DETERMINATION AND COMPARISON BETWEEN DIFFERENT HYDRAULIC AND TURBINE OILS' LIFETIMES

Darko Lovrec
University of Maribor, Faculty of Mechanical Engineering
Maribor
Slovenia

Vito Tič
University of Maribor, Faculty of Mechanical Engineering
Maribor
Slovenia

ABSTRACT
Conventional mineral hydraulic and turbine oils have relatively long service-lives that can reach even up to 10 or 20 years if the oil is properly monitored and maintained. The reasons are well-known as to why lubricants age and need to be replaced periodically. However, lesser-known is the fact that there are great differences in the durability of hydraulic oils when exposed to machine-operating conditions. Any extensions in the service-lifetimes of hydraulic and turbine oils can deliver both cost savings and environmental benefits. Therefore, it is reasonable to investigate and predict their service-lives using an accelerated oil-ageing test.
In order to evaluate the service-life of hydraulic and turbine oil, this paper proposes a novel method for testing the durability and oxidation stabilities of different hydraulic oils. The test results can be used to compare different oils and for selecting the more adequate oil with high oxidation stability and a long service-lifetime.

Keywords: hydraulic oil, testing method, useful lifetime

1. INTRODUCTION

Hydraulic systems are widely used within industrial automation systems and therefore their reliable and smooth operation is crucial for continuous uninterrupted production. One of the more important components of hydraulic systems is without a doubt the hydraulic fluid, as it directly affects the proper functioning of the whole system. The hydraulic fluid transmits forces and motion, lubricates all the tribological components, cools the hydraulic components, and prevents corrosion [1]. Therefore, in addition to proper maintenance of the hydraulic system itself, the maintenance of the hydraulic fluid is also crucial. Furthermore, the lifetime of the used hydraulic oil is highly dependent on the type of applied hydraulic oil (whether it is common mineral-based hydraulic oil, an additional pre-treated mineral oil, mineral oil with the additions of different additives or it is used as non-mineral oil based hydraulic fluid, e.g. synthetic esters).
In order to satisfy the above requirements, especially regarding the long service-lifetime, the different physical and chemical properties of the hydraulic fluid must remain within certain

limits. Unfortunately, throughout its life-cycle the hydraulic fluid is subject to several physical and chemical operational effects [2], e.g. high pressures and temperatures, oxidation, mechanical and/or fluid contamination and others, as shown in Figure 1. Consequently, over time the hydraulic fluid loses its abilities for performing the key functions and therefore must be changed.

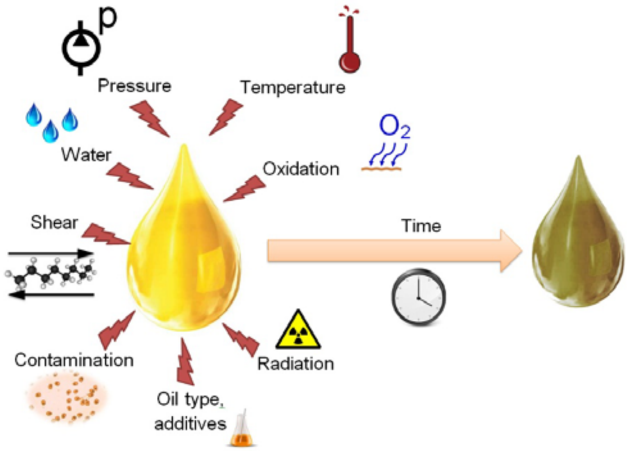

Figure 1. Operational effects on hydraulic fluid

Nowadays the lifetimes of the hydraulic fluids are still mainly determined by the machines' manufacturers, i.e. at certain fixed time intervals or number of hours [2]. In most cases these are empirically estimated time intervals with certain degrees of safety factors. The actual quality of a fluid is rarely taken into account, or the operating conditions of the machine. Therefore the quality of a fluid may be better than estimated and the fluid may be changed much earlier than actually needed.

All the above-mentioned depend of the used hydraulic oil. Therefore it is very important to know what the durability of the used hydraulic oil is (under normal operational conditions). Different test methods are used to obtain this information.

