

Monitoring oil degradation during operating tests

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Abstract. This paper deals with a lifetime test of the hydraulic and transmission oil, Shell Spirax S4 ATF (Universal Tractor Transmission Oil (UTTO)). This fluid was used in the hydraulic and transmission circuit of a John Deere 5720 tractor. The fluid was assessed in terms of a possible contamination of chemical elements. Fluid samples were taken from a John Deere 5720 tractor at intervals of 250 engine hours. These samples were subjected to an IR spectroscopy analysis, a measuring of the kinematic viscosity at 40 °C, and differential scanning calorimetry (DSC). The spectrometer, Spectroil Q100, has been used to monitor chemical elements.

Key words: hydraulic and transmission circuit, tractor, chemical elements.

INTRODUCTION

Hydraulic equipment is widely used in powerful mechanisms that are part of agricultural and forest machines, as well as in many other areas. The development of modern hydraulic components is aimed at increasing the transmitted power, reducing energy intensity (by the use of smaller reservoirs of hydraulic fluid), minimising environmental pollution, and increasing technical life and machine reliability (Tkáč et al., 2008; Hoffmann et al., 2013). Hydraulic and transmission fluid requires quality parameters to be monitored (regarding any concentration of metallic elements and any concentration of chemical elements representing the additives). Fluid purity is one of the most important features in the entire process (Máchal et al., 2013; Majdan et al., 2013). Very often, the questionable purity and general technical condition of hydraulic and transmission fluid are frequent the causes of failures in transmissions or hydraulic system in tractors. Contaminated fluid creates a risk to the machine in terms of wear and failure (Tulik et al., 2013). Pollution (a concentration of metallic elements) is dangerous because it accelerates the degradation and oxidation processes in the fluid. If the fluid is contaminated by dirt above the permitted level, it must be replaced (Majdan et al., 2014).

Universal Tractor Transmission Oils (UTTOs) are designed for hydraulic and transmission systems in agricultural tractors. These fluids provide lubrication functions for the gear box and the transmission of energy in the tractor's hydraulic system (Hujo et al., 2013). The friction points in the hydraulic and transmission circuit are made from several metals (mostly iron, aluminium, and copper components) (Kumbár et al., 2014). For this reason there is a need to check for other metals, such as aluminium, copper, chromium, lead, tin, nickel, silver, etc (Kumbár & Dostál, 2013). The behaviour of the oils at low temperatures is also important. Bai & Bai (2014) wrote that, in many cases, thermal analysis is required, especially for fluids that are viscous and have high freezing points or in cold weather conditions. Schubring (2009) deals with problems related to freezing of oil. Differential scanning calorimetry (DSC) has been used successfully in oil investigations for quite a long period of time (Kök et al., 1999; Santos et al., 2005). DSC has some advantages over other classic detection methods, as it is rapid and does not require excess sample preparation or solvent utilisation and, therefore, it is an environmental friendly technique (Dahimi et al., 2014).

MATERIALS AND METHODS

An operational test of a specific hydraulic and transmission fluid, Shell Spirax S4 ATF, was set at 500 engine hours (EH). Oil samples were taken after completing 250 and 500 engine hours. Subsequently, fluid samples were collected for analysis and the detection of any contamination. As regards the utilisation of hydraulic and transmission fluid in a machine, the most important factor is knowing the running properties of the fluid, ie. knowing the effect of the fluid on the technical condition of hydraulic and transmission system parts.

The hydraulic and transmission fluid, Shell Spirax S4 ATF, was used in the hydraulic and transmission circuit of a John Deere 5720 tractor. Table 1 shows the basic technical parameters of the hydraulic and transmission fluid.

Table 1. Technical parameters for Shell Spirax S4 ATF

Properties	Unit	Amount
Kinematic viscosity at 40 °C	mm s ⁻²	33.2
Kinematic viscosity at 100 °C	mm s ⁻²	7.2
Density at 15 °C	kg m ⁻³	847.0
Flash point	°C	185.0
Pour point	°C	-48.0

Determining the chemical composition of hydraulic and transmission fluid is something that has been measured using Spectroil Q100, which is a completely solid state spectrometer. Using this spectrometer, measurements can be taken of trace levels of elements which have been dissolved or deposited as fine particles in mineral or synthetic oil-based fluids using a long-established and reliable technique that involves a rotating disk electrode. This spectrometer meets the requirements of the ASTM D6595 standard when it comes to determining the wear rate of metals and the levels of contaminants in lubricating oils and hydraulic mixtures that are being used (Kumbár et al., 2014). The following parameters were evaluated:

- ✓ any concentration of metallic elements (Ag, Al, Cu, Cr, Fe, Mg, Mo, Mn, Ni, Ti, Si),
- ✓ any concentration of chemical elements representing the additives (B, Ca, P, Zn),
- ✓ kinematic viscosity at 40 °C,
- ✓ the pour point by means of differential scanning calorimetry.

