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TEST VERIFICATION OF THE CONDITION OF HYDRAULIC OIL OF CONSTRUCTION MACHINES FOLLOWING THE GUIDELINES OF ISO 4406 AND NAS 1638

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Abstract

The article aims to present the testing of hydraulic oil testing in accordance with the requirements of ISO and NAS standards and the results of oil testing from two selected construction machines, i.e. Liebher 566 first class wheel loaders. The article also takes into account the influence of hydraulic oil microfiltration on the cleanliness class and relative humidity, which is an indirect measure of the amount of water in the oil. Oil microfiltration was carried out regularly and allowed for the improvement of the oil condition, which is understood as a decrease in the cleanliness class by removing solid contaminants and water from the oil through the use of membrane filters. The hydraulic oil tests carried out by the authors also take into account the assessment of the oil condition determined before and after microfiltration.

Keywords: hydraulic oil, contamination in oil, oil testing, hydraulic oil cleanliness class, microfiltration

List of Symbols/Acronyms

ATF – automatic transmission fluid;
cSt – centistokes;
GOST – Gosudarstwiennyj Standard;
HV – Low Viscosity;
HV – High Viscosity;
ISO – International Organization for Standarization;
MF – microfiltration;
NAS – National Aerospace Standard;
PDA – polydopamine
PSI – Pound per Square Meter;
PVDF – polyvinylidene fluoride;
RH – Relative Humidity;
SAE AS – Society of Automotive Engineers Aerospace.

1. INTRODUCTION

In hydraulic systems, hydraulic oil plays a very important role. Its tasks include transferring energy, lubricating mechanical elements, cooling the hydraulic system and protecting against corrosion. The quality of hydraulic oil has a direct impact on the performance, durability and efficiency of the hydraulic system. The lack of oil or its improper condition in relation to its contamination will cause the most advanced hydraulic pumps and gears to not operate properly. Contaminants in hydraulic oil, such as dust, metal chips or water, can significantly reduce the efficiency of hydraulic pumps. These contaminants can cause blockage of filters, damage to working surfaces and increase friction, which leads to faster wear of pump elements. In extreme cases, it will lead to seizure and destruction of the pump [12].

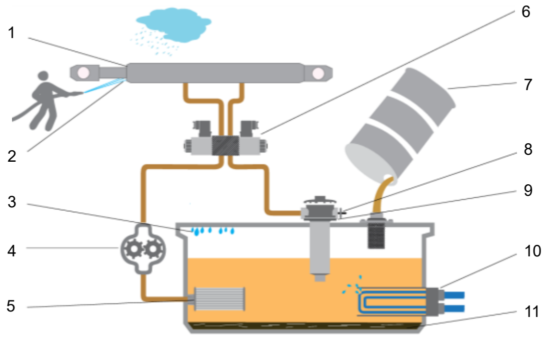

Fig. 1. Sources of contamination in hydraulic oil: 1-worn seals, 2-washing the system with water, 3-evaporation and condensation, 4-wearing mechanical elements, 5-damaged seals, 6-damaged hydraulic distributor, 7-contaminated oil, 8-lack of periodic filtration, 9-worn filters, 10-contaminated cooler, 11-sludge at the bottom of the tank [2]

However, poor quality hydraulic oil can also lead to corrosion and mechanical wear. Corrosion is particularly problematic in systems exposed to moisture. Mechanical wear caused by improper lubrication leads to shorter pump life and increased repair costs. In addition to the costs associated with

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restoring the technical condition of the hydraulic pump, losses associated with taking the construction or industrial machine out of operation must be taken into account. The sources of oil contamination are different and are shown in Figure 1.

According to Figure 1, contamination enters the hydraulic system through worn and damaged seals in hydraulic cylinders, by washing machines with a water jet and through the products of wear of mechanical elements of the system such as hydraulic pumps or distributors. Other sources of water in the system include evaporation and condensation of water in the hydraulic tank, untreated oil before flooding the hydraulic system or water ingress from a leaky radiator [4, 5].

