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Contamination of transmission and hydraulic oils in agricultural tractors and proposal of by-pass filtration system

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Abstract. Tractors use various types of lubricating oils in transmission and hydraulic system. Oils are contaminated by different ways depending on the work of the lubricated system. There are general requirements on the cleanliness level of the oil in the tractor transmission and hydraulic system according to the standard DIN 51524. According to all that, this paper presents research conducted by two tractors. The tractor John Deere 8100 used only its own implements (ploughs, trailers etc.) and it was operated in compliance with user manual. In this tractor, the oil cleanliness level met the standard DIN 51524 because reached the stage 7 (NAS 1638). The tractor Zetor Forterra 124 41 contained extremely contaminated oil, it reached stage > 12 (NAS 1638), due to the non-standard operation which was opposite to the user manual. Both ways of tractor operation are typical for farmers activity in the Slovak Republic, depending on the tractor type and style of agricultural production at most. The second part of this paper is aimed at the proposal of by-pass filtration system to eliminate the oil contamination. The by-pass filtration system is the second stage of the oil filtration in the tractor, whereas the first one means standard tractor filter. Function of the system was tested according to the decrease of chemical elements concentration characterising the oil contamination and visual method based on filter and its change after operating of tested tractor. There was evaluated the decrease of concentration of Fe (41.6%), Cu (28.7%) and Si (20.5%) after by-pass filtration system was running under operational conditions. It can be concluded that the by-pass filtration system was proposed correctly and it is suitable for tractors operation.

Key words: tractor oil, tractor maintenance, elimination of the oil contamination ~~elimination~~, quality of lubricants.

INTRODUCTION

Tribotechnical diagnostics is mainly aimed at qualitative changes of the oil properties and wear processes happened in machines. In this case, diagnostic parameters are obtained by means of the oil analysis. Changes of the oil technical state is the most common because of the chemical oxidation processes and contaminates presence. There are two sources of the hydraulic and transmission oil contamination (Fig. 1):

– external sources, as the dust and various liquids as the water from environment, the fuel for combustion, degraded oils from tractor implements (ploughs, seeders, trailers etc.), antifreezes from leakage of cooler etc.,

– internal sources (contamination coming from inside of the lubricated system), as wear processes of the machine (wear particles) and oil degradation processes (sludge, acids, etc.).

Fig. 1 shows the main sources of the oil contamination and contaminant types of the tractor hydraulic and transmission system. The external sources contaminate the oil from environment, the tractor implements and the tractor operation. Old, degraded and oxidized oils can contaminate the tractor oil if old and unknown implements (ploughs, trailers etc.) are connected to the tractor external hydraulic system. Lubricated systems are not ideally sealed, so certain amount of the dust and water can get to the oil. The tractor implement can be very significant source of the oil contamination if various tractors use the same implement. By using of incorrect type of the oil to refill or change the oil fill, the tractor operation can contaminate the oil.

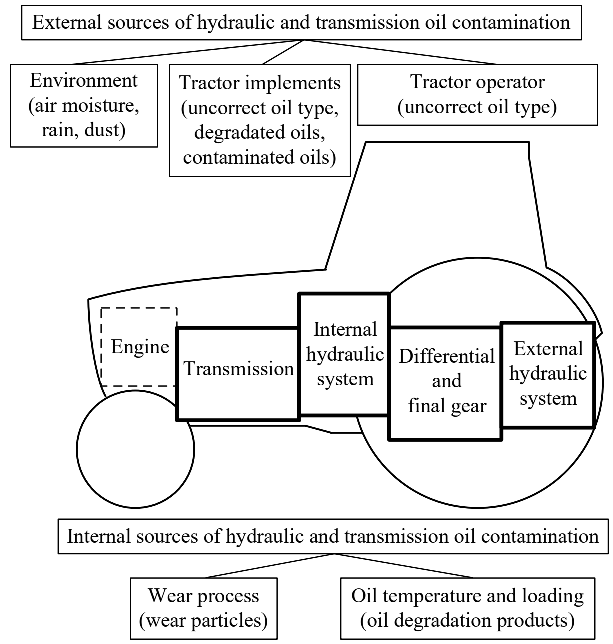

Figure 1. Internal and external sources of the oil contamination in hydraulic and transmission system of the tractor.

The tribotechnical diagnostics evaluates the technical state of machines based on the oil contamination coming from the wear process. In this case, adhesive, abrasive, erosion, and cavitation wear processes produce the contamination. The tribotechnical laboratories utilise the various techniques to detect failures of lubricated systems and lubricant degradation.

Hnilicová et al. (2016) presents, that hydraulic oil is subjected to the constant process of changes. Dust, water and wear particles constantly contaminate the oil systems. High operating temperature and contact with oxygen reduces its lifetime. The tribotechnical diagnostics uses several analytical methods to assess the degree of hydraulic oil degradation, thus its lubricating power and monitor the state of mechanical systems of the machines. Wang et al. (2016) presents, that the failure resulting from hydraulic oil contamination is the main mode in the case of the piston pumps. Thus, it had been established a life prediction model for aviation hydraulic piston pumps.

