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Microfiltration of oils in combustion engines in drive and hydraulic systems – research and review of solutions

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The article presents the issue of the cleanliness of oils and fuels used in combustion engines of automotive and rail vehicles. In the article, after a review of the membrane separation field, attention was drawn to the possibility of using additional oil and fuel filtering systems to increase the cleanliness class. For this purpose, a methodology for testing the condition of oil and fuels in a portable laboratory in accordance with the requirements of SAE AS 4059, ISO 4406:99, and NAS 1638 standards was presented. Solutions for portable devices for microfiltration of oils and fuels by Kleenoil were presented. Additionally, the results of tests of sample new engine, gear, and hydraulic oils were presented, which, according to the cited standards, are out-of-class oils and require additional microfiltration. The novelty of the article is the presentation of a simple method for examining the condition of oil in combination with microfiltration. Both the oil condition analyzer and the microfiltration machine are portable stations for field and laboratory applications.

Key words: *microfiltration, engine, gear and hydraulic oils, oil testing, metallic contamination, water in oil*

1. Introduction

Membrane separation process (MSP) is an operation of separating mixtures. In this process, the membrane acts as a filter, creating a permeable or semi-permeable barrier that partially or completely restricts the flow of some components in the flowing liquid stream [21]. The fluid flowing through the membrane is driven by the pressure difference. In this process, the solution is separated into a concentrate remaining on the membrane and a purified liquid (permeate) [20]. The concentrate contains components (contaminants) with particles larger than the membrane pores, and the liquid stream behind the membrane has components smaller than the membrane pore size. Figure 1 shows a diagram of membrane separation with the solution flow parallel to the membrane, i.e. tangential flow [3, 22].

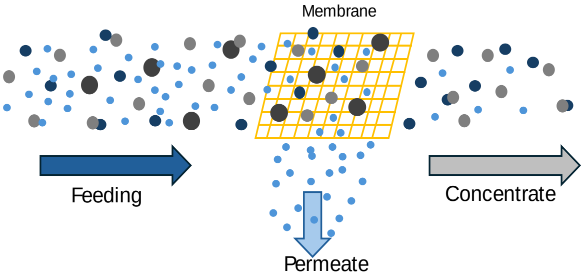

Fig. 1. The idea of tangential (cross) membrane separation [5]

Membrane separation processes are classified according to the size of the membrane pores and the particles that are retained in them, and the pressure in the system during filtration, which is included in Table 1.

Over time, the membrane can become more resistant to filtration, reducing the flow rate and separation efficiency (microfiltration). This is due to the accumulation of solid particles on the membrane surface or in the pores, which causes its clogging. The first way to improve membrane filtration in the long term is to use a serial (cascade) filtration system. In such a system, the MF microfiltration membrane performs the initial cleaning, and the UF ultrafiltration membrane performs the fine cleaning [6, 14]. Initial cleaning ensures that larger particles do not block the UF membrane channels. The MF pre-membrane does not block or change the flow. In the work [25], it was shown that the hybrid MF/UF system proved to be very effective in providing the purified fluid flow below the permissible limit.

Table 1. Classification of membranes according to their porosity [5, 23]

No.	Membrane	Pore diameter	Pressure
1	Microfiltration (MF)	0.1–10 μm (10^{-7}–10^{-5} m)	from 0.1 to 2 bars
2	Ultrafiltration (UF)	1–100 nm (10^{-9}–10^{-7} m)	from 1 to 7 bars
3	Nanofiltration (NF)	0.5–1 nm ($5\cdot10^{-10}$–10^{-9} m)	from 5 to 25 bars
4	Reverse Osmosis (RO)	0.1–0.5 nm (10^{-10}–$5\cdot10^{-10}$ m)	from 15 to 80 bars
5	Gas Separation (GS)	< 0.1 nm (10^{-10} m)	from 60 to 80 bars

The second way to increase the flow through filtration membranes and thus improve membrane stability is to incorporate nanoparticles and modify the membrane surface. This has led to the development of membranes capable of withstanding very high pressures [4, 19]. For highly polluted wastewater containing dissolved salts, polar and non-polar organic compounds, oils, and surfactants, more complex hybrid filtration systems of MF and UF series filtration are used. In such a case, according to the work [1, 18], a combined process of electrocoagulation EC, microfiltration MF and membrane distillation MD is used. Electrocoagulation and then microfiltration is the initial treatment of e.g. wastewater before the main membrane distillation [24].

