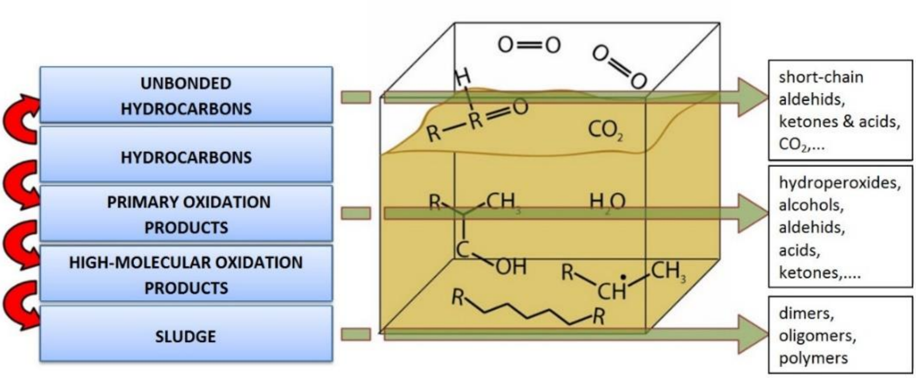


Figure 3.6: Oxidation process [48]

The oxidation level is influenced by temperature, oil-metal contact, water and oxygen quantity in oil and the presence of ionized radiation. In particular, the oxidation extent is affected by temperature doubling the oxidation rate in case of increase by 10 °C [63].

Oxidation may also be accelerated by the presence of wearing metal parts, i.e. catalysers in oil. That oil degradation aspect has already been known for a long time but, in fact, the cooperating mechanisms are not yet completely known. It has been proved that the oxidation of oil thin layer in a metal cup depends on the cup's material. Iron always accelerates the oil oxidation, while high concentrations of dissolved copper in oil restrict the oxidation. It has been discovered that copper hinders the oil oxidation if present in higher concentrations (2000 ppm), while in concentrations characteristic of used oils (100 ppm) it does not hinder the oxidation but accelerates it [65].

The oxidation rate also depends on the presence of oxygen which may be present in three forms, i.e. on the oil's surface, in the oil itself in the form of bubbles or is dissolved in oil. The accelerating effect of oxygen presence is hard to evaluate such that this is evaluated e.g. for the temperature increase [63].

Most lubricating oils used nowadays contain antioxidants – additives decelerating the occurrence of oil oxidation. These are natural or artificial antioxidants able to suppress the oxidation and possible oil structure changes. Oil resistance to oxidation largely depends on the presence of antioxidants. Compounds present in mineral oils, naturally containing sulphur and nitrogen, act as antioxidants bonding with radicals formed during the oxidation process. EP and anti-wear additives containing sulphur are very effective as antioxidants [65]. Great differences in oxidation resistance also exist between individual oil types themselves. Paraffin oils, as a rule, have higher oxidation stability than naphthenic oils.

Antioxidants often used are ZnDDP, metal deactivators, simple hydrocarbons, such as phenol derivatives, amines and organic phosphates. Efficient antioxidants are also sulphur and phosphorus either in elementary form or combined within organic compounds. Antioxidants are usually added into oils in very small quantities, around 1 % of mass share and can be classified into three basic categories [65]:

- metal deactivators,
- radical inhibitors (or propagation inhibitors),
- peroxide decomposers.

Metal deactivators hinder the oxidation acceleration on the basis of metal ion reaction. The main sources of metal deactivators are salicylic acid derivatives, but also derivatives of the lecithin, phosphoric, ethanoic, citric or gluconic acids [65].

Radical inhibitors (or inhibitors of oxidation propagation) act on the basis of peroxide radical neutralization. The anti-oxidation mechanism taking place at that time is shown in the form of equations (3.4) to (3.6) [65]:

$$\mathrm{A{-}H} + \mathrm{R{-}O{-}O^{\circ}} \rightarrow \mathrm{A^{\circ}} + \mathrm{R{-}O{-}O{-}H} \qquad \text{(production of hydro-peroxides)} \tag{3.4}$$

$$\mathrm{A^{\circ}} + \mathrm{R{-}O{-}O^{\circ}} \rightarrow \mathrm{A{-}O{-}O{-}R} \qquad \text{(termination of oxidation)} \tag{3.5}$$

$A^\circ + A^\circ \rightarrow 2A$ deactivation of additives) (3.6)

R – radical,
$R{-}O{-}O^\circ$ – peroxide radical,
$R{-}O{-}O{-}H$ – hydro-peroxide,
$A{-}H$ – additive,
A° – activated additive.

The first reaction shows the formation of hydrogen peroxides generated the additive reaction with the peroxide radical. Radical inhibitors usually consist of hydrocarbons with polarized or weakly bonded hydrogen atom, while during reaction the undesired organic acids are formed. The further step of this reaction is cessation of oxidation, when the peroxide radicals are fully neutralized and represent a relatively unimportant product. The antioxidant mechanism is concluded with the third reaction which indicates the additive deactivation. Activated additives tend towards mutual bonding resulting in better utilization of the additive [65].

Examples of these additives are diarilamines, dihydro-quinolenes and phenol inhibitors. These additives are also known as simple hydrocarbons. It is characteristic of them that they are stable, which is particularly important, since they can be used in very small mass shares 0.5 to 1 %. Moreover, their service-life is very long [65].

Peroxide decomposers act on the basis of reaction with hydrogen peroxide which would otherwise accelerate the oxidation process. An example of such an additive is ZnDDP which decomposes the peroxide radicals ($R{-}O{-}O^\circ$) and hydrogen peroxides ($R{-}O{-}O{-}H$) formed during oil oxidation and in that way prevent acceleration of the oxidation process [65].

Throughout the life cycle, most antioxidants decompose and are used up during the oxidation processes. After the drop of the antioxidant concentration in oil and when all antioxidant in oil has been spent, the oil oxidizes quickly, in most cases containing a high level of dissolved wearing metals. Of course, there are considerable differences in the oxidation rates of individual oils. In some cases, the period between the antioxidant exhaustion and oil oxidation can be very long or, in the opposite case, very short [65].

Finally, it must be emphasized that the used antioxidant depends on the purpose of the oil's use. For example, in systems where the EP or anti-wear properties are essential and the oil service-life is relatively short, the use of ZnDDP or sulphur and phosphorus EP additives gives the best results. On the other hand, in systems requiring long oil service-life at high temperatures the antioxidants based on amines are the better choice [65].

3.2.5 Hydrolysis

In addition to oxidation a further ageing mechanism is hydrolysis, which occurs negatively in particular in ester oils and in various oil additives on mineral basis and in biologically faster decomposable oils [48].

Hydrolysis is understood to be the stehiometric reaction of an ester with water decomposed into alcohol and carboxylic acid. The water ingress into oil cannot be completely prevented, particularly not in the systems of mobile hydraulic equipment. Water could be present already due to “breathing” itself of the oil volume in the tank, the moisture from ambient air penetrating into the tank and condensing at lower temperatures on the tank walls or cover and dripping into oil. While at room temperatures hydrolysis takes place very slowly, reactions are considerably faster in hydraulic machines when increased temperatures occur [48].

In general, acid- and base-catalysed hydrolyses are distinguished. The latter cannot be detected in lubricants. In the acid-catalysed hydrolysis the ester in the first step is protonated. The origin of the carbon proton can be e.g. one protolytic reaction of the water molecule. In the second step the water molecule is loaded on the formed carbonium ion. Based on that reaction as a consequence first alcohol and then still the protons are separated. A further remaining product is the carbon acid [48].

The formed carbon acids appearing during the hydrolytic separation of the ester molecules can again catalytically act on oil ageing. In addition, the problem arises of compatibility with filter, seal, hose and lacquer materials [48].

3.2.6 Corrosion inhibitors – anticorrosion additives

In this category, we can distinguish between two additive types: corrosion inhibitors and rust inhibitors. Corrosion inhibitors (anticorrosion additives) are used to protect non-ferrous metals (e.g. copper, aluminium, tin, cadmium etc.) and are intended for protecting surfaces against caustic matters present in oil. Rust inhibitors are used to protect ferrous metals and surfaces against corrosion [65].

Corrosion inhibitors are used to protect non-ferrous metals, surfaces of bearings, seals etc. against attacks from caustic compounds and additives, particularly those containing reactive elements like sulphur, phosphorus, iodine, chlorine and oxidation products. Some oxidation products are very acidic and must be neutralized before they cause irreparable damages to a device’s parts. The combination of caustic additives, oxidation products, high temperature and very frequently water, may cause a severe corrosive attack on the non-ferrous metallic parts used in almost any machine [65].

Rust inhibitors are used to protect iron parts against corrosion. The two main factors contributing to accelerated corrosion of iron parts are dissolved oxygen and water in oil. They may cause an electrolytic attack, which may be additionally accelerated by increased temperature. Rust inhibitors are usually compounds with long chains bonded to metal surfaces and strongly reducing the water access, as shown in Figure 3.7. In some cases both chain ends may be active so that the additive is fixed to the surface at both ends; in this case, less additive is necessary for corrosion prevention [65].

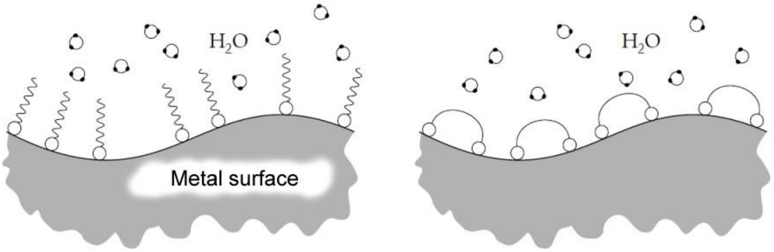


Figure 3.7: Rust inhibitors' surface mechanisms [65]

3.2.7 Detergents

Introduction of the internal combustion engine contributed to the development of a new additive group. Engine oils are normally exposed to fuel combustion products contaminating the oil [63]. Water also has an important role as it accelerates the oil oxidation and may form emulsion. If sulphur is present in the fuel, sulphuric or sulphurous acid may be formed during combustion. If any of these compounds dissolve in water, the engine corrosion process or corrosive wear are accelerated. There are also many other possible contaminants like soot (a consequence of ineffective fuel combustion), wear particles, unburned fuel, base oil decomposition products, corrosive products, particles (dust) from the atmosphere, organic waste of microbiological oil decomposition etc. Without proper contamination control, the oils would lose their lubricating capacities, become acidic and improper for further use. Various additives have been developed to control the acidity of products from impure fuel combustion (sulphur) and to prevent the formations of soot particles. Particle agglomeration may be devastating for the engine, as it blocks the pipes and even the filters. Additives preventing occurrences of these detrimental consequences are known in literature as detergents or dispersants [65]. The primary tasks of those additives are [65]:

- neutralization of all acids formed during the fuel combustion,
- preventing the formations of deposits and linings on the system's components,
- prevention of localization of deposits and linings suppressing and blocking the oil flow.

There are two groups of detergents, namely mild detergents and over-based alkaline detergents.

Mild detergents frequently consist of simple hydrocarbons or compounds without ash. More frequent are the methacrylate ester polymers with low molecular mass, long chains of alcohols and polar vinyl compounds. The function of those additives is to disperse soot (carbon) and wear particles [65].

Over-based detergents are calcium, barium or zinc salts of the sulfonic, phenolic or salicylic acids. The term higher implies that a surplus of alkaline compounds is used for preparations of those additives. The prepared additive serves to neutralize all acids accumulated in oil during functioning. The disadvantage of alkaline detergents is that they accelerate the oil oxidation and, therefore, need addition of the antioxidant [65].

Literature discusses a very quick and simple method for verifying the activity (content) of residual detergents in oil. It is best to use oil taken directly from the machine. An oil droplet needs to be dropped onto the filter paper. If the colour of the greasy dot is uniformly dispersed, the detergents work correctly. If in the center a black dot is formed with a greasy stain around it, the detergents are worn out [65].

3.2.8 Viscosity-temperature dependency improvers – VI improvers

The viscosity-temperature dependency improvers are additives reducing oil viscosity variations with temperature and generally known as viscosity index improvers. The viscosity index improvers are usually polymers with high molecular mass, dissolving in oil and changing their forms (from the ball form to linear form), when the temperature is increased. That effect results in higher polymer dissolubility in oil at higher temperatures and partly compensates for the viscosity drop of the basic oil with temperature. Linear molecules cause a viscosity increase in comparison with ball (spheroidal) and curled molecules. Typical viscosity improvers are polymethacrylates within the range of molecular masses between 10,000 and 25,000 [63]. The more effective are the linear polymer molecules with a small number of side-chains. Those additives are added in low concentrations, i.e. a few mass percent of base oil have been used as an active ingredient of multi-grade oils for many years [65].

The central difficulty in this additive type is their accelerated decomposition in the cases of increased shear stresses and presence of oxidation. A high shear stress degree in oil may cause permanent or provisional loss of fluid viscosity. Provisional viscosity loss is a consequence of extending polymer molecules under high shear and is reversible. On the other hand, permanent viscosity loss includes decomposition (cracking) of the large polymer molecules under high shear and is irreversible. Usually, the viscosity improvers increase the oil viscosity index from 110 to 150 but only under moderate shear and within a limited period. Polymer molecule degradation or decomposition may also be accelerated by oxidation. Polymer improvers of the viscosity index usually do not affect the pressure-viscosity coefficient. In general they are relatively inert and do not affect other additives, particularly ZnDDP [65].

3.2.9 Pour point depressants

Basically, the pour point depressants are the same compounds as the viscosity improvers. By dislocation of the wax structure at low temperature, they prevent the formation of wax crystals. They are indispensable in low temperature applications using paraffin-based oil. When it is known that the temperature never drops below 0 °C, they can be completely omitted from the oil formulation [65].

3.2.10 Anti-foam additives – Foam inhibitors

The principal role of anti-foam additives is destabilization of foam formed during machine operation. Usually long-chain silicone polymers are used in small amounts of around 0.05 to 0.5 % of mass share. The quantity of the used additive is rather critical since its excessive quantity is less effective [65].

3.3 Degradation mechanisms – Mineral oil ageing

In general, oil ageing is understood to be the physical-chemical property changes taking place in oil degradation throughout its service-life. In Chapter 3.2 the mineral oil structure was presented with the more important degradation mechanisms. Due to the diversity of base oils and additives used today and the resulting number of ingredients present in oil, it is impossible to provide an accurate and universal statement about the general ageing mechanisms and chemical processes taking place. The excessive number of possible chemical reactions and the vast number of consequential chemical reactions can only be imagined. Already in dealing with base oils it is possible to observe the great chemical diversity of structures. Also the additives, though in very low amounts, may have different effects on the oil behaviour, ageing process and oil degradation.

A further point preventing predictions of the processes of individual chemical reactions regarding ageing is that the chemical reactions depend on the current machine operating conditions, as shown in Figure 3.8. The more outstanding influencing values are the temperature, oxygen and water presence or the metal catalysers decisively affecting the ageing mechanism process. Empirical studies in the past researched in detail those influencing values in hydraulic fluids. Further values influencing the oil ageing are pressure, system volume, shear of long chain molecules and radiation [48].

The pressure as an influencing value causes direct oil temperature increase when damping a specific volume. In the presence of air bubbles in oil due to faster pressure increase local release of compression heat occurs, the temperature of the air bubbles being up to several 100 °C. The latter leads to oil molecular damage within the areas of the bubbles' surfaces. Further, an inflammable mixture igniting at the pressure increase due to compression heat can be formed in air bubbles. That phenomenon is called micro-diesel effect and results in further pressure increase and pressure peaks likely to lead to considerable oil and component damages.

All the described physical-chemical factors are additionally affected by the type of use, machine construction, maintenance and oil change intervals.

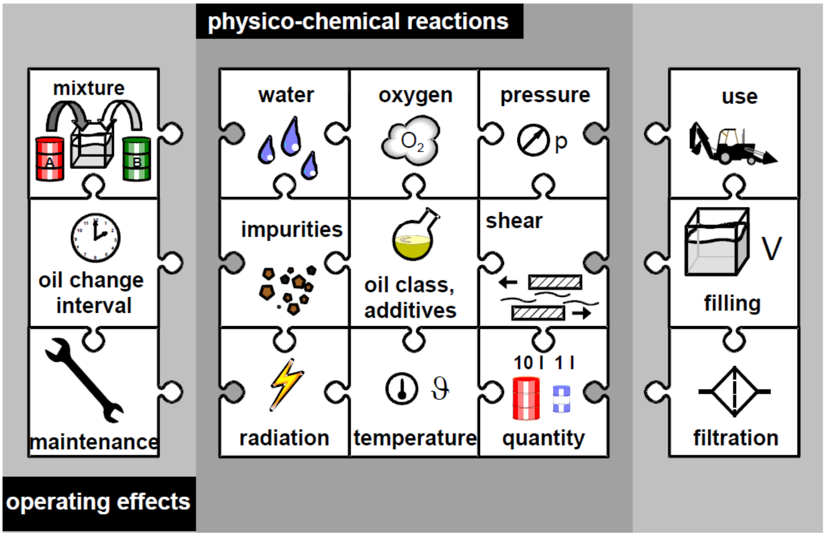


Figure 3.8: Various operating effects on mineral hydraulic oil ageing mechanisms [48]

Because of the described complexity of oil ageing, many mechanistic studies have focused on researching simple substances like oils or linoleic acids and their monoesters. The transfer of results to more complex oils can, in some cases, lead to good results but they cannot be used globally.

4 APPLICATION AND INSTALLATION OF ON-LINE SENSORS

For conceiving and implementing remote on-line condition monitoring of hydraulic devices, several factors are of key importance for reaching high-quality measurement data, including but not limited to:

- selection of proper sensors,
- proper installation of selected sensor,
- determination of proper sampling point (sample representativeness),
- data acquisition and processing,
- additional measures for improving the accuracies and credibility of measurements.

According to the abovementioned items, hereinafter the concepts and measures are presented for reaching proper high-quality measurement data and the concepts for improving the accuracies of on-line measurements.

4.1 Optimal set of on-line sensors

The research carried out included a thorough survey of the market regarding proper sensors for on-line hydraulic oil condition monitoring and/or sensors allowing detection of physical-chemical changes, described in Chapter 2.4. A complete survey of sensors on the market is hard to present, due to several reasons. As the first, on the market there are a lot of sensors advertised and promoted by the producers, but most of them more or less at the development and testing stage, are not available on the market, are available only to selected partners, or not entirely suitable for on-line application. Another problem making the sensor survey difficult was that during the research several sensors emerged on the market available only for a short time and then removed from the market for specific reasons (e.g. unreliability).

Table 4.1 shows, as an example, the situation of the availability of on-line sensors on the market, during the initial period of increased use of these sensors on machines and devices (between 2010 and 2015). The grey colour indicates the selection of sensors primarily used to carry out some initial studies described hereinafter. The selection of sensors was made on the basis of criteria like measuring the values measured by the sensor, sensor accuracy, price, availability…; the manufacturer’s responsiveness and support were also considered.

Table 4.1: Some on-line sensors on the market (period 2010 – 2015)

Manufacturer	**Sensor**	**Avaliable**	**Temperature**	**Viscosity**	**Relative humididty**	**Dielectric constant**	**Electric conductivity**	**Cleanliness level**
Hydac	AS1000	X	X		X			
Hydac	CS1000	X	X					X
Hydac	HLB1300		X		X	X		
Hydac	HLB1400		X	X	X	X		
Argo-Hytos	LubCos H2O+	X	X		X	X	X	
Argo-Hytos	LubVis+	X	X	X		X		
Argo-Hytos	OpCom	X	X					X
Internormen	IVS01	X	X	X		X		
Internormen	CCM 01	X						X
Internormen	CCT 01 Set	X						X
Internormen	WSTM 01 Set	X	X		X			
RMF	CMS	X	X		(X)			X
RMF	OQS	X	X			*Oil condition (%)*		
ANALEXrs	Particle Content Sensor	X						X
ANALEXrs	Oil Condition Sensor	X	X			*Oil condition (%)*		
ANALEXrs	Moisture Sensor	X	X		X			
Caledonia Instruments	RH Sensor	X	X		X			
Caledonia Instruments	Rotational Viscometer	X	X	X				
Caledonia Instruments	MFI – Multi Frequency Impedance	X	X			*High, medium and low frequency resistance*		
Parker	Icount PD	X			(X)			X
Parker	MS series	X	X		X			
Cambridge Viscosity	VISCOpro1600	X	X	X				
SenGenuity	ViSmart	X	X	X				

(X) – option

4.2 Installation of on-line sensors and selection of representative sampling places

Special attention must be paid to the proper installation of sensors within the monitored hydraulic system, since the sampling point may strongly affect the measurement accuracy. The best representativeness is reached by taking the fluid from the pressure or return line (Figure 4.1 – options 1 and 2), as in that way the condition of the hydraulic fluid circulating or having circulated through the system is measured.

For taking the fluid from the pressure line (option 2) a special pressure-flow control valve is needed behind the sensor block. It is urgently necessary, as sensors do not allow such high pressure as is usually present within the primary system. Such a unit incorporates the viscosity and pressure change compensation thus guaranteeing constant oil flow through the sensor system.

When taking the fluid from the return line such a preparatory unit is not needed. Oil is taken ahead of the return filter, otherwise cleaner oil would be measured instead of the actual oil having travelled through the system and valuable information about the fluid's condition would be lost. The oil flows through the sensor system by the pressure difference occurring due to the filter element on the primary hydraulic line.

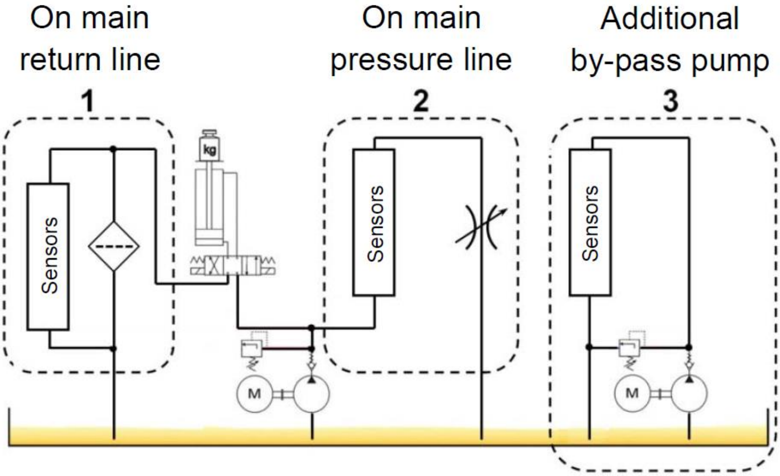


Figure 4.1: Different options for connecting a condition monitoring sensor system

Oil can also be taken from the tank by a special pump (by-pass system – option 3). On a larger tank the risk appears regarding the fluid being taken from the tank "dead" area (where the fluid does not circulate but rests), which may cause significant errors in measurements. Therefore, for determining the optimal location when taking hydraulic fluid from the tank, as well for its optimal shape, it is appropriate to use the CFD-simulation of the fluid flow in the tank. Hereinafter, a CFD-simulation example is illustrated as executed on the basis of an industrial 400 litre hydraulic power unit.

4.3 Simulation as a tool for finding the perfect sampling place

Correct design and shape of the tank is essential for the hydraulic system and its long-term operation. The hydraulic tank is a place where the hydraulic fluid can "recover and gather new forces for continuation of work". Solid particles, water and varnish products tend to collect at the tank's bottom, while air bubbles rise and are separated on the hydraulic fluid's surface. Hydraulic fluid contamination with air or solid particles can be prevented rather successfully by a proper tank shape. The tank should be so designed and conceived that it stabilizes and directs the hydraulic fluid flow and allows the hydraulic fluid to separate air bubbles and to deposit solid particles at the tank's bottom [23].

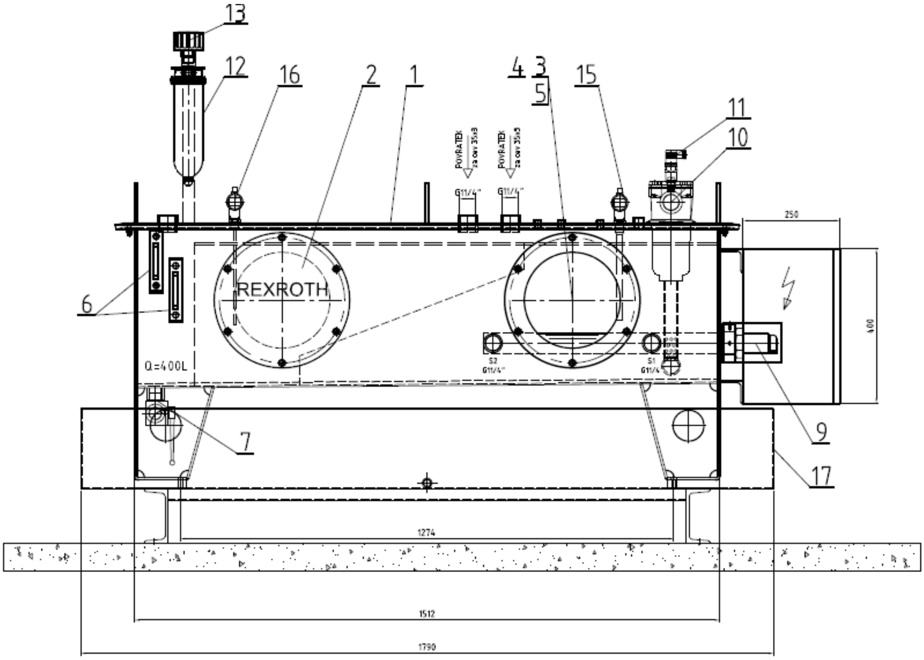
Air as one of the contaminants in the hydraulic fluid may appear due to incorrect maintenance or as a consequence of incorrect hydraulic system design and sizing. In addition to incorrect hydraulic system operation (air compressibility), the air presence in the hydraulic system causes accelerated oil degradation, cavitation, diesel-effect, and noise. Last but not least the air presence in oil strongly affects the on-line measurement results (measurements of cleanliness level, dielectric constant, electric conductivity and viscosity) as explained hereinafter.

On the other hand, solid contaminants within hydraulic fluid cause accelerated wear of the hydraulic system's components. The component wear rate depends on the gaps and tolerances within the interiors of hydraulic components, pressure and size and quantity of solid particles present in the hydraulic fluid. However, it is also important to have information about the layouts of solid contaminants within the hydraulic tank, since only in that way can the hydraulic fluid sampling place be determined (in case a fluid sample is taken from tank).

Within the frame of the study the hydraulic fluid flow simulation through a tank was performed, the fluid containing a considerable amount of air bubbles and solid contaminants of different sizes. It is shown that using modern, powerful simulation tools can be very helpful to get the more important information on selecting the right sampling place and avoiding death zones.

4.3.1 Tank modelling

The simulation model was conceived on the basis of an industrial 400 litre tank made according to standards AB Normen Rexroth (DN 400) with inside dimensions 1492 x 712 x 390 mm, as shown in Figure 4.2. The power unit is equipped with two external pumps and thus it has two suction connections.



Tank top lid
ALU maintenance lid
Maintenance lid holder
Plexiglas maintenance lid
Longitudinal baffle
Oil level indicator
Oil drain valve
Oil heather

10	Tank lid
11	Filter clogging indicator
12	Return filter
13	Breather – air filter
15	Oil level and temperature sensor
16	Oil temperature sensor
17	Oil catch pan

Figure 4.2: 400 L industrial tank according to AB Normen Rexroth DN400

As shown in Figure 4.3 three different versions of a tank interior with certain modifications were studied and compared:

- 1st model had the return pipe placed diagonally in relation to two suction pipes,
- 2nd model had in the interior a longitudinal baffle; the return pipe was moved to the other tank side (lengthening of oil circulation path),
- 3rd model differed from the second one in the return pipe shape – conventional return pipe was replaced by diffuser stabilizing and directing the oil flow. In addition, the longitudinal baffle shape was adapted so that the oil flow was only allowed only along the tank bottom as shown in Figure 4.3.

All return and suction pipes on the simulated models were cut at 45° angles as practiced within industrial environments. The models were simplified, as all inactive hydraulic pipes otherwise provided in the tank had been removed from them. Previous research [67] has shown that the mentioned inactive pipes had no effect worth mentioning on the simulation results in that previous research [67]. It was found that under the simulated flow conditions, discussed below, the hydraulic fluid surface level could be considered to be completely horizontal. Therefore, the simulation could be simplified in the way that the condition of outlet aeration surface was prescribed to the top surface (instead of freely movable surface).

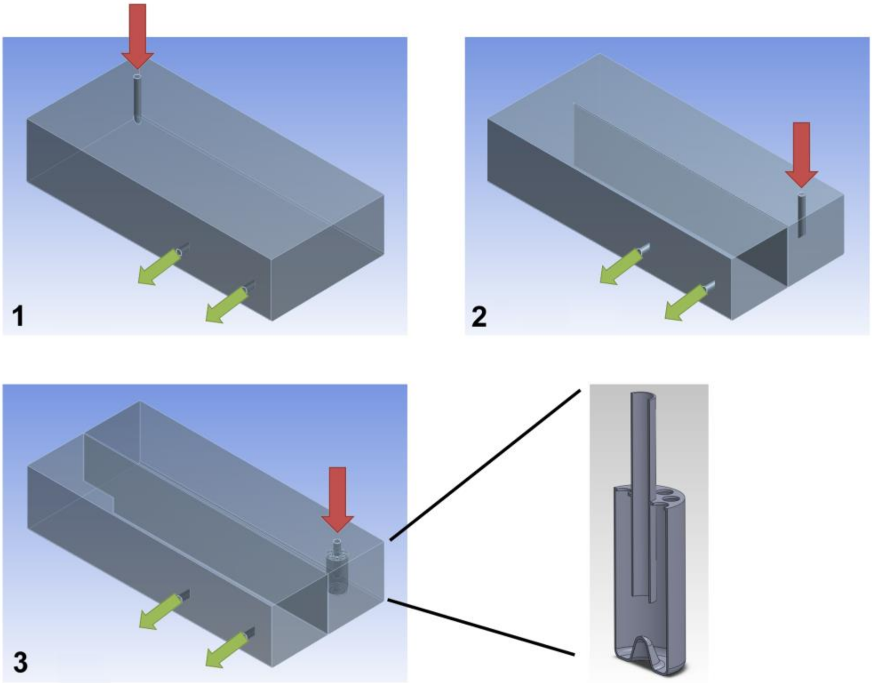


Figure 4.3: Simulation models – return pipes (red) and suction pipes (green)

The surface and volume mesh were automatically created by the use of Ansys CFX-Mesh with specific additional settings. In order to gain as real simulation results as possible, the mesh was made denser in the areas of the return and suction pipe. Due to the appearance of velocity gradients and the influence of solid walls, five inflation boundary layers were created in their surroundings. The results of meshing are shown in Figure 4.4 and presented in Table 4.2. More information on the study can be found in literature [72], [70].

Table 4.2: Results of mesh generation for individual models

	Nodes	**Elements**
1st model	210.498	630.869
2nd model	254.029	766.012
3rd model	275.710	821.144

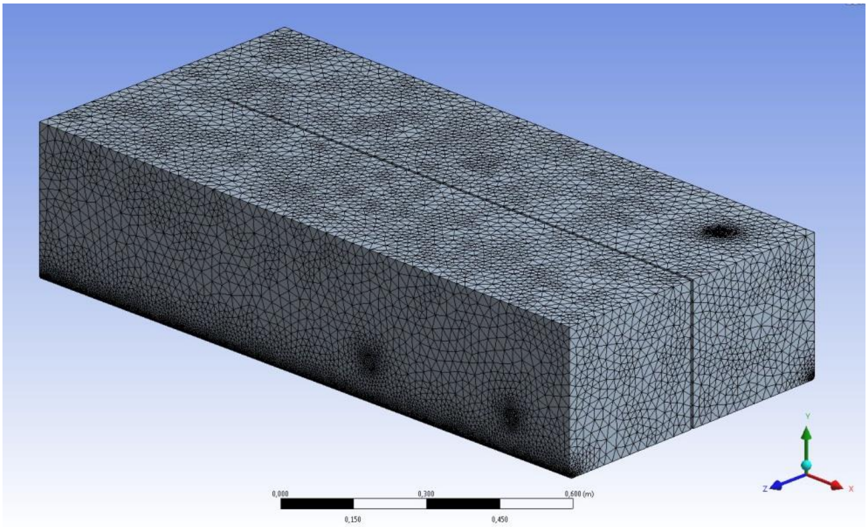


Figure 4.4: Generated mesh of 2nd model

4.3.2 Simulation of air and solid particles within a hydraulic tank

The multi-phase simulation covered three homogeneous materials: mineral hydraulic oil of viscosity grade ISO VG 46, air in the form of dispersed air bubbles and solid particles. Simulation was performed at constant temperature, i.e. usual hydraulic system operating temperature 50 °C. Changes in the material properties due to temperature change were neglected.

In order to reach proper simulation model convergence, first the steady state simulation was conducted followed by the transient simulation. The entire simulation time was 60 seconds and was divided into 1.0 s time intervals.

The main fluid phase was the mineral hydraulic oil of viscosity grade ISO VG 46 with estimated molar mass 380 kg/kmol [54]. As the simulation did not cover the temperature change phenomenon, the oil density was determined as constant value 850 kg/m^3. Also the viscosity at specific temperature and pressure is constant. It was estimated to be 30 mm^2/s which is equivalent to oil viscosity ISO VG 64 at 50 °C.

An important parameter when simulating the air bubble transition from the fluid phase is the surface tension coefficient, which equals $23 \cdot 10^{-3}$ N/m for hydraulic mineral oils [29].