2. OIL DEGRADATION AND AGEING TESTS

When properly maintained, mineral hydraulic oils have relatively long service-lives from 5 to 10 years and in the case of hydraulic turbine oils even more than 20 years. Therefore it is reasonable to obtain data regarding physical and chemical changes using an accelerated-ageing test.

Due to the diversity of the base-oils, and the diversity of additives present within the oil, it is impossible to provide a precise and unique statement regarding the general mechanisms of oil ageing and on-going chemical processes.

2.1. Oil degradation mechanisms

As already mentioned mineral oils oxidise during their service-lifetimes and this causes significant increases in friction and wear that affects the performance of the machine. The main effect of oxidation is a gradual rise in the viscosity and acidity of the oil.

The general mechanism of oil oxidation is believed to be a free-radical chain reaction - Figure 2. Any identification of the precise mechanism, however, is hindered by the complexity and variability of mineral oil composition. Basically, the end result is that the original hydrocarbons are converted into a series of carboxyl acids, ketones and alcohols, which can then form higher molecular weight components by condensation. The high molecular weight components form sludge and deposits that block the oil pathways.

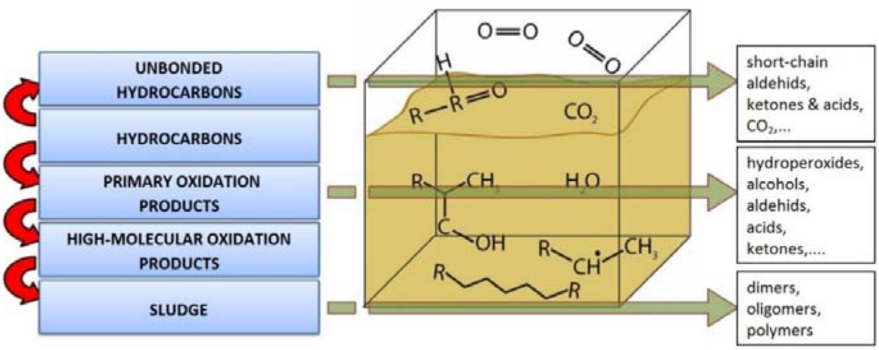

Figure 2. General mechanism of oil oxidation

The oxidation rates can be affected by temperature, metals in contact with the oil, and the amount of water and oxygen present within the oil. The temperature especially has a profound effect on oxidation rates, which can be doubled or even tripled by a temperature rise of 10 °C [1]. This is why accelerated oil-ageing tests usually involve high temperatures, high pressures and the additions of different catalysts, and water - Table 1.

Table 1. The impact of different catalysts on the service-lifetime of mineral oil

Catalyst	Water	Operating hours	Neutralisation number
None	No	> 3,500	0.17
None	Yes	> 3,500	0.90
Fe	No	> 3,500	0.65
Fe	Yes	400	8.10
Cu	No	> 3,500	0.89
Cu	Yes	100	11.20

2.2. Ageing test for lubricants

The commonly used accelerated oil-ageing tests can be divided into two main groups: the mechanical ones and the thermal or chemical ones.

The mechanically accelerated oil-ageing tests performed on specially built test rigs are otherwise closer to real conditions but they have very long testing times. Therefore these kinds of tests are performed using real hydraulic components under harsh, tougher usages: higher temperatures and pressures, smaller oil quantities, bigger pump-sizes, higher contamination with solid particles, higher water content or moisture, etc. Some of the more important tests of this-kind of (standardised) test are mentioned below:

- FZG – ASTM D5182 (transmission test),
- Eaton/Vickers 35VQ-25 – ASTM D6973 vane pump test [3],
- Similar pump tests: Denison T5D, Denison P46, JDQ-84 Sundstrand, Komatsu 500 h test, and others.

The main disadvantage of these tests is their long duration - in some cases over more than 1,000 hours there could be no noticeable changes inside the component parts, despite the harsh operating conditions.

By using the so-called thermal oil ageing tests we obtain quicker information regarding the oil durability.

There are several standardised accelerated-ageing tests available, mainly developed for the evaluation of oxidation stabilities regarding fresh and in-service hydraulic oils, e.g. [4, 5]. They are based on exposing the hydraulic fluid to high temperatures, air or oxygen, different contaminants such as water, copper, iron, that act as catalysts. A brief overview of the common tests and their operational conditions can be found in Table 2.