Wear particles have typical shape and size, depending on the type of wear process (adhesive, abrasive, erosive or cavitation). Metal wear particles are very dangerous for machines because they lead to the next wear processes if filters do not remove them and circulate in the system. All hard and insoluble particles (regardless of their origin) with larger size than is the clearance between moving parts are very dangerous, because they do not flow in the oil film and can stick in. To analyse the size, concentration, and origin of the wear particles, the following methods of the tribotechnical diagnostics can be used:

- Analytical ferrography, which uses strong magnetic field to separate particles from the oil sample. Non-ferromagnetic particles are separated while flow in the oil sample between ferromagnetic particles. Microscope allows observing shape, size and colour of the particles and states the particle origin by visual method. Tulík et al. (2014), Turis & Kučera (2016) and Tkáč et al. (2017) present evaluation of the contaminant particles in various hydraulic oils using the analytical ferrography.
- Direct reading ferrography (DR-ferrography), which measures amount of ferrous metals in the oil sample. Particles are classified into two groups. Particles larger than 15 μm (denoted DL) and particles smaller than 15 μm (denoted DS). The larger particles (DL) are produced by normal wear process and the smaller particles (DS) are produced by abnormal wear process.
- Filtration analysis, which separates contaminative particles from the oil sample using the paper filter disk. To separate the contaminative particles, the vacuum filtration unit is used. The particles on filter patch are evaluated by microscope. Comparing to the microscopic evaluation with reference photographs, the rapid assessment of the fluid contamination (cleanliness class classification by ISO 4406 or NAS 1638) can be made. This method can be also used for gravimetric analysis to determine the oil contamination.
- Gravimetric analysis, which quantifies the total mass of the particles from specific volume of the oil (mg dm^3). The gravimetric analysis cannot indicate the size of the particles. To state the distribution of the particle size, a particle counter is needed.
- Particle size distribution, which uses the particle counters to classify the contaminative particles according to their size. The particle distribution is expressed by one of the following standards:
    - ISO 4406-1999, which uses three figures (X_1 /X_2 /X_3) representing the level of the contamination grades for particles larger than 4 μm (X_1), 6 μm (X_2) and 14 μm (X_3). Rusnák et al. (2013), Kučera et al. (2015) and Kučera et al. (2016) present evaluation of the oil contamination according to the standard ISO 4406-1999.
    - NAS 1638, which applies one figure corresponding with the maximum allowed amount of the particles (i.e. worst-case) for the size range 5–15 μm, 15–25 μm, 25–50 μm, 50–100 μm and < 100 μm.
    - SAE AS 4059 (ISO11171), which uses six letters A, B, C, D, E and F representing the size of the particles (> 4 μm, > 6 μm, > 14 μm, > 21 μm, > 38 μm and > 70 μm) and number (X) representing the level of the contamination grade.
    - GOST 17216-2001, which uses one figure expressing the maximum level of the contaminative particles for the size range 5–10 μm, 10–25 μm, 25–50 μm, 50–100 μm and < 100 μm.
- Spectral analysis, which uses the principle of the spectroscopy to detect and quantify the chemical elements in the oil sample. If add back up energy to the oil sample, the chemical elements start to emit the spectrum with specific wavelengths. The spectral analysis involves various methods with different principles of chemical elements excitation f. e. the inductively coupled plasma spectrometry (ICP), the proton-induced X-ray emission (PIXE) or the rotating disc electrode optical emission spectroscopy (RDEOES). The spectral analysis is very precision

method specifying the concentration of the solid particles on the basis of the chemical elements concentration mainly for the smaller particles. Using the ICP spectrometry, Kosiba et al. (2013) and Tulík et al. (2017) monitored the solid particles in biodegradable oils. Research about RDEOES spectrometry is presented by Quazi & Khatavkar (2015).

All types of the oil contamination negatively affect machines and oils. In the extreme, the oil contaminants accelerate the wear process of very precision components of the machine. The solid particles generate other particles due to the abrasive were process. Metal particles and water are very harmful for oil oxidation stability and additives. Ecological oils are very sensitive to degradation. To apply the biodegradable oils, many researchers (Tóth et al., (2014a), Tóth et al., (2014b), Dobeš (2006) and Kučera et al., (2014)) require the highest possible oil cleanliness level to ensure the protection against degradation of the oil in machines. Machinery working in ~~an~~ agricultural sector is characterized by contact with primary food products and all elements of environment (Tkáč et al., 2014).

Therefore, it is necessary to research all factors affecting application of the ecological oils and also ensures reliable tractor operation. This paper presents the proposal of the by-pass filtration system and publish the observed results of the cleanliness level of the oils in the tractors hydraulic and transmission systems operating under standard and non-standard operation mode.

MATERIALS AND METHODS

Characteristics of monitored tractors and oils

The tractors were selected on the basis of cleanliness level of the universal transmission and hydraulic oils to present the difference between low and high level of the oil contamination. Regarding sources of the oil contamination (Fig. 1) of the tractor John Deere 8100 and Zetor Forterra 124 41 were selected.

The tractor Zetor Forterra 124 41 represents tractors which are often used on the small farms in the Slovak Republic because they are easy reparable and small farmers can repair it with reachable and relatively cheap spare parts. This tractor is an example of the simple construction of manual transmission and hydraulic system with external gear pump. The small farmers do not own all implements such as ploughs, trailers, seeders etc. so they can share them. Various tractors operate with various equipments because their simple construction allows it. So, the oil is often contaminated with degraded oils from the different tractors. These tractors do not immediately get out of order, but wear process of every lubricated part is accelerated and produces next solid particles. Zetor Forterra tractor uses the PP 90 (Slovnaft, Slovak Republic) gear oil type (Dynamax, 2017) in the hydraulic and transmission system. This gear oil is cheaper alternative for prescribed universal tractor transmission oil.

Tractor John Deere 8100 represents tractors which use the modern technical innovations and so its construction is more complicated and sensitive to operational conditions. It is equipped with automatic transmission and its hydraulic system is powered by removable piston pump. Both these main parts are very sensitive to the oil contamination and therefore the tractors owner has to pay attention to operate the tractor only with its own implements and use the same oil type and quality as is used in the tractor. We can assume that this lubricated system is producing only minimal amount of the solid particles due to normal operational wear process. Prescribed universal tractor transmission oil Shell Donax 5W30 (Shell, Netherlands) type was used in this tractor.