To maintain high efficiency of the hydraulic system, it is necessary to ensure high quality hydraulic oil. Methods to ensure that the oil is kept at the required level in terms of its condition free from metallic and other impurities and free from water are:

1. hydraulic oil filtration,
2. regular hydraulic oil testing,
3. periodic hydraulic oil replacement.

Due to the growing awareness of hydraulic system users about the need for periodic filtration, this method is now being used more and more often than periodic hydraulic oil replacement. Previously, it was believed that oil replacement in accordance with the machine's technical documentation was sufficient to maintain the technical condition of the hydraulic system. It should be noted that oil replacement accordance to [14] allows for the removal of approximately 95% of impurities from the system. Approximately 5% remains on the internal walls of the pump and other components of the hydraulic system. Regular filtration or microfiltration allows for the removal of impurities and water from the hydraulic system without changing the oil. The cleaned oil returns to the hydraulic system through an external system with bypass filters. The combination of filtration or microfiltration with hydraulic oil testing allows for the control of the oil condition in terms of compliance with the cleanliness class according to current regulations.

In the literature, the concept of microfiltration of hydraulic systems is related to construction vehicles, road vehicles, industrial and mining machines, power equipment and machines used in maritime transport. According to [3], contaminated oil in hydraulic systems causes damage in 80%. Contaminated oil is one in which insoluble materials have been collected, such as metals, dust particles, sand, water, rubber and varnish. The smallest particles below 2 μm are a common cause of damage to the system equipment. Microfiltration according to [7] is a low-pressure separation process using membranes with very open pores.

Microfiltration filters can be made of both organic materials, such as polymeric membranes, and inorganic materials, such as ceramics or stainless steel [32]. Work in the field of microfiltration is mainly related to the selection of the appropriate membrane as a microfiltration filter. Microfiltration membranes have the most open pores of all polymeric membranes. The range of pore sizes range from 0.1 to 10 μm. Microfiltration membranes are able to separate large suspended solids, such as colloids, particulates, fats and bacteria, while allowing sugars, proteins, salts and low molecular weight molecules to pass through the membrane. According to [19], microfiltration membranes are characterized by an asymmetric pore structure, with tighter surface pores to control rejection and more open macrovoids in the membrane cross-section to optimize flow flux.

Membrane MF technology is also found in the food industry and includes the removal of fats and microbiology in whey the protein concentrates or isolate, fractionation of casein or whey, clarification of fermentation broths, removal of microorganisms, clarification of plant extracts and purification of industrial wastewater [18]. A wide range of materials are used to produce membranes for the purification of aqueous wastewater using membrane technology. Polymeric membranes tend to foul when used for oil-water wastewater, reducing the membrane flux [6]. The 0.22 μm pore-size PVDF microfiltration membrane modified with PDA has a hydrophilic surface, with higher pure water flux and reduced fouling during emulsion filtration, compared to the commercial PVDF microfiltration membrane. The modification, creating a multilayer membrane, increases the flux of pure water up to 4 times after the membrane cleaning procedure [31].

Modern technology includes many methods of product purification, such as large-scale chromatography, precipitation, crystallization, centrifugation, distillation, and sedimentation. Membrane techniques for separating mixtures have long been treated as auxiliary separation methods on a laboratory scale [1]. Recent years have made it possible to use membrane techniques on a large scale. This is related to the development of plastic chemistry, and especially synthetic polymers, from which most permeable and selective membranes are built [8].

Microfiltration uses membranes with pores of the order on 0.l-5.0 μm. This process removes fine suspensions, bacterial cells, some viruses, plant material particles, and fat particles in emulsions (e.g. milk) from the solution. The visual effect of this process may be a change in the color of the filtrate, a decrease in turbidity, a decrease in the intensity of light scattering. The main application of this technique is the clarification of solutions, the separation of cell biomasses, and the sterilization of media, that is, substances on which bacteria are grown [13].

The microfiltration process is based on the difference in hydrostatic pressure on both sides of the partition in the range of 0.05-0.5 MPa [20]. Microfiltration is often carried out in a tangential system, which largely prevents the deposition of sediment on the membrane surface. Filters used in membrane processes are usually made of ceramic materials or synthetic polymers, such as polysulfone, Teflon, or cellulose acetate. These materials are not cytotoxic, nor do they affect the filtered solution in any other way. The walls of the filter membranes are characterized by an anisotropic structure, i.e. the pore channels expand from the membrane surface into its structure. Thanks to this, the molecules that are retained by a given membrane, are retained on its surface and do not clog the lumen of the capillaries inside it. In industry, flat, spiral, capillary and tubular filters are distinguished [30].