Table 2. Overview of standardised thermal oxidations tests

Test (ASTM)	Gas	Pressure	Temp	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 listed tests are unsuitable for further extensive research related to the determinations and identifications of variations in the physical and chemical properties of the tested oils, as they are tested on smaller quantities of oil. The more established and more frequently used RPVOT [4] and TOST [5] tests are performed on only small amounts of oil samples: namely RPVOT – 50 g and TOST – 300 mL.

Therefore we were forced to develop our own thermal test for accelerated oil-ageing using a larger sample volume of 1,500 mL, which would suffice for all subsequent laboratory analyses (so-called the thermal dry LaOH test). Our own novel test is based on the more established and more frequently used standardised RPVOT and TOST tests. During our test, the oil is heated using a magnetic mixer to 160 ± 0.1 °C whilst 3 ± 0.1L/min of air is being constantly induced. The test also includes a catalyst in the form of a 1.5mm^2 copper wire of which 15m is bent into a spiral

Figure 3. Thermal durability LaOH test for hydraulic oils

The test is carried out under atmospheric pressure within a sealed chamber with a dedicated system oil extraction of oil vapour. As shown in Figure 3, the chamber allows for the testing of both single and multiple samples at the same time.

The used test does not have specific (prescribed) end-times because its main goal is to record and capture the process of accelerated oil-ageing over its service-life. Thus multiple tests over various durations are carried out on one type of oil in order to achieve different degrees of oil-ageing and oxidation rates. In this way, we obtain several different degraded samples on which we can carry out further laboratory analyses. After the test, all the samples are first measured using several on-line sensors and then sent to a laboratory for further in-depth chemical analysis.

Figure 4. Hydraulic mineral oil samples after the different testing hours; different degrees of ageing and oxidation;sludge formation on copper wire

2.3. Test results

The tests and laboratory analyses conducted (Table 3 and Figure 5) revealed that the oil-ageing and oxidation processes can best be monitored and evaluated using the following parameters:

- colour (ASTM D 1500) [6],
- viscosity (ASTM D 445) [7],
- neutralisation number (ASTM D 974) [8],
- FT-IR oxidation (ASTM E 2412) [9],
- ...

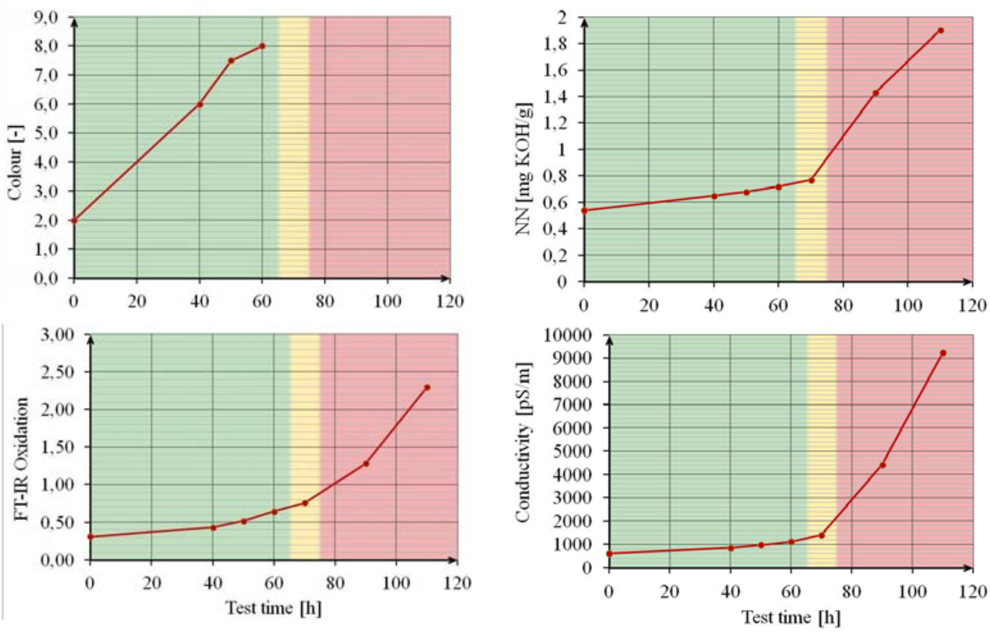

Figure 5. Accelerated oil-ageing test results

Table 3. Results from individual samples after the accelerated thermal ageing test