Therefore, we can consider that the mode of the tractor operation mostly affects the oil contamination. The tractors were classified into the two groups as follows:

- Standardly operated tractor. The tractor John Deere 8100 was operated in compliance with the user manual. This tractor was using only its own implements with correct oil type and with the same cleanliness level as is in the tractor oil fill. The tractor operator took care about the prescribed volume of the oil fill and refilled the oil loss with the correct oil type. This tractor was garaged to protect it against the water. Authorized tractor service realised the change of the oil fill and periodical maintenance.
- Non-standardly operated tractor. The tractor Zetor Forterra 124 41 was not operated in compliance with the user manual. The tractor was using various implements with degraded oil fill. The oil change and refilling were not realised in authorized tractor service but on the farm and the tractor operator used only the universal tools. The tractor operator used the cheapest oil type and not the prescribed one. The tractor was yearly parked in the space without protection against the water and atmosphere moisture.

Considering operation of the tractor hydraulic system at normal pressure (< 25 MPa), standard DIN 51524 requires the minimum cleanliness classes 7, 8 according to the NAS 1638. The tractors classification mentioned above, reflects the minimum recommended cleanliness level (Table 1) in case of the tractor operated standardly and maximum level 12 in case of the tractor operated non-standardly.

Table 1. Required cleanliness classes for hydraulic systems (Casey, 2004)

Type of hydraulic system	Minimum recommended cleanliness level NAS 1638
Silt sensitive	4
Servo mechanisms	5
High pressure (25 to 40 MPa)	6
Normal pressure (10 to 25 MPa)	7
Medium pressure (5 to 15 MPa)	9
Low pressure (< 5 MPa)	10
Large clearance	12

Evaluation of the oils properties

This paper is aimed at the oil contamination in transmission and hydraulic system of the two tractors and at suggestion of the design of the by – pass filtration system improving the oil cleanliness level. Following base physical properties of the oils were evaluated in accredited laboratory Wearcheck (Hungary):

- kinematic viscosity at 40 °C and 100 °C,
- viscosity index,
- water content (Carl Fisher).

The same laboratory evaluated the oil contamination on the basis of the chemical elements content (Fe, Cu, Si, Al, Pb, Sn and Cr) in the oil samples according to the ICP spectrometry.

Besides the oil sample evaluation in laboratory Wearcheck, the FT-IR spectroscopy was realized in accredited tribotechnical laboratory Intertribodia (Slovak Republic) to state the oxidation stability, additive depletion and water content.

Proposal of by – pass filtration system for tractors

The by-pass filtration system was installed in the tractor Zetor Forterra 124 41 operated with the oil type PP 90. The system was tested at 1,889 engine hours of tractor operation. The prescribed oil change interval is 2,000 engine hours. The volume of the oil fill in the transmission and hydraulic system is 56 dm^3.

The filtration system uses the internal hydraulic system of the tractor. The hydraulic pump supplies the filtration system with universal oil from the transmission. After filtration, the oil returns to the transmission through T-fitting and hydraulic return line. This system uses the filter body FT-B68 with filter element FT-V68 (Filtration technology, Czech Republic). The main parameters of the filter body and the filter element are listed in Table 2. The by-pass filtration system is the second stage of the oil filtration. The first stage is operational oil filtration with 20 µm filter ability (standard oil filters in tractor).

Function of the by-pass filtration system was evaluated according to the decrease of the chemical elements content (Fe, Cu and Si) characterising significant oil contamination. The chemical elements (Cr, Pb, Al and Sn) characterized non-significant oil contamination because concentration before the oil filtration reached non-significant value. Using the ICP spectrometry (Wearcheck, Hungary), the chemical elements concentration in the oil was measured.

Table 2. The main parameters of the filter body and the filter element

Parameter	Unit	Value
Nominal flow rate	dm^3 min^{-1}	1.8
Nominal filter ability of the filter element	µm	1
Volume of the oil fill	dm^3	50–300
Oil viscosity	cSt	9–220
Operation pressure	MPa	0.2–0.4
Weight	kg	4.5

The decrease of the chemical elements content characterising the oil contamination was calculated by formula (Majdan et al., 2016):

$$\Delta_C = \frac{C_{BF} - C_{AF}}{C_{BF}} \cdot 100 \qquad (1)$$

where Δ_C – decrease of chemical elements content characterising the oil contamination, %; C_{BF} – chemical elements content before the oil filtration, mg kg^{-1}; C_{AF} – chemical elements content after the oil filtration, mg kg^{-1}.

The oil circulation number states, how often the oil fill circulates in the unit for time (Mang, 2014). The oil circulation number is calculated as follows:

$$o = \frac{Q_f}{V}, \text{ s}^{-1} \qquad (2)$$

where o – oil circulation number, s^{-1}; Q_f – flow rate dm^3 s^{-1}; V – volume if the oil fill in the tractor, dm^3.

Using the oil circulation number, we can state how many times the oil flew through the filter element during the tractor operation with by-pass filtration system. The count of the oil circulation through the filtration system is calculated as follows:

$$C = o t_o \qquad (3)$$

where C – count of the oil circulation -; o – oil circulation number, s^{-1}; t_o – tractor operation, s.

If the oil flows through the by-pass filtration system, the filter element has to be dirty when it is removed from the filter body. Therefore, the function of the oil filtration system was also visually checked after tractor testing in operation.