Air in form of air bubbles as the next simulation phase was simulated as a dispersed fluid with three different prescribed mean diameters, i.e. 20, 100 and 500 μm. It was assumed that larger air bubbles in viscous fluid would rise faster, as their buoyancy force is greater than in case of smaller bubbles.

For simulation of the solid phase, i.e. small solid particles in oil, a very frequent contaminant found in hydraulic oil was selected, i.e. copper. Copper has higher density than steel, i.e. around 8940 kg/m^3. Similarly, as for air bubbles, it was assumed that larger particles would better resist the fluid viscous flow and would be faster deposited at the tank's bottom (the contrary applies to small particles).

The simulation boundary conditions were determined on the basis of data on the two pumps each having 42 L/min flow. Therefore, at the individual cross-section of two suction pipes (Figure 4.3 – indicated in green) the total mass flow of 0.60 kg/s was determined on the basis of the volume flow and oil density. The mentioned total hydraulic oil flow returns via the return pipe (Figure 4.3 – indicated in red), therefore at the cross-section of that pipe the total mass flow of 1.20 kg/s was prescribed, consisting of:

- 94 volume per cent of mineral hydraulic oil fluid phase,
- 2 volume per cent of air phase – bubbles of mean diameter 500 μm,
- 2 volume per cent of air phase – bubbles of mean diameter 100 μm,
- 2 volume per cent of air phase – bubbles of mean diameter 20 μm,
- 4 different groups of copper particles with specific diameters 5, 25, 125 and 500 μm.

Though particles of size 125 μm and larger are usually absent in the hydraulic tank, they were also covered in the simulation in order to illustrate the worst case scenario. In order to simulate the transition of dispersed air bubbles from the fluid phase onto the surface, the degassing outlet boundary condition was prescribed on the fluid phase (hydraulic oil) surface.

The flow of the main fluid phase (oil) and the dispersed phase (air bubbles) were calculated by the use of the Euler-Euler and SST turbulence model. The Lagrange model of particle tracking was used for solid particle motion simulation during the fluid phase. The interphase resistance between oil and solid particles was treated according to the Schiller-Neumann's model, while the interphase resistance between oil and dispersed air bubbles was treated according to the Grace drag model. Detailed information about the concerned simulation [68] and the relevant simulation models [51] can be found in the literature [69].

4.3.3 Possible measures assuring a proper OCM environment in tank

In the frame of study, many steady state simulation and transient simulation results have been studied. It is difficult to present all the studied 3D simulation results in the condensed form of a 2D picture; nevertheless some significant results are presented. Figure 4.5

shows the horizontal plane at the suction pipe level (100 mm from the bottom), coloured in relation to the volume share of air bubbles of size 500 μm from 0 (blue) to 1.0 % (red).

The model 1 separates the least bubbles. The second model with conventional return pipe and longitudinal baffle is a much better solution, as much less bubbles come across into the second tank compartment.

The best results are reached by the use of the third model – with diffuser on the return line and changed baffle shape allowing the oil to flow only along the tank bottom. Results in graphical and numerical form are presented in Tables 4.3 and 4.4. Greatest differences occur in the presence of large air bubbles, where as much as 4 times less air bubbles (of size 500 μm) are present at the suction pipe inlet on the second model in comparison with the first model. On the third model, one half less bubbles were present. Slightly worse results were gained in the case of air bubbles size 100 and 20 μm. Simulation confirmed the fact that smaller air bubbles are subject to much lower buoyancy forces, therefore they rise more slowly. In addition, their relative force is much higher than in larger bubbles due to viscous fluid motion. Therefore, smaller bubbles move very much in accordance with the hydraulic fluid flow and rise (are separated) very slowly.

Table 4.3: Average air volume share in suction pipes

	20 μm	**100 μm**	**500 μm**
1. model	1.85 %	1.71 %	0.31 %
2. model	1.75 %	1.61 %	0.08 %
3. model	1.75 %	1.58 %	0.05 %

Table 4.4: Air percentage separated from oil on transition through tank

	20 μm	**100 μm**	**500 μm**
1. model	7.50 %	14.50 %	84.30 %
2. model	12.50 %	19.50 %	95.90 %
3. model	12.50 %	21.00 %	97.70 %

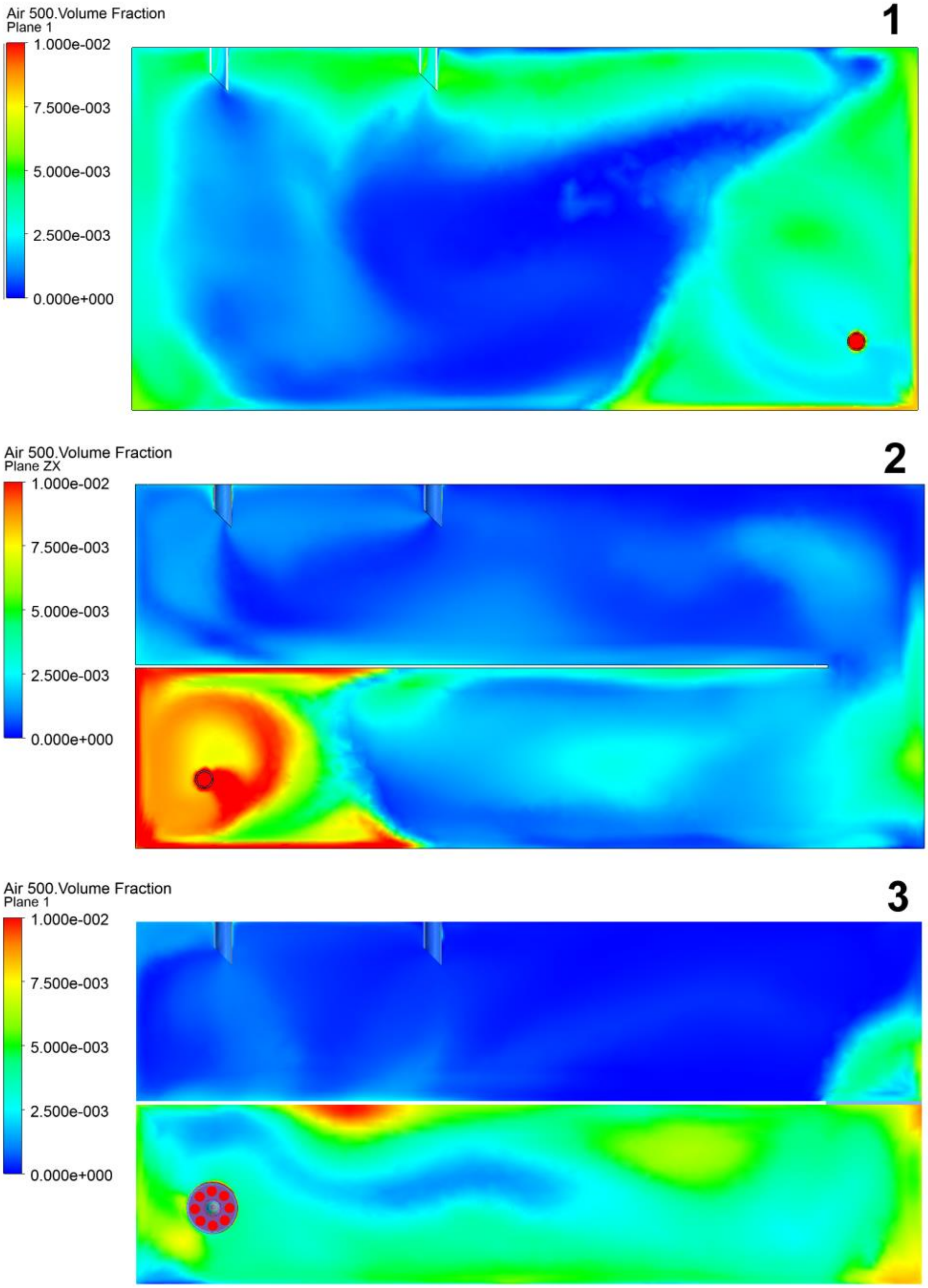


Figure 4.5: Volume percentage of air bubbles of mean size 500 µm on a horizontal plane at suction pipe height (h=100 mm)

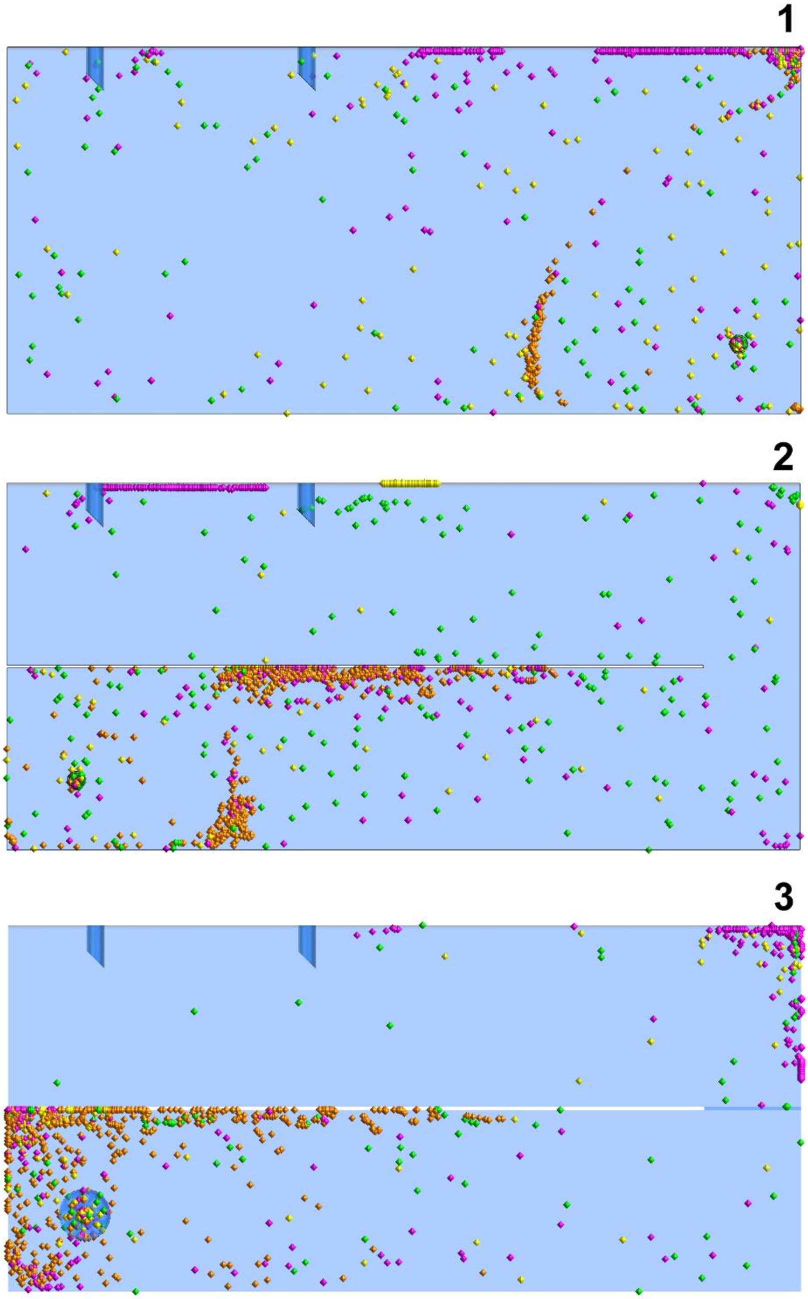


Figure 4.6: Position of copper particles at tank bottom 500 µm – orange, 125 µm – violet, 25 µm – green, 5 µm – yellow

The position of solid contaminants of different sizes at the tank bottom is shown in Figure 4.6. Again the worst results were observed in the first tank design version (first model), where particles of all sizes were distributed over the entire tank bottom. Exceptions were the particles of size 125 and 500 μm (which are not usually found in hydraulic tanks). They tended to be deposited at the tank bottom within a certain circle round the return pipe.

The second tank design (second model) was more successful in separating solid contaminants from oil; in Figure 4.6 it can be seen that much less contaminants were present within the vicinities of suction pipes and that they were deposited mostly in the first chamber. The best solution was the third model in which the greatest quantity of solid contaminants was separated from the oil already in the tank itself – larger particles were deposited within the immediate vicinity of the return line (diffuser), while the majority of smaller particles were deposited in the first chamber.

Figure 4.5 clearly shows that the internal tank shape is very important, since the concerned models separated the air bubbles very differently in spite of identical outside dimensions. To guarantee proper environment for on-line condition monitoring (OCM) system and to reach the highest possible reliability and accuracy of measurements of the on-line sensors, the fluid, when taken from the tank must be taken from the space with the least possible content of air bubbles (Figure 4.5 – blue). Figure 4.6 shows that here also the tank shape and layout were very important, as in spite of their identical exterior the solid contaminants were laid out very differently.

The presented simulation process of the hydraulic fluid flow and the trajectory of air and solid particles can be used for optimization of the hydraulic tank design and for optimization of the selection of the sampling point for designing the on-line condition monitoring of hydraulic fluid. Simulation results allow an insight into the phenomena in the tank interior and help in selecting the most appropriate sampling point (e.g. to avoid dead zones, where air bubbles and solid contaminants accumulate). In that way the accuracies and credibility of measurements are improved, since the influence of the mentioned contaminants strongly affects the results given by the on-line sensor.

If an on-line condition monitoring system is located on the hydraulic pressure or return line, the air bubbles already separated in the tank itself do not affect the OCM unit operation (particularly the cleanliness level). It does not need to be emphasized that the correct concept of the tank interior with as many separated contaminants as possible already in the tank itself is the first step to the long-term lifetime of the hydraulic oil as well as the hydraulic device and machine.

4.4 Sensors and data acquisition

Conducting measurements by on-line sensor imposes the creating of a data collection and processing unit that will communicate with on-line sensors, as well indicate and record their measurements. Various systems of different manufacturers are available for designing modern systems of industrial automation and machine control systems.

Usually, the manufacturers offer the basic controller and additional input /output modules allowing configuration of the system depending on the case of machine application. As a wide choice of products is available on the market, the appropriate system is selected with respect to:

- required sampling rate,
- processing capacity of the system,
- required memory,
- input/output modules which may be added to the system,
- operation reliability,
- operating environment (temperature, dust etc.),
- visualization requirements.

In consideration of the above system properties the control-processing system serving to acquire and evaluate the signals and to record and present the collected data, is to be selected optimally with respect to the economic aspect of the design of the entire machine condition control system. In general, two different systems can be used: controller or panel PC.

The advantages of controllers are higher speed and operational reliability. They are intended for industrial machine automation where they are used for control of the machine's primary function as well as for the control of safety functions.

Recently, great strides have been made within the sphere of industrial panel PCs usually used in combination with controller and serving as a human machine interface (HMI). In simpler applications, the modern PC systems can also perform control functions and recording of specific parameters. Compared with considerably more expensive industrial controllers, such systems feature lower sampling speed, lower operation reliability and limited possibilities of input/output modules. It must be emphasized that such systems are still always rather fast (sampling rate easily reaches 1 kHz) and reliable enough, since they are adapted to industrial application. They also have a major advantage, i.e. data can be displayed on site.

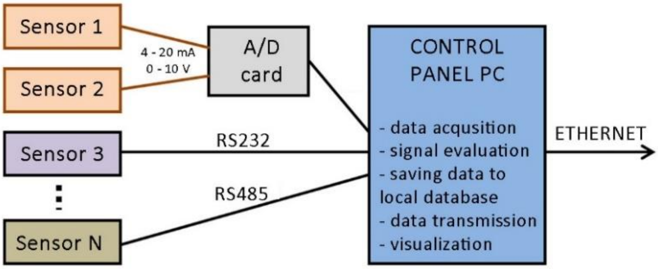


Figure 4.7: Architecture of data acquisition, processing and transfer

The system architecture to be used must be created prior to selecting individual components. Figure 4.7 shows, as an example, a part of the architecture of the data acquisition, processing and transfer system.

The basic structure of data transfer and archiving is shown in Figure 4.8. The control panel PC receives the data from sensors, evaluates and then stores them in its own data base saved on the Compact Flash memory. The last data record is always displayed on the screen also (Figure 4.9) and is sent into the waiting list for sending data to the server hosting the central (SQL) data base. The panel PC sends the data up to the e-mail server through SMTP protocol, verifying the status of sending. It deletes the last data set from the waiting list if it is successfully sent. In this way it allows the data to be saved in case of failure of the internet line up to the e-mail server, and in the case of failure of the server itself.

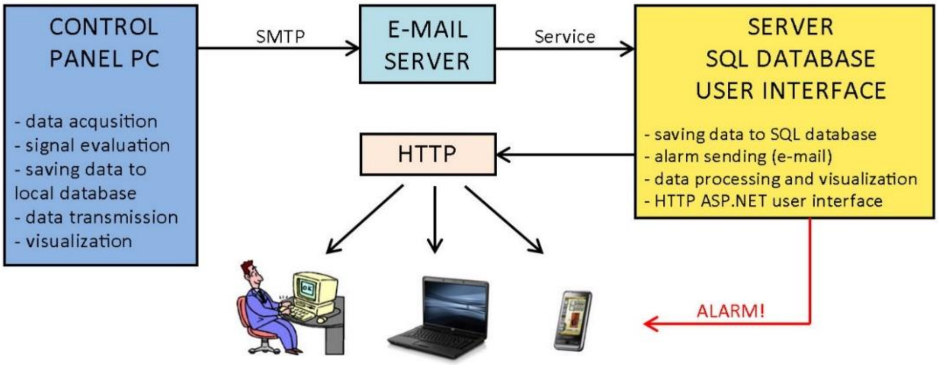
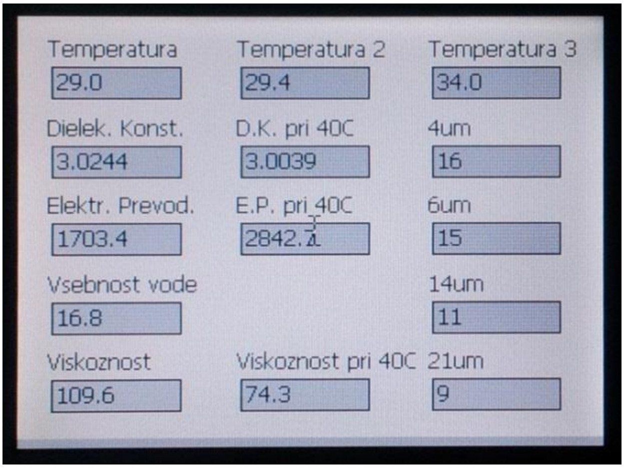


Figure 4.8: Architecture of data transfer and display

The server hosting the central data base (with a considerable number of machine control systems) periodically collects the data from the e-mail server through POP3 protocol. If a fault occurs on the internet line between the e-mail server and the central SQL base server, the data accumulates on the e-mail server. When the connection has been re-established, the data are transferred in packets replacing the missing part of data. The system can also inform the user if the internet lines fail and the data transfer through e-mail does not function.

The measurement data of on-line sensors transferred through POP3 protocol are added to the relevant data base to the individual hydraulic fluid condition control system. The data transfer between the panel PC and the central data base server can also take place through other protocols like direct SQL table insert, data transfer through web service, FTP protocol etc.



Temperatura
29.0
Temperatura 2
29.4
Temperatura 3
34.0
Dielek. Konst.
3.0244
D.K. pri 40C
3.0039
4um
16
Elektr. Prevod.
1703.4
E.P. pri 40C
2842.7
6um
15
Vsebnost vode
16.8
14um
11
Viskoznost
109.6
Viskoznost pri 40C
74.3
21um
9

Figure 4.9: Panel PC screen example at the measuring location

The system allows data receiving and displaying at the place of measurement as well as sending of data to the central data base. An example of the panel PC screen and the record of values at the measurement place are shown in Figure 4.9.

4.5 Importance and purpose of user interface for interpretations of results

As the maintenance personnel are often absent from the place of measurement, an internet interface was also created to allow data display to the lubricant producer as well as to the company's maintenance personnel, whenever and wherever possible (where internet is available).

Web interface based on a central SQL base, where all measurement data are stored from different dislocated systems in individual applications of hydraulic fluid condition monitoring. As the interface based on the ASP.NET technology, it is accessed simply through the conventional internet browser and in contrast to some other systems additional software or hardware are not necessary.

The user first performs the registration then the administrator confirms the user and assigns him the proper rights for accessing individual systems. For example, the individual maintenance person from the selected company can only see and monitor his/her system, while the lubricant producer's technical personnel have access to all systems.

Show	Channel	Min	Max
☐	AH H2O+ Temperature	0	60
☐	AH H2O+ Permittivity	2	2.5
☐	AH H2O+ Conductivity	0	5000
☐	AH H2O+ Humidity		
☐	AH H2O+ Permittivity 40C	2	2.5
☐	AH H2O+ Conductivity 40C	0	5000
☐	AH H2O+ Permittivity gradient		
☐	AH H2O+ Conductivity gradient		
☑	AH VIS+ Temperature		
☐	AH VIS+ Piezo temperature		
☐	AH VIS+ Kin. Viscosity	0	150
☑	AH VIS+ Kin. Viscosity 40C	0	150
☐	AH VIS+ Kin. Viscosity (calculated) 40C		
☐	AH VIS+ Kin. Viscosity change 40C		
☐	AH VIS+ Permittivity		
☐	AH VIS+ Permittivity 40C		
☐	AH VIS+ Permittivity change 40C		
☐	AH VIS+ Permittivity gradient		
☐	AH OPCOM ISO 4		
☐	AH OPCOM ISO 6		
☐	AH OPCOM ISO 14		
☐	AH OPCOM ISO 21		
☐	AH OPCOM Temperature		
☐	AH OPCOM Status		
☐	ISO 4	0	25
☐	ISO 6	0	25
☐	ISO 14	0	25
☐	ISO 21		

Current View:
1 - Temperatura & viskozr

● 1 - Temperatura & viskoznost
○ 2 - Temperatura & voda
○ 3 - Temperatura & elek prevodnost
○ 4 - Temperatura & DK
○ 5 - Stopnja östosti
○ 6 - (prazno)

Figure 4.10: Internet user interface for remote on-line condition monitoring of hydraulic oils

The main part of the web interface is shown in Figure 4.10 and consists of the following segments described:

Menu for navigating between windows on the left side.

Drop-down menu above graph serving for selection of the system the user wants to display. The user has access only to the systems assigned by the administrator.

Table of measured values for chosen system on the right side, where all available parameters monitored within a chosen system are displayed. The user adapts his chart view to display the values of his interest by checking the box in-front of the desired parameters. For each parameter he can choose between automatic or manual scaling. Because of the strong interdependence between measured parameters the system allows simultaneous displays of several parameters.

The user often wants to have a look at a chart with identical settings as he did the last time. Thus, a field is added under the table where the desired view settings can be named and saved under one of the six numbers. For example, under number 1 the user can save the view named “Temperature and water content”, which he configured that the chart indicates two parameters, namely the temperature with scale from 0 to 80 °C and the relative water content with scale from 0 to 100 %. Then he repeats the process for other view settings and, consequently, on the next login, he will only switch between those views. The described settings are personalized, i.e. they are saved for each user separately.

Graph for the display of values in the middle, where the user can display the trend of changes for the entire time period available. If he wants to display in detail a specific phenomenon and/or change, he simply selects the graph time section with simple drag and drop function. Afterwards, the slider allowing the user to move along the graph on the time axis appears to the user at the bottom. Of course, the dragging and dropping process can be executed several times (more and more detailed observation – range zooming).

The control system also allows alarming when the selected value exceeds certain pre-set maximum or minimum values. The user has the option of determining personal limits for the individual system (to which access is allowed to him) and for any controlled value in the system in order to trigger alarming only to his e-mail entered while registering into the system.

4.6 Measures for improving measurement accuracy and repeatability

In order to reach high-quality measurement data by on-line sensors, several tests were performed, contributing to improvements in measurement accuracy and repeatability, and higher credibility of results. Hereinafter, they are presented parameter by parameter.

4.6.1 Temperature

As already pointed out many on-line parameters strongly depend on the oil temperature. Therefore, it is necessary to calculate the individual values to their reference values at 40 °C. In the process of measuring and calculating the values to the reference temperature the temperature measurement accuracy is of key importance. A practical test was performed i.e. parallel temperature measurement by three on-line sensors located in a purpose-made support at the minimum possible distance. The sensors were dipped into discussed HLP ISO VG 46 hydraulic oil in a glass cup which was heated, while the oil in it was mixed on a magnetic mixer as shown in Figure 4.11. The manufacturers' data with respect to sensor accuracy are indicated in Table 4.5.

The measurements performed by the process of heating in the glass cup on the magnetic mixer, as shown in Figure 4.11, are called »stationary measurements on mixer«.

Figure 4.11: Temperature test of three on-line sensors – stationary measurement on mixer

Table 4.5: Temperature measurement accuracies by three different on-line sensors

	Measuring range	Accuracy	Absolute accuracy
Sensor S1	-20 to 120 °C	±0.5 °C	±0.5 °C
Sensor S2	-20 to 120 °C	±2 % FS	±2.8 °C
Sensor S3	-50 to 150 °C	not specified	not specified

Figure 4.12 shows the measurement results, where for the reference temperature i.e. abscissa axis, the temperature of sensor S1 was used having the least absolute deviation. Depending on the mentioned temperature of sensor S1 on the abscissa axis, the two bold lines, red and green, show the parallel temperature measurements by sensors S2 and S3. The relative error with respect to the entire measuring range of sensors S2 and S3 (% FS) is indicated by thinner lines and relates to the right auxiliary ordinate axis.

The actual measured deviations of the temperatures of sensors S2 and S3 with respect to e sensor S1 temperature are shown in Table 4.6. By this measurement, the accuracy of sensor S2 was confirmed and the measuring uncertainty of sensor S3 estimated, which was not determined by the manufacturer.

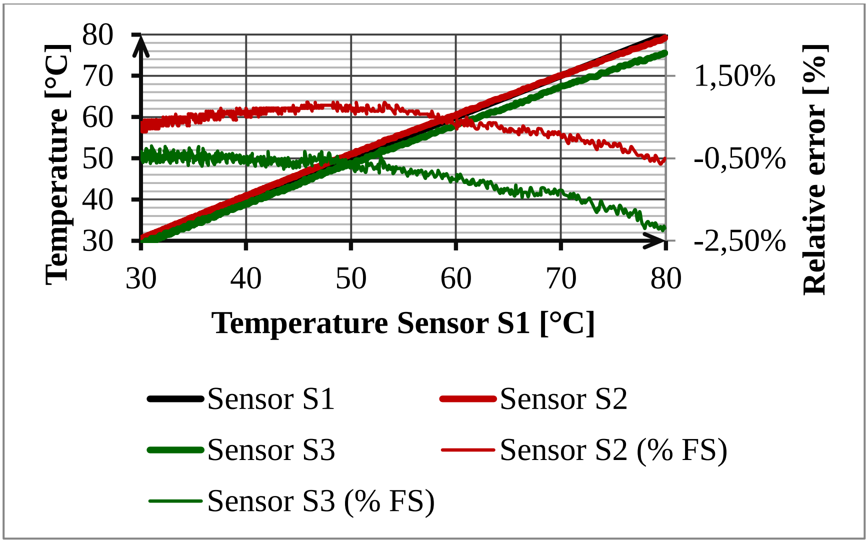


Figure 4.12: Parallel test – accuracy of temperature measurements by on-line sensors

Table 4.6: Measuring accuracies of sensors S2 and S3 temperatures with respect to sensor S1

	Absolute accuracy	**Relative accuracy**
Sensor S2	-0.9 to +1.2	-0.64 to +0.86 % FS
Sensor S3	-4.5 to -0.4	-0.20 to -2.26 % FS

4.6.2 Relative humidity

On-line sensors detect the relative humidity in mineral oil and indicate it in percentage. The oil is 100 % saturated when it contains the maximum water quantity at specific temperature and pressure – saturation limit. In contrast, in conventional chemical laboratory analyses of oil the absolute water content is measured according to the Karl Fischer method giving the water quantity in weight percent or ppm. The difference between the relative and absolute water content in hydraulic fluid was explained in detail in Chapter 2.4.2.

The saturation point can vary considerably with respect to the measured hydraulic fluid type and with respect to different base oils and different formulations of mineral hydraulic oil additive packages. Therefore, it is appropriate to perform tests determining the saturation limits of specific oil types, since it represents the limit above which the water content in hydraulic oil becomes harmful. Here below two different methods are presented for determining the mineral hydraulic oil ISO VG 46 saturation limit, as used in these studies.

Determinations of saturation point by on-line sensors and by the Karl Fischer method were performed in the following ways. Different water quantities were added to one litre of hydraulic oil. Then, the individual samples were measured by the two on-line sensors using the stationary measurement method on the magnetic mixer (Figure 4.11) and the temperatures read, at which the individual sensor reached the limit oil saturation with water (i.e. when the sensor indicated the oil relative humidity in value of 100 %). Then, on the mentioned samples, the comparisons between the laboratory analyses of the absolute water content were still performed by the Karl Fischer method.

Table 4.7: Measurement results of saturation limit by on-line sensors and by KF method

Sample	**Absolute water content Karl-Fischer (ppm)**	**Saturation temperature (°C) RH=100 %**	
		Sensor S1	**Sensor S2**
1	65.9	29	29
2	76.1	41	36
3	123.7	49	49
4	149.7	53	53

According to the data shown in Table 4.7 the curve giving the concerned mineral hydraulic oil saturation limit with water – Figure 4.13 could be found. The curve shows that the concerned oil saturation point lies at working temperatures from 40 to 60 °C between 90 and 180 ppm.

It may also be pointed out that the results of sensors S1 and S2 differ only in one point. It may be indirectly concluded that the used sensors (of relative oil humidity) are rather accurate and reliable.

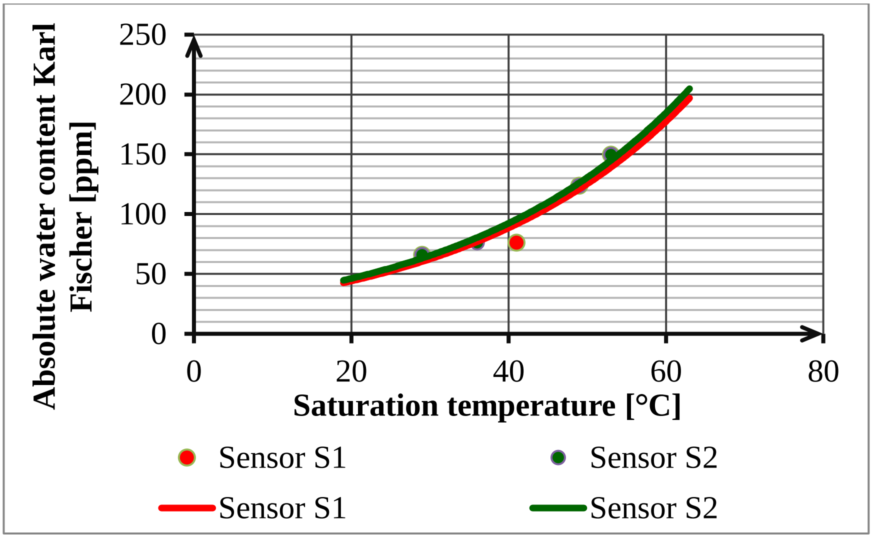


Figure 4.13: Saturation limit of concerned mineral hydraulic oil with water

For comparison and confirmation of results, the saturation limit was also determined by the **laboratory measurement of water content according to oil cloudiness**. The mineral hydraulic oil on the magnetic mixer was tempered at specific constant temperature. Then, a certain (measured) water quantity was added to the oil, until the oil became cloudy. The oil became saturated with the maximum water quantity, however a small surplus of water could no longer be absorbed in oil as it had reached the saturation limit. That water surplus appeared as the emulsified phase causing cloudiness. The cloudiness extent was determined by the use of black line pattern on white base put behind the oil cup as shown in Figure 4.14. The absolute water content was then also determined by laboratory analysis using the Karl-Fischer method. The measurement results are gathered in Table 4.8 and shown in Figure 4.15.

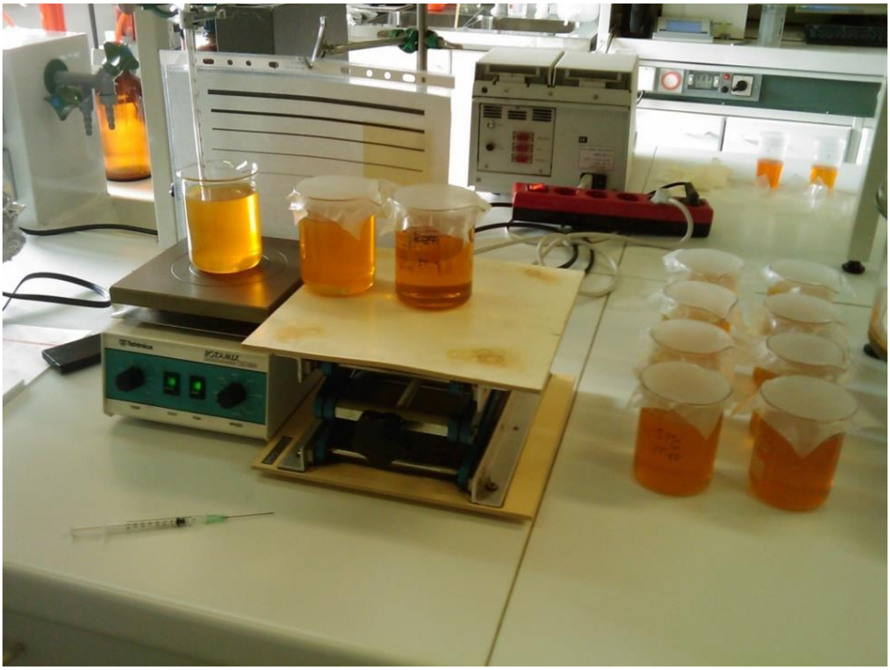


Figure 4.14: Laboratory determination of saturation limit of concerned mineral hydraulic oil with water according to oil cloudiness

The saturation limit data obtained by both methods differ. The absolute limit of mineral hydraulic oil ISO VG 46 saturation determined by relative humidity sensors is considerably lower than the absolute saturation limit determined by the laboratory oil cloudiness method due to several factors. Of course, one of the reasons is that during determination by the laboratory method the oil contains a certain surplus of water so that the emulsified phase (cloudiness) appears. The oil is then no longer at the saturation limit but has already exceeded it.