Membranes can be made of polymer, ceramic, metal, or carbon materials. Polymer membranes are widely used in industry, made of materials such as polyamide, cellulose acetate, and cellulose triacetate [9]. The membrane consists of a polymer material, the chains of which are relaxed at atmospheric pressure, and the application of pressure promotes the densification of the polymer chains [16, 27]. Carbon membranes are made of sintered carbon, while ceramic membranes are manufactured as multi-channel tubular ones. Apart from the mechanical industry, another important application of filtration membranes is the chemical and food industry, especially in the processing of liquid food. When using conventional separation methods, many volatile food aromas tend to be separated. However, in membrane processes, these flavor components are retained in the food [10, 25]. Membrane ultrafiltration (UF) is a basic technology in the treatment of oily wastewater [7, 16]. Microfiltration, in addition to its basic purpose of purifying various liquid substances from contaminants, also has a reverse application. An example of this is the extraction of microalgae, i.e., autotrophic microorganisms, from fresh and seawater. The most commonly extracted microalgae is the green marine microalga Nannochloropsis oculata [14].

2. Microfiltration in industry and automotive

The microfiltration technique dates back to the 1970s, when there was a conflict in the Middle East between Israel and the Arabs. At that time, American troops reported problems with military vehicles in terms of lubrication of hydraulic systems due to the desert climate. Additional external filters were then installed in military vehicles. In the 1980s, the technique entered civilian use in the United States, and in the 1990s, it became common in Europe. In Poland, around 2000, it began to be noticed by companies servicing hydraulic systems in construction vehicles, agricultural vehicles, municipal equipment, and in power hydraulics. In automotive and industrial applications, microfiltration is a method of removing water, solids, and other components from oil mixtures in the form of colloidal systems or suspensions using filters from 1 to 4 μm. Microfiltration takes place under a small overpressure of up to 6 bar. The holes (pores in the membrane) of 1 to 4 μm are small enough to retain bacteria found in oils or fuels [11]. Microfiltration is performed on portable stations, as shown in Fig. 2, in a bypass manner. Oil filtration in the tank is performed during the operation of the hydraulic system. This minimizes the downtime of the device, financial outlays, and the amount of used oil, related to its more frequent replacement.

In industrial applications, microfiltration of hydraulic oil is already very common. It is observed when cleaning filter systems in construction and road machines, tractors, and agricultural machines, as well as in production machines with hydraulic systems.

Figure 3 shows the application of the Kleenoil MS2+MM5 microfiltration station during oil cleaning in a Libher 566 wheel loader and in a Billion H3500/550 injection molding machine. These are examples of the use of a filtration machine with simultaneous examination of the condition of hydraulic oil by the authors of the article. In automotive applications, microfiltration is used for engine fuels, engine oils, and transmission oils. Kleenoil by-pass filter systems have already been used to remove contaminants and wear products from rolling bearings, sliding bearings, gear wheels, or the interaction of the engine piston with rings with the cylinder liner. The problem of engine oil contamination has already been analyzed in [13, 28]. Figure 4 shows the diagram of the operation of the additional filter system in the lubrication system of the combustion engine and an example of the use of the system on a city bus.

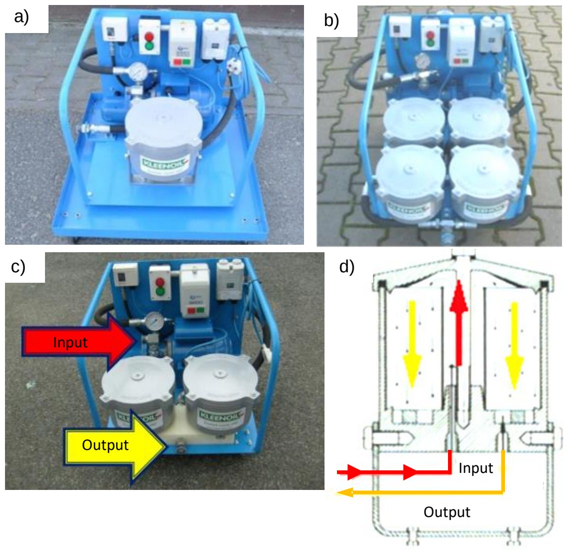

Fig. 2. View of a portable hydraulic oil filter unit with: a) one filter element, b) four filter elements, c) two filter elements, d) oil flow diagram through the filter element