The microfiltration method has also found wide application in biotechnology for cold sterilization in the beverage production process and in the pharmaceutical industry. Where the milk subjected to the microfiltration process is microbiologically clean and then typical pasteurization, clarification of juices, wine and beer are not required. In wine production, the use of microfiltration and ultrafiltration, e.g. of finished wine, ensures, on the one hand, the removal of undesirable microflora, and on the other hand, deprives the wine of compounds causing its turbidity. In this way, the production process is eliminated from the troublesome stages of filtration using clarifiers and sulphurization as a factor the destroys that microflora [21].

The separation of bacteria from water (biological water purification) is performed in cases where particles larger than 0.1 mm must be removed from the liquid. Microfiltration is also performed in the purification of water wastewater, the separation of oil-water emulsions, the pre-purification of water before nanofiltration and reverse osmosis processes, and the separation of liquid-solid substances in the pharmaceutical and food industries [29].

Biotechnological progress has revolutionized the commercial production of many biochemical products, especially industrial enzymes. Traditional methods of collecting cells and purifying enzymes produced using fermentation, genetically modified organisms are centrifugation and filtration using an auxiliary filter layer. Cross-flow membrane filtration is increasingly replacing the above separation steps due to lower investment costs and increased enzyme production, as well as simplification of the other processing methods of biochemical products [22].

The literature review on microfiltration shows that it is a very broad concept, and this technology is used not only in mechanical or civil engineering but also in chemical and process engineering and agri-food engineering. The literature is dominated by works on materials for filtration membranes and the efficiency of these membranes [11, 28]. There are also works on filtration techniques or microfiltration [9, 27]. However, in relation to mechanical and civil engineering, there are few works such as [10] on the impact of microfiltration on the mechanical wear of hydraulic system units and works related to hydraulic oil tests or the impact of oil waste on the natural environment.

The aim of the article is to present the methodology of testing hydraulic oil in accordance with the requirements of ISO, SAE and NAS standards and to present the results of testing hydraulic oil on two selected Liebher 566 first class wheel loaders in different periods. An additional objective of the article is to determine the effect of microfiltration on the class of oil cleanliness. The condition of the oil is understood by the authors as oil contamination due to dissolved water and the presence of metallic wear products, which increases with the age of the oil and the number of hours worked and requires periodic inspection.

2. STANDARDS FOR OIL PURITY CLASSES

In terms of regulations governing the cleanliness of hydraulic and lubricating oils, the following standards should be indicated:
- ISO 4406 [23],
- SAE AS 4059 [24],
- NAS 1638 [25],
- GOST 17216 [26].

The ISO 4406:99 standard was published by the Turkish Standards Institute (TSE) under the title: Hydraulic Fluid Power - Fluids - Method for Coding the Level of Solid Particle Contamination. The SAE Aerospace standard, the full name of this standard is: SAE AS 4059 Aviation Fluids - Cleanliness Classification for Hydraulic Fluids. This standard specifies cleanliness classes for particulate contamination of hydraulic fluids and includes methods to report relevant data. The NAS 1638 standard is an American aviation standard, and the GOST 17216 standard is a Russian oil cleanliness standard. The NAS 1638 standard was replaced by SAE AS 4059 in 2001. Both ISO 4406 and SAE AS 4059 standards refer to the number of particles recognized as contamination larger than 4 μm, 6 μm, 14 μm and 21 μm. To assess the condition of the oil in terms of its contamination, the first 3 contamination values (4, 6 and 14 μm) found in 100 ml of the tested oil are selected. For example, hydraulic oil, which after testing (according to ISO 4406) received a cleanliness class result of 22/20/17 means that it contained the following number of contaminants [14]:
- from 20,000 to 40,000 with a size greater than 4 μm,
- from 5,000 to 10,000 with a size greater than 6 μm,
- from 640 to 1,300 with a size greater than 14 μm.