RESULTS AND DISCUSSION

Impact of the tractor operation mode on the universal oil

Before discussing the oil contamination, the tractor operation and its impact on the oil contamination should be characterised.

Agricultural tractors can be classified into the two groups on the basis of tractor operation in practice. The first group includes the tractors operated standardly, with standard oil care. The owner of the tractor pays attention to the cleanliness during the routine maintenance, checks the oil level, stuffs the oil leaks, and mainly connects only its own implements with the right type of the clean oil.

Regarding to the standard tractor operation mentioned above, it had been selected the tractor John Deere 8100 with Shell Donax 5W30 universal oil type. The contamination (Fig. 2) and the physical properties (Table 1) hint the excellent technical condition of the oil after 1,900 running hours (prescribed oil change was after 2,000 running hours). This way of the tractor operation allows eliminating of the abnormal wear process and risk of the catastrophic failure. Concretely, this tractor was operating almost 13,000 running hours without any problems mentioned above.

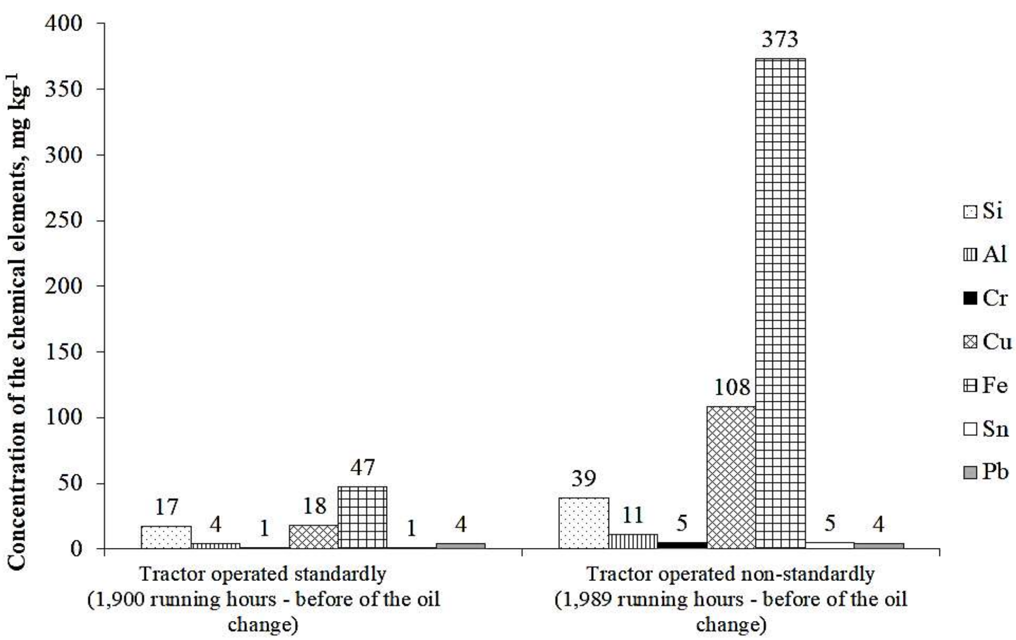

Figure 2. The oil contamination of the tractors operated standardly and non-standardly.

The tractor Zetor Forterra 124 41 with the oil PP 90 was selected as the example of the tractors operated non-standardly. The oil was strongly contaminated which extreme content of the iron (373 mg kg^{-1}) and copper (108 mg kg^{-1}) as demonstrated in Fig. 2. This level of the oil contamination does not allow reliable operation of the tractors for a long time. In this tractor, the low–quality oil was used instead of the required universal oil. Aleš (2009) observed the same oil type (PP 90) in the tractor Zetor 121 45 with the same transmission and hydraulic system. In this tractor, the kinematic viscosity did not exceed the limits. Aleš (2009) also confirms the fact, that the higher particle contamination of this oil type could indicate the lower ability to form the boundary lubricating film. This confirms the fact, that the right tractor operation mode significantly influences the cleanliness level and quality of the oil. Considering the tractor operated non-standardly, that means with different and unknown implements (trailers, ploughs, etc.), or with old and degraded oils of unknown types which are mixed with tractor oil fill, all this means higher oil contamination.

The tractor operated non-standardly (in this case Zetor Forterra 124 41) was operated incorrectly in comparison with the tractor operated standardly (in this case John Deere 8100) which was used only with its own implement and with the same oil as was used in the tractor. On the other hand, simply construction and manual transmission of the tractor Zetor Forterra 124 41 made it less sensitive to the oil contamination compared with the tractor John Deere 8100 with power shift automatic transmission requiring higher oil cleanliness level. Kosiba et al. (2016) evaluated the oil contamination of the universal oil Shell Spirax S4 in hydraulic and transmission system of the tractor John Deere 5720.This tractor is also equipped with automatic transmission and it is very sensitive to the oil contamination. Therefore, the owner of this tractor pays high attention to the oil cleanliness level. During the tractor operation, the content of iron (49.63 mg kg^{-1}), copper (20.47 mg kg^{-1}) and aluminium (3.41 mg kg^{-1}) reached values similar to the tractor John Deere 8100.

The physical properties of the oils in the tractors operated standardly and non-standardly are represented by kinematic viscosities at 40 °C and 100 °C, viscosity index and water content (Table 1). Jánošová et al., 2016 presents that hydraulic system is sensitive to the viscosity of the oil. The viscosity influences oil's ability to flow through the hydraulic system, therefore affects pressure required to push the oil and make the necessary flow.