Sample	**HL 0**	**HL 40**	**HL 50**	**HL 60**	**HL 70**	**HL 90**	**HL 110**
Test time [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
Neutralisation nr. [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 [kg]	130/140	130/140	130/140	130/140	130/140	130/140	140/150
Four-ball (1 hour) [mm]	0.5	0.5	0.5	0.5	0.5	0.55	0.7
Additives [Ut. %]							
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 [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 the basis of the described test and after the detailed laboratory analysis of the more important physical and chemical parameters of the oil, comparative testing of three different turbine oils was carried out.

3. DETERMINATION OF DIFFERENT HYDRAULIC AND TURBINE OILS' LIFETIMES

In regard to testing the useful lifetimes or durability of hydraulic turbine oils three different turbine hydraulic oils types have been used: mineral turbine oil (TO1), pre-treated mineral turbine oil (TO2), and saturated synthetic ester as a turbine oil (TO3). All three types of turbine oils were tested according to the described procedure - the durability dry thermal test. The tests and laboratory analysis conducted revealed that:

- Certain oils resist the oxidation and ageing processes much better than others and may have double or even several multiple extended service lifetimes.
- The results can be used for carefully selecting more appropriate high quality oils with high oxidation stabilities, which would have extended service -lives.

After the completion of a more detailed analysis using laboratory results for the physical and chemical parameters of the tested oils, the results revealed that oil-ageing can best be monitored and evaluated by (for comparison see Table 3):

- colour (ASTM D 1500),
- viscosity (ASTM D 445),
- neutralisation number (ASTM D 974),
- FT-IR oxidation (ASTM E 2412)
- and electrical conductivity.

The electrical conductivity as a physical-chemical parameter and as an oil-ageing degree indicator is especially appropriate for an on-line Condition Monitoring system.
A direct comparison between the results on the same graph certainly provides better insight into the changing of individual parameters during the testing times, using the same time-scale - Figure 6.

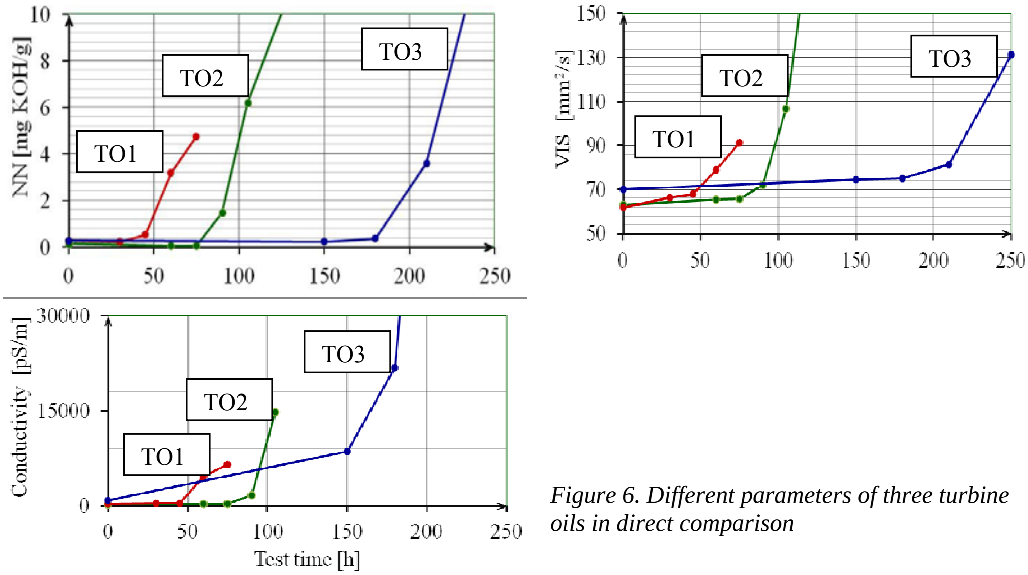

Figure 6. Different parameters of three turbine oils in direct comparison

If we take a closer look at the graphs shown in Figure 6, we can make comparisons between three different turbine oils' performances during the test. We can see the poor performance of 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 the turbine oil TO2 (green line), which 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 higher than those of TO1 and TO3.