The cleanliness classes according to the ISO 4406 standard have been correlated with the average cleanliness classes according to the NAS 1638 standard, which is presented in Table 1. The table also presents the requirements for various units of the hydraulic system in terms of oil cleanliness.

If the hydraulic oil purity class is too high for the requirements set by the hydraulic system units and its intended use, it is possible to reduce the oil class using microfiltration.

Table 1. Hydraulic oil cleanliness classes according to ISO 4406 and NAS 1638 standards [14]

Cleanliness class		Required oil cleanliness class			
ISO	NAS	Pumps and motors	Valves	Bearings	Drivers
23/21/18	12	Highly contaminated oil. Absolute oil change or microfiltration with system cleaning			
22/20/17	11				
21/19/16	10				
20/18/15	9	gear	return		
19/17/14	8	vane, piston	proportiona, mushroom	sliding	cylinders
18/16/13	7				
17/15/12	6			roller	hydrost atic
16/14/11	5	Aircraft applications, high-pressure systems up to 32 MPa with proportional elements and high working load			
15/13/10	4				
14/12/9	3				
13/11/9					
12/10/8	2	Highly precise hydraulic systems above 32 MPa			
10/9/8					
10/9/7	1				
10/8/6					
9/8/6	0				

According to the work [15], microfiltration allows the reduction of oil purity by up to 6 classes. This depends on the filtration time and the number of filter inserts used.

3. METHODOLOGY AND RESEARCH OBJECT

The object of the research in the field of assessing the condition of hydraulic oil were two Liebherr 566 wheel loaders. The view of one of the loaders is shown in Figure 2, while the basic technical data are included in Table 2.

Table 2. Technical data of the Liebherr 566 loader [17]

Parameter	Value	Unit
Weight	22500	kg
Bucket width	3.0	m
Bucket capacity	4.0	m³
Tracking force	264	kN
Engine power	190	kW
Capacity	10.52	l
Transport length	9.0	m
Transport height	3.55	m
Transport width	3.0	m
Loader speed	40	km/h

Fig. 2. View of the Liebherr 566 wheel loader [fot. S. Kołodziejski]

The first wheel loader had a multi-piston hydraulic pump replaced. Figure 3 shows a view of the damaged and disassembled multi-piston pump. Due to the seizure of the pistons in the cylinder housing, the joints on the brass ball sockets were torn off, which is also visible in Figure 3 around the cylinder.

Fig. 3. View of the damaged Liebherr 566 loader multi-piston pump. Red circles mark damaged pump piston joints. [fot. S. Kołodziejski]

The hydraulic system of the first loader, after being filled with hydraulic oil, required microfiltration of the hydraulic oil using a portable filtering device.

The second loader was waiting for the hydraulic system to be inspected and the hydraulic oil to be replaced. The oil condition tests on the two wheel loaders were of a passive experiment nature, i.e. the condition of the hydraulic oil was tested at different times in different periods of time.

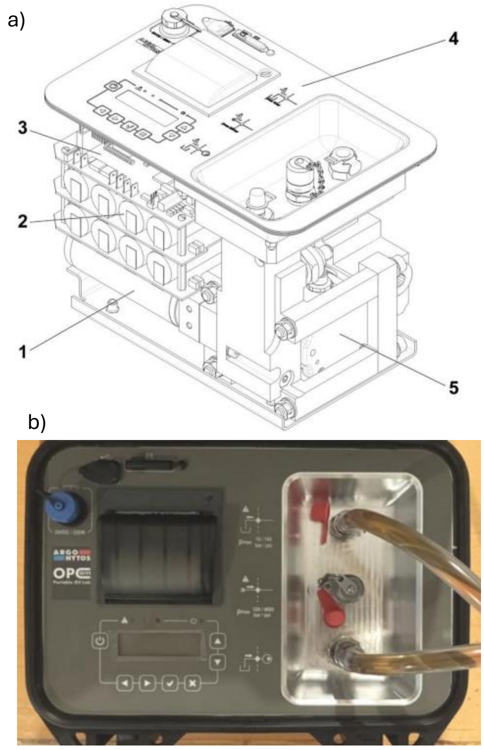

Fig. 4. a) General structure of the oil condition analyzer: 1- Engine with pump and electric gear,2- Battery, 3- Control electronics, 4- Top side with control panel, 5- Particulate monitor, b) View of the portable oil condition analyzer OPComII Portable Oil Lab PPCO 300-1000 by ArgoHytos