Differential scanning calorimetry (DSC) is a technique in which any difference in heat flow (power) to a sample and to a reference is monitored against time or temperature while the temperature of the sample, in a specified atmosphere, is programmed (Haines, 1995). The differential method compares the thermal behaviour of reference material against a sample. This method provides information on thermal effects which are characterised by an enthalpy change and by a temperature range, such as phase transitions (melting, crystallisation, etc).

Differential scanning calorimetry (DSC) was carried out on a Mettler Toledo DSC unit (Fig 1). Samples with a weight of between 8–13 mg were hermetically sealed in aluminium crucibles and thermally treated at a speed of heating of 2K min⁻¹ within a temperature range of 20 °C and minus 60 °C. The measurement was carried out in an ordinary air atmosphere. As a result we got a DSC thermogram, which was evaluated using STAR[®] software.



Figure 1. Mettler Toledo DSC unit.

RESULTS AND DISCUSSION

Table 2 show an increase in the concentration of chemical elements in hydraulic and transmission fluid during tractor operation. A concentration of chemical elements represents fluid contamination. Any increase of chemical content (for 250 engine hours) and then decrease of chemical content (for 500 engine hours) is caused by the filtration of particles in the tractor filter system. Hydraulic fluid (fluid filling) is not homogeneous. During the tractor being operated under normal conditions, wear particles are absorbed by the tractor's oil filter system.

Table 3 shows the base elements that characterise the set of additional packages. The chemical properties of the hydraulic fluid, being used as the quality evaluation parameters, were monitored in publications by authors Kučera & Rousek (2003), Majdan

et al. (2014), Phillips & Staniewski (2016). The authors focused on kinematic viscosity, additive content, and fluid contamination.

Table 2. Concentration (mg kg⁻¹) of chemical elements

Chemical content	Count of engine hours		
	0	250	500
Ag	0.04	0.09	0.1
Al	0.39	3.41	2.87
Cu	0.29	20.47	19.13
Cr	0	0.64	0.79
Fe	0	49.63	37.24
Mg	11.73	12.85	11.5
Mo	0.48	1.47	1.85
Mn	2.8	4.17	3.98
Ni	0.55	0.62	0.69
Ti	1.2	1.19	1.7
Si	4.44	14.7	12.16

Table 3. Concentration (mg kg⁻¹) of chemical elements representing the additives

Chemical content	Count of engine hours			ΔE (%)
	0	250	500	
B	83.34	69.28	63	24.41
Ca	2531	2,196	2,067	18.33
P	1,222	1,195	1,153	5.65
Zn	1,438	1,242	1,230	14.46

The biggest increase of deposited metals in the oil were observed in relation to copper (Cu), iron (Fe), and Silicon (Si). Iron (Fe) and Silicon (Si) are used as construction material in the transmission, and copper (Cu) is used as construction material in the oil cooling system. Any concentration of Cu, Fe, and Si are standard values of content, as shown in publications by the authors, Kumbár et al. (2014) and Tarasov, et al. (2002). Other changes in the chemical content of hydraulic and transmission oil are almost negligible.

The concentration levels of any additives were monitored on the basis of the relevant content of chemical elements (B, Ca, P, and Zn). The concentration of these chemical elements decreases due to a gradual depletion of additives in the hydraulic and transmission fluid. A decrease in the concentration of chemical elements that represents additives, ΔE , was calculated according to Eq. (1). A decrease in the content of these chemical elements is calculated by using the following formula:

$$\Delta E = \frac{E_0 - E_{500}}{E_0} \cdot 100 \quad (1)$$

where: ΔE is an increase of the content of chemical elements (%); E_0 is the content of chemical elements at zero engine hours (at the start of the test) (mg kg⁻¹); and E_{500} is the content of chemical elements at 500 engine hours (at the end of the test) (mg kg⁻¹).

The largest decrease was observed in the measuring of boron (B) at 24.41%. Zinc (Zn) is used as an anti-wear agent or as an antioxidant. Hydraulic and transmission oils with zinc additives that are too high have the habit of leading to metal corrosion as they chemically attack the metal surfaces (Nicholls et al., 2005). The decrease was observed in the measuring of zinc (Zn) at 14.46%. This decrease is relatively low according to publications by the authors Kumbár et al. (2014) and Hernández Battez et al. (2008).