The oil samples of the new oil and used oil were analysed to state the changes in the oil properties. In the case of the tractor operated standardly (John Deere 8100), the values of the kinematic viscosity at 40 °C reached 7.3% and at 100 °C it reached 4.2%. Both values did not exceed the limit value 10%. Therefore, this oil was only minimally degraded during the operation in the tractor operated standardly. The value of the kinematic viscosity at 40 °C reached 27.9% and at 100 °C it reached 19.8% in the case of the tractor operated non-standardly (Table 3). Therefore, the values of the kinematic viscosity exceed the limit value 10%.

Table 3. Properties of the oils in tractors operated standardly and non-standardly

Parameter	Unit	Tractor operated standardly		Tractor operated non-standardly	
Type of oil		Shell Donax 5W30		PP 90	
Tractor operation	Running hour	0 (new oil)	1,900	0 (new oil)	1,989
Kinematic viscosity at 40 °C	$mm^2 s^{-1}$	38	41	172	124
Kinematic viscosity at 100 °C	$mm^2 s^{-1}$	7.1	6.8	15.6	12.5
Viscosity index	-	151	123	92	91
Water content	ppm	N*	N*	N*	N*

* Non-measurable value (Wearcheck laboratory).

The results of Eissa, Mohammed, Abd-Allah, and El-Sheltawy (2013) show that water content considerably affects the most of the oil properties. In the case of the both tractors, the non-measurable value of the water content (Table 3) is typical for the most of tractors because the transmission and hydraulic system is well protected against the water from the environment. Liquefied water from the ambient air represents only the negligible amount regarding the high-volume of the oil fill.

The tractor operated non-standardly contained the highly contaminated oil. Fig. 3 shows the layer of the contaminants which covers the filter patch. Dark colour of the filter patch expresses that the white filter paper is completely covered by contaminants. We can observe a lot of very small particles of the dark colour which create the layer on the filter paper and originate from the old and contaminated oil fills from the tractor implements. The left figure shows the larger particles from the wear process. The right figure shows the typical colourless transparent particles of silicium from the dust. The oil also contains two types of the small yellow particles. The transparent yellow particle is typical for varnish which originates from oxidative or thermal oil degradation. Shiny and non-transparent yellow particles can originate from the wear process of the single parts of the tractor components made of copper alloys (brass or bronze).

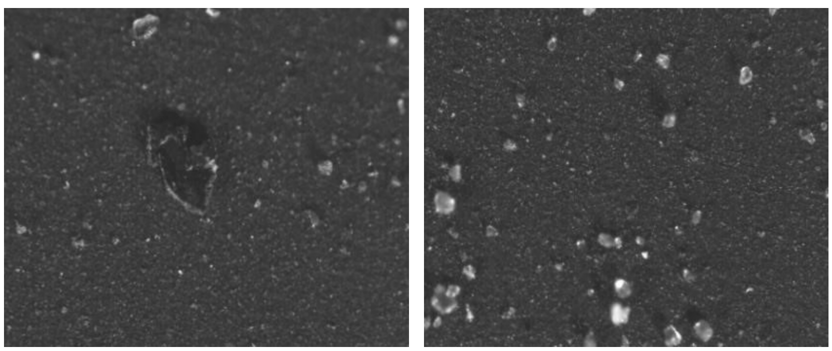

Figure 3. The filter patch of the oil PP 90 from the tractor operated non-standardly.

Fig. 4 shows the filer patch of the oil from the tractor operated standardly. Left and right figures show the white background of the filter paper which separated only the low amount of the oil contaminants because the cleanliness level of this oil is very high. Small dark particles of overheated steel can be observed. These particles are typical for common wear process and can originate from the high pressure contact in the roller bearings or teeth of gear wheels.

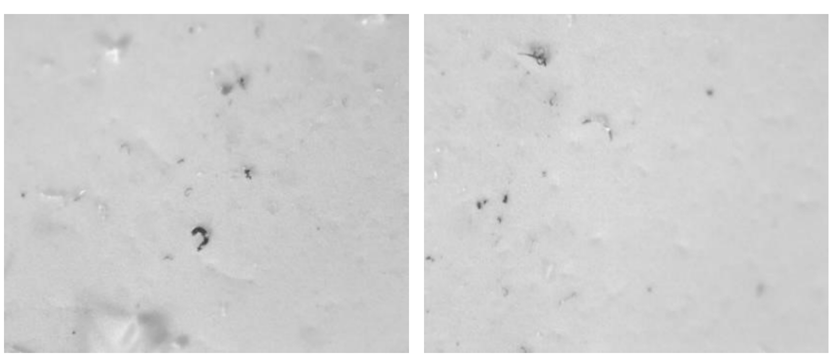

Figure 4. The filter patch of the oil Shell Donax 5W30 from the tractor operated standardly.

Comparing Figs 3 and 4, it is possible to observe the high cleanliness level of the oil from the tractor operated standardly and high contamination level of the oil from the tractor operated non-standardly.

The NAS 1638 class is usually reported as the number representing the maximum allowed particle counts (i.e. worst case) for designated size ranges of the particles. The cleanliness level according to the standard NAS 1638 reached the class 7 in the case of the oil in the tractor operated standardly and the class > 12 for tractor operated non-standardly, Table 4. These results show the high level of the oil contamination in the case of the tractor operated non-standardly in comparison to the typical level of the oil contamination in the case of the tractor operated standardly.