The hydraulic oil condition tests were carried out on the portable analyzer OPComII Portable Oil Lab PPCO 300-1000 by ArgoHytos. The general construction of the analyzer and its view are shown in Figure 4. The principle of the analyzer's operation consists in shining a laser beam through the flowing oil through a solid particle monitor. The contaminants in the oil block the beam of light falling from the source onto the detector. Then a signal is generated proportionally to the size of the particles in the oil. The electronic system signals to assign of the particles size in µm and the number of particles in the oil.

Table 3 shows the parameters and values measured by the oil analyzer.

Table 3. Measured parameters and values of the OPComII Portable Oil Lab PPCO 300-1000 device [2]

Parameter	Abbreviation	Unit
Temperature	T	°C / °F
Relative permittivity	P	-
Conductivity	C	pS/m
Relative oil humidity	RH	%
ISO cleanliness level	ISO	-
SAE cleanliness level	SAE	
NAS cleanliness level	NAS	
GOST cleanliness level	GOST	
Concentration	Conc	p/ml
Flow rate	Findex	ml/min

The basic parameters of the device are [2]:

1. Operating pressure range from 2.5 to 350 bar (35–5000 psi),
2. Operating viscosity range from 1 to 300 cSt,
3. Operating temperature from –30°C to +80°C,
4. Operating temperature for oil from +5°C to +80°C,
5. Operating temperature for fuel from –20°C to +70°C,
6. Relative humidity in the range of 0% RH to 100% RH.

In hydraulic oil condition tests, oil with the designation HV46 was used, which was used in wheel loader installations. This is a high viscosity index hydraulic oil, which used in control systems and hydraulic systems operating at variable temperatures.

Two parameters were measured in the tests, i.e. the oil cleanliness class according to ISO and NAS and relative humidity RH. According to [16], above 70% RH, the water contained in the oil is dissolved. For hydraulic oils, the allowed relative humidity of the oil is exceeded and oil microfiltration is recommended. Based on the oil cleanliness class and relative humidity, a decision was made during the tests to microfiltrate the hydraulic oil. Figures 5 and 6 show a view of the oil microfiltration test on a wheel loader prior to the next oil tests.

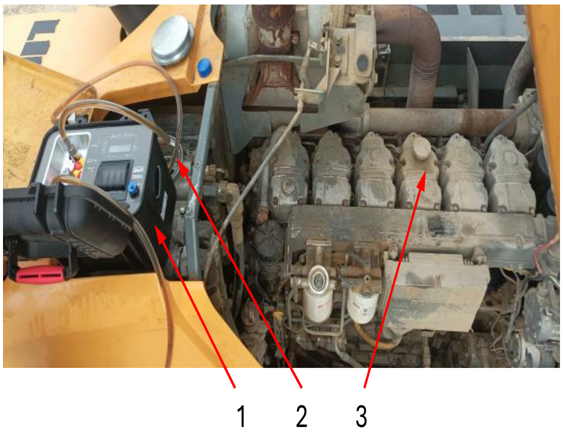

Fig. 5. View from the hydraulic oil test of a Liebherr 566 wheel loader: 1- View of the portable oil condition analyzer, 2- Hydraulic oil filler (place where the oil sample is taken for testing), 3- Loader combustion engine