The Neutralisation number (NN) and Electrical conductivity are two very important or revealing parameters regarding the state of oil degradation were recalculated to ‘real time’ and ‘real operating’ conditions - at operating oil temperatures of 60°C, as shown in Figure 7.
As known from the literature, at temperatures higher than 70°C for every 10°C the status changes by a factor of 2oz, and the same condition increases the time by a factor of 2. This should be at a temperature of 80°C instead of 70°C, and thus the lifetime of a mineral oil is halved. This can be written in the equation below:

$$f = 2^{\frac{T - T_{ref}}{10}} . \qquad \dots (1)$$

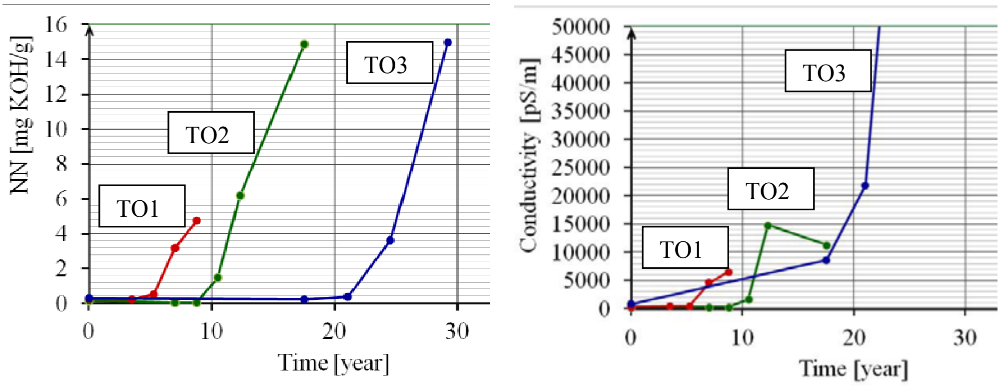

Figure 7. Results of measurements converted to real-time and real operating conditions

Both Figure 6 and Figure 7 show the differences between the various turbine oils' resistances to ageing and are very significant, even more than 4 times. The reason is, that saturated esters (TO3) do not readily react with oxygen and are, therefore, significantly more stable than non-saturated ester products. This is also a major factor in their 'lifetime fulfilling' characteristics.

4. CONCLUSION

The extensions of service-lives regarding 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 and hydraulic oil with the highest durability, several economic and environmental benefits can be obtained over a longer period of time.

The presented novel method for testing the durability and oxidation stabilities of hydraulic fluids can be simultaneously used in two ways. Firstly for comparing different hydraulic oils and for selecting more adequate oils with higher oxidation stabilities and longer service-lifetimes and secondly for the development of a prognostic model for an accurate prediction of an oil's condition and its remaining useful lifetime, which could help to extend the service life of the oil without concerns about damaging the equipment.

5. REFERENCES

[1] Meindorf T., Dyck H.: New Maintenance Concepts by Continuous Oil Monitoring. Proceedings of OilDoc 2011 conference. Rosenheim, Germany, 2011.,

[2] Lovrec D., Kambič M.: Hidravlične tekočine in njihova nega. Faculty of Mechanical Engineering, Maribor, 2007.,

[3] ASTM D6973 Standard Test Method for Indicating Wear Characteristics of Petroleum Hydraulic Fluids in a High Pressure Constant Volume Vane Pump.,

[4] ASTM D2272 Standard Test Method for Oxidation Stability of Steam Turbine Oils by Rotating Pressure Vessel.,

[5] ASTM D943 Standard Test Method for Oxidation Characteristics of Inhibited Mineral Oils,,

[6] ASTM D1500 - 07 Standard Test Method for ASTM Color of Petroleum Products.,

[7] ASTM D445 - Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and Calculation of Dynamic Viscosity).,

[8] ASTM D974 - Standard Test Method for Acid and Base Number by Color-Indicator Titration.,

[9] ASTM E2412 - Standard Practice for Condition Monitoring of Used Lubricants by Trend Analysis Using Fourier Transform Infrared (FT-IR) Spectrometry.