Table 4.8: Results of laboratory determination of saturation limit of concerned mineral hydraulic oil with water according to oil cloudiness

Sample	Temperature [°C]	Karl-Fischer [ppm]
1	25	552
2	31	639
3	36	723
4	40	749
5	44	797
6	47	873
7	52	967
8	57	1055

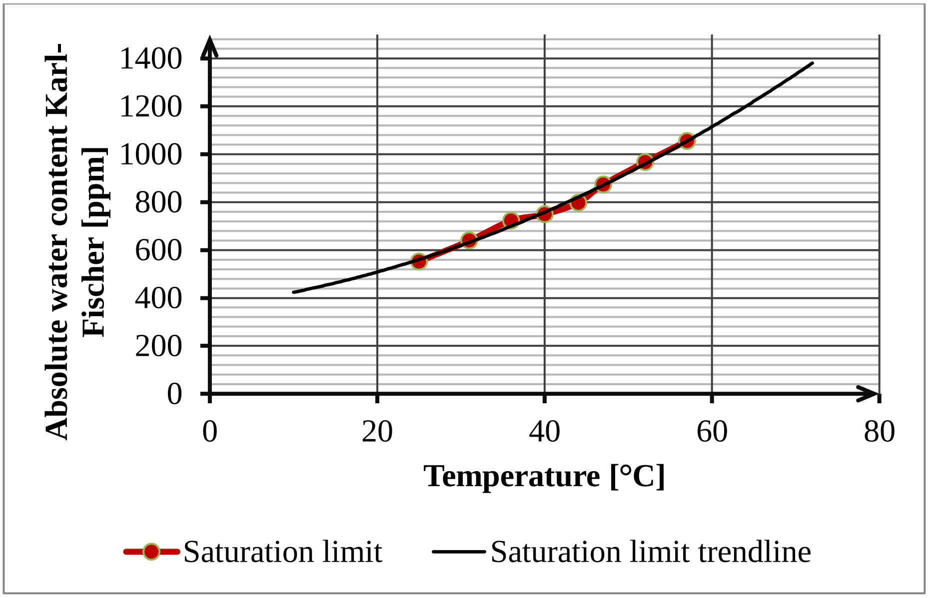


Figure 4.15: Saturation limit of a mineral hydraulic oil determined in the laboratory by the oil cloudiness method

It is necessary to also mention water dissolving in oil and hydrolysis of oil and additives. A specific share of water is gradually decomposed in oil and is bonded with oil and additives as elementary hydrogen and elementary oxygen. Furthermore, the content of water in oil is reduced due to water evaporation at higher temperatures.

4.6.3 Viscosity

Hydraulic fluid viscosity is one of the more important properties which must be permanently monitored and was discussed in chapters 2.3.6 and 2.4.3. Analyses of accuracies of two on-line sensors for measuring oil viscosity was made on the concerned mineral hydraulic oil according to the stationary measurement on magnetic mixer (Figure 4.11) within the temperature range between 30 and 80 °C. The results are shown in Figure 4.16.

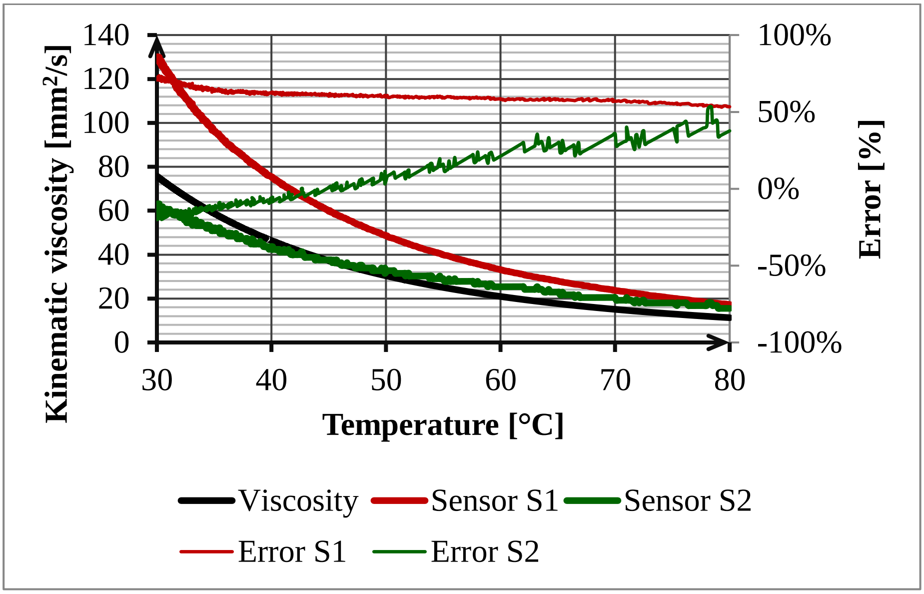


Figure 4.16: Measurement results of two on-line oil viscosity sensors

The black line represents the “actual” oil viscosity measured in the chemical laboratory according to procedure ASTM D 445 at two characteristic temperatures, i.e. 40 and 100 °C. Kinematic viscosity over the entire span was then calculated by the use of the simplified Walther equation originating from standard ASTM D 341 [5]:

$$\log(\log(\nu + 0{,}7)) = A - B(\log T) \tag{4.1}$$

A and B – constants,
ν [m^2/s] – kinematic viscosity,
T [K] – absolute temperature.

Bold red line in Figure 4.16 represents the measured results of on-line sensor S1 already giving kinematic viscosity at different temperatures, which can be directly compared to the actual oil viscosity. The bold green line shows the measured kinematic viscosity of sensor S2. The latter, differently than sensor S1 gives the results as the dynamic viscosity which must be converted into kinematic viscosity by the use of the known oil density at the temperature 20 °C:

$$\nu(T) = \frac{\eta(T)}{\rho(T)} \tag{4.2}$$

The oil density at constant pressure changes according to the equation [41]:

$$\rho(T) = \frac{\rho(T_{20})}{1+\alpha(T-T_{20})} \tag{4.3}$$

$\rho(T)$	[g/cm^3]	– density at temperature T,
$\rho(T_{20})$	[g/cm^3]	– measured density at 20 °C,
α	[C^{-1}]	– temperature volume coefficient of specific oil.

The measurement results (Figure 4.16) indicate a strong deviation of measured values of sensor S1 and sensor S2 kinematic viscosity compared with actual kinematic viscosity. The deviation is also illustrated in the form of the relative measurement error (thinner coloured lines) amounting to 50 to 70 % on sensor S1 and to -20 to 40 % on sensor S2.

Of course, such deviation is too large and measurements by such two sensors would be completely unusable. It is supposed that such deviations occur because the sensors are factory calibrated only with a specific fluid type. The measurement accuracy can be significantly improved by calibrating a certain sensor to a specific hydraulic fluid type as shown here below. In Figures 4.17 and 4.18 the actual viscosity is indicated on the ordinate axis depending on the viscosity measured by the individual sensor.

The illustration of the actual viscosity dependence on the viscosity measured by the individual sensor allows the determination of the individual sensor transfer function serving as the so-called calibrating curve. The two calibrating curves for the individual sensor were determined as the third degree polynomial and are presented in Figures 4.17 and 4.18. When measuring the viscosity by a calibrated sensor this allows the calculation and estimation of the actual viscosity υ in relation to the measured sensor viscosity υ_s like for example for sensor S1 and concerned mineral hydraulic oil:

$$\nu(\nu_s) = -8 \cdot 10^{-6} {\nu_s}^3 + 0.0012 {\nu_s}^2 + 0.5614 \nu_s + 1.2781$$

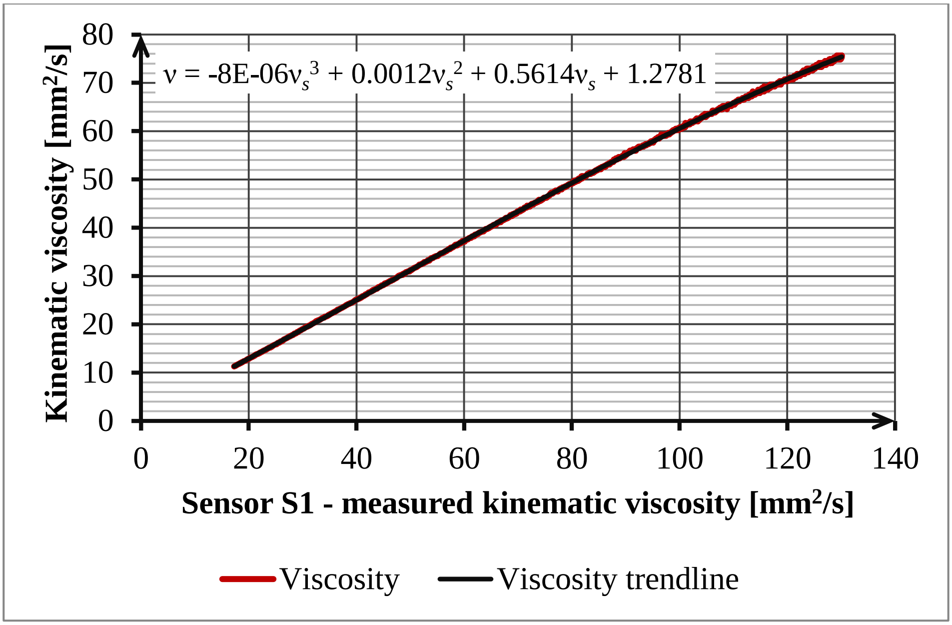


Figure 4.17: Actual viscosity depending on sensor S1 measured viscosity

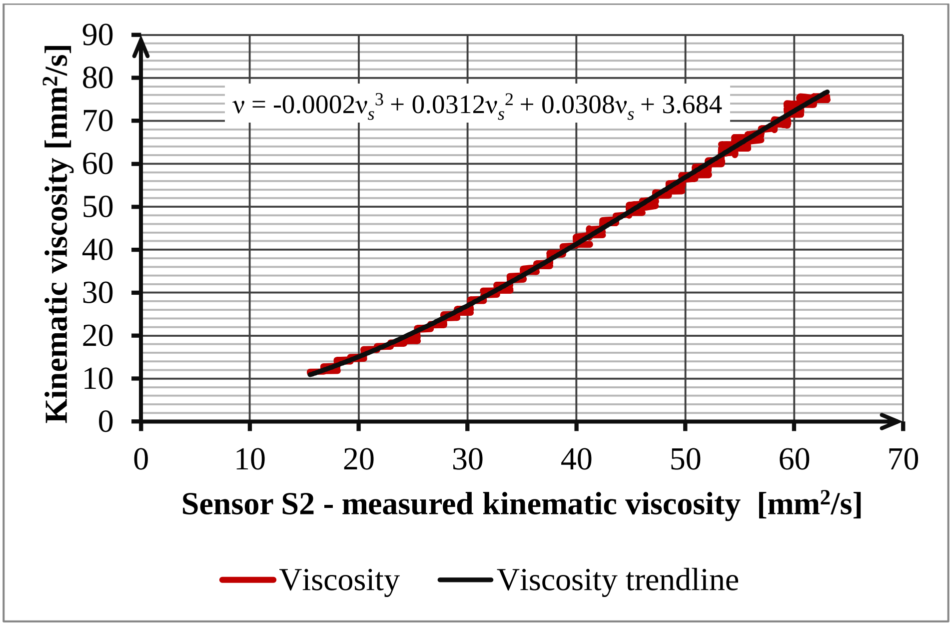


Figure 4.18: Actual viscosity depending on sensor S2 measured viscosity

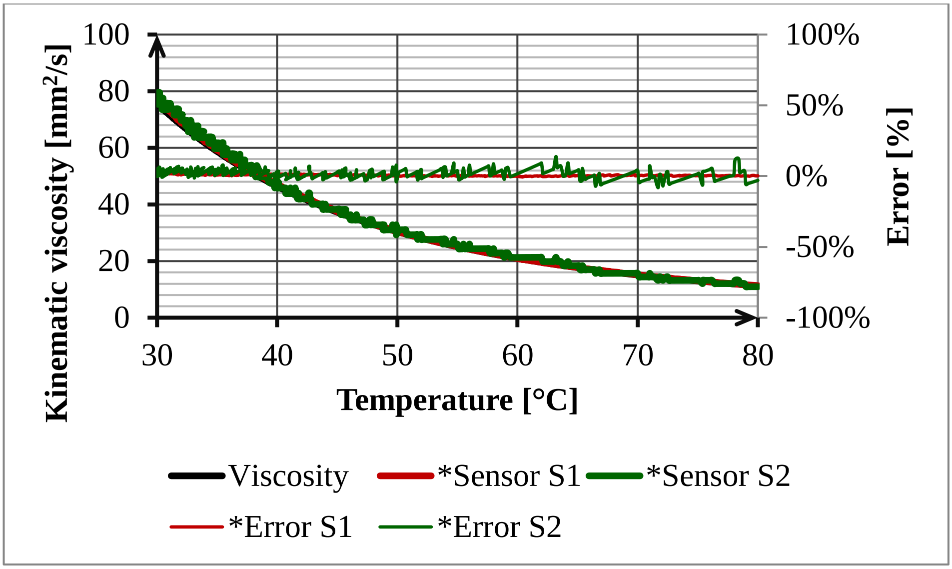


Figure 4.19: Measurement results of two on-line oil viscosity sensors by considering calibration curve for specific type of oil and sensor

In comparison with the actual output sensor values indicated in Figure 4.16, the Figure 4.19 presents the measurement results using the considered calibration curves. The Figure shows that thanks to the two calibration curves defined on purpose for the used on-line sensor and used hydraulic fluid, the on-line viscosity measurement accuracy had largely improved. Within the entire range the relative sensor S1 error varies in the order ±5 %, while the relative sensor S2 error within the range of lower viscosities is slightly higher because of low values of output signals and the inaccuracy of the used A/D card for signal receiving.

In addition to implementing the purpose-created calibration curve for specific oil type and sensor, the viscosity can be more accurately monitored if the measured kinematic viscosity at the measurement temperature is calculated to viscosity at the characteristic temperature 40 °C. For the above calculation a purpose-created program based on standards ASTM D341 and D2270 [5], [3] and on searching for solution by bisection was conceived. Based on input parameters (kinematic viscosity at specific temperature, temperature and viscosity index) it calculates the hydraulic fluid viscosity at 40 and 100 °C. In that way, the trend of hydraulic fluid viscosity at 40 °C can be better monitored in spite of temperature oscillations in the on-line system.

4.6.4 Dielectric constant and electric conductivity

In the frame of the studies the dielectric constant of the concerned mineral hydraulic oil was measured by three on-line sensors, while one sensor was available for measuring electric conductivity. The parameter measuring ranges and the accuracies are given by the manufacturer and indicated in Table 4.9. Like for other on-line parameters, also for the dielectric constant and electric conductivity the accuracy analysis of our sensors was also performed by the stationary test on the magnetic mixer.

Table 4.9: Sensors' measuring ranges and accuracies

	Dielectric constant		**Electric conductivity**	
	Measuring range	**Accuracy**	**Measuring range**	**Accuracy**
Sensor S1	1 to 7 [-]	±0.015 [-]	100 to 1000000 [pS/m]	Typ. < 10 %
Sensor S2	1 to 5 [-]	±0.2 [-]	-	-
Sensor S3	1 to 10 [-]	not specified	-	-

Accurate absolute values of the dielectric constant and electric conductivity on the concerned mineral hydraulic oil were not known. Accurate measurements for our needs were performed by an external laboratory. A summary of results is indicated in Table 4.10.

Table 4.10: Summary of measurement results of dielectric constant and electric conductivity

Temperature [°C]	**ε [-]**	**σ [pS/m]**
30	2.2636	155.6
40	2.2492	245.7
50	2.2403	407.3
60	2.2314	670.6

The results of dielectric constant measurements by three on-line sensors (sensor S1, S2 and S3) compared with accurate laboratory measurement (DC-dielectric constant) are shown in Figure 4.20 indicating that the dielectric constants measured by on-line sensors largely deviate from the actual dielectric constant of oil.

At this moment, similarly as for the on-line viscosity measurement presented in chapter 4.6.3, the calibration curve for specific hydraulic fluid type and for each sensor separately could be found. As for each hydraulic fluid type separately the measurements of the dielectric constant accuracy would have to be left again to an external laboratory, it was decided for economic reasons to carry out only the proper calculation of the value to the reference value at 40 °C and to neglect the absolute dielectric constant value since, in the on-line oil condition monitoring, we only track changes of dielectric constant and not its absolute value.

Figure 4.20 shows that the dielectric constants change linearly with temperature, therefore their relevant temperature gradient must be found.

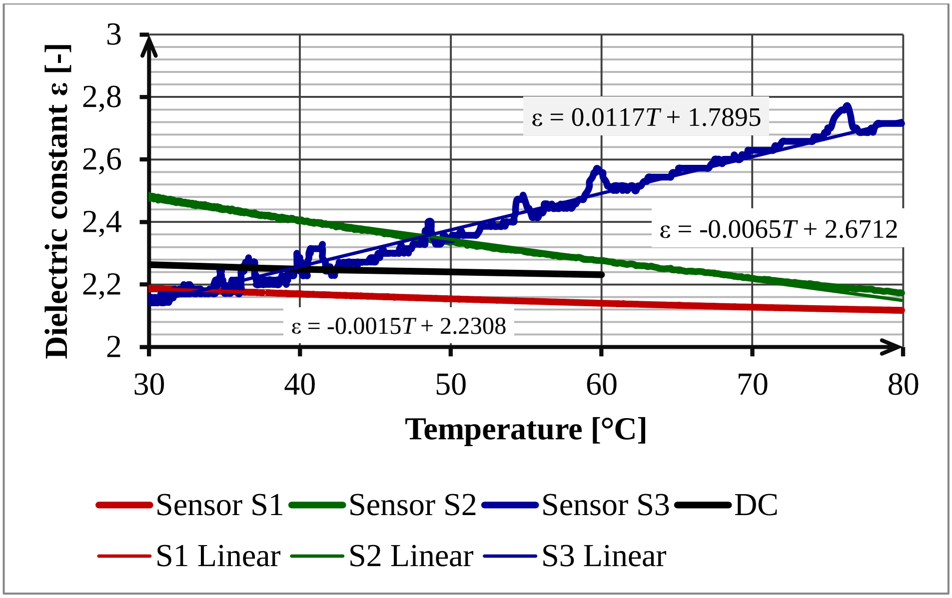


Figure 4.20: Measurement of dielectric constant by three on-line sensors

The linear dielectric constant g_ε gradients for the concerned mineral hydraulic oil and for the individual sensor are indicated in Figure 4.20 in the form of the linear straight-line coefficient and are equal to:

• Sensor S1:	-0.0015	[C^{-1}]
• Sensor S2:	-0.0065	[C^{-1}]
• Sensor S3:	+0.0117	[C^{-1}]

The calculation to the reference value of the dielectric constant at 40 °C $\varepsilon(T_{40})$ for the individual sensor is made by the use of the measured dielectric constant g_ε temperature gradient, e.g. for sensor S1:

$$\varepsilon(T_{40}) = \varepsilon(T) - g_\varepsilon(\Delta T) \tag{4.5}$$

$\varepsilon(T_{40})$	[-]	– dielectric constant at 40 °C,
$\varepsilon(T)$	[-]	– measured dielectric constant at temperature of measurement,
g_ε	[C^{-1}]	– temperature gradient of dielectric constant,
ΔT	[C]	– difference between measurement temperature and ref. 40 °C.

By calculating the dielectric constant of the measured temperature to the dielectric constant at the reference temperature 40°C the trend can be better monitored.

Identical procedure as for measuring the dielectric constant was also executed for the electric conductivity measurement, except that it was discovered in this case (Figure 4.21) that the electric conductivity does not change linearly with temperature. The relevant equation for the calculation to the electric conductivity reference value at 40 °C can be found by vertical displacement of the measurement curve (red line) so that it intersects the abscissa at the reference temperature as shown in Figure 4.22. It can be observed that the proper quality of the calculation is assured by the third degree polynomial equation.

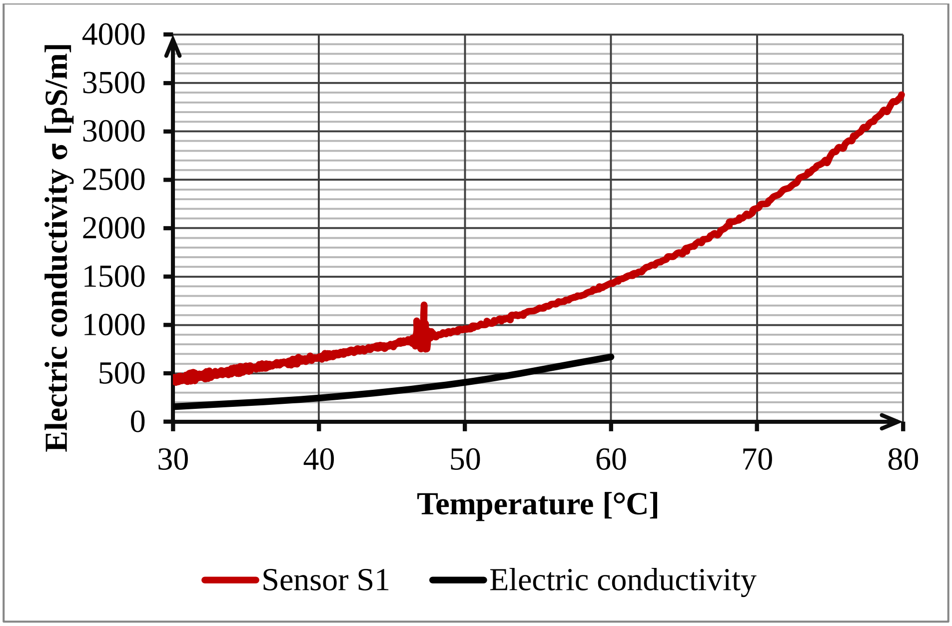


Figure 4.21: Measurement of electric conductivity by on-line sensor

According to Figure 4.22 the electric conductivity at reference temperature 40 °C σ(T40) will be calculated on the basis of the measured electric conductivity σ(T) at the measurement temperature T according to the following equation:

$$\sigma(T_{40}) = \sigma(T) - g_{\sigma}(\Delta T) \tag{4.6}$$

$$\sigma(T_{40}) = \sigma(T) - (0.0201(\Delta T)^3 - 2.1216\,(\Delta T)^2 + 97.987(\Delta T) - 1811.2 \tag{4.7}$$

$\sigma(T_{40})$	[pS/m]	– electric conductivity at 40 °C,
$\sigma(T)$	[pS/m]	– electric conductivity at measurement temperature,
g_{σ}	[pS/mC]	– function of electric conductivity temperature gradient,
ΔT	[C]	– difference between measurement temperature and ref. 40 °C.

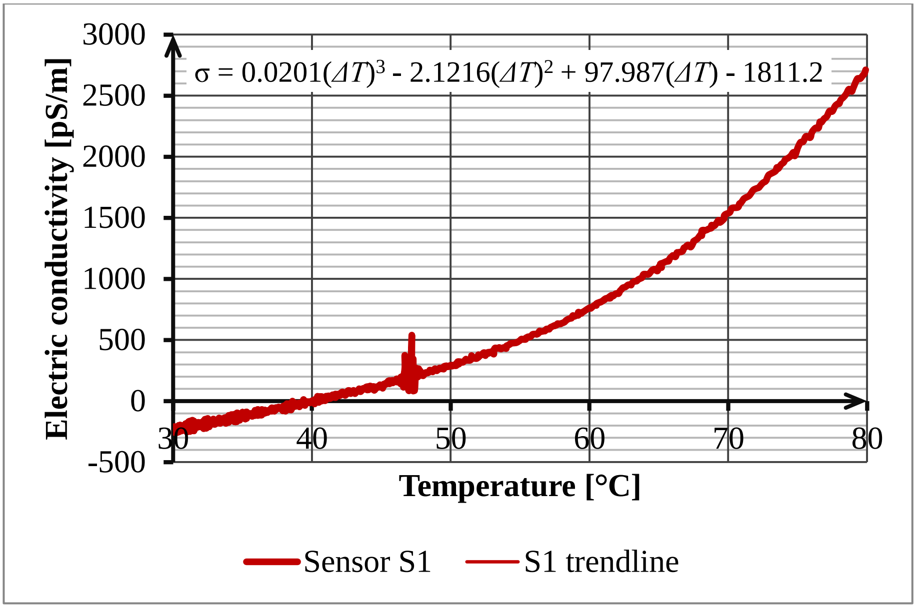


Figure 4.22: Determination of equation for calculating electric conductivity

4.6.5 Cleanliness class

The market offers a variety of on-line sensors for monitoring hydraulic oil cleanliness level, the difference being made between the sample cleanliness level indicators and more complex particle counters. In addition to particle counters, the indicators do not usually contain a special oil flow meter but assess the oil flow quantity on the basis of the speed of the particle traveling through the sensor cell. As already mentioned, the particle counters usually work on the principle of light scatter. The numbers and sizes of particles are determined on the basis of the shadow projected by particles onto the photocell (detector), as shown in Figure 4 23 (left).

When measuring, the credibility of the measured values is important. Therefore, we decided to perform a comparison test between some different on-line cleanliness level sensors (available on the market) and to compare the measured results by the use of the precise laboratory instrument Internormen CCS 2. The executed comparison analysis covered four on-line cleanliness level sensors. The measuring system was based on the by-pass principle, where the flow through the sensors was assured by a small by-pass pump pressing the hydraulic fluid through series-connected sensors, interconnected by measuring minimess tubes, as shown in Figure 4.24. In that way, equal flow conditions were assured through all on-line sensors.

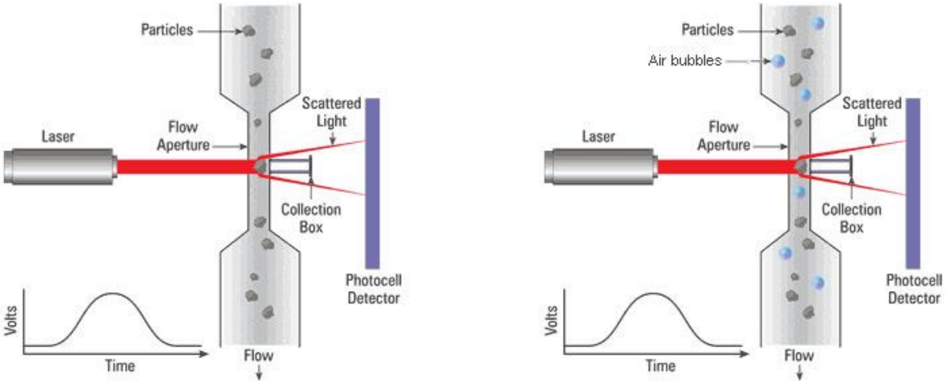


Figure 4.23: Principle of light-scattering measurement of oil cleanliness class and effect of air bubbles on measurement (right) [55]

During measurements the flow conditions through on-line sensors were as follows:

- pressure measured at the entry of the sensor system 30 to 35 bar,
- flow 80 to 100 mL/min.

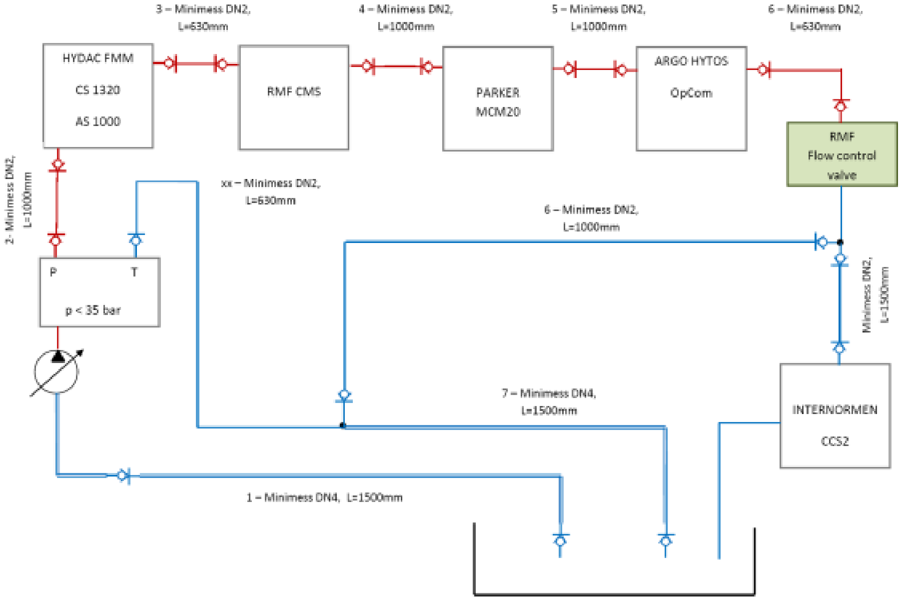


Figure 4.24: Diagram of oil cleanliness class measuring system

Table 4.11 shows the deviations of the individual sensor in the ISO 4406 class with respect to the laboratory instrument Internormen CCS 2 calibrated to ±0.1 ISO class, parallel connected in the hydraulic system. During the measurements, at least four or more readings were made; the results are indicated as the average of those readings.

The indicated accuracy of on-line particle counters is ±0.5 of ISO class for measurements within the range 13/11/10 to 23/21/18. The results of executed tests show that, regrettably, the on-line sensors do not reach that accuracy. Tests have shown that the counters usually work with accuracy ±1 ISO class, the differences occurring between the sensors themselves. It can be summarized that the on-line particle counters usually measure 1 ISO class less, i.e. the fluid cleaner for 1 ISO class (which is a “a more dangerous” result for the user).

Table 4.11: Results regarding research into accuracies of on-line cleanliness level sensors

Average deviation (ISO class)	**ISO 4**	**ISO 6**	**ISO 14**
Particle counter PC1	0.3	0.7	-0.15
Particle counter PC2	-1.15	-1.2	-0.85
Particle counter PC3	-1.1	-0.55	0.25
Particle counter PC4	-1.4	-0.85	-1.25

It was found that difficulties also occurred during the on-line measuring of cleanliness levels of oils in hydraulic units during their operations. Therefore, tests were also performed to verify the responses of sensors to certain phenomena like the effect of air bubbles, the temperature effect etc.

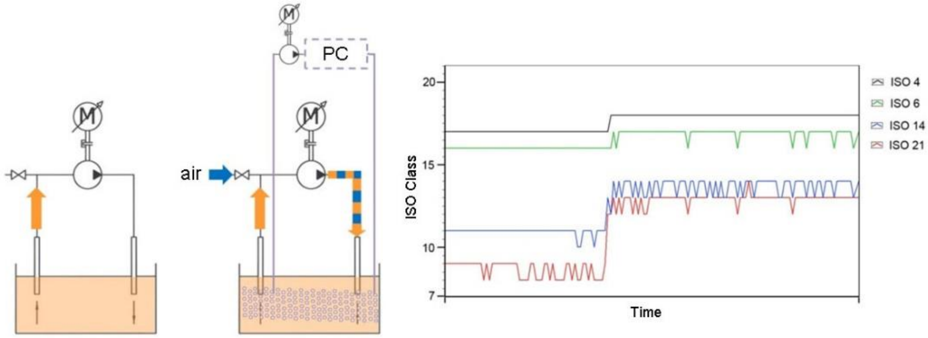


Figure 4.25: Research into effect of air bubbles on oil cleanliness class measurement left – measuring system, right – sudden change at the beginning of air induction

When distinguishing between other parameters the hydraulic fluid cleanliness level measurement does not depend on the temperature, however the condition of the fluid measured is important. Air bubbles or water droplets in the hydraulic fluid inflect the light, which is detected by the sensor as a particle (Figure 4.23 right). Therefore, before measurements it is necessary to remove from the fluid any air bubbles and water droplets (or make them not disturbing), otherwise false results would be displayed.

Figure 4.25 (left) shows the measuring system used to research the effect of air bubbles on the cleanliness level measurement. From the open tank (20 L) the oil was only pumped over by the use of a gear pump. At a specific moment, the valve on the suction side was opened so that air entered into the system and the oil in the tank became saturated with air bubbles. The by-pass system accommodated another gear pump assuring the flow through three series-connected particle counters (PC). Figure 4.25 (right) shows the sudden change of one of the sensors on oil saturating with air bubbles.

The results of oil condition measurements without and in the presence of air bubbles and the relevant differences are summarized in Table 4.12. The table shows that air bubbles most affect the measurement of ISO 14 and ISO 21 class, therefore it can be concluded that most air bubbles have diameters larger than 21 μm.