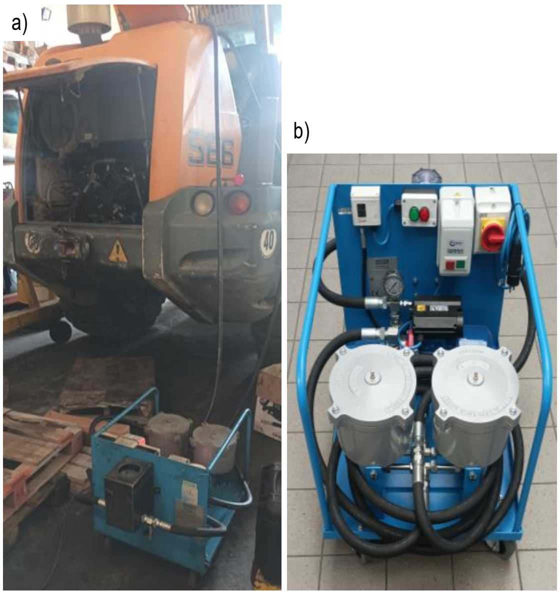

Fig. 6. View of: a) the microfiltration process of the hydraulic oil of the Liebher 566 wheel loader on the portable Kleenoil MS2+MM5 device, 1- filtering machine, 2- hydraulic line sucking oil for filtration, 3- hydraulic line with purified oil, b) the filtering device [fot. S. Kołodziejski]

For each test, 3 measurements were taken in terms of oil cleanliness according to ISO and NAS and relative humidity. Tables 4 and 5 present the results of the tests of the class of cleanliness of hydraulic oil and relative humidity on two wheel loaders. Figures 7 and 8 graphically present the average results of the change in the cleanliness class of hydraulic oil and relative humidity in the subsequent stages of microfiltration on the portable device MS2 + MM5.

Table 4. Results of tests on oil cleanliness class and relative humidity of the first Liebher 566 wheel loader

No.	ISO 4406			NAS 1638	RH [%]	Comments
	4 µm	6 µm	14 µm			
1	20	18	15	11	3.2	New oil from the barrel
2	19	17	14	11	3.1	
3	19	17	14	11	2.8	
4	23	20	16	12	27.7	Oil without filtration in the machine
5	23	20	16	12	27.5	
6	22	19	15	12	27.1	
7	19	17	15	10	25.3	After first filtration
8	19	17	14	10	25.2	
9	19	17	14	10	25.2	
10	18	15	14	9	20.5	After second filtration
11	18	15	13	9	20.4	
12	18	15	13	9	19.2	
13	17	14	12	8	15.3	After third filtration
14	17	14	12	8	15.1	
15	17	14	11	8	14.8	
16	16	14	11	7	10.5	After fourth filtration
17	16	14	11	7	10.2	
18	16	14	10	7	10.1	

Table 5. Results of tests on oil cleanliness class and relative humidity of the second Liebher 566 wheel loader

No.	ISO 4406			NAS 1638	RH [%]	Comments
	4 µm	6 µm	14 µm			
1	22	20	17	12	74.3	Without filtration
2	22	20	17	12	74.1	
3	22	20	17	12	73.7	
4	19	17	16	12	63.7	After first filtration
5	19	17	16	12	63.2	
6	19	17	16	12	62.8	
7	19	17	15	11	57.9	After second filtration
8	19	17	15	11	57.4	
9	19	17	15	11	56.7	
10	19	17	14	10	42.8	After third filtration
11	19	17	14	10	42.1	
12	19	17	14	10	41.3	
13	19	16	13	9	35.3	After fourth filtration
14	19	16	13	9	35.0	
15	19	16	13	9	34.6	

Analyzing Figures 7 and 8 in terms of the class of the hydraulic oil cleanliness, it was found that in both cases the class of permitted cleanliness of the hydraulic oil was exceeded. In the case of the second loader, such a diagnosis was expected, due to the age of the old oil with which the machine's hydraulic system was filled and due to the loader's parking in a yard without a roof. In the case of the first loader, it turned out that even new oil from the barrel turned out to be off-grade oil (above the 10th cleanliness class of the oil). Filling the system with new oil and the first filtration allowed the oil cleanliness class to be reduced from 12 to 10. Only the second microfiltration on the first wheel loader allowed obtaining oil in the last permissible cleanliness class, i.e. 9. It should be noted that this is clean oil and permissible for use in simple hydraulic systems without proportional valves.