Table 4. The cleanliness level and the count of the particles (NAS 1638) of the oils of the tractors operated standardly and non-standardly

	NAS 1638 class	Maximum contamination limit (particles per 100 mL of the oil)				
Size range		5–15 µm	15–25	25–50	50–100	< 100
Unit			µm	µm	µm	µm
Tractor operated standardly	7	32,000	5,700	1,012	180	32
Tractor operated non-standardly	12	1,024,000	182,400	32,400	5,760	1,024

Aleš et al. (2015) presents that the failures of the machines are caused by variety of external and internal effects and processes that cause ultimately interruption of the operation. These factors have resulted in changes of properties of the machines parts and these changes are the first cause of technical failures. Fig. 3 shows solid particles from wear process as internal effect that does not cause the interruption of the operation because it is normal wear process in the case of tractor operated standardly. The more dangerous is the oil contamination from the old and degraded oil fills in the old equipment (the external effect) which were connected to the tractor operated non-standardly. This high oil contamination can lead to the ultimate interruption of the tractor operation by the reason of abnormal wear process.

The effect of oxidation is that the oil becomes acidic and the oil viscosity increases. The increase of the viscosity may be masked by other factors such as other oil type dilution. The characteristic spectral region for the oil oxidation is about 1,720 cm^{-1}. The spectrum changes of the new oil (0 running hours) and of the used oil were observed in this region in the case of the oil PP 90 type, Fig. 5. Table 2 do not show the typical increase of the oil viscosity if the oil is oxidized on the contrary, the oil viscosity decreased. This fact confirms our assumption that the oil was contaminated with the oil fills from the unknown tractor implements.

The next increase in absorbance was observed in the spectral region of the nitration formation (the characteristic of infrared absorbances of nitration formation was found out between 1,180 and 1,120 cm^{-1}). Various oxides of sulphur and water react together to form sulphuric acid. This acid is neutralized by ~~a~~ basic reserve in the additive package of the oil and normally results in formation of metallic sulphates. Sulphur is the typical component of the crude oil and it is also used as additive. The new oil PP 90 contains relatively high concentration of the sulphur (12,203 mg kg^{-1}) compare with the oil Shell Donax 5W30 with lower concentration of the sulphur (5,050 mg kg^{-1}). In case of this oil type, decrease of sulphur (in region between 1,180 and 1,120 cm^{-1}) is observed probably due to the sulphur additives depletion (Fig. 5). Kržan & Vižintin (2003) also measured the sulphur concentration in tested oils to state the additive depletion. These authors presented that the lower concentration of the sulphur mentions the higher quality of the base oil because it needs lower additive concentration. In our case, the low quality of the oil PP 90 contains the higher sulphur concentration than oil with higher quality Shell Donax 5W30.

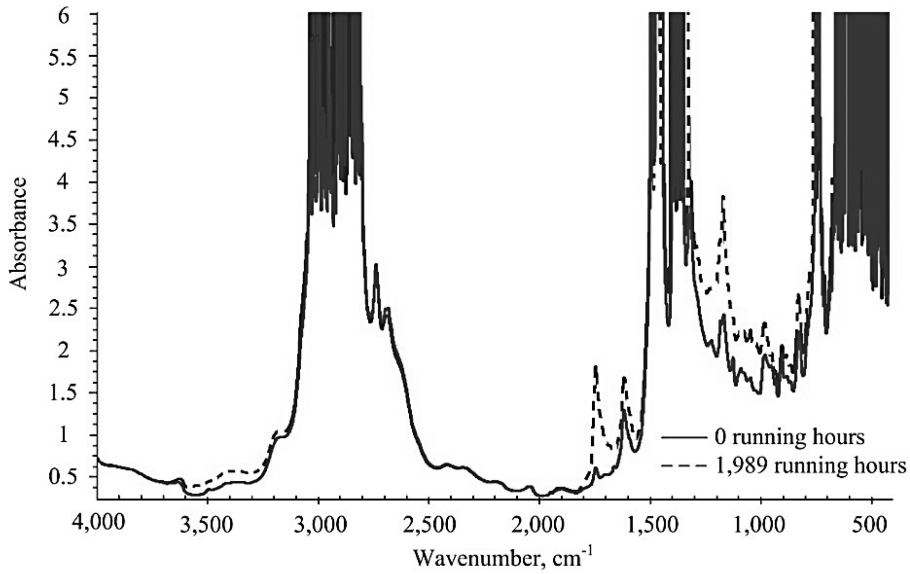

Figure 5. FT-IR spectrum of the oil PP 90.

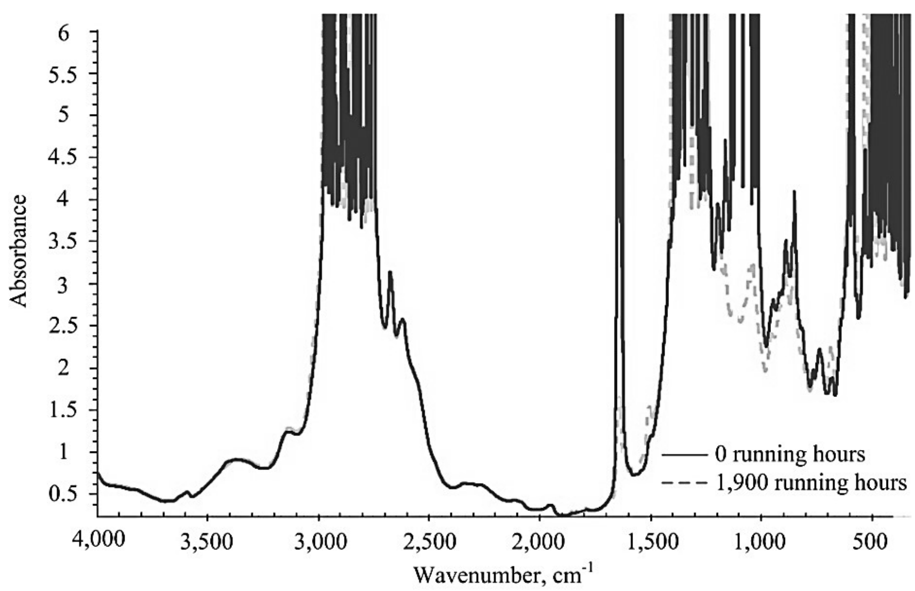

Figure 6. FT-IR spectrum of the oil Shell Donax 5W 30.