Table 4 gives acceptable accuracy readings for chemical elements as a function of the standard concentration. Column 1 in Table 4 gives concentration values in mg kg^{-1} . For example, if a 50 mg kg^{-1} multi-element standard is burned on the Spectroil Q100, an average of ten burns for iron is expected to be 50 mg kg^{-1} , plus or minus 8.29 mg kg^{-1} . Therefore, an average in the range of 41.71 to 58.29 mg kg^{-1} would be acceptable.

Table 4. Acceptable accuracy indices for chemical elements (mg kg^{-1}) (Spectroil M Family of Spectrometers, 2009)

Conc.	Al, Cr, Ni, Si	Ti, B	Fe, Ag, Mo	Cu, Mg	Pb, Sn	Zn	Na	V, Mn, Cd, Ba	Ca	P
0	0.88	0.89	0.91	0.92	1.60	0.96	1.01	0.50	0.50	N/A
5	1.20	1.30	1.50	1.61	1.98	1.99	2.59	N/A	N/A	N/A
10	1.59	1.78	2.21	2.44	2.43	3.19	4.36	1.50	1.50	N/A
30	3.33	3.93	5.23	5.91	4.47	8.15	11.6	3.25	3.25	15.5
50	5.12	6.14	8.29	9.43	6.64	13.1	18.9	5.50	5.50	18.2
100	9.65	11.7	16.0	18.2	12.2	25.6	37.1	10.0	10.0	20.0
300	27.8	33.9	46.7	53.5	34.3	75.6	110	32.0	32.0	35.0
500	46.0	56.1	77.5	88.8	56.6	126	183	53.0	53.0	60.0
700	64.2	78.3	108	124	78.8	176	255	N/A	N/A	N/A
900	82.4	101	139	159	101	226	328	95.0	95.0	105
5000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	500	500

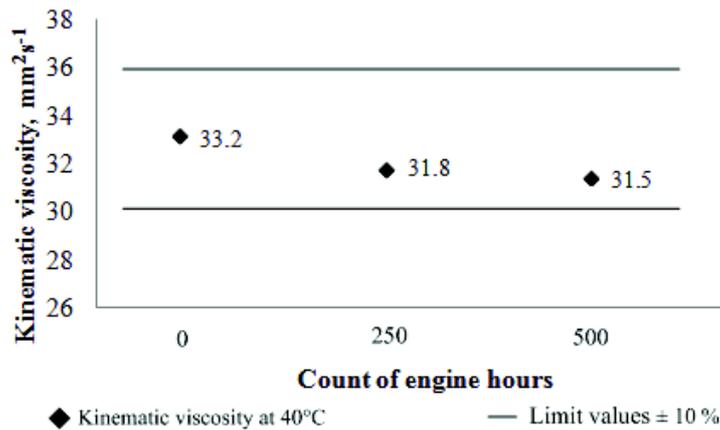


Figure 2. Kinematic viscosity at 40 °C during operating test.

Kinematic viscosity at 40 °C (Fig 2) is evaluated based on the positive or negative tolerance of the measured values in comparison with the value of new oil (at zero engine hours). Therefore, the kinematic viscosity at 40 °C of new oil must be evaluated. The deviation of kinematic viscosity at 40 °C is calculated by using the formula:

$$\Delta V = \frac{V_0 - V_{500}}{V_0} \cdot 100 \quad (2)$$

where: ΔV is the deviation of kinematic viscosity at 40 °C (%); V_0 is the kinematic viscosity at 40 °C at zero engine hours ($\text{mm}^2 \text{s}^{-1}$); and V_{500} is kinematic viscosity at 40 °C at 500 engine hours ($\text{mm}^2 \text{s}^{-1}$).

The decrease of kinematic viscosity at 40 °C was calculated as follows: $\Delta V = 5.12\%$ according to Eq. (2), based on the value of new oil, $v_0 = 33.2 \text{ mm}^2 \text{ s}^{-1}$, and the value of used oil, $v_{500} = 31.2 \text{ mm}^2 \text{ s}^{-1}$. The decrease of kinematic viscosity at 40 °C does not exceed the limit of 10% which is prescribed for the UTTO (the limit of kinematic viscosity changes from the beginning of the operating test). Alias et al. (2009) evaluated kinematic viscosity at 40 °C of palm oil-based TMP ester (TMPE) and found the increase in kinematic viscosity after completing 400 hours, $\Delta V = 1.72\%$.