Table 4.12: Research results of effect of air bubbles on on-line particle counters

	Without air bubbles [ISO]			**Presence of air bubbles [ISO]**			**Difference [ISO]**			**Average difference [ISO]**
	PC1	**PC2**	**PC3**	**PC1**	**PC2**	**PC3**	**PC1**	**PC2**	**PC3**	
ISO 4	17.9	17.0	17.4	18.9	18	18.5	1	1	1.1	1.0
ISO 6	16.0	16.0	16.1	17.6	16.9	17.1	1.6	0.9	1	1.2
ISO 14	11.9	11.0	11.2	16.2	13.7	14.7	4.3	2.7	3.5	3.5
ISO 21	10.2	8.7	9.1	16.5	12.9	13.8	6.3	4.2	4.7	5.1

5 ANALYSIS OF FRESH HYDRAULIC FLUIDS

While monitoring the condition of hydraulic fluid it is necessary to know not only the current hydraulic fluid condition, but also the detailed initial parameters. They are of key importance for all further analyses and for monitoring the trends of individual parameters. Thus, the analysis of various fresh hydraulic fluids was executed, whereas the results will serve as a data base for further work and analyses. Analysis of fresh oils was carried out on the following hydraulic fluids:

- HLP ISO VG 46 – mineral hydraulic oil,
- HLP ISO VG 68 – mineral hydraulic oil,
- HLP ISO VG 22 – mineral hydraulic oil,
- DIN 51 517/2: CL ISO VG 220 – high viscosity mineral circulation oil,
- DIN 51 517/2: CL ISO VG 460 – high viscosity mineral circulation oil,
- HFDU ISO VG68 – fire resistant hydraulic fluid,
- BO 10/95 – base oil,
- BO 30/90 – base oil,
- BO N 150 – base oil.

The analyses of physical-chemical properties (Chapter 2.3), as well as the measurements by on-line sensors within the wider temperature range, were performed on the samples of the above fluids by the method of stationary measurements on a magnetic mixer. The laboratory analysis results and the measurement results by on-line sensors at the reference temperature 40 °C are indicated in Tables 5.1 and 5.2, while measurement results by on-line sensor within a wider temperature range are shown in Figures 5.1 to 5.6.

The results show that the fresh hydraulic fluid parameters considerably differ in spite of their related chemical structures. For example, the concerned HLP mineral hydraulic oils of different viscosities have a very different neutralization number, dielectric constant and electric conductivity.

It can also be indicated that HLP hydraulic oils have a lower neutralization number, dielectric constant and higher electric conductivity, if compared with DIN 51 517/2: CL lubricating oils. In regard to those facts it is of key importance to know in detail the fresh fluid parameters that will allow high quality and accurate monitoring of changes in the individual fluids.

Table 5.1: Analysis results of different fresh hydraulic fluids (1st part)

Sample	**Standard / unit**	**HLP – VG 46**	**HLP – VG 68**	**HLP – VG 22**	**DIN 51 517/2 CL VG 220**	**DIN 51 517/2 CL VG 460**
Density at 20 °C	ISO 12185	0.8634	0.8662	0.8586	0.8837	0.8914
Viscosity at 40 °C	ASTM D 445 [mm^2/s]	46.42	66.13	21.94	229.07	463.64
Viscosity at 100 °C	ASTM D 445 [mm^2/s]	6.89	8.66	4.29	19.14	30.60
Viscosity index	ASTM D 2270 [-]	104	102	100	93	95
Neutralization number	ASTM D 974 [mg KOH/g]	0.66	0.72	0.53	0.90	0.94
Water content	ISO 12937 [ppm]	63.23	63.95	80.13	59.31	58.65
Additive elements	ASTM D-6481 [wt. %]					
Phosphorus (P)		0.032	0.032	0.031	0.032	0.059
Sulfur (S)		0.702	0.708	0.696	0.698	1.729
Calcium (Ca)		0.004	0.005	0.005	0.004	0.006
Zinc (Zn)		0.0452	0.0454	0.0462	0.0464	0.0535
Wear metals	TXMS-06A [mg/kg]					
Chromium (Cr)		< 5	< 5	< 5	< 5	< 5
Copper (Cu)		< 3	< 3	< 3	11	9
Iron (Fe)		< 3	< 3	< 3	< 3	< 3
Lead (Pb)		< 3	< 3	< 3	< 3	< 3
Tin (Sn)		< 20	< 20	< 20	< 20	< 20
On-line sensors at 40°C	**Unit**	**HLP – VG 46**	**HLP VG 68**	**HLP VG 22**	**DIN 51 517/2 CL VG220**	**DIN 51 517/2 CL VG460**
Dielectric constant S1	[-]	2.1701	2.1644	2.1510	2.2429	2.2747
Dielectric constant S2	[-]	2.4050	2.3960	2.3330	2.5020	2.5430
Dielectric constant S3	[-]	2.2859	2.2286	2.1999	2.2715	2.2859
Electric conductivity S1	[pS/m]	668	450	1001	358	309
Relative humidity	[%]	27.1	26.3	16.6	33.6	37.0
Viscosity S1	[mm^2/s]	72.6	103.8	36.9	(*)	(*)
Viscosity S2	[mm^2/s]	61.7	85.6	34.0	260.3	461.8

(*) – viscosity out of measuring range

Completely different parameters were obtained on HFDU fire resistant hydraulic fluid. Its initial neutralization number, as well as its dielectric constants and electric conductivity, are rather high in comparison with common mineral oils.

Opposite phenomenon can be observed on the base oils, since their neutralization number, as well as their dielectric constant and electric conductivity, are very low. It can be concluded that the additive packets added to the base oil increase the mentioned parameters.

The measurement results of viscosity in the chemical laboratory (by method ASTM D 445) strongly differ from the viscosity measurement results measured by on-line sensors. Therefore, an analysis of measurement results was made and the relevant calibration curve was found for each of the mentioned hydraulic fluids separately (base oils were excluded).

Table 5.2: Analysis results of different fresh hydraulic fluids (2nd part)

Sample	**Standard / unit**	**HFDU VG 68**	**BO 10/95**	**BO 30/90**	**BO N150**
Density at 20 °C	ISO 12185	0.9165	0.8573	0.8705	0.8433
Viscosity at 40 °C	ASTM D 445 [mm²/s]	71.48	31.94	91.81	33.02
Viscosity at 100 °C	ASTM D 445 [mm²/s]	12.15	5.36	10.34	5.68
Viscosity index	ASTM D 2270 [-]	168	100	93	112
Neutralization number	ASTM D 974 [mg KOH/g]	1.81	0.004	0.009	0.015
Water content	ISO 12937 [ppm]	462.21	35.11	42.50	38.18
Additive elements	ASTM D-6481 [wt. %]				
Phosphorus (P)		0.005	0.000	0.000	0.000
Sulphur (S)		0.038	0.601	0.508	0.000
Calcium (Ca)		0.000	0.000	0.000	0.001
Zinc (Zn)		0.0007	0.0022	0.0019	0.0024
Wear metals	TXMS-06A [mg/kg]				
Chromium (Cr)		< 5	< 5	< 5	11
Copper (Cu)		< 3	< 3	< 3	< 3
Iron (Fe)		< 3	< 3	< 3	< 3
Lead (Pb)		< 3	< 3	< 3	< 3
Tin (Sn)		69	< 20	< 20	< 20
On-line sensors at 40°C	**Unit**	**HFDU VG 68**	**BO 10/95**	**BO 30/90**	**BO N150**
Dielectric constant S1	[-]	3.1013	2.1391	2.1615	2.0704
Dielectric constant S2	[-]	3.3470	2.3360	2.3910	2.2850
Dielectric constant S3	[-]	3.3740	2.1713	2.1570	2.0568
Electric conductivity S1	[pS/m]	2689	234	275	384
Relative humidity	[%]	34.2	20.7	27.9	22.1
Viscosity S1	[mm²/s]	85.2	53.1	162.9	50.5
Viscosity S2	[mm²/s]	95.0	45.3	116.6	46.0

The results of measurements by on-line sensors over a wider temperature range by the method of stationary measurement on a magnetic mixer are indicated in Figures from 5.1 to 5.6 and served as a basis for data processing according to procedures described in Chapters 4.6.3 and 4.6.4.

The calibration viscosity curves for both used sensors were determined for all hydraulic fluids to improve the accuracy of our measurements. The relevant temperature gradients of the dielectric constants and electric conductivity were determined for each hydraulic fluid to allow calculation of the mentioned parameters to the reference value at 40 °C. The results concerned are indicated in Table 5.3 in the form of functions of calibration curves.

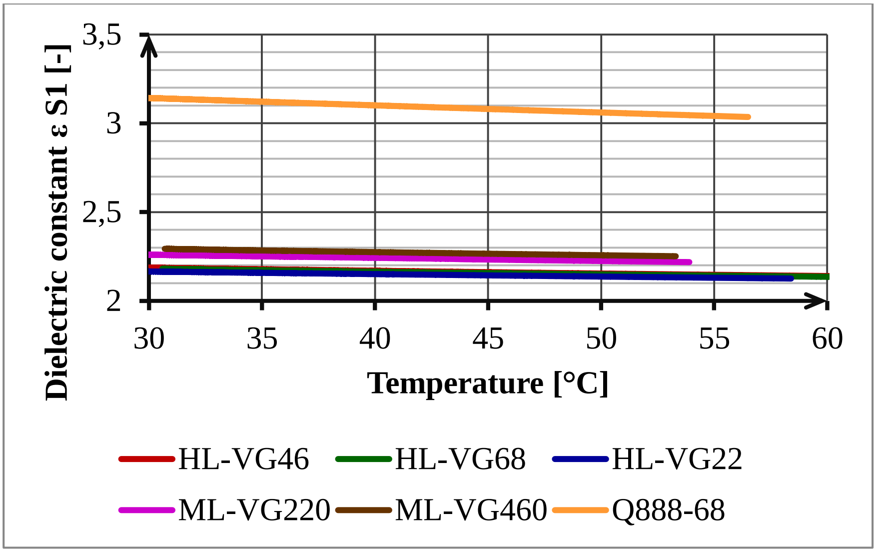


Figure 5.1: Dielectric constant of on-line sensor S1 throughout temperature range

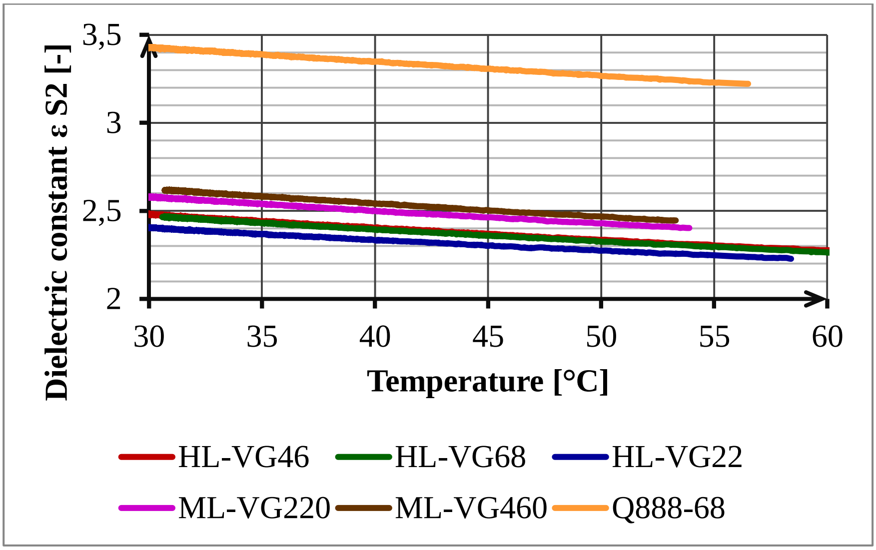


Figure 5.2: Dielectric constant of on-line sensor S2 throughout temperature range

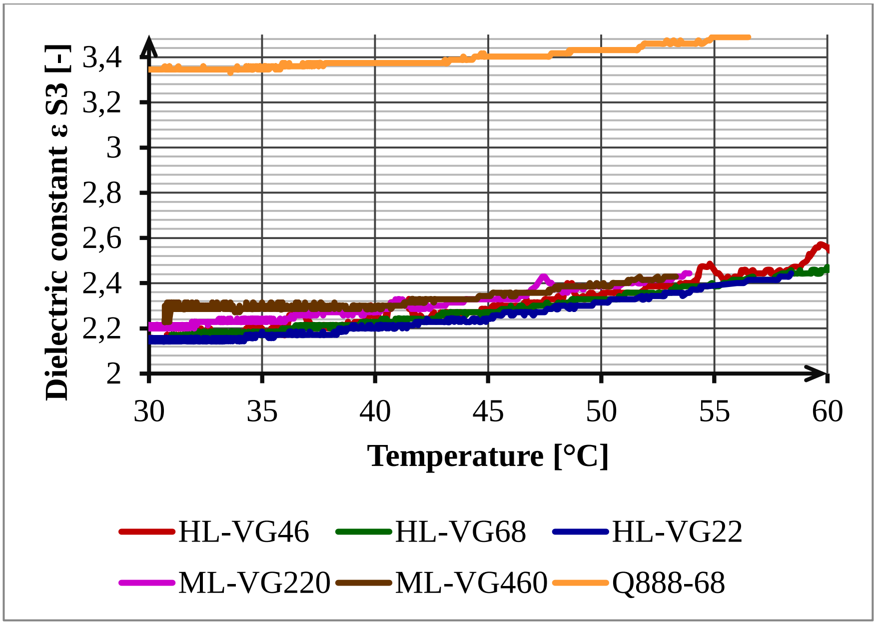


Figure 5.3: Dielectric constant of on-line sensor S3 throughout temperature range

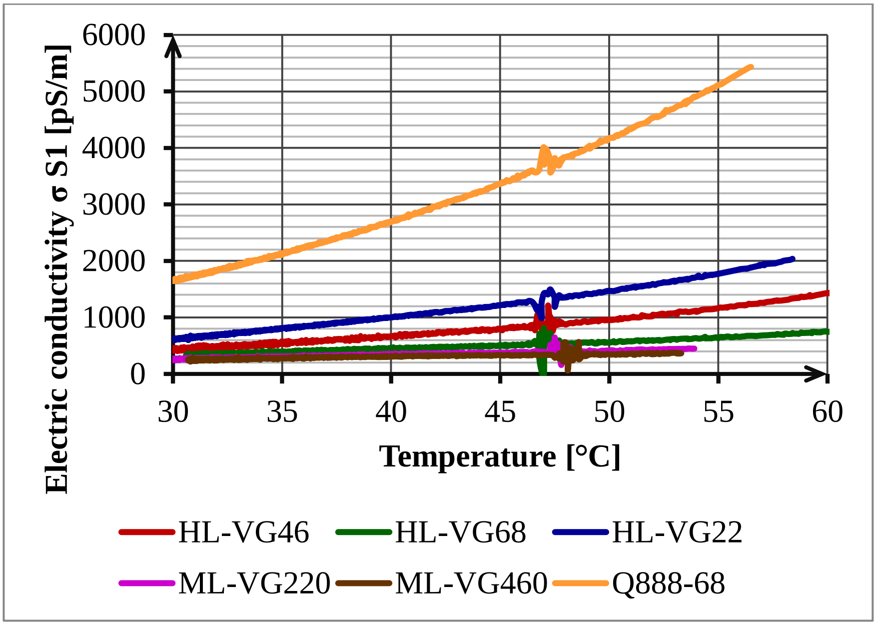


Figure 5.4: Electric conductivity of on-line sensor S1 throughout temperature range

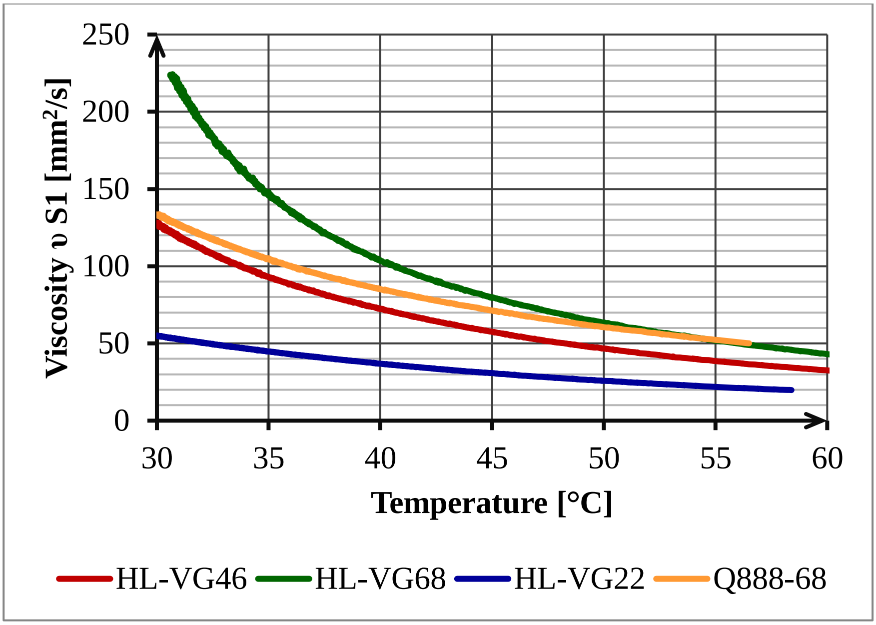


Figure 5.5: Viscosity of on-line sensor S1 throughout temperature range

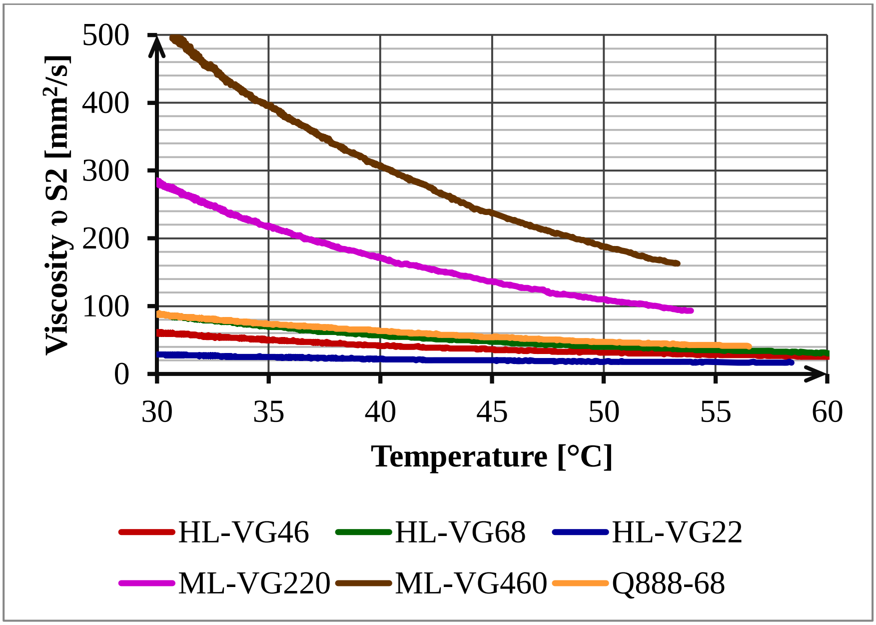


Figure 5.6: Viscosity of on-line sensor S2 throughout temperature range

Table 5.3: Functions of calibration curves for individual hydraulic fluids

	HLP VG 46	**HLP VG 68**
DC S1	$-0.0015(\Delta T)$	$-0.0015(\Delta T)$
DC S2	$-0.0065(\Delta T)$	$-0.007(\Delta T)$
DC S3	$0.0117(\Delta T)$	$0.0099(\Delta T)$
EC S1	$0.02(\Delta T)^3 - 2.1121(\Delta T)^2 + 97.481(\Delta T) - 1802.7$	$0.0139(\Delta T)^3 - 1.7236(\Delta T)^2 + 82.021(\Delta T) - 1413.6$
Viscosity S1	$-8\text{E-}06\nu^3 + 0.0006\nu^2 + 0.6482\nu - 0.4289$	$2\text{E-}06\nu^3 - 0.0025\nu^2 + 0.9519\nu - 8.7124$
Viscosity S2	$-7\text{E-}05\nu^3 + 0.0138\nu^2 + 0.1167\nu + 0.99$	$2\text{E-}05\nu^3 - 0.043\nu^2 + 1.345\nu - 26.893$
	HLP VG 22	**DIN 51 517/2: CL VG 220**
DC S1	$-0.0014(\Delta T)$	$-0.0018(\Delta T)$
DC S2	$-0.0064(\Delta T)$	$-0.0076(\Delta T)$
DC S3	$0.0090(\Delta T)$	$0.0089(\Delta T)$
EC S1	$0.0259(\Delta T)^3 - 2.7087(\Delta T)^2 + 132.76(\Delta T) - 2633.2$	$0.0052(\Delta T)^3 - 0.6992(\Delta T)^2 + 38.505(\Delta T) - 765.21$
Viscosity S1	$8\text{E-}06\nu^3 - 0.0002\nu^2 + 0.5866\nu + 0.1484$	(*)
Viscosity S2	$-0.0003\nu^3 + 0.0244\nu^2 + 0.6291\nu - 13.447$	$-1\text{E-}06\nu^3 + 0.0017\nu^2 + 0.5227\nu + 5.5757$
	DIN 51 517/2: CL VG 460	**HFDU VG 68**
DC S1	$-0.0019(\Delta T)$	$-0.0041(\Delta T)$
DC S2	$-0.0079(\Delta T)$	$-0.0080(\Delta T)$
DC S3	$0.0045(\Delta T)$	$0.0045(\Delta T)$
EC S1	$0.0066(\Delta T)^3 - 0.9462(\Delta T)^2 + 48.868(\Delta T) - 862.52$	$0.0241(\Delta T)^3 - 0.7824(\Delta T)^2 + 70.289(\Delta T) - 3096.4$
Viscosity S1	(*)	$-1\text{E-}05\nu^3 + 0.0009\nu^2 + 0.9441\nu - 9.6644$
Viscosity S2	$-1\text{E-}06\nu^3 + 0.0022\nu^2 + 0.0073\nu + 99.457$	$-3\text{E-}05\nu^3 + 0.0106\nu^2 - 0.1339\nu + 15.905$

(*) – viscosity out of measuring range

6 CHANGE MECHANISMS OF PHYSICAL-CHEMICAL PROPERTIES – ACCELERATED OIL AGEING

The studies carried out also included activities leading to recognition of changes in the physical-chemical properties of mineral hydraulic oils. If the mineral hydraulic oil condition is monitored and correctly maintained, the hydraulic oil has a relatively long service-life – from 5 to 10 and even more years. Therefore, it is necessary to know the change mechanisms of physical-chemical properties on the basis of different procedures of accelerated ageing – ageing tests. The analysis of the results acquired allows insight into the change mechanisms of the physical-chemical properties of mineral hydraulic oils, recognition of the influences of various operating parameters, determination of the more important values for the oil condition monitoring, evaluation regarding the adequacies of used sensors for on-line oil condition monitoring and evaluation of an oil's current condition and remaining useful lifetime.

This chapter is restricted only to mineral hydraulic oils.

6.1 Oil degradation mechanisms and accelerated oil ageing processes

The influencing factors accelerating the ageing of oil (or lubricants in general) were already presented in Chapter 3. Here only their quantitative and qualitative influences are presented in detail. The better-known influences on oil degradation accelerators are increased temperature, presence of water, shear stresses, pressure load and presence of the catalysts.

Here below, three different examples are presented of the effects of oil degradation accelerators. Table 6.1 shows the influence of a combination of various present metal catalysers and the controlled degree of oil oxidation. The oxidation degree is comparably shown in the form of the neutralization number value as an important parameter for evaluation of the oxidation and ageing process [19].

On the basis of the reached operating hours in the presence of various catalysers it is evident that the worst combination is the presence of iron or copper and water. In all those cases, the number of operating hours was drastically reduced in the presence of one of the catalysers, either iron or copper and, of course, water.

Table 6.1: Catalytic effect on oil oxidation [19]

Catalyst	Water	Test hours	Neutralization number
none	no	> 3500	0.17
none	yes	> 3500	0.90
Fe	no	> 3500	0.65
Fe	yes	400	8.10
Cu	no	> 3500	0.89
Cu	yes	100	11.20

On the basis of the results shown in Table 6.1 it can be claimed that the presence of water and metals with catalytic effect leads to a reduction in oil service-life. In the additional presence of alternating operating pressure, increased temperature and shear of hydrocarbon molecules it is possible to reach a combination of all influencing factors, thus allowing fast degradation of oil during a test and deterioration of its lubricating and other physical-chemical properties required for proper protection of components and the entire device, and for their long service-lives and reliable operations.

After consideration of all such tests used for testing various lubricants, two own tests for accelerated hydraulic fluid ageing are presented. The tests could be in principle divided into two groups, namely: mechanical tests carried out on the real hydraulic equipment and chemical tests carried out in laboratories.

6.2 Mechanical accelerated oil-ageing tests

One of the more important tasks to be performed by mineral oils is without a doubt the ability to prevent direct contact with two lubricated metal parts – prevention of metal-metal contact or in other words: assurance of anti-wear properties. Producers of hydraulic components take this task very seriously and thus they pay significant attention to it. Inadequate lubricating properties and prevention of metal contact largely affect the component degradation and the machine operation reliability. Therefore, a great number of standardized tests have been developed (and also used) in order to establish the relation between the mineral oil (or lubricants in general) condition and the current lubricating properties, and its effect on the component wear.

During execution of those tests the load is applied to the tested component (e.g. vane pump, bearing…) under specifically prescribed conditions and at the end of the test the wear of certain component parts is measured e.g. by weighing or inspecting the wear traces (traces of conventional wear, changed geometry because of wear etc.).

6.2.1 Brief overview of common mechanical tests for determining lubricant resistance to ageing

The tests concerned with lubricating properties and the service-lives of components usually use techniques and procedures similar to those occurring during the actual component usages. Therefore, testing is performed in approximately identical environmental conditions as during actual use. Particularly important are the temperature conditions, presence of contamination, presence of water and various metals, presence of alternating pressure, stop – start intervals…

However, usually the time necessary for executing tests in actual operating conditions is not available, as such testing would last too long (even several years). As usable results are wanted sooner than by testing in real and normal component use conditions (like prescribed by the producer), various different procedures of faster component degradation under tightened-up conditions of use are used. In that way, the results can be gained in a reasonable time by retaining all characteristics of functioning conditions since the matters are only accelerated. A very appropriate solution of the problem is the use of various methods of accelerated testing on purpose-made test beds. In practice, such tests have proved to be the best tool for predicting events and changes.

Here below, various lubricant testing procedures will be shortly presented. The emphasis being on testing of wear and utilization of additives directly associated with wear and wear mechanisms. Basically, the tests are similar: application of load to components or their parts under more severe conditions, the tests being adapted to the types, structures and purposes of components' usages (gears, bearings, pumps etc.). The emphasis is on following up the values and parameters interacting in the real components' usages.

All tests have in common the testing of lubricant usages where either gearbox hydraulic, turbine oil or lubricating oil for bearings are concerned. Basically, the matter of tests are mineral oils having additives for intentional improvement of certain properties (e.g. lubricating properties), more or less equal oil degradation mechanisms, reducing the oil condition (degree of component protection against its degradation) acting on all those oils. The matter of interest is the influences of increased temperature, presence of water, presence of high and changeable loads, and effects of various catalytic metals. All these factors have in common that they more or less reduce the oil condition and service-life. The effects of specific factors reducing the oil's useful lifetime were quantitatively and qualitatively presented in Chapter 6.1.

The **FZG – ASTM D5182 test** [7] deals with power transmission, where toothed gearing is used on many automobile and industrial applications. For higher operating speeds the additives helping to prevent slipping wear (adhesive wear) and tooth damages are added to gearing lubricants. The FZG test was conceived to find out the slipping wear protection and lubricating film of oils used for lubrication of gearings with spur and worm gears. The subjects of the test are hardened and tempered gearings lubricated with EP (extreme pressure) gearing-type oils. The test is also reliable with respect to predicting steel-steel contact wear, when using hydraulic oils.

For the **Eaton/Vickers 35VQ-25 – ASTM D6973 test** [9] a precisely determined type of Vickers (now Eaton-Vickers) vane pump, model 35VQ25A is used built-on to a 189 L (150 US gallons) tank. The pump is driven at 2400 rev/min, the oil at the inlet (suction) side having 93 °C temperature. The pump supplies 144 L/min at 207 bar (3000 psi).

In the frame of this test three consecutive tests are performed, each testing lasts 50 hours. After completion of the test the pump is dismantled then the pump vanes and rotor are precisely weighed. The mass loss due to wear is calculated on the basis of the weighed mass of same parts prior to the beginning of test. The still permissible limit indicating the mass loss is 90mg, whereas mass losses lower than 30 to 40 mg can be achieved by hydraulic oils with anti-wear additives.

There are three tests similar to this standardized test, e.g. [28]:

- Denison T5D,
- Denison P46,
- JDQ-84 Sundstrand,

for which either axial piston pumps or vane pumps are used.

For the **Komatsu 500 hour test** [28], the piston pump is used. In distinction to other tests based on pump wear at constant loading and presence of increased temperature and pressure, the profile of applying pressure to the pump is alternating in this test.

The Komatsu HPY35 axial piston pump is used for the test. This pump is connected to a 60 L (US 16 gallons) tank and is driven by 2100 rev/min, the temperature at the inlet into the pump amounting to 80 °C. The pump supplies 73 L/min, the pressure alternates according to the following cyclical profile:

- from 10 to 410 bar in t=2 s,
- 410 bar = const., t=1 s,
- from 410 bar down to 10 bar, t=1 s,
- 10 bar = const., t=1 s,

afterwards the cycle is repeated.

After the test's completion, i.e. 500 hours, the pump is disassembled and all internal parts are measured. Simultaneously, the oil analysis is executed for the presence and concentration of wear metals. The results gained are then compared to reference results obtained by the use of reference mineral oil ISO VG 46 on the basis of which the criterion acceptable/unacceptable is determined.

6.2.2 Development of own mechanical test – power unit for accelerated oil ageing

Due to various shortcomings and limitations of presented standardized test, we have conceived our own test for mechanical accelerated ageing of mineral hydraulic oils. The test based on presented standardized tests and on other influencing factors having great influence on ageing and degradation regarding the physical-chemical properties of lubricants. The test and equipment used is adapted for accelerated ageing of hydraulic fluids and includes all influencing factors that have been proven to accelerate oil ageing.

Real operating conditions – fluid flow through real hydraulic components on which fluid shear loads appear.

Increased temperature ~93 °C generated by resistive fluid flow through hydraulic components. The temperature is generated by cyclical pressure changing and maintained to 93 ±1 °C by the use of the installed oil-water heat exchanger.

Shear loads are generated by fluid flow over the control edges of the proportional pressure valve and two throttles.

Cyclic mechanical fluid loading is executed by changing the pressure between 18 and 150 bar. The changes in pressure do not repeat in fixed time intervals (like in the Komatsu or Vickers tests) but is conditional on the temperature change. In the case of temperature decrease the pressure abruptly increases to 150 bar and in the case of temperature increase over the desired value it abruptly decreases to 18 bar. In that way, the pressure changing is non-periodically but rather depends on the current temperature conditions and represents the random pressure changes occurring within the real hydraulic system.

Dimensionally the test system is conceived in such a way so that the circulating number is much higher than under real conditions. According to the tested sample quantity a 20 L tank was selected; the fluid flow was provided by a gear pump driven by an 18 kW three-phase induction motor assuring about 40 L/min flow at 1450 rev/min. With the use of an optimal frequency converter, the circulation number can be increased or maintained at constant value. While taking a sample of the fluid from the tank (about 1 L) the fluid quantity in the tank is reduced and the circulation number is changed.

The tank size and all parameters related to test execution are specifically selected: required fluid quantity for execution of the entire set of tests on the basis of which it would be possible to recognize the pattern of physical-chemical fluid properties, interdependence of parameters and to execute the tests on the basis of which the oil condition and remaining useful lifetime could be inferred.

The test unit with all components is shown in Figure 6.1.

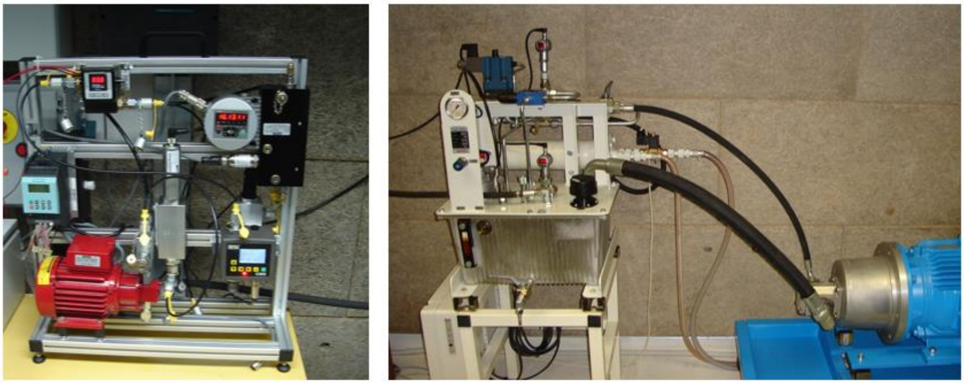


Figure 6.1: Test power unit (right) and OCM unit (left)

A catalytic unit was additionally built-on to the system on the return line. It consists of a set of plates in combination with copper-iron which, in the presence of water and increased temperature, have considerable influence on faster oil ageing (presence of these two metals is also anticipated during execution of the standard oxidation test TOST [11]). The dimensions of the catalytic unit insert are based on the standardized TOST test, except that in this case the fluid sample is much greater and the presence of pure catalytic copper and iron is proportionally increased approximately. The catalytic unit housing designed to that end is shown in Figure 6.2.

Figure 6.2: Catalytic plate packet unit in housing

The catalytic unit is located onto the housing of the test bed and is hydraulically connected by pipes to the return line, directly in front of the inlet into the cooling unit. In that way, high temperature of fluid is guaranteed inside the catalytic unit.

The iron and copper plates with thickness of 0.5 mm (Fe) and 0.55 mm (Cu) are inserted into the catalytic unit housing. The plates having been first mechanically and then chemically cleaned after machining (cutting and drilling of connection holes). The plate's appearance is shown in Figure 6.3 (left). The individual plate dimensions are 160 x 120 mm; therefore, the oil is in contact with approximately 1 m2 of copper and 1 m2 of iron.