The water content is an interesting parameter because the Wearcheck laboratory state non-measurable value of the water content in all oil samples according to the Carl Fisher method, whereas the FT-IR spectrum shows absorbance increase in the typical spectral region for water (between 3,500 and 3,100 cm^{-1}). FT-IR is very precise method to state the water content because it is very strong absorber of infrared radiation. Water appears in the region, where the few other compounds that appear in petroleum oils will have significant absorbencies. This difference probably results in the oil sampling errors due to the poor oil sample homogeneity by the reason of high contamination level.

Absorbance decreases in the spectrum region between 1,500 and 1,700 cm^{-1} illustrates the common degradation process of the oil Shell Donax 5 W 30 (Fig. 6). It characterises the moderate level of the ester additives depletion.

By-pass filtration system in the tractor Zetor Forterra 124 41

The second part of this contribution is oriented on the design of the by-pass filtration system to improve the cleanliness level of the universal tractor oil (Fig. 7).

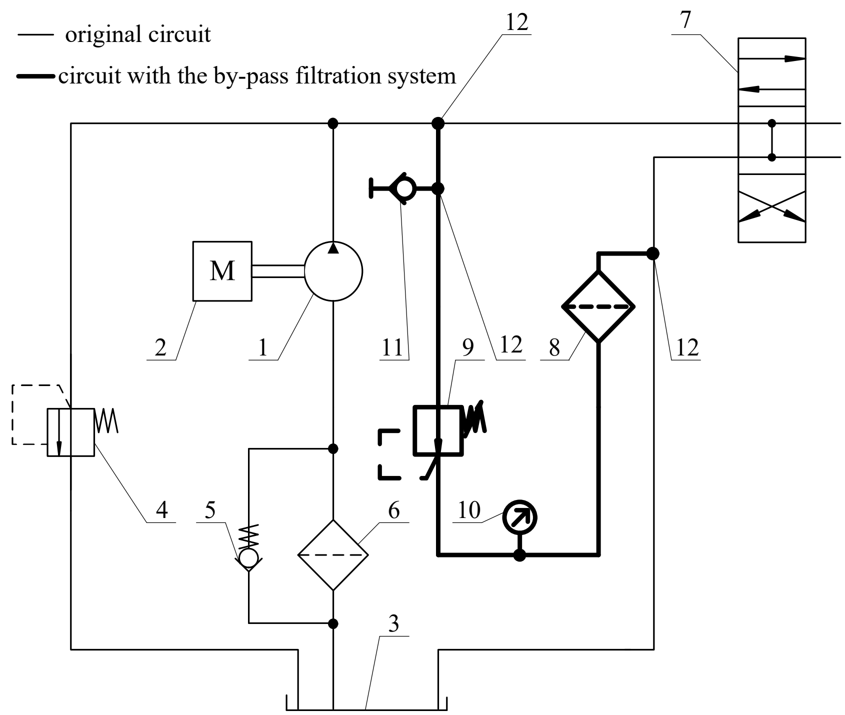

Figure 7. Tractor hydraulic circuit with the by-pass filtration system: 1 – hydraulic pump; 2 – combustion engine; 3 – oil fill of the tractor transmission; 4 – pressure relief valve; 5 – one direction valve; 6 – operational filter; 7 – directional control valve; 8 – by-pass filter; 9 – pressure-reducing valve; 10 – pressure gauge; 11 – minimess type valve; 12 – T-fitting.

There was used the oil circulation in the hydraulic system. The hydraulic pump (1) sucks the oil from the transmission system (3) through the operational filter (6). The one direction valve (5) allows the oil to flow when the operational filter is strongly contaminated. The pressure relief valve (4) limits the maximum pressure of the tractor hydraulic system. Components of the by-pass filtration system are marked by thick lines. The pressure and return lines were disconnected and the T-fittings were mounted to the tractor hydraulic system. The oil flows through the by-pass filter because the hydraulic pump generates the pressure indicated by the pressure gauge (10). Using the minimess type valve (11), the oil samples were taken to evaluate the function of the filtration system.

Regarding the tractor oil fill (56 dm^3), the size of the by-pass filter body with element (1 μm nominal filter ability) were proposed. In the case of the larger by-pass filter system, it could allow to filter the oil faster. On the other hand, it is more expensive and the next size complicates its placement in the tractor. Therefore, this proposal takes into account the oil filtration time, the price, and the size of the filter body. The by-pass filter system was placed in the cab behind the engine on the tractor chassis. This place is appropriate because it is easily to check and maintain the filter, Fig. 8, a).

a) b)