In the case of testing the oil condition analyzer for relative humidity RH, only in the case of the second wheel loader not protected against

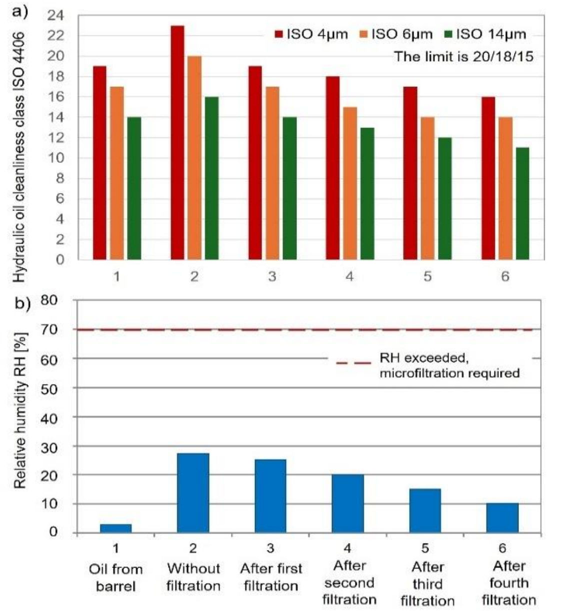

Fig. 7. Dependence of: a) oil cleanliness class according to ISO 4406, b) relative humidity RH, in subsequent microfiltration operations for the first charger

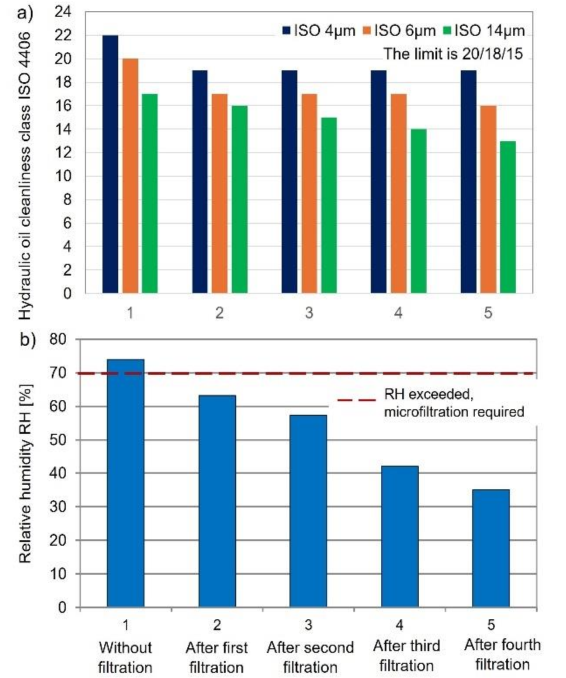

Fig. 8. Dependence of: a) oil cleanliness class according ISO 4406, b) relative humidity RH, in subsequent microfiltration operations for the second charger

atmospheric influences in the form of a roof or parking in a garage - was the relative humidity exceeded. In this case, water was already present in the hydraulic oil in a dissolved form and microfiltration was necessary to remove water from the oil. Subsequent filtrations reduced the water content and after the fourth microfiltration, the relative humidity dropped from 74% to 35%. In the case of the first loader after the hydraulic pump was replaced, the relative humidity was at 10% after the fourth microfiltration of the hydraulic oil.

6. CONCLUSIONS

The literature study conducted in the field of microfiltration and the research conducted by the authors allow for the formulation of the following conclusions:

1. The use of portable hydraulic oil condition analyzers allows for ongoing diagnostics of hydraulic oil in all conditions, especially in the field where vehicles or work machines are used.
2. The use of portable oil microfiltration devices together with an oil condition analyzer allows for the hydraulic oil cleaning process to be carried out to the required cleanliness class resulting from the hydraulic units used. The microfiltration time will depend on the current cleanliness class of the oil and the components used in the hydraulic system.
3. New oil purchased from a poured barrel is out of class (11 cleanliness class) and requires microfiltration before filling the hydraulic system, which was confirmed by the authors.
4. A single microfiltration of hydraulic oil lasting about 8 hours allows for a reduction of the cleanliness class of hydraulic oil by one.
5. The operation of work or road machines in the open air as well as parking and storage even with a closed hydraulic system from atmospheric influences significantly affects the increase in relative humidity. This requires microfiltration even if the hydraulic system is not in use.

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Declaration of competing interest: *The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.*

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