Prior to the insertion into the catalytic unit housing the, plates had been assembled into a proper plate packet in combination Fe-Cu-Fe…Cu-Fe. The plates are separated by 1.0 mm thick iron washers ensuring uniform distance between plates; they are interconnected by a threaded rod. Each corner of the catalytic plate packet is provided with distance plates assuring permanent position of the plate packet in the catalytic unit housing so that forced transition of fluid through gaps between plates is guaranteed. In that way, the greatest possible contact surface is assured between oil and metal. The assembled plate packet is shown in Figure 6.3 (right). In addition to increased catalytic effect through the plate packet, the influence of increased shear loads, causing tearing of long hydrocarbon chains and, as a result, increased oil degradation was additionally reached.

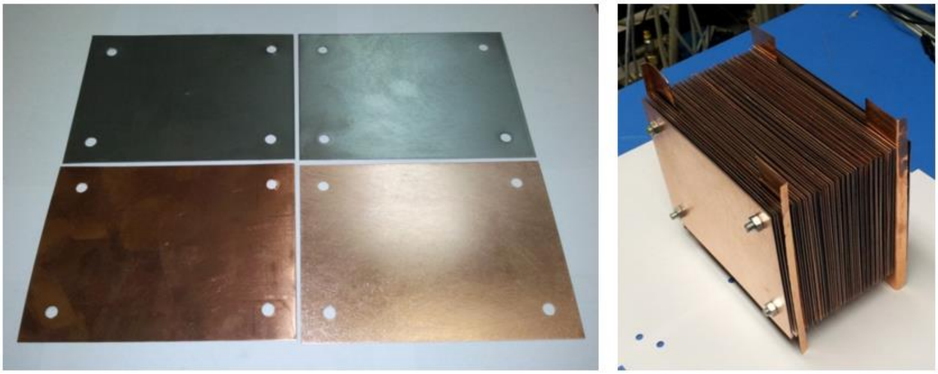


Figure 6.3: Iron and copper plates of catalytic unit: before and after cleaning (left); catalytic plate packet before installation (right)

In order to increase the catalytic effect on oil **ageing a suitable quantity of demineralized water** keeping the oil at saturation limit with water is cyclically added. Water is added automatically by the use of a small dosing pump so that relative humidity is kept above 100 %.

6.2.3 Implementation of mechanical accelerated ageing test

The presented conceived mechanical test for accelerated ageing of hydraulic fluid was implemented in duration of 787 hours, without interruption, by the use of the presented hydraulic unit. The temperature changes during execution of test are shown in Figure 6.4.

As after that time no visible changes of physical-chemical oil properties were detected, the test was stopped for economic reasons, i.e. excessive consumption of electric power and cooling water.

During the test, the oil condition was continuously monitored by the OCM unit (Figure 6.1 left), i.e. by on-line sensors located in the by-pass line of the main hydraulic system. The flow through the by-pass system was assured by a small gear pump with about 150 ml/min flow. The oil condition was also monitored by periodical sampling and appropriate chemical analyses executed in the laboratory.

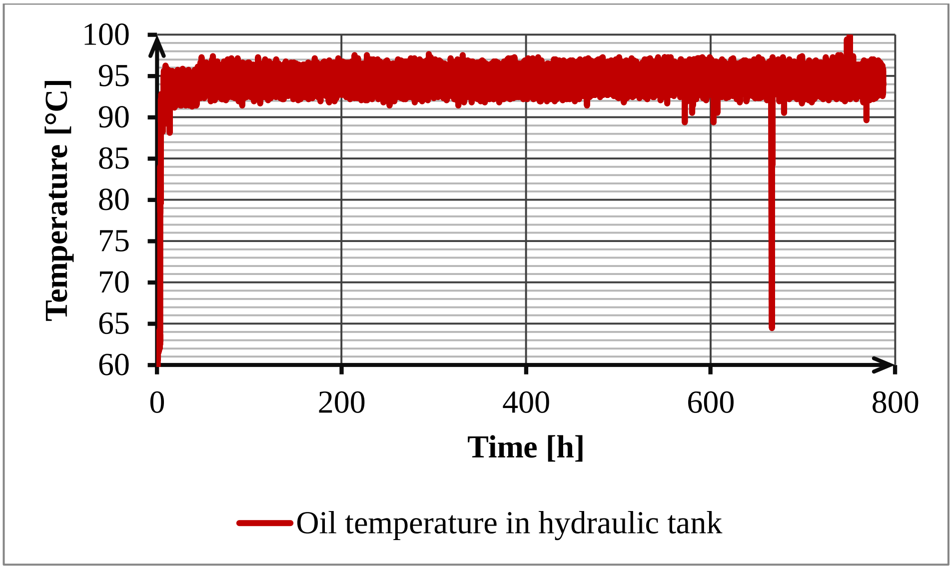


Figure 6.4: Temperature profile of load application to hydraulic fluid during mechanical test

6.2.4 Test results

Performing measurements by on-line sensors during the execution of the test was very difficult. Operation of on-line sensors under harsh (tightened-up) conditions would lead to improper measurements and trouble in sensor functioning (sensors are anticipated for normal mild operating conditions). As they worked under such conditions for a longer time, some of them failed, too.

On the basis of the results gained, it can be claimed that the sensors used are, nevertheless, suitable for on-line oil condition monitoring since they resist even tightened-up operating conditions. The circumstances to which they were exposed during the described test with a hydraulic unit are not to be expected within real industrial environments. Such conditions can only occur in a real system in the case of heavy sudden damage to the hydraulic system, e.g. very fast and strong water ingress into the system or breakdown in the interior of one of the hydraulic components (e.g. hydraulic valve) and are of short duration, as the machine is stopped immediately after such detected condition changes. In such cases, the sensors would certainly detect the damage to the hydraulic system immediately. If the hydraulic system is not stopped in time and continues the on-line measurement, the increased presence of contaminants (water or metal parts) would strongly change the electric conductivity and the dielectric constant of oil and would cause false functioning and false sensor signals and then possibly still permanent sensor damage and failure.

In regard to all those problems, we were compelled to execute additional measurements by on-line sensors on the basis of four periodically taken samples at certain numbers of operating hours, as shown in Table 6.2. The samples were taken during operation of the test hydraulic unit by means of the discharge valve (pipe) located near the bottom of the aluminium tank. As in the fluid discharge piping some fluid may remain from the previous discharge, a certain oil quantity was first poured out and returned into the tank. Only then a representative sample was taken and sent for analysis, in that way avoiding the sample being contaminated.

The presented measurements of periodically taken samples by on-line sensors were performed by the stationary method on the magnetic mixer, while the laboratory sample analyses were made in the outsourced chemical laboratory. The analysis results are shown in Table 6.2. They indicate that the concerned test did not achieve proper oil degradation and accelerated ageing of tested HLP ISO VG 46 mineral hydraulic oil, as its physical-chemical properties during the test did not change as intended. It is true, that the described test procedure is very near to the real operating conditions with respect to the use of components, like pump, valves, flow through pipes and gaps, oil pumping over etc. Solely the operating conditions were harsher, eg. increased operating temperature but limited to about 93 °C due to the adding of water the evaporation of which had already been accelerated at that temperature, presence of catalysers (Fe and Cu), higher pump circulation number, fluid flow over the control edges, accelerating the fluid shear stresses (and, as a result, tearing of long hydrocarbon chains), and the presence of alternating pressure load.

Table 6.2: Hydraulic oil analysis results on accelerated oil ageing

Sample	**Standard / Unit**	**0 h**	**192 h**	**408 h**	**596 h**	**787 h**
Flash point	ASTM D 92 [°C]	232	230	236	226	228
Viscosity at 40 °C	ASTM D 445 [mm²/s]	46.42	46.27	47.04	46.13	47.16
Viscosity at 100 °C	ASTM D 445 [mm²/s]	6.89	6.87	6.92	6.88	6.93
Viscosity index	ASTM D 2270 [-]	104	103	102	104	102
Neutralization number	ASTM D 974 [mg KOH/g]	0.66	0.64	0.61	0.65	0.67
Water content	ISO 12937 [ppm]	63.23	59.13	94.62	113.27	103.65
Additive elements	ASTM D-6481 [wt. %]					
Phosphorus (P)		0.032	0.034	0.035	0.029	0.032
Sulphur (S)		0.702	0.695	0.694	0.696	0.691
Calcium (Ca)		0.004	0.003	0.003	0.003	0.003
Zinc (Zn)		0.0452	0.0451	0.0449	0.0441	0.0446
Wear metals	TXMS-06A [mg/kg]					
Chromium (Cr)		< 5	< 5	< 5	< 5	< 5
Copper (Cu)		< 3	155	165	182	167
Iron (Fe)		< 3	< 3	< 3	< 3	< 3
Lead (Pb)		< 3	< 3	< 3	< 3	< 3
Tin (Sn)		< 20	< 20	25	< 20	21
On-line sensors at 40°C	**Unit**	**0 h**	**192 h**	**408 h**	**596 h**	**787 h**
Dielectric constant S1	[-]	2.1686	2.1707	2.1789	2.1780	2.1855
Electric conductivity S1	[pS/m]	362	405	377	288	292
Relative humidity	[%]	11.0	8.4	10.5	25.6	18.5

The air and, as a result, oxygen presence was possible only through the contact surface of the oil plane with ambient air. In this test, additional induction of air into oil was not possible, since intensive oil foaming and cavitation on the pump and valves would appear. Consequently, destruction of components would occur too soon. Also the on-line sensor functioning would be questionable.

6.3 Thermal accelerated oil ageing tests

The mechanical test of accelerated hydraulic oil ageing by means of a purpose-made unit based on the use of real industrial components, regrettably did not lead to the desired target, i.e. desired deterioration of oil physical-chemical properties, in a test run for more than one month. Therefore, other options for establishing tighter testing conditions were looked for.

Another group of tests are the tests developed for establishing the lubricant resistance to ageing, where the emphasis of the test is on evaluating the resistance to oil oxidation. Oxidation is the dominant reaction in the process of hydraulic oil use and ageing, and causes many physical-chemical changes evidenced in the viscosity increase, varnish and deposit formation, additive decomposition, "breakdown" of base oil, increased foaming, increased neutralization number and increased corrosion and rusting [75]. The lubricant oxidation is accelerated by increased temperature and presence of well-known contaminants like water, air and metals (catalysers). Accordingly, all these test types can be called the thermal tests, as the temperatures during testing are much higher than in mechanical tests. Oil degradation results in weak organic acids and insoluble oxidation products which gradually gather on the hydraulic component surfaces [30].

Practically all lubricants and oils on the mineral basis contain additives for oil oxidation control. They are called antioxidants and act on the principle of sacrificing mechanisms since they react and oxidize before oxidation of the bas oil expires. That is in fact also the sole protection and safety mechanism against premature oil degradation and loss of its properties [79].

6.3.1 A brief overview of common thermal tests for determination of lubricant resistance to ageing

Over the course of time, several standardized thermal oxidation tests have been introduced to establish the oxidation stabilities of fresh and used hydraulic fluids. They are based on exposing the hydraulic fluid to high temperatures and catalysers like air (oxygen), water and metals, copper and iron being the more important. A short survey of tests and the operating conditions is shown in Table 6.3 [78].

Table 6.3: Summary of oxidation tests and operating conditions [78]

Oxidation test (ASTM)	Gas	Pressure	Temperature	Catalyst
PDSC (D6186)	O_2	34.5 bar	180 °C	Fe
RPVOT (D2272)	O_2	6.2 bar	150 °C	Cu/Fe
UOT (D6514)	Air	Atmospheric	155 °C	Cu/Fe
UOT (D5846)	Air	Atmospheric	135 °C	Cu/Fe
TOST (D943)	O_2	Atmospheric	95 °C	Cu/Fe/H_2O

The more established and more frequently used tests are RPVOT [4] and TOST [12] serving as a basis for our own developed thermal test, appropriate for testing greater oil test-volumes as in previously mentioned standardized thermal tests.

In the **ASTM D2272 – RPVOT (rotating pressure vessel oxidation test) test** a pressure vessel with oxygen containing oil in the presence of water and copper is used to determine the oxidation stabilities of fresh and used oils. The weighed oil sample (50 ±0.5 g) is poured into the vessel into which still 5 ml of water and 3 m of copper wire of 1.63 mm diameter are added. After the vessel has been closed, it is to be filled with oxygen up to 6.2 bar at room temperature 25 °C. The vessel is then dipped into the tempering bath (150 °C) at a 30° angle. During the test, the vessel content is mixed at 100 rev/min. After the closed vessel has been dipped into the bath, the temperature and pressure in the vessel start to increase. On the pressure gauge, located on the vessel's cover, the maximum pressure reached during heating of the system is read. In the course of the test the oil in the vessel reacts with oxygen (and water and copper), therefore the pressure in the system starts to decrease slowly. The test is considered to be completed when a certain quantity of oxygen has reacted with oil, which is detected as pressure drop in the vessel for 1.75 bar of the read initial maximum pressure. The test result is indicated in the form of time in minutes from the detected maximum pressure to pressure drop for 1.75 bar.

The **ASTM D943 – TOST (turbine oxidation stability test) test** is used to determine the oil oxidation stability in the presence of oxygen, water, copper and iron. Copper wire of 1.63 mm diameter and iron wire of 1.59 mm diameter coiled into a spiral of 225 ±5 mm length are added to the oil sample (300 mL) poured into the oxidation cell. The cell is also provided with an oxygen supply pipe closed by a special cover into which water is added during the test and which functions as a moisture condenser. The cell is then dipped into the tempering bath at 95 °C, the oxygen supply being adjusted to flow 3 ±0.1 L/min. During the test, the oil reacts with oxygen in the presence of water and catalysers (copper and iron wire) at 95 °C. The test continues until the oil neutralization number increases to 2.0 mg KOH/g or more. The test result is the elapsed number of hours and can also be called the oxidation lifetime of oil.

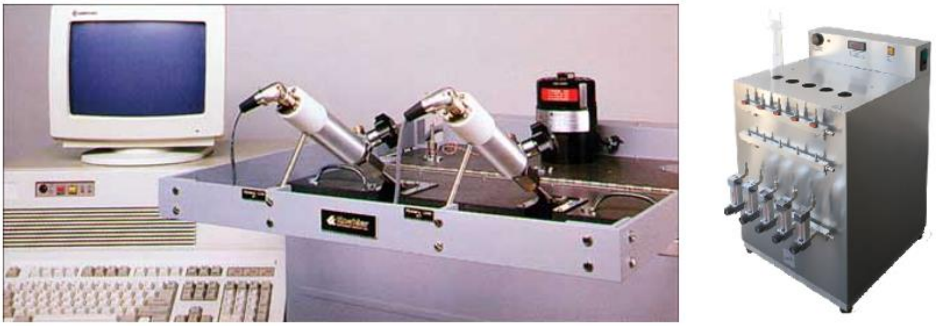


Figure 6.5: Apparatus for RPVOT [30] and TOST test [57]

6.3.2 Development of own dry thermal test

During the research it was discovered that the presented two tests were not quite adequate for intended research, since they included only a minor oil sample quantity (RPVOT – 50 g and TOST – 300 mL). Therefore, we were compelled to conceive our own thermal test allowing execution of accelerated oil ageing on a greater sample quantity in amount of 1500 mL, that is sufficient for all further extensive laboratory analyses of physic-chemical properties of tested mineral hydraulic oil. Test is based on the mentioned RPVOT and TOST tests and comprises oil heating on the magnetic heater/mixer in the presence of air blowing-in and in the presence of a copper catalyser.

The test apparatus consists of two glass cups, the smaller (3 litre) being located in the larger one (5 litre) by means of a special support as shown in Figure 6.6. The larger 5-liter cup contains the rapeseed oil, serving as a heat transmitter and a heating bath for the smaller 3-liter cup. In that way, the strongly increased temperatures at the bottom of the smaller 3-liter cup containing the tested oil were avoided. Each of the cups contains also a magnetic tablet serving for oil mixing during execution of the test (the tempering bath oil as well as the oil tested are mixed). The smaller cup contains 15 ±0.1 m of 1.5 mm^2 copper wire wound into a spiral of 10 mm diameter as shown in Figure 6.6. Then a measured quantity of the tested oil sample 1500 ±10 mL is poured into the cup. The test and heating is executed in parallel on three magnetic heaters/mixers placed into the purpose made chamber with oil vapour suction. By the use of previously inserted tablets, the magnetic mixers mix the oil in the tempering bath, as well as the tested oil in the smaller cup, at the rate of 300 ±50 rev/min. During the test the temperature 150 ±0.5 °C of the tested oil is maintained by means of additional temperature regulators (PID) and temperature sensing elements wetted into the tested oil. Prior the start of testing all temperature sensing elements were calibrated by dipping them into the same fluid at 150 °C to ±0.1 °C precision.

Figure 6.6: Preparation of glassware and copper wire for implementation of the test

After the start of the thermal test, when all samples reach 150 °C by means of heating and mixing, the blowing-in of air through a diffuser made of sintered balls starts. Compressed ambient air with 3 ±0.1 L/min flow, previously de-wetted by the use of the preparation group for the pneumatic system is blown-in into the test oil.

The test takes place under the atmospheric pressure, within a closed purpose made chamber with a built-on system for oil vapour extraction. The chamber allows execution of the test on the individual sample or on all three samples simultaneously as shown in Figure 6.7.

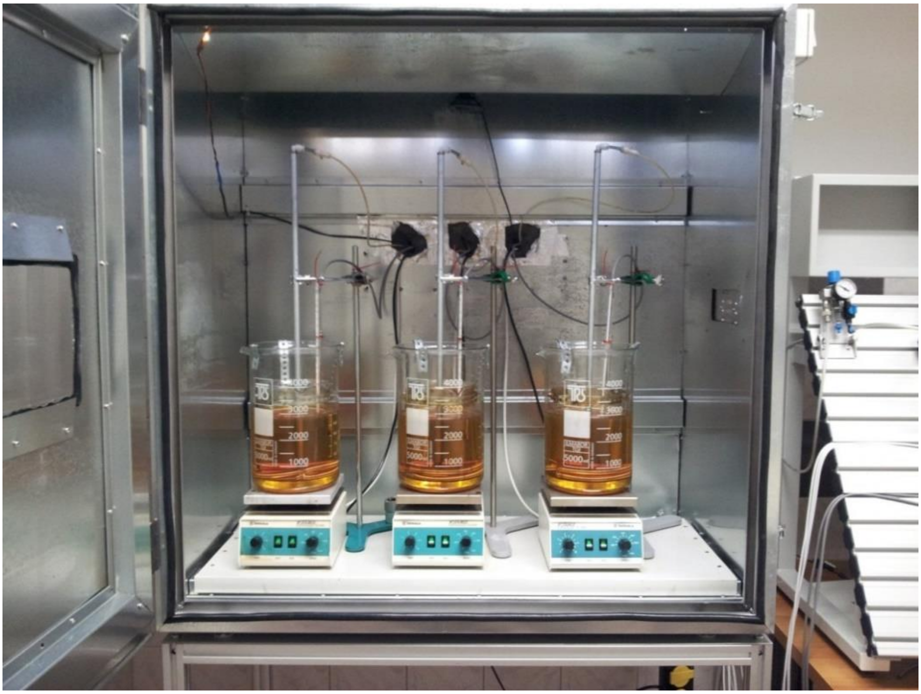


Figure 6.7: Preparation of implemented dry thermal test for accelerated oil ageing

6.3.3 Implementation of thermal accelerated oil ageing test

As distinct from the RPVOT and TOST tests, our test has no accurate fixed end-time, as our aim is not only to measure the tested oil oxidation stability but to “record” the accelerated oil ageing process throughout its entire service-life. Therefore, the test was executed on six identical samples of HLP ISO VG 46 mineral hydraulic oil exposed to accelerated ageing conditions for different numbers of hours. In that way, six differently degraded and oxidized samples were obtained for executing further analyses.

After completion of the thermal test, first the measurements by on-line sensors according to the stationary process on the magnetic mixer were performed on the samples. Afterwards, the samples were further analysed in the chemical laboratory, in accordance with the procedures described in Chapter 2.3.

When the testing had been completed, a strong change of colour (Figure 6.8 top) and an express, distinctive odour of burnt oil could be detected on the samples. Inscriptions on presented samples represent the test duration in hours, e.g. HL 60 – hydraulic oil after 60 hour of testing. On the samples tested longer a strong formation of insoluble lacquer products adhering to the copper wire (Figure 6.8 bottom) could be noticed, i.e. varnish products. Moreover, on the concerned samples varnish products could also be observed on the cup walls and at the bottom of the glassware (Figure 6.9).

Figure 6.8: Samples after completion of the test (above) and formation of varnish on copper wire (below)

Figure 6.9: Formation of varnish products on glassware

6.3.4 Results of thermal test

The results of the laboratory sample analysis and the results of measurements by on-line sensors are summarized in Table 6.4 and commented on hereinafter. The physical-chemical values allowing prediction of the current oil condition and further estimation of the remaining useful lifetime are grey-shaded in the table.

Table 6.4: Analysis results of individual samples after accelerated thermal ageing test

Sample	**HLP 0**	**HLP 40**	**HLP 50**	**HLP 60**	**HLP 70**	**HLP 90**	**HLP 110**
Test duration [h]	0	40	50	60	70	90	110
Colour [-]	2.0	6.0	7.5	> 8.0	> 8.0	> 8.0	> 8.0
Flash point [°C]	220	226	236	220	224	224	218
Viscosity at 40 °C [mm^2/s]	46.45	48.35	49.07	49.30	49.75	51.74	62.18
Viscosity at 100 °C [mm^2/s]	6.91	7.06	7.15	7.18	7.21	7.40	8.08
Viscosity index [-]	104	104	104	104	103	103	96
Neutralization number [mg KOH/g]	0.54	0.65	0.68	0.72	0.77	1.43	1.9
FT-IR Oxidation [-]	0.31	0.43	0.51	0.64	0.76	1.28	2.30
Four ball welding load [kg]	130/140	130/140	130/140	130/140	130/140	130/140	140/150
Four ball wear test [mm]	0.5	0.5	0.5	0.5	0.5	0.55	0.7
Additive elements [wt. %]							
Phosphorus (P)	0.032	0.032	0.031	0.032	0.032	0.031	0.031
Sulphur (S)	0.702	0.708	0.696	0.698	0.685	0.672	0.653
Calcium (Ca)	0.004	0.005	0.005	0.004	0.004	0.005	0.004
Zinc (Zn)	0.0452	0.0454	0.0462	0.0464	0.0469	0.0482	0.0477
Wear metals [mg/kg]							
Chromium (Cr)	7	7	< 5	6	5	8	7
Copper (Cu)	7	10	10	16	41	158	213
Iron (Fe)	< 3	< 3	< 3	< 3	< 3	3	3
Lead (Pb)	< 3	< 3	< 3	< 3	< 3	< 3	< 3
Tin (Sn)	< 20	< 20	< 20	< 20	< 20	< 20	< 20
Foaming test [ml/ml]							
Sequence I.	0/0	20/0	10/0	0/0	60/0	50/0	610/0
Sequence II.	30/0	20/0	30/0	10/0	30/0	70/0	30/0
Sequence III.	0/0	0/10	0/0	0/0	0/0	0/0	570/50
On-line sensors at 40°C	**HLP 0**	**HLP 40**	**HLP 50**	**HLP 60**	**HLP 70**	**HLP 90**	**HLP 110**
Dielectric constant S1 [-]	2.1287	2.1034	2.1068	2.1112	2.1339	2.1844	2.2300
Dielectric constant S2 [-]	2.5063	2.4344	2.4321	2.4312	2.4873	2.5189	2.5513
Dielectric constant S3 [-]	2.2072	2.2347	2.2070	2.2346	2.2130	2.2943	2.3680
Electric conductivity [pS/m]	607	853	972	1121	1410	4421	9219
Relative humidity [%]	22.8	18.8	16.7	15.5	20.3	17.5	16.0
Viscosity S1 [mm^2/s]	49.9	51.8	51.8	52.6	52.3	55.4	57.8
Viscosity S2 [mm^2/s]	49.3	53.1	51.2	52.7	51.3	56.5	57.0

Figures 6.10 to 6.19 also show the trends of the more important (classical) physical-chemical properties, the estimated oil condition being indicated by the background colours (green, yellow, red). The oil condition estimation and its service-life in the frame of tests are defined and explained in detail in Chapter 7.4.1. With respect to specific oil

service-life, amounting to 75 h (Chapter 7.4.1) in the frame of the presented test, the green background colour denotes the oil's useful lifetime followed by a yellow band defined as the recommended time of oil change. The red band represents the period of time when oil starts to lose its physical-chemical properties at accelerated rate and is no longer fit for further use.

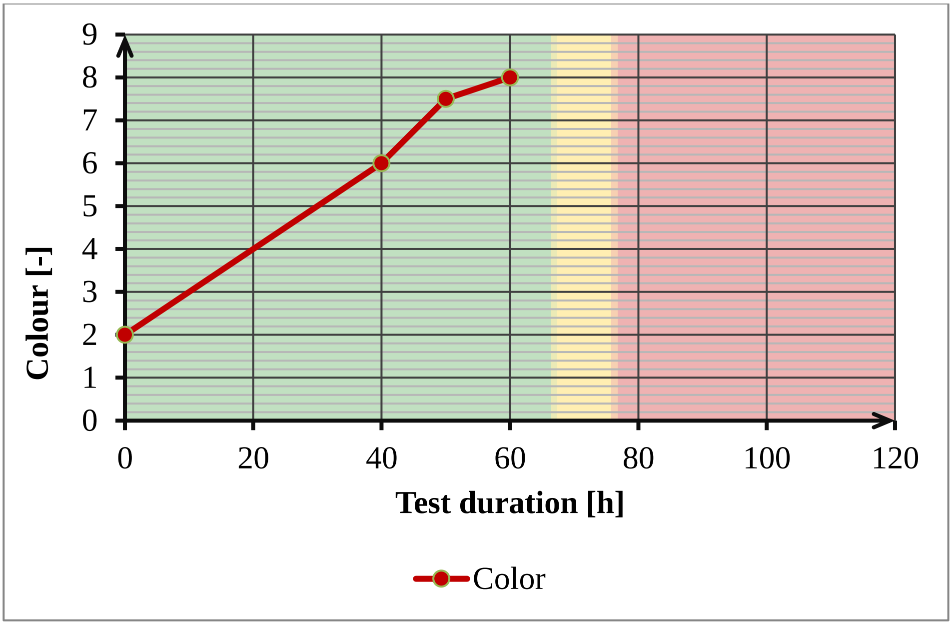


Figure 6.10: Oil colour in the process of accelerated thermal oil ageing

The oil **colour** is one of the first and principal oil ageing indicators. During the process of accelerated thermal oil ageing the colour changes almost linearly from an initial value of L 2 up to a maximum value of L 8 which was reached by sample HLP 60. Figure 6.10, showing the progresses of the oil colour changes during testing, does not indicate the values of samples HLP 70 and higher, with even longer duration of testing. That is to say, the method ASTM D 1500 by which the sample colour was analysed anticipates the maximum colour index L 8. All higher values are indicated uniformly in the form of the result L > 8. Nevertheless, it can be seen in Figure 6.10 that the oil colour change is an excellent indicator of oil degradation, therefore, hereinafter, it will be used for estimation of the oil condition and remaining useful lifetime.

The results of oil **flash point** analyses given in Figure 6.11 do not indicate a logical trend of oil changes in the ageing process. Therefore, they will not be used for estimating oil condition. Otherwise, the oil flash point analyses are usually executed on samples when oil contamination with foreign matters (e.g. another oil or fuel) is in doubt. Nevertheless, the said analyses were included within the research however the results led to the conclusion that the mentioned method produces unreliable accuracy and repeatability.

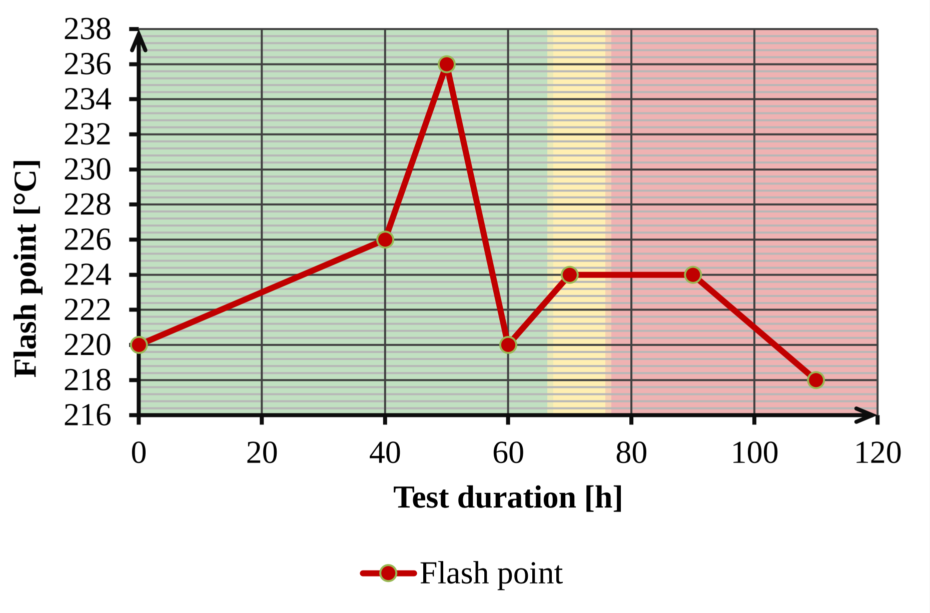


Figure 6.11: Flash point in the process of accelerated thermal oil ageing

The oil **viscosity** analysis results indicated in Figure 6.12 show that in the process of accelerated oil ageing the viscosity more or less linearly increased throughout the oil useful lifetime, when after 90 hours of testing it started to increase at an accelerated rate. Due to the detected continuous trend in the green area, the viscosity analysis will be included in the method of estimating oil condition and its remaining useful lifetime.

The trend of oil **viscosity index,** change in accelerated ageing is shown in Figure 6.13, where it can be seen that the oil viscosity index does not change during an oils useful lifetime (green area). A major viscosity index change occurs only after 90 hours of testing, which is already strongly outside the oil's useful lifetime. As the viscosity index does not change in the green area, it is not suitable for use when estimating the current oil condition.

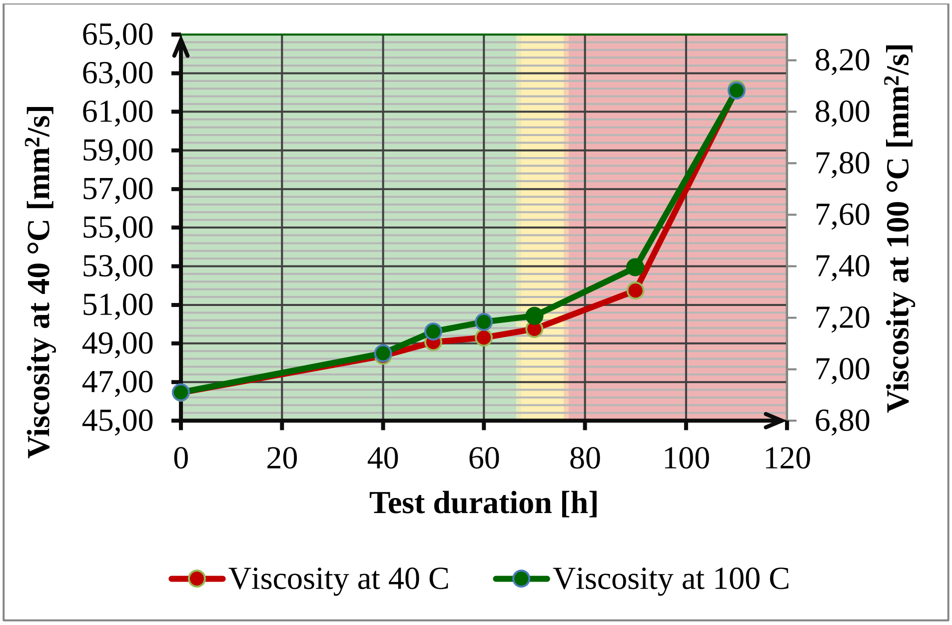


Figure 6.12: Viscosity in the process of accelerated thermal oil ageing

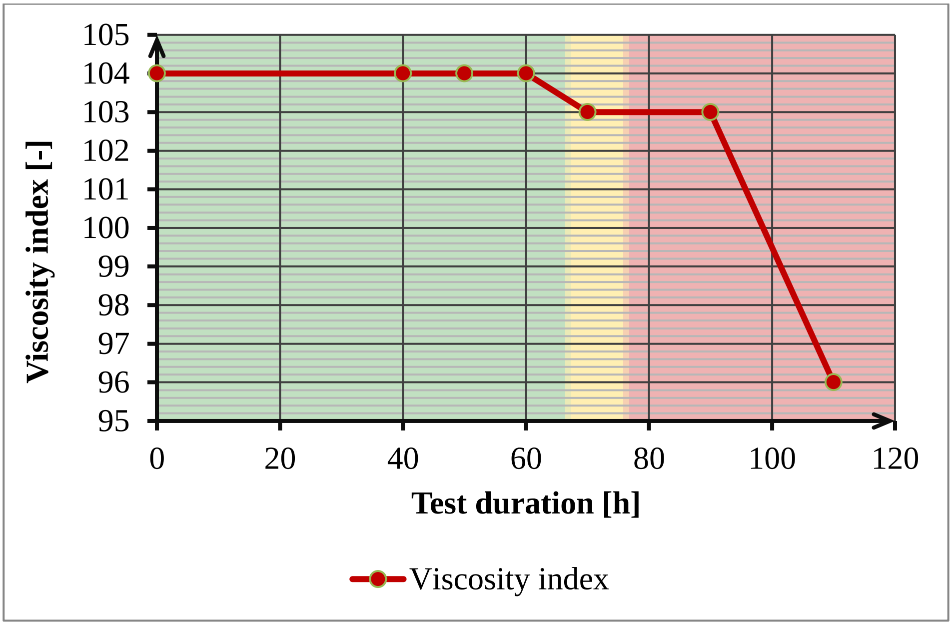


Figure 6.13: Viscosity index in the process of accelerated thermal oil ageing

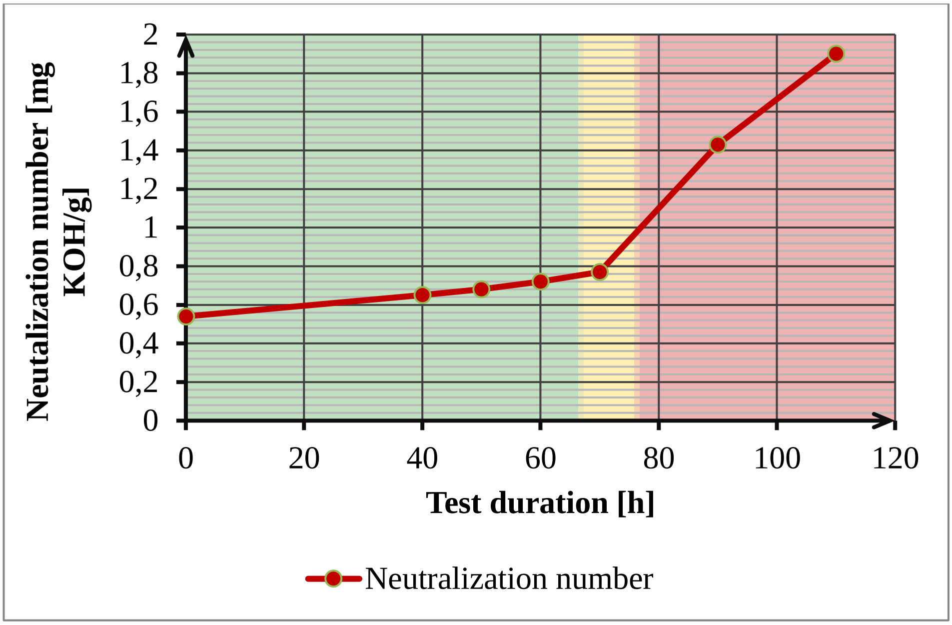


Figure 6.14: Neutralization number in the process of accelerated thermal oil ageing

The **neutralization number** as one of the more frequently and widely used indicators for evaluation of oil degradation degree, linearly increases in the accelerated ageing process until the end of its useful lifetime. When it has been exceeded (red area), the neutralization number starts to increase exponentially. The detected oil neutralization number changes during its useful lifetime (green area) allowing helpful use of the neutralization number when estimating oil ageing and its remaining useful lifetime.