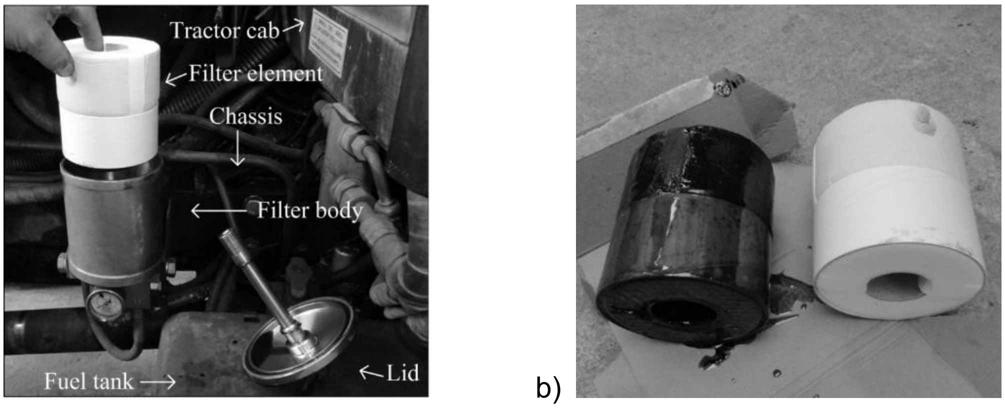

Figure 8. The change of the filter element after the tractor testing operation with the by-pass filtration system: a) placement of the filter body in the cab-behind-engine; b) the new and the used filter element.

The by-pass filtration system was tested under the real operation conditions of the tractor. Considering the oil fill volume (56 dm^3) and the flow rate (0.5 dm^3 min^{-1}) through the by-pass filtration system, the oil circulation number $o = 0.0089$ was calculated according to the Eq. (2). The count of the oil circulations through the filtration system $c = 107$ was calculated according to the Eq. (3) during 201 running hours of the tractor operation with the oil filtration system.

Pošta (2010) and Pošta et al. (2016) presents, that problems with hydraulic pressure fluids and oils are caused by their contamination and aging, which leads to the wear of the precise components. The important solution of this problem appears the external purification in addition to the operational filter. The additional filtration system reaches the higher filtration ability comparing to the operational filter. The results of this research present the improvement of the oil cleanliness level using the by-pass filtration system with the higher filtration ability (1 μm) compare to the operational filters (20 μm).

Schmitz & Lennartz (2006) and Phillips & Staniewsky (2016) noticed, that the filtration surface can be saturated after the several hundred running hours and the filtration system does not effectively clean the oil. This problem can also negatively affects the filter efficiency of the by-pass filtration system in the case of the non-standardly operated tractors. Firstly, the extreme oil contamination (Fig. 2) must be solved by elimination of the contamination sources (Fig. 1). Considering the normal oil contamination in the case of the tractors standardly operated, the problem mention above is not important and the by-pass filtration system as the second stage of the oil filtration (the operational filter is the first stage of the oil filtration) can improve the reliability and durability of the tractor.

Majdan et al. (2016) presented the filtration system for the hydraulic and transmission oil in agricultural tractors using the external filtration device. This solution does not filter the oil during common operation of the tractor. On the other hand, the by-pass filtration system allows to clean the oil immediately after the tractor starting.

The decrease of the chemical elements characterising the oil contamination according to the ICP spectrometry is the main parameter to evaluate the function of the by-pass filtration system and it was calculated according to the Eq. (1). All dangerous chemical elements were classified into the two groups namely significant (Fe, Cu and Si) (Table 5) and non-significant (Al, Cr, Sn and Pb) (Table 6) oil contaminants, considering their concentration in the oil. Concentration of Fe decreased to 41.6% during the test operation of the tractor with the by-pass filtration system. The significant decrease occurred also in the case of Cu (28.7%) and Si (20.5%). The decrease of the chemical elements concentration was also observed in the case of Al, Cr, Sn and Pb, but low concentration makes it non-significant.

Table 5. The content of the chemical elements characterising the significant oil contamination

Chemical element	Unit	Before the by-pass filtration (1,889 running hours)	After the by-pass filtration (2,100 running hours)	Difference, %
Fe		373	218	41.6
Cu	mg kg^{-1}	108	77	28.7
Si		39	31	20.5

Table 6. The content of the chemical elements characterising the non-significant oil contamination

Chemical element	Unit	Before the by-pass filtration (1,889 running hours)	After the by-pass filtration (2,100 running hours)
Al		11	7
Cr	Mg kg^{-1}	5	3
Sn		5	5
Pb		4	3

It was also visually checked the function of the oil filtration system. Fig. 8 shows the change of the filter elements after the tractor operation with the by-pass filtration system. The dark colour of the used filter elements shows that the oil was flowing through the filtration system.

Considering the decrease of the chemical elements characterising the oil contamination and visual checking of the filter elements after the testing operation, it could be stated that the filtration system is functional and suitable for exploitation in the tractor hydraulic system.

CONCLUSIONS

The oil cleanliness level affects the wear processes, oil degradations~~,~~ and durability of the all machines. The hard operation conditions affect the oil contamination in the tractor hydraulic and transmission system. The paper presents the oil cleanliness level in compliance with the standard DIN 51524 in the case of the tractor operated standardly and the strongly contaminated oil in the case of the tractor operated non-standardly. The results confirmed the fact, that the tractor operation mode in compliance with the user manual significantly and positively affect the oil cleanliness level. On the other hand, the usage of the tractor in conflict with the user manual (usage of the unknown implement, incorrect oil type used in tractor, tractor parking without protection against the environment etc.) causes the strong oil contamination.

The by-pass filtration system was proposed and applied to improve the oil cleanliness level. It was used as the ~~a~~ second stage of the oil filtration while the operational filter is the first one. Concentration of iron (373 mg kg^{-1}), cooper (108 mg kg^{-1}) and silicium (39 mg kg^{-1}) showed the decrease as follow 41.6% (Fe), 28.7% (Cu) and 20.5% (Si) after the tractor testing operation with the by-pass filtration system. The decrease ~~in~~ of the chemical elements characterising the oil contamination and the visual checking of the filter elements after the testing operation affirmed the right function of the by-pass filtration system in the tractor.

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