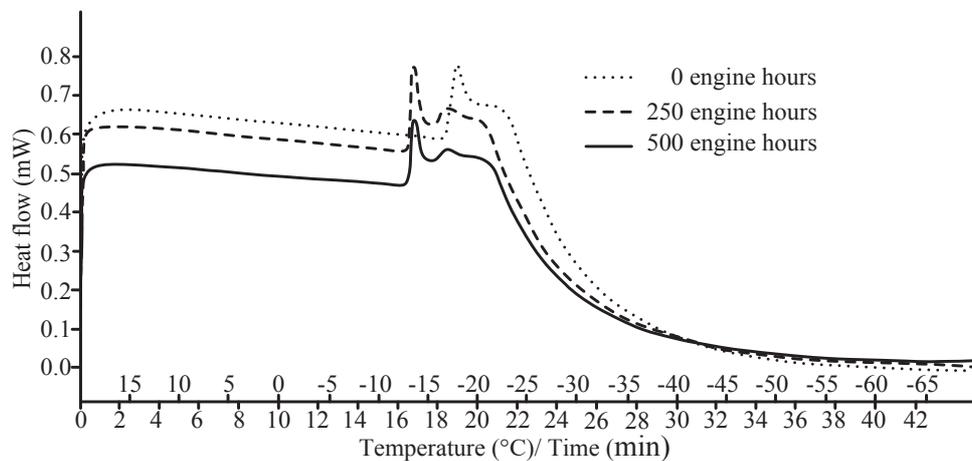


Figure 3. A comparison of oil samples by DSC.

DSC curves which correspond to a change of enthalpy due to thermal effects in the samples are shown in Fig 3. In the process of oil freezing and in the case of a new oil sample being used, we observed an exothermic peak at a temperature of $-17.85 \text{ }^\circ\text{C}$, corresponding to the pour point at which solidification occurs. Generally, the temperature for phase transition depends on chemical composition and on the crystalline structure of the materials. Since oil (at zero engine hours) is an amorphous matter, the point for the actual pour point takes place not only at one point, but in a range of temperatures which are shown in the graph (with an onset at $-16.89 \text{ }^\circ\text{C}$ and an endset at $-20.00 \text{ }^\circ\text{C}$). In the case of oil at 250 engine hours, the peak temperature was $-13.55 \text{ }^\circ\text{C}$ (with an onset at $-13.08 \text{ }^\circ\text{C}$ and an endset of $-14.75 \text{ }^\circ\text{C}$). In the last sample, representing used oil at 500 engine hours, the temperature for the exothermic peak was almost the same as the previous results, $-13.53 \text{ }^\circ\text{C}$ (with an onset at $-13.04 \text{ }^\circ\text{C}$ and an endset at $-14.78 \text{ }^\circ\text{C}$).

CONCLUSIONS

Tribotechnical diagnostics use oils as media that help when it comes to obtaining information about processes and changes in the systems that they lubricate. If tribodiagnostics are applied properly and thoroughly, they result in significant savings in many areas; for example, they contribute to an increase in the lifetime of machines and equipment, to a decrease in the consumption of energy, and to a limiting of idle time (Kučera et al., 2013).

The DSC graph indicates that peaks corresponding to the pour point for worn out samples are almost identical, so we can infer that the difference between 250 engine hours and 500 engine hours is not especially significant. But we can see the difference between a new and worn out sample. The pour point (or freezing temperature) from both worn out engine oil samples increased by more than 4 °C in comparison with a new sample: -13.55 °C (at 250 engine hours) or -13.53 °C (at 500 engine hours) and -17.85 °C (for a new engine oil sample). We consider that oil wear has a negative impact on thermal stability and temperature when the phase transition (solidification) occurrence is higher. Our results for the pour point are considerably different from the figures that have been indicated by the oil's producer (Table 1); the pour point introduced into the producer's specifications is set at -48 °C. This difference may be caused by several factors (incorrect data being provided by the producer, inappropriate storage conditions, or other unknown factors such as, for example, thermal history). The figure should be verified by means of experimentation in the next phase of research.

After completing 500 engine hours the operating test for hydraulic oil was completed. In Table 3 the decreasing trends for oil additives can be seen. The biggest decrease in oil additives was observed with boron (B) and cadmium (Ca). Boron (B) content decreases from 83.34 mg kg⁻¹ to 63.0 mg kg⁻¹, and cadmium (Ca) content decreases from 2,531 mg kg⁻¹ to the 2,067 mg kg⁻¹. Boron is used as corrosion inhibitor and cadmium is used as a detergent additive.

Kinematic viscosity is one of the most important properties for the characterisation of lubricants and their transport properties, and is a measure of internal friction in a fluid (Alias et al., 2009). For this reason we need to remember the differences for kinematic viscosity during the operating test.

Experimental results deliver important areas of information from the point of view of oil degradation. The majority of tractors are subjected to conditions (especially during the winter) which can cause an undesirable phase transition of oil in hydraulic systems. It is necessary to further develop and improve oil flow by means of the correct operation of hydraulic equipment. The oil flow rate is important to the life of the hydraulic system.

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