The oxidation analysis by FT-IR is another excellent indicator for establishing the extent of the oil ageing process and can be used when estimating the oil's condition and its remaining useful lifetime. As shown in Figure 6.15, it does not increase linearly during the oil lifetime, like for example the colour or the neutralization number but increases in the second half of the oil's lifetime faster than in the first half. If the points were connected along a curve, exponential progress of the curve would be visible. When oil has reached the end of its useful lifetime and accelerated oil degradation has started, that can be detected by a steep increase of the FT-IR oxidation in the red area.

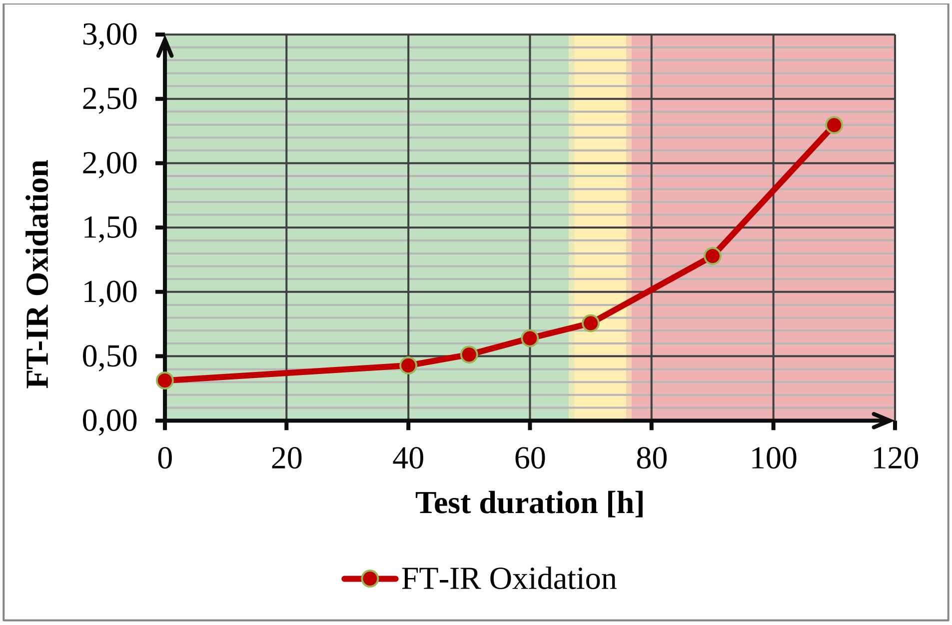


Figure 6.15: FT-IR Oxidation in the process of accelerated thermal oil ageing

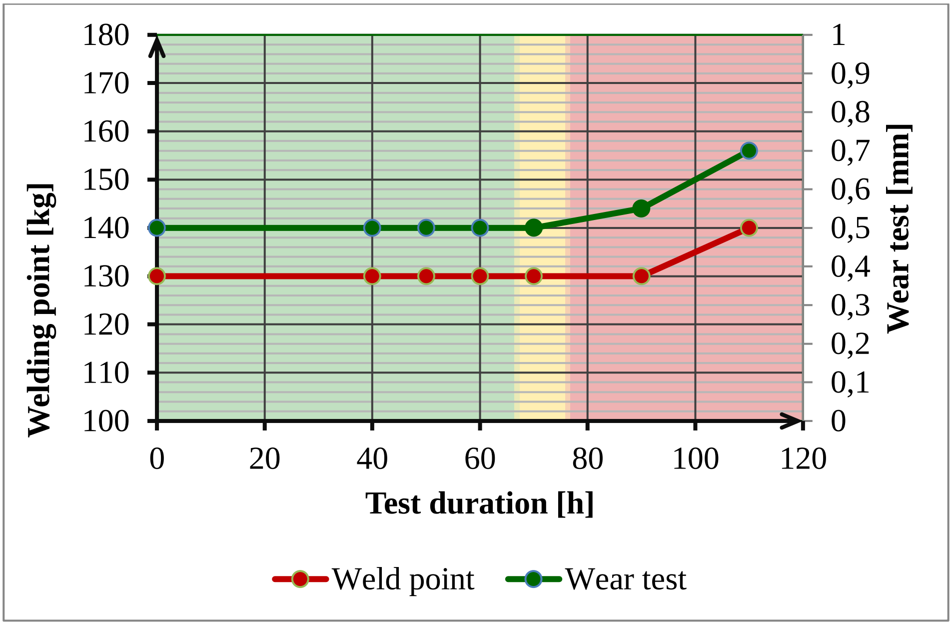


Figure 6.16: Four-ball welding point and wear tests in the process of accelerated thermal oil ageing

Four-ball welding point and wear tests as indicators of oil lubricating properties disclose very interesting results. At first glance, deterioration of oil lubricating properties in the red area would be expected, when oil starts to lose its properties at an accelerated rate. However, the results shown in Figure 6.16 reveal that oil in the process of accelerated ageing did not lose its lubricating properties but its lubricating properties even started to improve towards the end of the test. This phenomenon is not entirely in conformity with real operating conditions but is the result of accelerated thermal oil ageing by the use of heating and intensive oxidation causing an increase in the oil viscosity. Due to increased oil viscosity, the aged oil has better lubricating properties than the fresh oil having, in fact, lower viscosity. As the lubricating properties in the green area are constant, they cannot be appropriately used for estimation of the oil condition (in addition, the test itself is not very convenient).

The **additive elements content** analysis in the accelerated oil ageing process did not indicate distinct changes of the content and diminution of additive elements (Table 6.4). Only a sulphur content decrease was detected as shown in Figure 6.17. The sulphur content change is minimal in the useful area of the oil lifetime (green area) and is not diminishing at constant rate. That is to be attributed to inaccuracy of the measuring method (X-ray). Due to those facts the additive element content will not be considered when estimating the oil condition and in predicting its remaining useful lifetime. However, if a more accurate measurement method (e.g. ICP-OES) were used, trend monitoring of the contents of some additives could also successfully contribute to accurate estimation of the oil condition.

The **wear metals content** analysis is usually used to find out the hydraulic component condition and the possible future breakdown (e.g. chromium, as an element of the piston rod, appears in oil, which indicates incorrect operation of one of the cylinders, or copper arising from failure inside a hydraulic pump or motor,…). Therefore, it cannot be used for estimation of the oil condition and prediction of its remaining useful lifetime, as the change of chromium is a result of the piston rod wear. On the other hand, it is appropriate for monitoring the content of copper, which was added as a catalyser in the accelerated oil ageing process. Copper content changing is shown in Figure 6.18. The curve shown in this figure reveals that oil starts to react intensively with wearing metals only at the end of its useful lifetime.

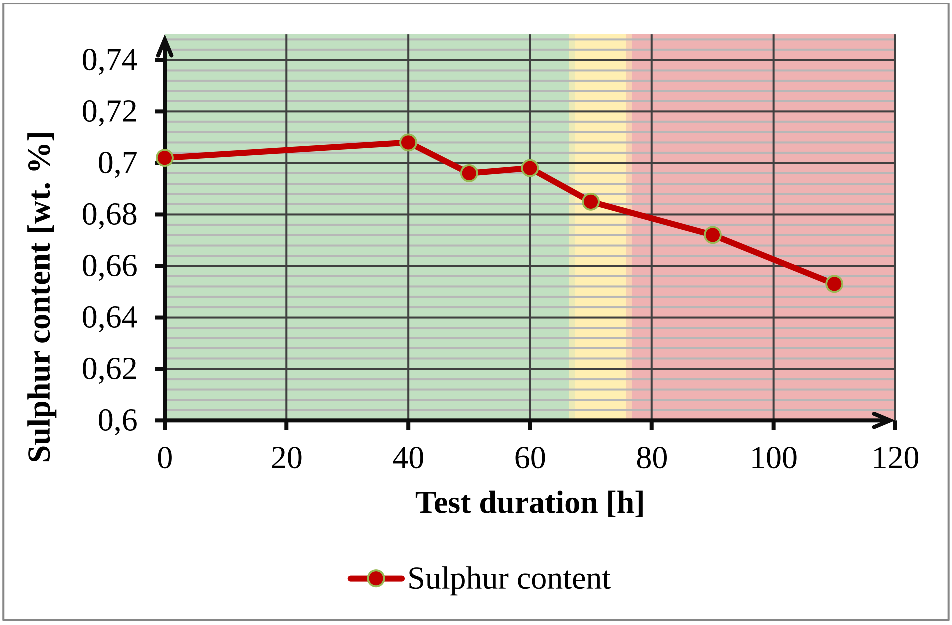


Figure 6.17: Sulphur content in the process of accelerated thermal oil ageing

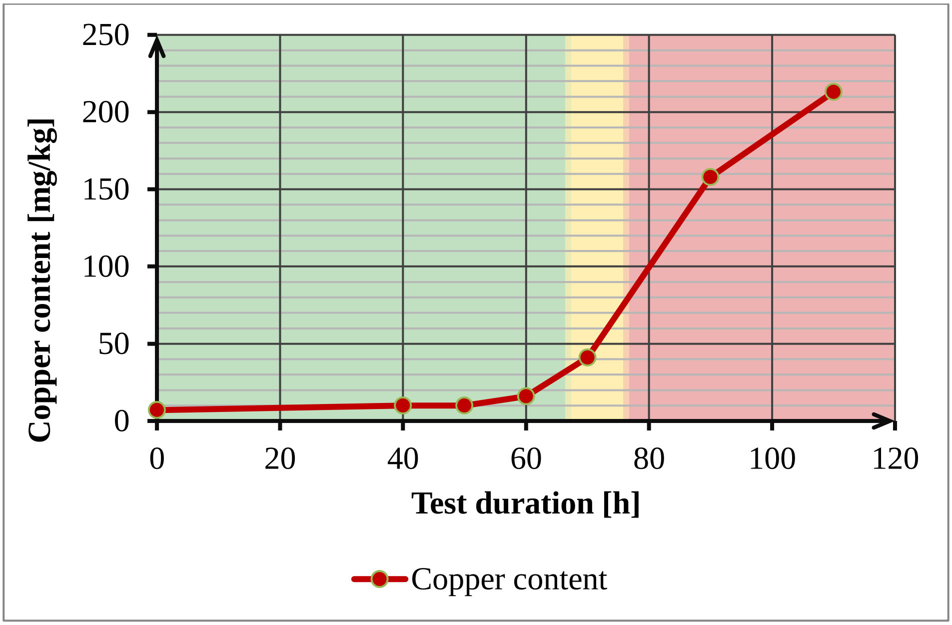


Figure 6.18: Copper content in the process of accelerated thermal oil ageing

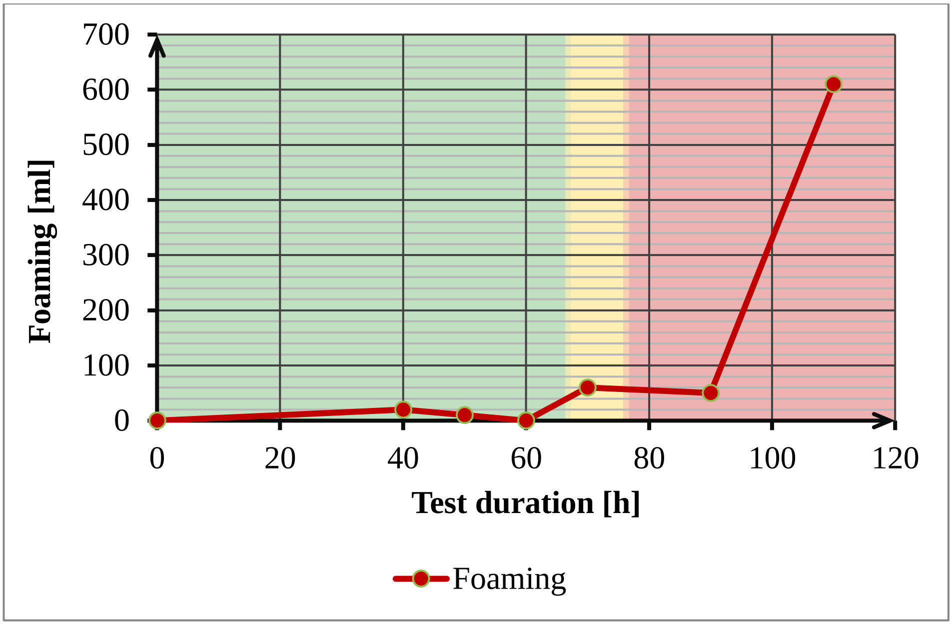


Figure 6.19: Foaming in the process of accelerated thermal oil ageing

Analysis of **foaming** in accelerated oil ageing also showed that foaming does not change in the green area, therefore it is not possible to use this parameter for estimation of the oil condition. Oil starts to foam intensively only in the red area (Figure 6.19), when its useful lifetime has already expired. Figure 6.19 shows only foaming in the I. sequence, which changes the most. Also the foaming analysis cannot be performed on-line, nor previously presented parameters, e.g. welding point, flash point…

As an important aspect for on-line condition monitoring of hydraulic oils tracking of individual parameters should be mentioned. Therefore, the measurements performed by on-line sensors need to be discussed. Figure 6.20 shows changes of the **dielectric constant** measured by three different on-line sensors (S1, S2, S3) in the process of accelerated thermal ageing of oil. The figure shows that the dielectric constant changes in the area of the oil useful lifetime (green area) are minimal and that sensors detect them very differently. It can be noticed that the dielectric constant in the green area fluctuates and starts to increase (in the red area) only after expiration of the oil's useful lifetime. Due to that specific feature, the oil condition, estimated based on dielectric constant change, would not be reliable and, accordingly, is not included in the method for estimating the oil condition and its remaining useful lifetime.

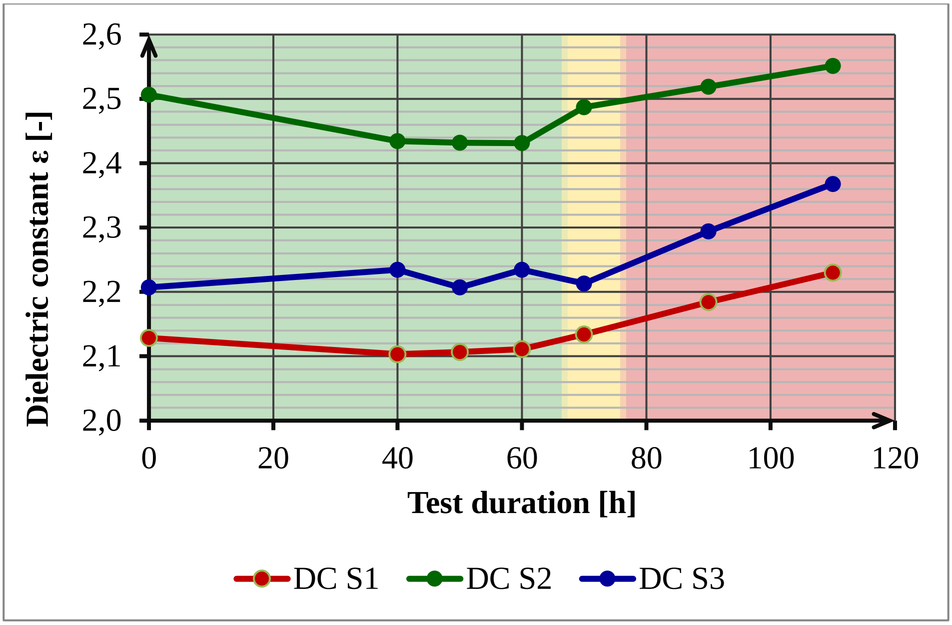


Figure 6.20: Dielectric constant in the process of accelerated thermal oil ageing

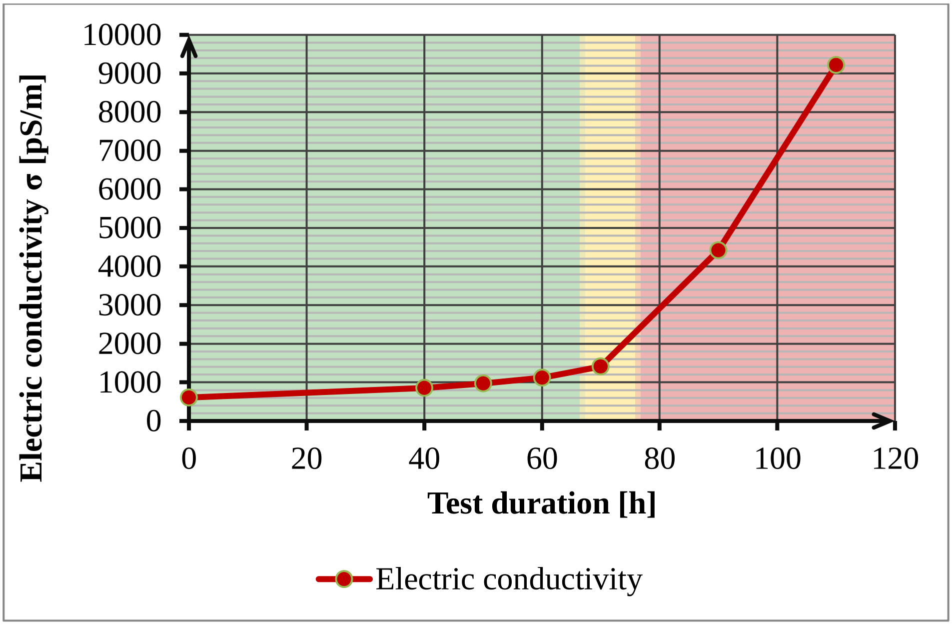


Figure 6.21: Electric conductivity in the process of accelerated thermal oil ageing

In the accelerated thermal ageing process the oil **electric conductivity** increases almost linearly during its useful lifetime (green area), as shown in Figure 6.21. Afterwards, it starts to increase exponentially in the red area. The increase in oil electric conductivity is attributed to the formation of metallic acid products and is an excellent indicator for estimating the oil condition and its remaining useful lifetime.

The oil **viscosity** increase in the accelerated thermal ageing process was already previously shown by the laboratory viscosity analysis (Figure 6.12). Figure 6.22 shows the viscosity increase measured by on-line sensors. High inaccuracy of on-line sensors compared with laboratory measurements can be observed. Nevertheless, the sensors detected the viscosity increase well in the area of oil useful lifetime. Therefore, the viscosity changes detected by on-line sensors can be used for estimating the oil condition and its remaining useful lifetime.

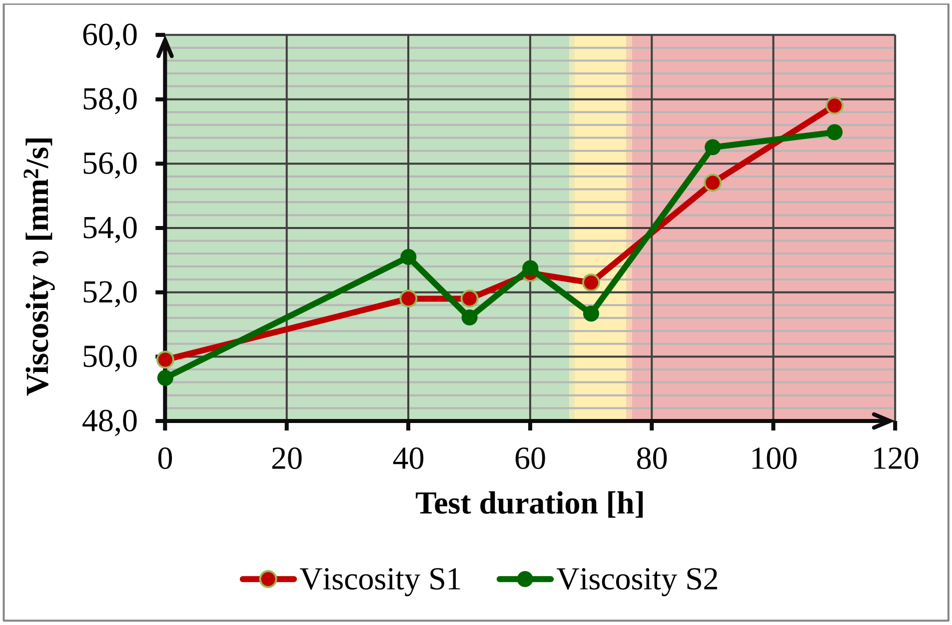


Figure 6.22: Viscosity in the process of accelerated thermal oil ageing

When examining the analysis results of accelerated thermal oil ageing, the samples' physical-chemical oil properties were determined, which allow an insight into the time progress of oil ageing and degradation, and thus, estimation of the condition of oil, when it is still in the useful, i.e. green area.

It must be emphasized, that the remaining analyses are not excluded. All the presented (in Chapter 2.3) and executed laboratory analyses are of key importance for obtaining an overall picture and for complete estimation of the oil condition. Some analyses do not regrettably allow an insight into the time progress of oil ageing and degradation but are used only for monitoring specific physical-chemical oil properties, which must remain within prescribed limits. In other words, alarming (sudden property deterioration) is affected on the basis of all measured parameters. At this point those parameters were selected which, in addition to alarming, also allow a detailed insight into the oil ageing and degradation process itself. Those parameters will be used for estimating the current, already occurred oil degradation, and for estimating the current oil condition and its remaining useful lifetime.

At the end of accelerated hydraulic fluid ageing according to the described thermal method with overheating, air blowing and presence of copper as catalyser, it is necessary to still point out the following fact: though the method illustrates excellently the accelerated oil degradation, it is not in complete conformity with real operating conditions occurring within the industrial environment. The greatest deviation from real ageing conditions is represented by viscosity, which in the case of accelerated ageing increases due to intensified oxidation, as long molecule chains with high molecular mass are formed. In real industrial circumstances, the oxidation process affects the viscosity less than the process of tearing off long molecules due to shear stresses occurring in hydraulic fluid during its transition through gaps at high pressures and velocities. Therefore, in real conditions, even a viscosity decrease can be observed with oil ageing and degradation.

It may be concluded that the oil condition estimate and the remaining useful lifetime prediction can be given based on the following parameters:

- colour,
- viscosity (at 40 °C) – measured in laboratory,
- neutralization number,
- FT-IR oxidation,
- electric conductivity – on-line measurement,
- viscosity – on-line measurement.

7 METHODS FOR EVALUATING OIL CONDITION AND PREDICTING REMAINING USEFUL LIFETIME

In Chapter 6, accelerated oil ageing tests and trends of physical-chemical properties during the tests were presented. On the basis of sample analysis results, obtained by accelerated oil thermal ageing according to newly implemented method, oil condition and its remaining useful lifetime can be estimated. During the examination of literature a proper method for estimating the oil condition could not be found, therefore, hereinafter, the more frequent methods will be presented for estimating the conditions of various machines and components.

7.1 Brief overview of common methods

The engineering sphere focused on condition estimation and remaining useful lifetime predictions of systems and components is called prognostics [73]. The term “end of lifetime” or “useful lifetime” of the system or component more often implies the time after which the system or component are no more capable of reaching the desired efficiency. The anticipated time up to the expiration of this lifetime is called the remaining useful lifetime (RUL).

Prognostics try to predict the remaining effectiveness or capacity of components by evaluating the functioning deviation or the system degradation from the expected usual operating conditions [58]. The methods are usually based on analysing the faults and discovering early signs of wear and ageing. Those indicators are then usually related to the model of damage propagation. The discipline studying the association of the fault occurrence mechanisms with the management of the lifetime cycles of systems is called prognostics and health management (PHM).

Many different prognostic methods contained within different applications have been developed recently and implemented for estimating conditions and predicting the remaining useful lifetimes of systems. They are hard to categorize as they cover a wide set of differently used techniques. In literature [73] the following division of the prognostic methods into three main groups can be found:

- methods based on empirical models,
- methods based on previously acquired data (history or trend),
- methods based on previously created physical-mathematical models.

Certain features like performance, usability and complexity (price) can also be attributed to the individual groups in this categorization. Figure 7.1 shows that those methods based on accurate physical-mathematical models are more capable but at the same time more expensive and complex. They are adapted usually for some specific application, which is the reason for their exactness and narrow area of use. In contrast, the methods based on empirical models (at the bottom) are less accurate but less expensive and more widely usable.

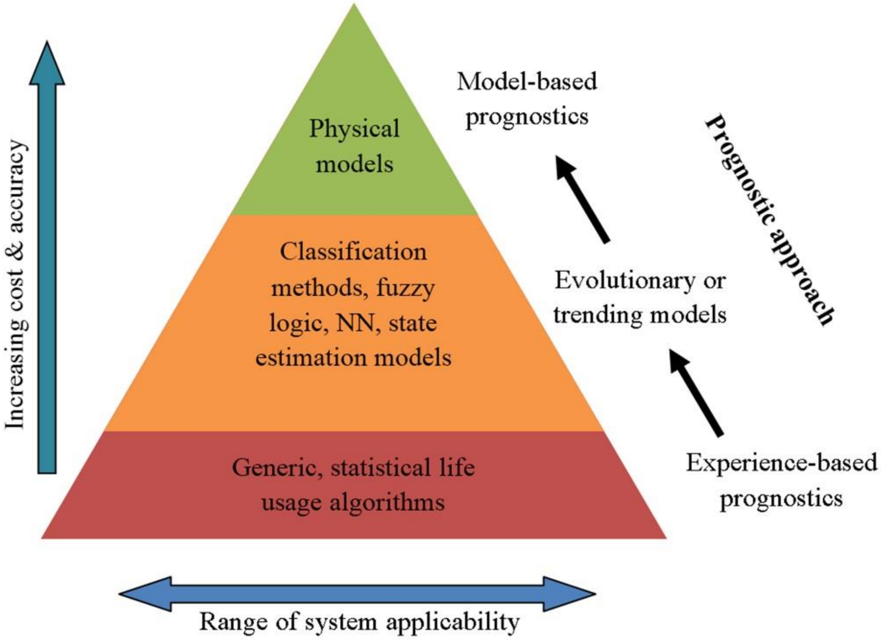


Figure 7.1: Technical approaches to system prognostics [73]

The more simple prognostic methods are based on collated statistical information describing the history of faults on certain systems or their components. The system life cycle model showing anticipated system failures and their distribution over a long period can be developed and implemented from the collated data. Such approaches are usually used for conceiving the preventive maintenance plans, where the maintenance interventions are determined on the basis of meantime between failures. In fact, the mentioned method has no capacities of prognostics and/or prediction of the remaining useful lifetime of the system and can hardly be classified as an actual prognostic method.

The physical-mathematical models are usually very accurate and robust but in many cases the complexity of the system prevents their use [76]. Similarly, in our case the diverse and complex mineral oil composition (Chapter 3) prevents the creation of a suitable physical-mathematical model allowing conclusions about the changes of physical-chemical oil properties, therefore, hereinafter the focus will be on the methods based on previously acquired data, in our case the data gained by the use of sample analyses of accelerated oil ageing.

The prognostic methods based on previously acquired data for estimating the conditions of systems or components usually use pattern recognition and artificial intelligence methods [76]. Conventional prognostic methods of non-linear systems on the basis of previously acquired data include the use of stochastic models, e.g. auto-regression model, auto-regression model with threshold function, bilinear model, projection searching, models of adaptive multi-variant regression splines, etc. Over the last decade the express development of flexible systems, e.g. various types of neural networks and fuzzy logic took place. The prognostic methods based on previously acquired data are used when understanding of the basic principles of the system functioning is not complete and insufficiently accurate or when the system is too complex for creation of the accurate physical-mathematical model. The principal advantage of those methods compared with complex physical-mathematical methods is that their implementation is usually faster and cheaper. The principal disadvantage is their inaccuracy and wide trust interval, since they need an enormous quantity of data for learning. In our case particularly when the oil condition and its remaining useful lifetime are estimated, it is difficult to acquire the relevant data base for all possible oil conditions from the beginning of filling (fresh oil) to different undesired conditions or faults like degraded oil due to ageing, ingress of different contaminants (water, air, foreign oil), failure of one of the hydraulic components (pump, cylinder, valve) etc.

The advantages of physical-mathematical prognostic methods and prognostic methods based on previously acquired data are combined by the hybrid mathematical approaches. When it is impossible to create an accurate physical-mathematical model of the system due to its complexity or insufficient knowledge of the basic system's operational principles, a dynamic mathematical model can be created describing the system degradation on the basis of previously acquired data.

In accordance with the literature stating hitherto findings within the sphere of prognostic methods, a new very efficient and useful method is proposed for the development of a hybrid prognostic system for estimating hydraulic oil condition and its remaining useful lifetime.

7.2 Architecture of proposed system

Figure 7.2 presents the architecture of the proposed system. The results of measurements by on-line sensors are automatically added into the central data base, where the results of periodically performed laboratory analyses are also added. Based on a control database a mathematical oil degradation model, developed on the basis of accelerated oil ageing analysis, has been carried out on the basis of the last available data. Before entry into the mathematical model the input data are selected and standardized as presented in the next chapter. On the basis of those input data the mathematical model, as a result, gives the current oil condition estimate expressed in percentage and the estimate of the remaining oil useful lifetime (RUL) in days.

In addition to the mathematical model estimating the oil (ageing) condition, the results of measurements by on-line sensors are permanently controlled for exceeded limit values.

All on-line measured parameters are controlled as distinct from the mathematical model using only some of them. As conditioned here below, for example, the mathematical model for estimation of the oil degradation extent does not use the relative humidity and dielectric constant parameters.

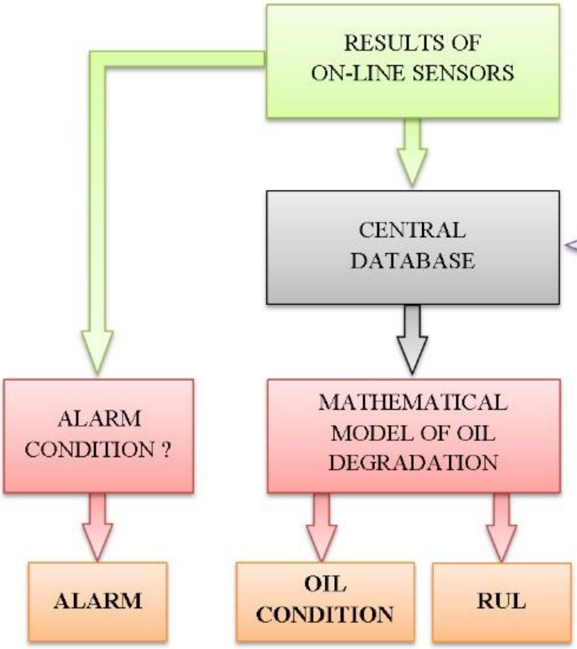


Figure 7.2: The architecture of the proposed system

7.3 Selection and normalization of input parameters

In Chapter 6.3.4 the trends of various physical-chemical properties in accelerated oil ageing was discussed, pointing out the fact that some physical-chemical properties and parameters during the oil lifetime intensively change relatively while some parameters remain constant or their change cannot be foreseen. When interpreting the results of analyses of the hydraulic fluid accelerated ageing (Table 6.4, Figures from 6.10 to 6.22 and appurtenant text) those values were exposed on the basis of which it is possible to conclude about the oil degradation extent and therefore can be properly used as input values into the mathematical model of the oil degradation:

- colour,
- viscosity (at 40 C) – measured in laboratory,
- neutralization number,
- oxidation extent (FT-IR),
- electric conductivity – on-line measurement,
- viscosity – on-line measurement.

It was mentioned previously that fresh oils of the same type can have different initial physical-chemical properties or parameters as a consequence of using different base oils or additives. Consequently, only the values of those parameters cannot be monitored but their difference from the initial value (fresh oil fill) must be monitored. Therefore, the values of the abovementioned parameters representing input values into our mathematical model will be standardized by subtracting from them the values measured in the fresh filling.

7.4 Mathematic model based on analyses of accelerated oil ageing

For creating a hybrid prognostic model or mathematical model based on accelerated oil ageing analyses, a relevant measurement data base is needed as previously acquired by execution of the accelerated oil thermal ageing test. In addition to the acquired data the relevant value of oil condition at a certain moment, expressed in percentage, must be assigned to the individual acquired samples and oil conditions. The value of the oil condition of the individual sample must be expressed as a percentage in such a way that fresh oil represents the condition 100 %, while the oil having reached the end of its useful lifetime represents the condition 0 %.

Due to the nature of the mathematical model itself and for searching for proper transfer functions for the oil condition estimate, it is better to use in the model the opposite value of oil condition, i.e. oil degradation, having the value 0 % for fresh filling and the value 100 % for fully degraded oil at the end of its lifetime.

7.4.1 Determination of an oil's useful lifetime

In order to be able to evaluate as percentages the individual oil samples acquired by accelerated thermal ageing with respect to their degradation extent, first the entire oil lifetime in the case of accelerated ageing test must be determined. Consequently, in the frame of the test, the accurate time for which it is assumed that it represents the end of its lifetime must be determined. Determination of sharp delimitation between "still usable" and "unusable" oil is very difficult, since no accurate specifications for its estimation are available. Only some basic instructions can usually be found indicating the form of limit values, e.g. in the continuous test method 791B (Table 7.1) or in the experts' recommendations (Table 7.2).

Table 7.1: Hydraulic fluid oxidation – Federal Test Method 791B [29]

	Hydraulic fluid – degree of oxidation		
	Mild	**Moderate**	**Severe**
Viscosity at 40 °C [mm^2/s]			
Initial	68	68	68
Final	60 to 75	48 to 60 : 75 to 88	< 48 : > 88
Difference (%)	0 to 10 %	10 to 25 %	> 25 %
Neutralization number [mg KOH/g]			
Initial	2.0	2.0	2.0
Final	1.6 to 2.4	1.2 to 1.6 : 2.4 to 2.8	< 1.2 : > 2.8
Difference (%)	0 to 20	20 to 40	> 40

Table 7.2: Limit values for hydraulic fluids [61]

Analysis	Warning	Critical
Neutralization number [mg KOH/g]	+ 0.2	+ 0.4
Viscosity at 40 °C [mm^2/s]	+ 5 %	+ 10 %
FT-IR Oxidation	0.3	1.0
Water content [ppm]	100 to 300	> 300

We can determine the end of the oil useful lifetime on the basis of three different methods or aspects presented here below.

The precise time considered to represent the end of the oil useful lifetime in our thermal test of accelerated ageing can be **determined on the basis of recommended limit values** from Tables 7.1 and 7.2. Already a mutual comparison of recommendations has already disclosed that great deviations existing between them. The values already representing the critical change in Table 7.2 are evaluated as moderate oxidation in Table 7.1. According to the extensive and longstanding experience of the oil producer’s in the sphere of oil condition analyses, it was decided to use the limit values from Table 7.2 appearing to be more suitable for the concerned HLP ISO VG 46 mineral hydraulic oil.

The survey of analysis results regarding accelerated oil ageing (Figures 6.12, 6.14, 6.15) discloses that oil reaches the critical limit at the time of test 75 h, as shown in Table 7.3.

The next method serving to estimate the service-life of systems and components was presented briefly in Chapter 2.1 in Figure 2.1 interpreting that the end of the useful lifetime of the system is considered to be the condition at which its condition starts to deteriorate at an accelerated rate.

Table 7.3: Determination of oil lifetime in accelerated oil ageing test

Analysis	Test – accelerated oil ageing			Critical from Table 7.2
	Initial	At 75 h	Change	
Neutralization number [mg KOH/g]	0.54	0.94	+ 0.4	+ 0.4
Viscosity at 40 °C [mm^2/s]	46.54	50.20	+ 8 %	+ 10 %
FT-IR Oxidation	0.31	0.8	/	1.0

In our case, in Figures from 6.10 to 6.22 showing the change of physical-chemical oil properties during the test, the so-called point of curve (and condition) deflection can be found indicating the start of accelerated deterioration of oil properties. Detailed examination of those analysis results in the form of curves discloses that this point complies with the statement in the previous paragraph and can be found within the range of 75 hours from the test start.

Although the presented two methods are in good compliance, the formation of varnish products on the hydraulic components must not be neglected. Formation of those products is irreversible and strongly affects the narrow geometrical tolerance ranges of hydraulic component parts. Varnish formation in different samples and testing times is illustrated in Figure 6.8 showing the condition of copper wire after completion of testing. It can be seen in the figure that accelerated formation of varnish products already occurs between the samples HLP 60 and HLP 70, i.e. between the 60th and 70th hour of testing. Therefore, on the basis of the method of observation of varnish formation it can be concluded that the oil lifetime is 60 hours.

The useful lifetime estimated by the method of accelerated property deterioration and by the method of limit values amounts to 75 hours, while by the method of varnish formation it amounts to 60 hours. Due to excellent conforming of the first two methods it was concluded that the accurate time within our test, considered to represent the end of the oil useful lifetime, amounts to 75 hours.

In the proposed mathematical model the condition at 75 hours represents the critical condition corresponding to oil RUL=0 %. With respect to the method of varnish formation to that critical condition, a condition warning will be added to the oil condition at RUL=20 % at which a recommendation for the oil filling change will be issued in the frame of executing the method. When analysing the results of accelerated hydraulic fluid ageing, the useful oil lifetime was indicated in green illustrating the oil condition from 100 to 20 % in the background of Figures from 6.10 to 6.22. The transition into yellow colour indicates the oil condition RUL=20 % at which the recommendation for a filling change is issued. The transition into red colour represents the critical condition, when the oil condition reaches the value RUL=0 %.

7.4.2 Designing the mathematical oil degradation model

On the basis of the selection and standardization of input values (Chapter 7.3) and on the basis of specific useful oil lifetime (Chapter 7.4.1) in Table 7.4 the data are summarized that will be used for creating an oil degradation mathematical model based on the data acquired from accelerated oil ageing analyses.

Table 7.4: Data for creation of mathematical oil degradation model

Sample	**HLP 0**	**HLP 40**	**HLP 50**	**HLP 60**	**HLP 70**	**HLP 90**	**HLP 110**
Test duration [h]	0	40	50	60	70	90	110
Oil degradation [%] vs. 75 h	0	53.33	66.67	80.00	93.33	120.00	146.67
Colour [-]	0	4.0	5.5	6.0			
Viscosity at 40 °C [mm^2/s]	0	1.90	2.62	2.85	3.30	5.29	15.73
Neutralization number [mg KOH/g]	0	0.11	0.14	0.18	0.23	0.89	1.36
FT-IR Oxidation [-]	0	0.12	0.20	0.33	0.45	0.97	1.99
Electrical conductivity S1 [pS/m]	0	246	365	514	803	3814	8612

As already mentioned, due to the nature of the mathematical model and searching for proper transfer functions the mathematical model output will be defined as the oil degradation degree amounting to 100 % at the end of the oil lifetime at 75 hours.

Here below, an approach is presented, how to find mathematical models for individual values, where the concerned input value will be selected as the input into the individual model and the oil degradation extent as the output. In other words, the oil degradation extent (y-axis) will be presented depending on the input variables (x-axis) and the proper transfer function found. That procedure was executed by the use of purpose-made software [31].

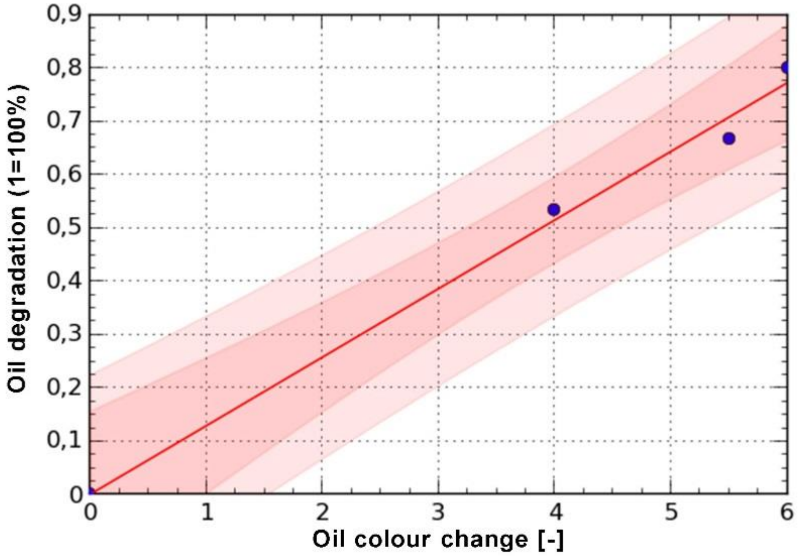


Figure 7.3: Linear function of oil degradation rate estimated on the basis of its colour change

The oil degradation rate according to colour change D_c was discovered to be a linear function of the oil colour change indicated in Figure 7.3, given by equation:

$$D_c = a \cdot x + 0 \tag{7.1}$$

D_c – oil degradation rate according to oil colour change, 0 %=fresh, 100 %=fully degraded,
a – experimentally defined coefficient, a=0.1284507,
x – measured oil colour change.

The oil degradation rate based on viscosity change D_v is best described by the nonlinear function shown in Figure 7.4, given by equation:

$$D_v = \frac{a \cdot x^c}{b^c + x^c} \tag{7.2}$$

D_v – oil degradation rate according to viscosity change, 0 %=fresh, 100 %=fully degraded,
a – experimentally defined coefficient, a=1.51677683592059,
b – experimentally defined coefficient, b=2.7146086681148,
c – experimentally defined coefficient, c=1.96804358156407,
x – viscosity at 40 °C [mm^2/s].

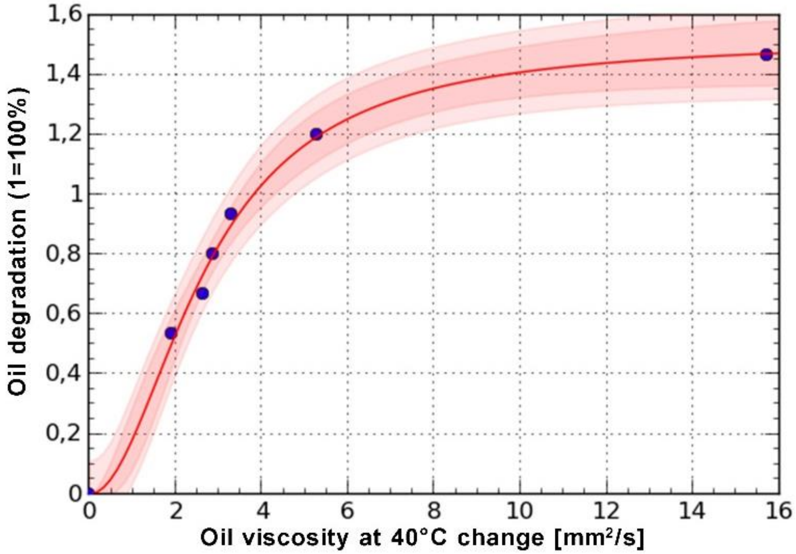


Figure 7.4: Non-linear function of oil degradation rate estimated on the basis of its viscosity change

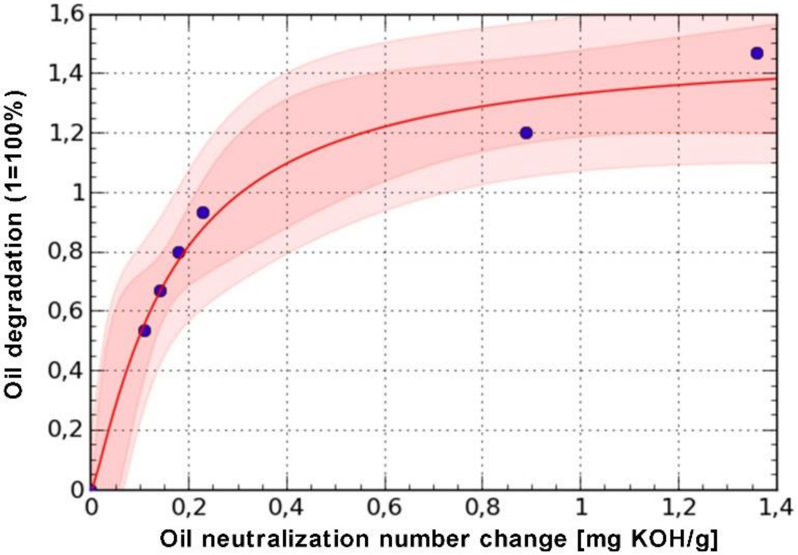


Figure 7.5: Non-linear function of oil degradation rate estimated on the basis of its neutralization number change

The oil degradation rate based on neutralization number change D_n is best described by the nonlinear function shown in Figure 7.5, given by equation:

$$D_n = \frac{a \cdot x^c}{b^c + x^c} \tag{7.3}$$

D_n – oil degradation rate according to neutralization number change, 0 %=fresh, 100 %=fully degraded,
a – experimentally defined coefficient, a=1.50156188915641,
b – experimentally defined coefficient, b=0.167879303694358,
c – experimentally defined coefficient, c=1.16698477350745,
x – neutralization number [mg KOH/g].

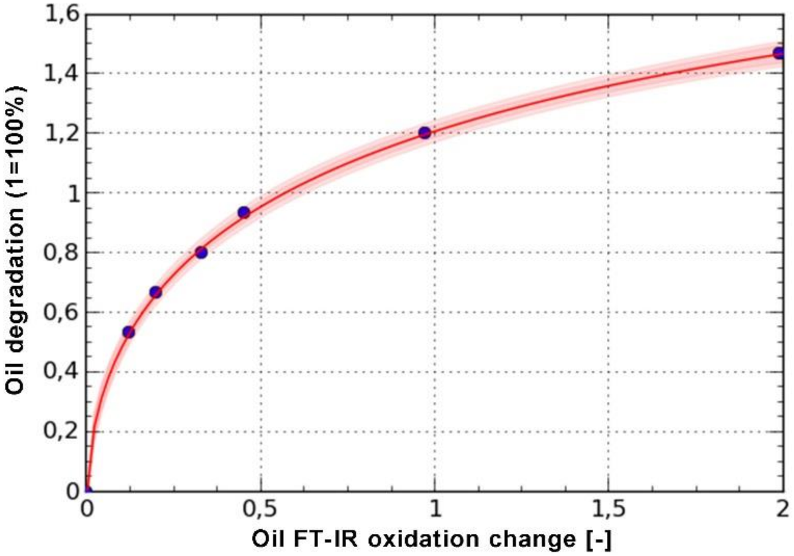


Figure 7.6: Non-linear function of oil degradation rate estimated on the basis of its FT-IR oxidation change

The oil degradation rate based on FT-IR oxidation change D_f is best described by the nonlinear function shown in Figure 7.6, given by equation:

$$D_f = \frac{a \cdot x^c}{b^c + x^c} \tag{7.4}$$

D_f – oil degradation rate according to FT-IR oxidation change, 0 %=fresh, 100 %=fully degraded,
a – experimentally defined coefficient, a=2.61542583223926,
b – experimentally defined coefficient, b=1.29749939262253,
c – experimentally defined coefficient, c=0.575565548710708,
x – FT-IR oxidation [-].

The oil degradation rate based on electric conductivity change D_e is best described by the nonlinear function shown in Figure 7.7, given by equation:

$$D_e = \frac{a \cdot x^c}{b^c + x^c} \tag{7.5}$$

D_e – oil degradation rate according to electric conductivity change, 0 %=fresh, 100 %=fully degraded,
a – experimentally defined coefficient, a=1.70566577232505,
b – experimentally defined coefficient, b=704.041630789411,
c – experimentally defined coefficient, c=0.646270645600464,
x – electric conductivity [pS/m].

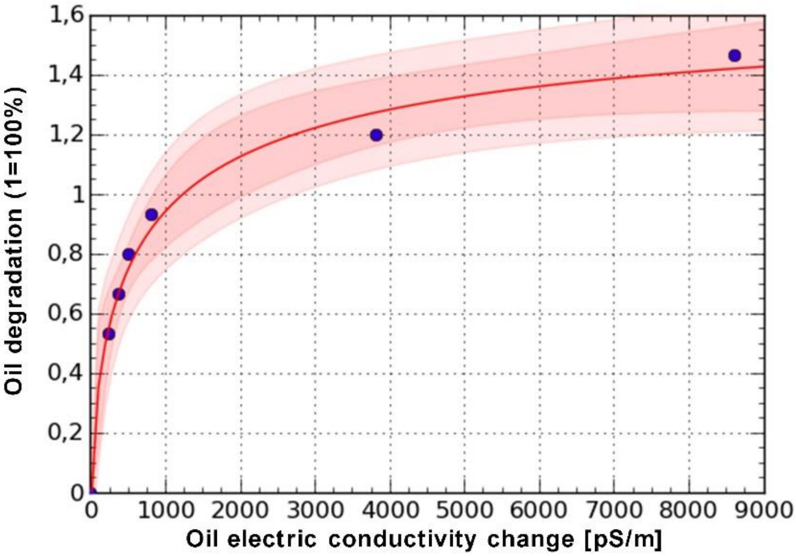


Figure 7.7: Non-linear function of oil degradation rate estimated on the basis of its electric conductivity change

From the individual oil degradation extent (D_i) it is possible to calculate the evaluated oil condition C_i representing its difference from 100 % by equation:

$$C_i = 100\,\% - D_i \tag{7.6}$$

C_i [%] – individual condition of the oil (C_c, C_v, C_n, C_f, C_e), 100 %=fresh, 0 %=fully degraded,
D_i [%] – individual oil degradation rate (D_c, D_v, D_n, D_f, D_e), 0 %=fresh, 100 %=fully degraded.

After all individual oil conditions have been calculated, the system has to estimate the overall oil condition C. The more common and plain approach would be to calculate the overall oil condition as an average of individual oil conditions but in a worst case scenario when only one parameter would change substantially, such a method would fail.

When performing oil laboratory analyses in praxis, where the overall oil condition is given by a human expert, the overall oil condition is not just one parameter given as a number but rather a written report. The report usually emphasizes those parameters that have changed significantly and are thus considered critical. Further on, the oil condition is often evaluated based on the most critical parameter that was measured. Similarly, to such a human expert report, our system could evaluate the overall oil condition as the lowest of the five calculated individual conditions. However, when using such a method and only one parameter would change substantially, the system would output very low oil condition based on that parameter, although the oil condition might be much better (e.g. only oil electric conductivity would increase due to the small amount of water in the oil).

As we join the two extreme methods given above, the overall oil condition C could be estimated by the weighted average with bisectional weights of the individual oils' conditions C_i; equation (7.7). Such an approach allows the most critical (lowest) individual condition C_{i1} to have the most power (50 %) and the least two critical individual conditions C_{i4} and C_{i5} to have the least power (6.25 %):

$$C = C_{i1} \cdot 0.5 + C_{i2} \cdot 0.25 + C_{i3} \cdot 0.125 + C_{i4} \cdot 0.0625 + C_{i5} \cdot 0.0625 \tag{7.7}$$

C [%] – estimated overall oil condition,
$C_{i1} – C_{i5}$ [%] – individual conditions of the oil (C_c, C_v, C_n, C_f, C_e), arranged by their current values from the lowest (C_{i1}) to the highest (C_{i5}).

The remaining useful lifetime RUL of the oil is estimated on the basis of current oil condition C and the time elapsed since fresh oil was put into service - oil change was made. We assume that the rate of degradation will be maintained as unchanged:

$$RUL = \frac{C \cdot t_o}{(1-C)} \tag{7.8}$$

RUL [days] – remaining useful lifetime of the oil,
C [%] – current overall oil condition,
t_o [days] – time elapsed since fresh oil was put into service.

7.5 Verification of the mathematical model

The developed oil degradation mathematical model, i.e. the model of estimated oil condition and its remaining useful lifetime was first verified on the basis of the data base of analyses of accelerated thermal oil ageing, on the basis of which the model was created (Table 6.4).

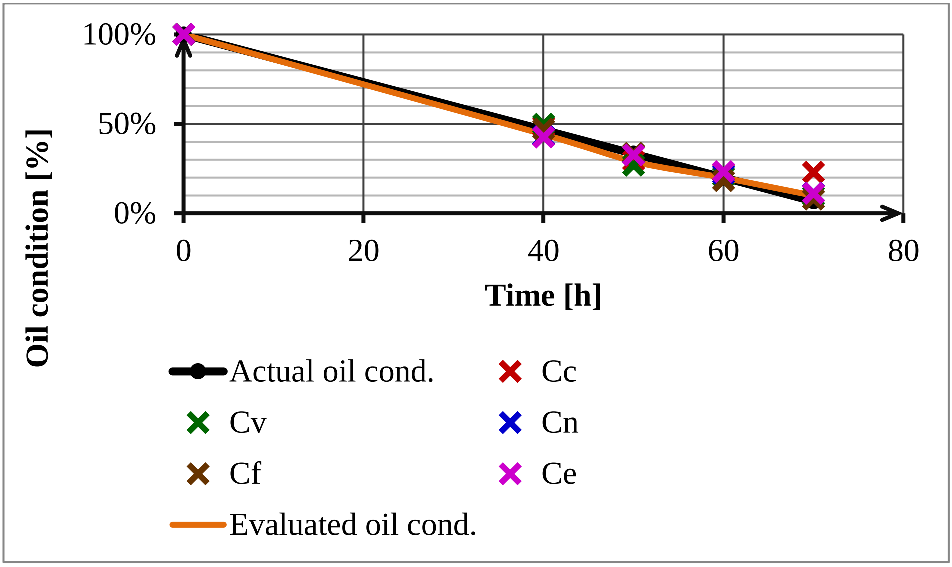


Figure 7.8: Estimated oil condition C on the basis of mathematical model developed, carried out on the database of accelerated thermal oil ageing

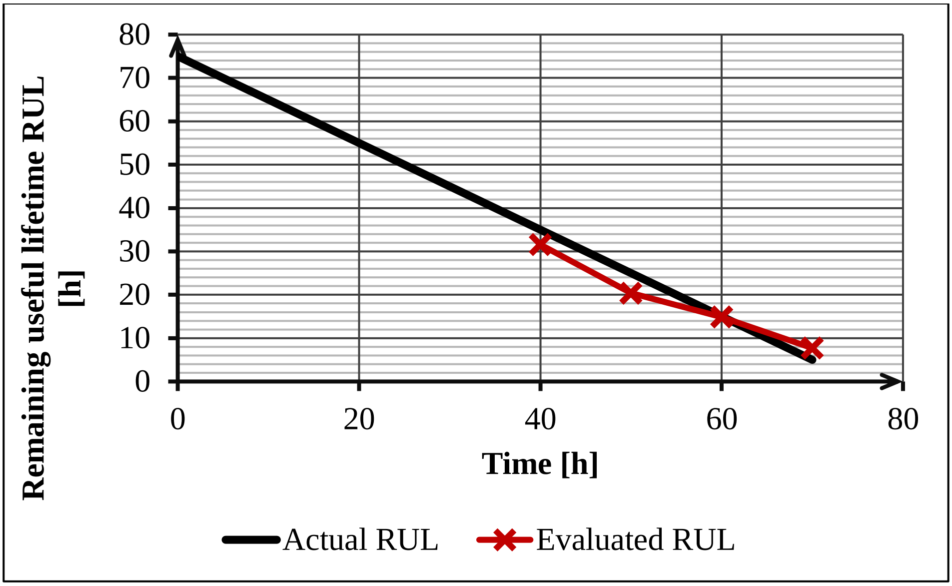


Figure 7.9: Estimated remaining useful lifetime RUL on the basis of mathematical model developed, carried out on the database of accelerated thermal oil ageing

The oil condition estimate on the basis of the developed mathematical model carried out on the data base of accelerated thermal oil ageing is indicated in Figure 7.8 showing that a proper mathematical model was conceived with success: estimated oil condition *C* (orange) is in excellent agreement with actual oil condition (black). The figure also shows the oil condition estimate with respect to individual input values (C_c, C_v, C_n, C_f, C_e), where in the last step it is possible to observe a deviation of the condition estimate on the basis of colour. This is caused by the laboratory oil analysis method itself anticipating that the highest method result is L>8.0 – the oil condition then being 22 % with respect to colour analysis. In spite of that, the oil condition estimate itself on the basis of colour because of the calculation of the total estimate on the basis of weighted average has a relatively low influence on the total condition estimate.

Thanks to the conceived mathematical model on the accelerated hydraulic oil ageing data base the remaining useful lifetime of oil was successfully estimated as shown in Figure 7.9.

The indicated results confirm the adequacy of the mathematical model. Therefore, in the next step it will be implemented on a real industrial system.

7.6 Implementation of developed method on real industrial system

Several on-line condition monitoring systems for hydraulic oil were installed in industrial applications in order to acquire real operating data (Figure 7.10). As already mentioned, the mineral hydraulic oils have a relatively long service-life, i.e. from 5 to 10 years. Therefore, the proper database comprising complete history from fresh filling to complete oil degradation could be acquired only on one system. Regrettably, that system is one of the more modest ones, since it comprises only one multi-sensor of older generation. Here below, the implementation of the developed mathematical model on the mentioned industrial system, functioning under real operating conditions, will be presented.

Temperatura 29.0
Temperatura 2 29.4
Temperatura 3 34.0
Dielek. Konst. 3.0244
D.K. pri 40C 3.0039
4um 16
Elektr. Prevod. 1703.4
E.P. pri 40C 2842.2
6um 15
Vsebnost vode 16.8
14um 11
Viskoznost 109.6
Viskoznost pri 40C 74.3
21um 9

Figure 7.10: Different industrial applications of hydraulic oil condition monitoring, implemented during the studies in order to acquire real operating data

The results of laboratory analyses and on-line measurements on the mentioned industrial system used for implementation of the proposed method for evaluation of oil condition and its useful lifetime are indicated in Table 7.5.

Table 7.5: Results of laboratory analyses and on-line measurements on the industrial system

Operating time [days]	**0**	**24**	**49**	**85**	**113**	**146** $^{(1)}$	**171**	**221**
Colour [-]	2.0	3.0	3.5	4.5	5.0	5.5	6.0	7.0
Flash point [°C]	234	240	244	244	236	234	240	240
Viscosity at 40 °C [mm^2/s]	46.55	46.47	46.07	46.09	46.02	45.76	46.33	46.59
Visc. at 100 °C [mm^2/s]	6.88	6.83	6.82	6.80	6.81	6.81	6.84	6.87
Viscosity index [-]	102	101	102	102	102	103	102	102
NN [mg KOH/g]	0.47	0.50	0.55	0.54	0.51	0.61	0.67	0.71
FT-IR Oxidation [-]	0.354	0.383	0.385	0.431	0.486	0.519	0.554	0.606
Cleanliness level [ISO 4406]	18/16/11	20/17/12	19/17/13	18/15/10	18/16/12	22/19/15	19/16/13	20/17/12
Additive elements [wt. %]								
Phosphorus (P)	0.028	0.035	0.035	0.034	0.035	0.035	0.037	0.038
Sulphur (S)	0.584	0.592	0.613	0.606	0.607	0.606	0.615	0.619
Calcium (Ca)	0.000	0.004	0.003	0.003	0.004	0.003	0.003	0.004
Zinc (Zn)	0.0450	0.0438	0.0425	0.0432	0.0428	0.0418	0.0418	0.0412
Wear metals [mg/kg]								
Chromium (Cr)	10	9	8	10	8	9	9	4
Copper (Cu)	9	8	< 5	8	7	< 5	6	< 5
Iron (Fe)	3	4	3	3	2	5	< 3	< 3
Lead (Pb)	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3
Tin (Sn)	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20
Foaming [ml/ml]								
Sequence I.	10/0	270/0	30/0	200/0	260/0	0/0	0/0	0/0
Sequence II.	40/0	50/0	160/0	220/0	200/0	0/0	0/0	40/0
Sequence III.	0/0	20/0	30/0	200/0	260/0	0/0	0/0	0/0
On-line sensors at 40°C								
Dielectric constant [-]	2.0970	2.0956	2.0947	2.0992	2.1044	2.1127	2.1178	2.1371
E. conductivity [pS/m]	338	356	351	394	476	528	(2)	(2)
Relative humidity [%]	12.6	14.7	13.8	15.3	12.9	17.3	14.6	11.8

(1) – anti-foaming additive was added; (2) – error on sensor

The results of the oil condition estimate with respect to the individual parameter and total condition estimate are graphically indicated in Figure 7.11 and commented thereinafter.

Figure 7 11 shows that the oil condition estimate on the basis of colour C_c is excellent in the first half of its useful lifetime, afterwards it gives a slightly better condition than actual.

A very bad oil condition estimate is given by the method on the basis of viscosity C_v, as Table 7.5 shows that the viscosity remained almost unchanged under real operating conditions. In real operating conditions the oil is affected by many more factors than in our accelerated thermal hydraulic fluid ageing test on which the mathematical model was based.

Consequently, the mathematical model estimates the oil degradation well when based on the viscosity increase due to oil oxidation causing propagation of long molecule bonds in oil. It estimates the oil degradation to be much worse in the case of real operating conditions, where the factors reducing viscosity like shear stresses splitting the long molecules in oil are also present.

The oil condition estimate has the greatest result fluctuation, when based on the neutralization number C_n as a result of inaccuracy of the laboratory measurement method of neutralization number.

The oil condition estimate based on the oxidation extent (FT-IR) C_f also indicates well the actual condition. It is in good agreement with the actual oil condition with the exception of the first step, where the method estimates the condition as worse than the actual condition.

Very good results were also reached by the oil condition estimate based on electric conductivity C_e. Regrettably, the electric conductivity sensor has started to signal an error in the last quarter, thus preventing the calculation of condition estimate based on electrical conductivity.

The total oil condition estimate is shown in Figure 7.11 by the orange curve which in the first third of the oil lifetime strongly deviates from the actual oil condition. Although the first impression is that within the range of early oil lifetime the mathematical model is inaccurate, maybe that is not so. The phenomenon can be explained by the fact that when changing the oil filling the hydraulic system still contains a part of old degraded oil (pump, cylinders, pipes etc.) which, when mixed with fresh oil, on the first start-up causes sudden deterioration of its properties.

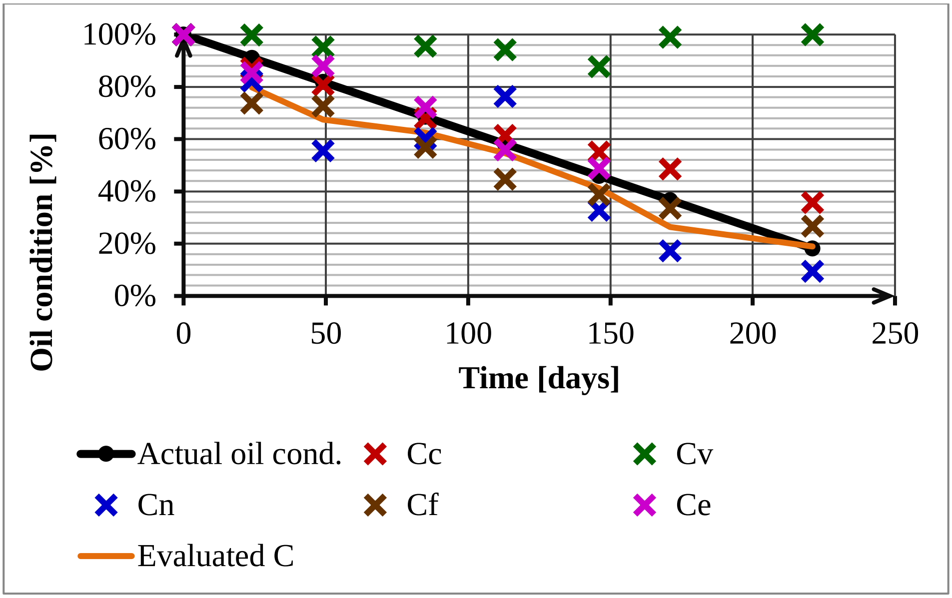


Figure 7.11: Estimated oil condition C on the basis of the mathematical model developed, carried out on the data base from a real industrial system

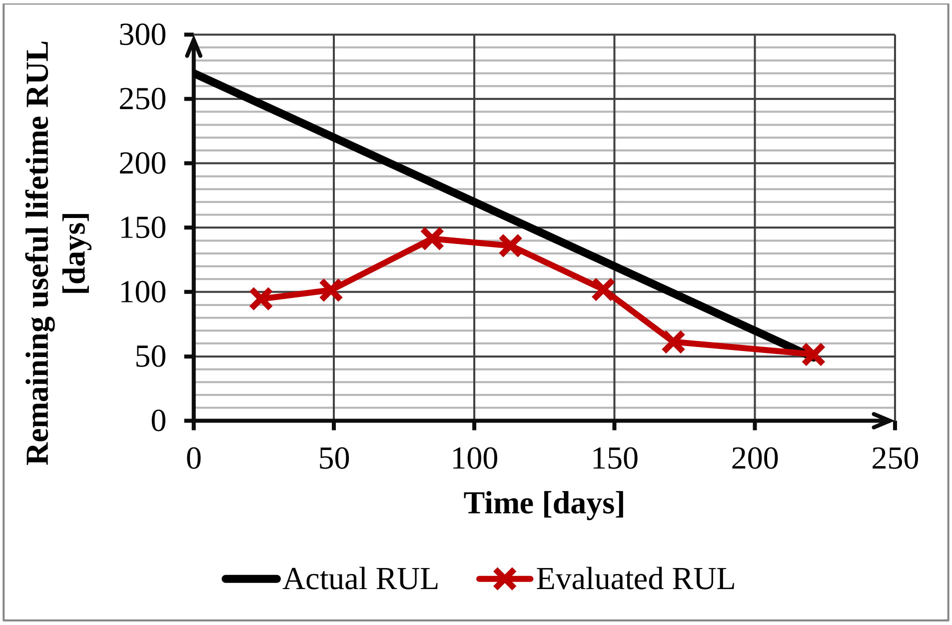


Figure 7.12: Estimated RUL on the basis of mathematical model developed, carried out on the data base from a real industrial system

That inaccuracy of the oil condition estimate in the early stage of its lifetime affects even more strongly the estimate of its remaining useful lifetime (Figure 7.12). Due to sudden oil property deterioration at the beginning of operation after the filling change (remains of old oil) the model estimates accelerated oil degradation rate which it projects into the future and, consequently gives a too low estimate of the remaining lifetime. As shown in Figure 7.12, gradually the effect of the old degraded oil is reduced and approximately after the first third of the oil lifetime the model is already capable of estimating the remaining oil useful lifetime with 20 % precision.

Taking into account complexity of the system, particularly the complexity of the mineral hydraulic oil composition, degradation mechanisms, physical-chemical effects of the real operating conditions, laboratory analysis errors, inaccuracy of on-line sensors and taking into account the early stage of the system lifetime (30 to 35 %), it is a very good approximation, appropriate for practical use for determining the remaining useful lifetime of the used mineral hydraulic oil.

8 COMPARISONS BETWEEN OXIDATION STABILITIES AND EXPECTED SERVICE-LIVES OF TURBINE OILS

One of the important factors when selecting the more appropriate hydraulic fluid for use in applications is definitely its long service-life. By using hydraulic fluid with long service-life, together with enhanced condition monitoring of the fluid, we can significantly reduce costs and minimize environmental impact due to less lubricant production, logistics, and disposal.

As the world is coming to face a shortage of crude oil, a rising trend of fossil fuels' cost and environmental issues imply that lubricants should be utilized efficiently. The extensions in service-lives of hydraulic and lubricant fluids can deliver both cost savings and environmental benefits like reduced pollution and CO_2 emissions, without sacrificing the equipment’s life. Major economic benefits associated with extended fluid service-life include reduced fluid costs, as well as reductions in serviced fluids’ disposal costs. Secondary benefits include reduced maintenance costs and machine downtimes that, in many applications, can result in significant economic savings. The extensions in the service-lives of hydraulic fluids can also contribute to the minimization of environmental impacts across the whole range of manufacturing, transport, and serviced fluid disposal. All these factors are especially important in systems with 24/7 operation and long service life, for example, turbine oil systems.

The service-life of a hydraulic fluid can be extended in two ways: by introducing modern condition monitoring techniques that ensure oil changes at just the right times and by carefully selecting the more appropriate modern high-quality lubricant with high oxidation stability.

8.1 Comparisons between expected lifetimes – pre-selection testing

In Chapter 7 we have already presented an advanced method for assessing current oil condition and its remaining useful lifetime, which can be used to optimize oil consumption, reduce costs and minimize environmental impact. The method is based on the accelerated thermal oil ageing test presented in Chapter 6.3. However, the test itself can also be used for testing the durability and oxidation stabilities of different hydraulic oils since the key property of hydraulic oil that determines its service life is its oxidation stability [30]. As already mentioned, oils oxidize at operating temperatures by a chemical reaction with oxygen that, over time, results in the formation of sludge and acids, increases viscosity, reduces the ability to handle contaminants, and decreases in filterability. In other words, the lubricating oil has lost its ability to perform key functions and should be changed.

Rapid oil oxidation and degradation has become a major issue in modern turbine systems where turbine oils are nowadays exposed to harsher conditions: new technologies (components), higher pressures and smaller oil volumes. Thus, the service-life of turbine oils, which were known to last even up to 30 years, are now significantly shortened.

Here below the test of oxidation stabilities of three different turbine oils is presented, from which it can be clearly seen that some oils resisted the oxidation and ageing processes much better than others and may have double or even several multiple extended service life-times.

8.2 Comparisons between expected lifetimes – test results

In regard to testing the expected lifetimes or durability of hydraulic turbine oils three different turbine hydraulic oils types have been used:

- TO1: group I mineral turbine oil,
- TO2: group II mineral turbine oil and
- TO3: turbine oil based on saturated synthetic ester.

All three types of turbine oils were tested according to the described procedure of accelerated thermal oil ageing, as described in detail in Chapter 6.3. However, since the turbine oils have excellent oxidation stability, the test was not performed at 150 °C, but rather at 160 °C in order to shorten the test duration.

The test and analysis results are presented in Tables 8.1 to 8.3 and are further compared in Figures 8.1 to 8.6. The useful lifetimes of each oil during the test was evaluated according to methods described in Chapter 7.4.1:

- TO1: 46 hours,
- TO2: 80 hours,
- TO3: 185 hours.

The charts shown in Figures 8.1 to 8.6 show comparison between three different turbine oils' performances during the test. We can see the poor performance of group II mineral turbine oil TO1 (red) in every aspect. It lasted the least time until the values started to increase exponentially. A much better performance was achieved by turbine oil TO2 (green line), which is also based on group II base oil and lasted almost twice as long as the TO1. The interesting thing is that they basically have the same price. Turbine oil TO3, which is a synthetic saturated ester had the best performance but it's price is also much higher than those of TO1 and TO2.

Table 8.1: Analysis results of TO1 samples after accelerated thermal ageing test

Sample	**TO1 0**	**TO1 30**	**TO1 45**	**TO1 60**	**TO1 75**
Test duration [h]	0	60	90	120	150
Colour [-]	L 0.5	L 4.5	> L 8	> L 8	> L 8
Flash point [°C]	228	-	-	238	228
Viscosity at 40 °C [mm^2/s]	61.98	66.38	67.8	78.85	91.44
Viscosity at 100 °C [mm^2/s]	8.26	8.65	8.76	9.653	10.66
Viscosity index [-]	102	102	101	100.00	99
Neutralization number [mg KOH/g]	0.27	0.22	0.52	3.17	4.75
FT-IR Oxidation [-]	0.34	0.46	0.47	4.55	7.93
Four ball welding load [kg]	90/100	-	-	110/120	140/150
Four ball wear test [mm]	-	-	-	-	-
Additive elements [wt. %]					
Phosphorus (P)	0.011	0.01	0.013	0.027	0.002
Sulphur (S)	0.081	0.075	0.073	0.075	0.048
Calcium (Ca)	0.001	0	0	0.001	0
Zinc (Zn)	0.0116	0.0124	0.0105	0.0086	0.003
Wear metals [mg/kg]					
Chromium (Cr)	12	14	15	10	9
Copper (Cu)	10	69	80	109	16
Iron (Fe)	3	5	3	4	4
Lead (Pb)	<3	<3	<3	<3	<3
Tin (Sn)	31	28	34	<20	26
Foaming test [ml/ml]					
Sequence I.	240/0	530/10	740/340	190/0	510/10
Sequence II.	20/0	30/0	30/0	30/0	30/0
Sequence III.	30/0	590/10	270/10	150/0	590/90
On-line sensors at 40°C	**TO1 0**	**TO1 30**	**TO1 45**	**TO1 60**	**TO1 75**
Dielectric constant S1 [-]	2.0635	2.0389	2.0544	2.2715	2.3619
Dielectric constant S2 [-]	2.4217	2.3846	2.3978	2.6115	2.6922
Dielectric constant S3 [-]	2.1008	2.1115	2.1460	2.3016	2.4706
Electric conductivity [pS/m]	290	408	445	4603	6521
Relative humidity [%]	35	28	27.34	18.73	20.2
Viscosity S1 [mm^2/s]	61.8	65.5	66.9	75.0	88.4
Viscosity S2 [mm^2/s]	64.5	67.2	71.1	76.0	94.9

Table 8.2: Analysis results of TO2 samples after accelerated thermal ageing test

Sample	**TO2 0**	**TO2 60**	**TO2 75**	**TO2 90**	**TO2 105**	**TO2 150**
Test duration [h]	0	60	75	90	105	150
Colour [-]	L 0.5	L 3.5	L 4	> L 8	> L 8	> L 8
Flash point [°C]	236	-	-	-	-	244
Viscosity at 40 °C [mm^2/s]	63.02	65.31	65.75	72.15	106.8	330.5
Viscosity at 100 °C [mm^2/s]	8.33	8.53	8.54	9.035	11.63	23.43
Viscosity index [-]	101	101	100	99.00	96	89
Neutralization number [mg KOH/g]	0.14	0.05	0.05	1.47	6.19	14.9
FT-IR Oxidation [-]	0.35	0.15	0.26	3.53	11.71	21.72
Four ball weld load [kg]	90/100	-	-	-	-	140/150
Four ball wear test [mm]	0.7	-	-	-	-	0.65
Additive elements [wt. %]						
Phosphorus (P)	0	0	0	0	0	0
Sulphur (S)	0.019	0.019	0.017	0.015	0.012	0.009
Calcium (Ca)	0.001	0.001	0	0	0	0.001
Zinc (Zn)	0.003	0.0032	0.0033	0.0031	0.0027	0.0023
Wear metals [mg/kg]						
Chromium (Cr)	16	16	16	11	10	7
Copper (Cu)	8	14	13	17	22	27
Iron (Fe)	5	5	4	4	3	<3
Lead (Pb)	<3	<3	<3	<3	<3	<3
Tin (Sn)	21	22	<20	22	22	<20
Foaming test [ml/ml]						
Sequence I.	0/0	250/0	550/0	750/340	30/0	70/0
Sequence II.	10/0	60/0	20/0	140/0	90/0	360/0
Sequence III.	0/0	40/0	50/0	70/10	80/0	40/0
On-line sensors at 40°C	**TO2 0**	**TO2 60**	**TO2 75**	**TO2 90**	**TO2 105**	**TO2 150**
Dielectric constant S1 [-]	2.0640	2.0218	2.0188	2.2089	2.6005	2.8163
Dielectric constant S2 [-]	2.4274	2.3989	2.3912	2.6305	2.9297	3.0744
Dielectric constant S3 [-]	2.0760	2.0636	2.0790	2.3795	2.7156	3.0738
Electric conductivity [pS/m]	268	278	285	1634	14800	11288
Relative humidity [%]	39.1	24.4	24	19.6	13	10.1
Viscosity S1 [mm^2/s]	62.8	90.7	91.0	101.9	128.8	159.5
Viscosity S2 [mm^2/s]	64.5	69.3	69.2	77.4	112.4	227.6

Table 8.3: Analysis results of TO3 samples after accelerated thermal ageing test

Sample	**TO3 0**	**TO3 150**	**TO3 180**	**TO3 210**	**TO3 250**
Test duration [h]	0	150	180	210	250
Colour [-]	L 1	> L 8	> L 8	> L 8	> L 8
Flash point [°C]	256	262	-	-	262
Viscosity at 40 °C [mm^2/s]	70.21	74.52	74.96	81.4	131.3
Viscosity at 100 °C [mm^2/s]	11.43	12.03	12.07	12.44	16.06
Viscosity index [-]	157	158	158	150.00	130
Neutralization number [mg KOH/g]	0.28	0.23	0.36	3.6	15
FT-IR Oxidation [-]	42.85	41.01	41.81	46.49	50.27
Four ball weld load [kg]	120/130	130/140	-	-	150/160
Four ball wear test [mm]	0.7	0.6	-	-	0.9
Additive elements [wt. %]					
Phosphorus (P)	0	0	0	0	0
Sulphur (S)	0	0	0	0	0
Calcium (Ca)	0.001	0.001	0.001	0	0.001
Zinc (Zn)	0.0018	0.0018	0.0019	0.0017	0.0015
Wear metals [mg/kg]					
Chromium (Cr)	<5	<5	<5	<5	<5
Copper (Cu)	<3	6	11	13	30
Iron (Fe)	<3	<3	<3	<3	<3
Lead (Pb)	<3	<3	<3	<3	<3
Tin (Sn)	<20	<20	<20	<20	22
Foaming test [ml/ml]					
Sequence I.	0/0	0/0	0/0	10/0	0/0
Sequence II.	70/0	10/0	310/0	350/0	380/0
Sequence III.	10/0	0/0	10/0	50/0	0/0
On-line sensors at 40°C	**TO3 0**	**TO3 150**	**TO3 180**	**TO3 210**	**TO3 250**
Dielectric constant S1 [-]	3.0890	3.0820	3.0884	3.3838	4.0132
Dielectric constant S2 [-]	3.5457	3.4730	3.4635	3.7867	4.3333
Dielectric constant S3 [-]	3.3663	3.4590	3.4010	3.6543	4.4135
Electric conductivity [pS/m]	823	8625	21802	101325	232723
Relative humidity [%]	14.3	8.7	6.4	11.6	9.6
Viscosity S1 [mm^2/s]	52.2	55.4	76.3	87.0	107.0
Viscosity S2 [mm^2/s]	72.6	78.4	82.1	89.1	144.5

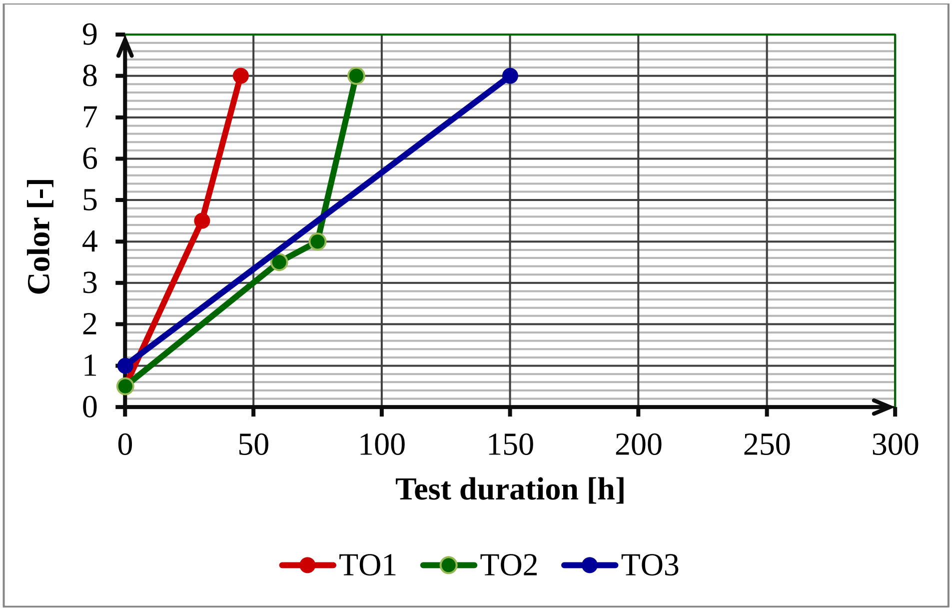


Figure 8.1: Colour comparison by accelerated thermal oil ageing

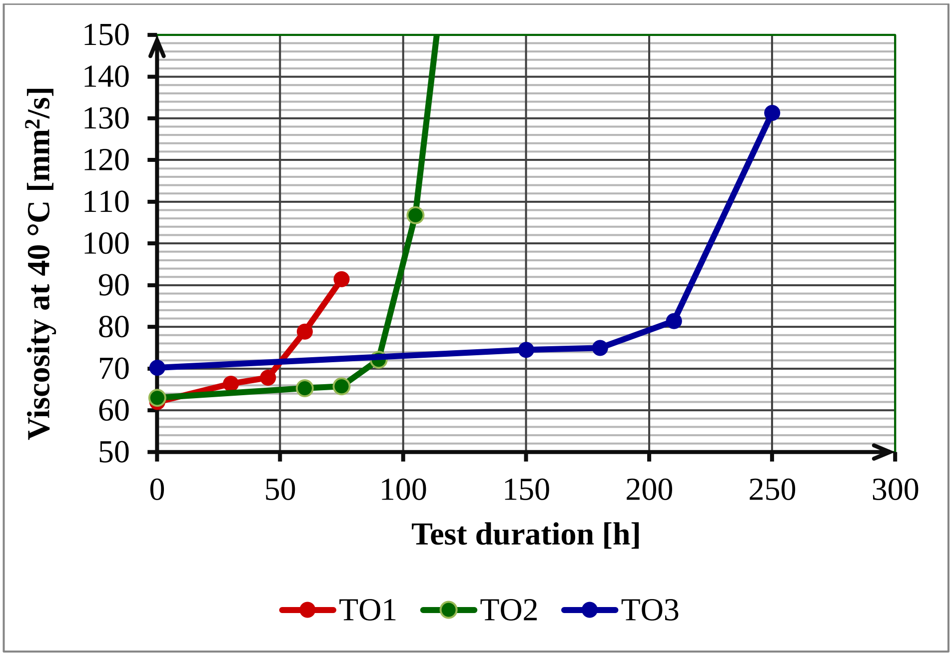


Figure 8.2: Viscosity comparison by accelerated thermal oil ageing

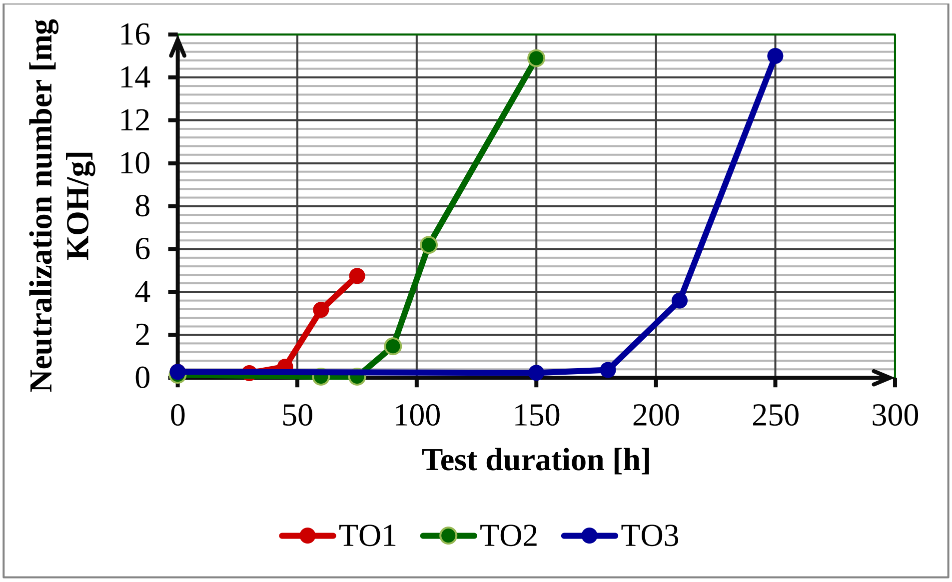


Figure 8.3: Neutralization number comparison by accelerated thermal oil ageing

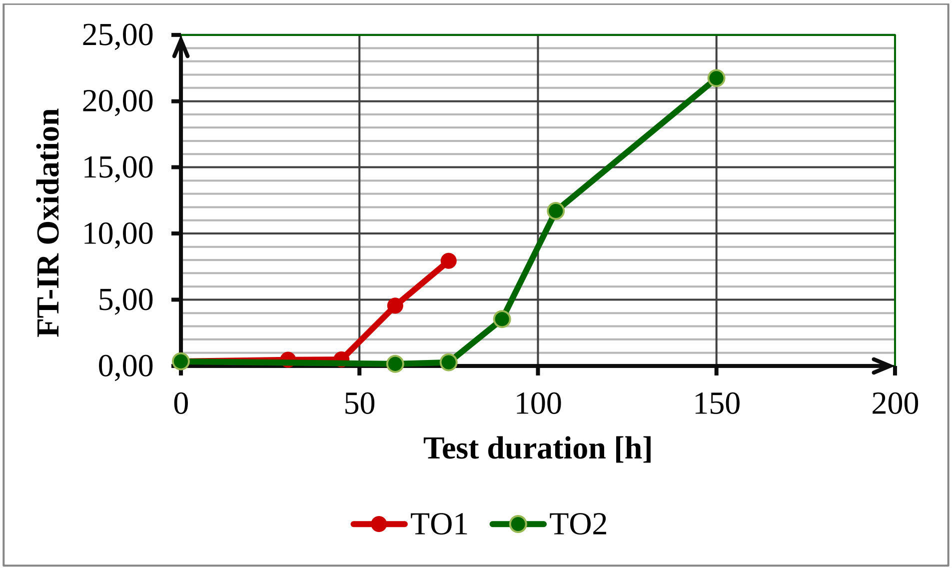


Figure 8.4: FT-IR oxidation comparison by accelerated thermal oil ageing (TO3 is not included since it is not a mineral oil and thus cannot be evaluated by the same method

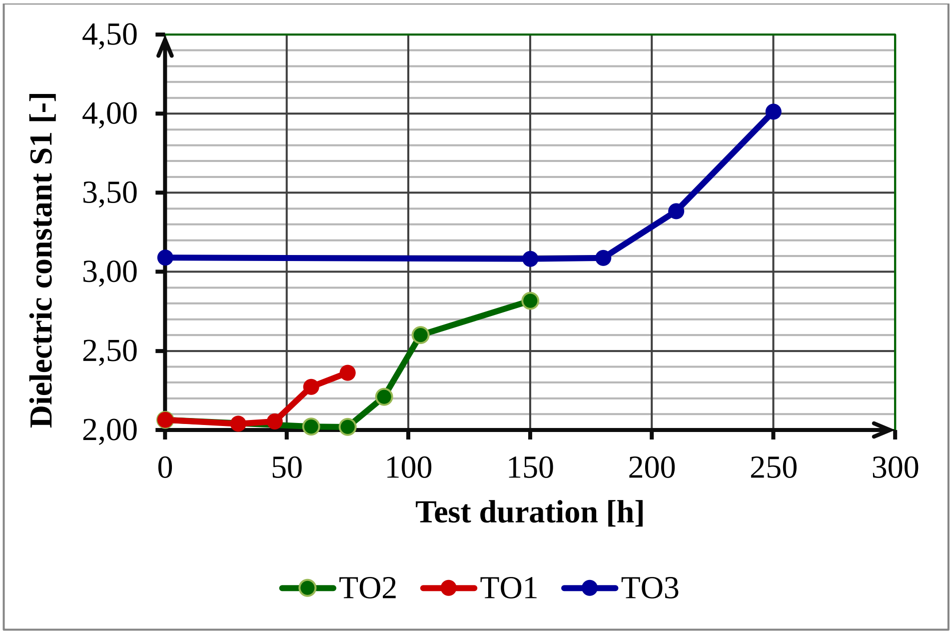


Figure 8.5: Dielectric constant comparison by accelerated thermal oil ageing

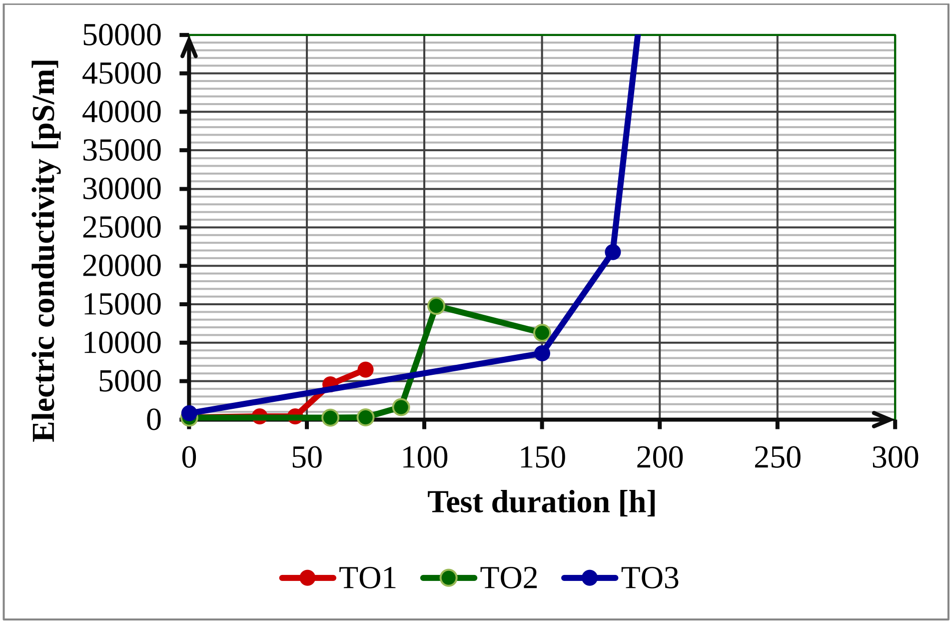


Figure 8.6: Electric conductivity comparison by accelerated thermal oil ageing

9 CONCLUSION

Extending the service-lives of hydraulic fluids is gaining prominence due to several considerations including environmental pollution, conservation of natural resources and the economic benefits associated with extended service-life.

By using the enhanced fluid management techniques several economic and environmental benefits could be obtained over a longer period of time, including reduced fluid and disposal costs, reduced machine downtime and maintenance costs, as well as reduced environmental impact due to less manufacturing, transport, and fluid disposal.

The presented novel method for testing the durability and oxidation stabilities of hydraulic fluids could be simultaneously used in two ways. Firstly, to compare different hydraulic oils and select the most adequate oil with high oxidation stability and a long service-lifetime. Secondly, on the basis of the test results, an intelligent health and prognostic method is proposed for providing accurate assessment of an oil's condition and its remaining useful lifetime, which could help extend the service life of the oil without concerns about damaging the equipment.

The presented method is effective and assesses the condition of the oil and its remaining useful life with sufficient precision after approximately one third of the oil's service-life. The maximum error can be seen during the early stages after oil refill due to the old oil residue which can be located in the hydraulic pipeline when the oil fill is being changed. After the initial system start-up the deteriorated oil residue "contaminates" the fresh oil resulting in a sudden change in overall oil condition. The presented mathematical model is based on regular HLP ISO VG 46 mineral oil and can be, according to the identical procedure include accelerated oil ageing and creation of a proper mathematical model, transferred to the very wide spectrum of other hydraulic fluids and machines such as central lubricating systems, gearings etc.

As already mentioned the developed mathematical model is adapted only to the fluid concerned, whereas it does not consider the design of the hydraulic device and operating conditions to which it is exposed. Further development options could cover the creation of a mathematical model that would also consider the operating circumstances to which the observed oil is exposed, where the input data for creation of the hybrid mathematical model would be acquired from the individual industrial application. Therefore, for the first model implementation into the real industrial environment, the use of the hybrid mathematical model based on accelerated hydraulic fluid ageing is recommended, while for the next iteration or filling the model can be up-dated with real data acquired at the time of the previous filling.

In contrast to a vast variety of condition monitoring signals on the same device that the user does not understand, our method outputs only two simple, straightforward quantities: oil condition and its RUL. The method was developed according to the user preferences and it is based on many years of practical experience. We have obtained good results regarding correlation of our model with the real conditions, as presented in Chapter 7.

Since the process of oil degradation is known to have exponential progress, the new method was specially designed to linearize this phenomenon unlike certain other methods, where monitored value drops suddenly before oil change is needed. Consequently, such methods cannot ensure adequate linear information on the remaining useful lifetime of mineral hydraulic and turbine oils.

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[5] *ASTM D341 Standard Practice for Viscosity-Temperature Charts for Fluid Petroleum Products*

[6] *ASTM D445 - Standard Test Method for Kinematic Viscosity of Transparent and Opaque Fluids (and Calculation of Dynamic Viscosity)*

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[12] *ASTM D943 Standard Test Method for Oxidation Characteristics of Inhibited Mineral Oils*

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LIST OF ILLUSTRATIONS

LIST OF TABLES

LIST OF ABBREVIATIONS

The interpretation of symbols, quantities and their units, used in each equation, are given directly after the equation or they are explained in the text before or after the equation.

EP – Extreme pressure
FS – Full scale
FT-IR – Fourier transform infrared spectroscopy
ICP-OES – Inductively coupled plasma atomic emission spectroscopy
IDT – Inter-digital transducer
IR – Infrared
OCM – On-line condition monitoring
PHM – Prognostics and health management
QMB – Quartz microbalance
RUL – Remaining useful lifetime
SAW – Surface acoustic wave

REVIEW

ŽELJKO ŠITUM

Hydraulic fluid is the most vital component of hydraulic systems, which are very often used under extremely close tolerances. In order to certify fluid cleanliness levels, fluid analysis and condition monitoring of hydraulic fluids throughout their life-cycles have become essential in many engineering systems for ensuring optimum performance level.

This scientific level monograph provides an extensive description of quantitative assessing conditions for mineral hydraulic and turbine oils, and methods for predicting their remaining useful lifetime, making it a source of practical guidance supported by basic theory. The comprehensive text has been designed to assist engineers within companies in the methods and devices used to monitor the fluid condition of machinery, and to assist in explaining the physical -chemical properties of fluid that are important to ensure convenient operation of the plant.

It also provides undergraduate students in Mechanical Engineering with a good coverage of the topics related to the condition monitoring and on-line analyses of hydraulic fluids, oil degradation mechanisms, accelerated oil ageing processes, methods for predicting the remaining useful lifetime, etc., required for hydraulic systems examinations.

The text is accompanied by a large number of pictures, diagrams and Tables of hydraulic oil analysis results in different working conditions to make reading easier. Based on a thorough review of literature, standards and product information, as well as on-line measurement on real -world industrial systems, this book offers modern access to intelligent systems for assessing oil's condition in engineering systems, and points to the benefits that such strategies can bring to end users of hydraulic plants.

The text introduces ideas of enhanced fluid management techniques that can yield certain economic and environmental benefits for engineering problems of general interest. The monograph is oriented mainly towards Mechanical Engineers for a better understanding of efficient methods for assessing oil condition and models that can predict oil's useful life, although parts can be read without special knowledge of these issues. At the same time, the book can be a useful manual for explaining the properties of hydraulic fluids, the influence of additives, the proper oil sampling used for the analysis process, overview of oil ageing tests, etc. Where appropriate, the reader is referred to more specialised literature of particular topics.

The book content has been written in a concise format that is integrated with the relevant results carried out on a large number of oil samples. As experienced hydraulic fluid analysis experts, the authors manage to provide a very useful overview of this topic, and also introduce their own idea, especially for durability testing and oxidation stabilities of hydraulic fluid and the implementation of these methods in practice.

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REVIEW

FRANC MAJDIČ

The monography "*On-line condition monitoring and evaluation of remaining useful lifetimes for mineral hydraulic and turbine oil"* presents very important technical field. The quality of mineral hydraulic and turbine oils plays an important role in the efficiency and durability of the hydraulic system or electric transformer. Sampling of fluid and laboratory analyses are, in general, used mostly for time interval control of fluid quality. The advantages of such laboratory approach are in the relevance and comparability of the results. Disadvantages of laboratory analyses are in poor repeatability of taken samples, the time-consuming process from taking the sample to getting the result, lower availability, lower comparability of results, and high price. The development of modern measurement techniques offers an alternative to the aforementioned laboratory analysis. The present monograph covers the missing field of the technique of on-line analysis of the condition of hydraulic and transformer oils. On-line monitoring offers a lot of advantages, primarily permanent, continuous control of the condition of the fluid, the accessibility of results over the Internet and mobile networks, directly to anywhere. Continuous monitoring of the fluid conditions allows the immediate action of the maintenance workers, given its significant degradation. Such approach is closely related to the industry 4.0 and IoT.

The monograph consists of nine chapters; Introduction, Condition monitoring of hydraulic fluid, Composition and degradation mechanisms of mineral hydraulic oil, Application and installation of no-line sensors, Analysis of fresh hydraulic oil, Change mechanisms of physical-chemical properties-accelerated oil ageing, Methods for evaluating oil condition and predicting remaining useful lifetime, Comparisons between oxidation stabilities and expected service-lives of oils and Conclusion.

In the Introduction, the authors first describe the benefits of oil condition monitoring, and then continue with the background of the development of an on-line condition monitoring system for hydraulic fluids. The background of condition monitoring of hydraulic fluid is described in the second chapter. Advantages and disadvantages of laboratory analyses are shown. A number of conventional laboratory analyses are presented below.

The third chapter presents the mechanisms of the degradation of mineral hydraulic oils. Very useful guidance on how to choose and where to install the proper sensor, and how to acquire and evaluate measuring signals, are given in the fourth chapter, and in the next, the fifth chapter, tips for users about analyses of fresh fluids.

The sixth chapter deals with physical-chemical properties and accelerated oil ageing mechanisms and procedures. This knowledge is needed in the industry to understand how to avoid too fast ageing of hydraulic fluids. In the following seventh chapter, the methods for evaluating oil condition and predicting the remaining useful lifetime are presented, and the eight chapter help to answer the question about the influence of oxidation on expected service-lives of oils.

The Conclusion repeats briefly all the important facts about on-line monitoring of hydraulic fluids.

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The book content has been written in a concise format that is integrated with the relevant results carried out on a large number of oil samples. As experienced hydraulic fluid analysis experts, the authors manage to provide a very useful overview of this topic, and also introduce their own idea, especially for durability testing and oxidation stabilities of hydraulic fluid and the implementation of these methods in practice.

Željko Šitum, Ph.D.

The monography "On-line condition monitoring and evaluation of remaining useful lifetimes for mineral hydraulic and turbine oil" presents very important technical field. The quality of mineral hydraulic and turbine oils plays an important role in the efficiency and durability of the hydraulic system or electric transformer.

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