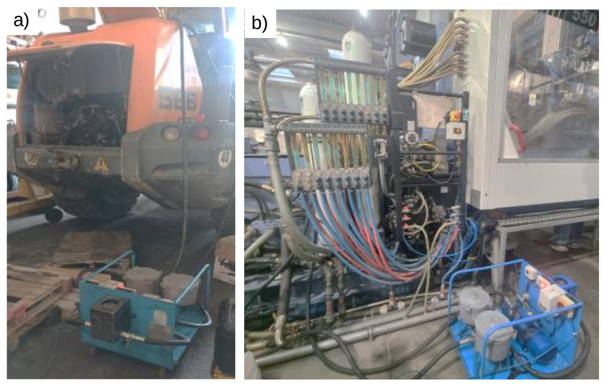

Fig. 3. View of the machine's use during microfiltration of hydraulic oil in: a) Liebher 566 wheel loader, b) Billion H3500/550 injection molding machine [fot. S. Kołodziejski]

Research conducted by Kleenoil on city buses in Lublin showed that adding an additional engine oil microfiltration system working in parallel with the combustion engine lubrication system extended the oil life to the next change by 4 times. During the engine oil filtration period, the oil was periodically tested for changes in kinematic viscosity during the use of buses.

Kleenoil has also conducted research into fuel purity by installing an additional diesel fuel microfiltration system on a vehicle and at fuel stations. Figure 5 shows a view of a vehicle with an additional KleenFuel filter in the fuel system. Figure 6 shows a view of the use of the MS4+MM5 microfiltration machine at a fuel station in a transport company.

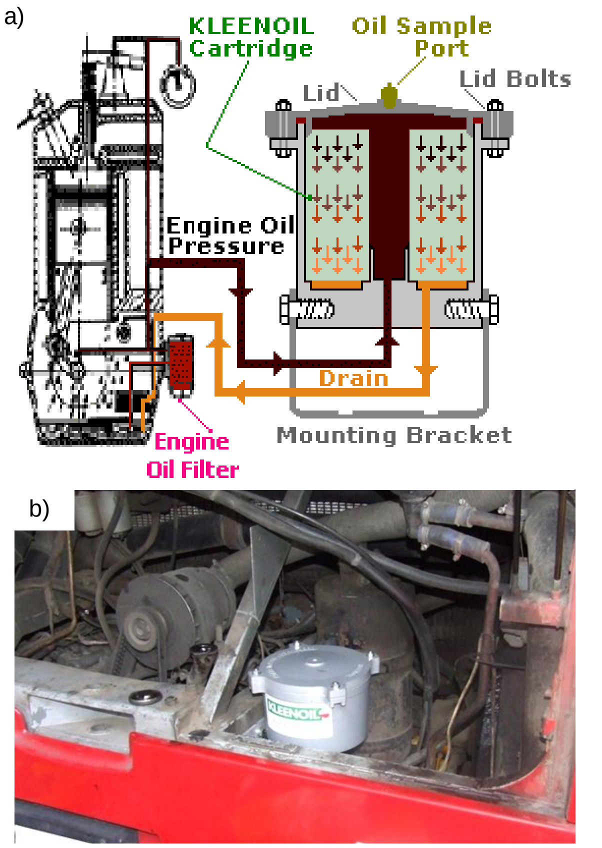

Fig. 4. a) Diagram of the filter system in the combustion engine lubrication system, b) View of the additional engine oil microfiltration system mounting in a city bus [fot. Ł. Kubacki]

Fig. 5. View of the additional tank with a fuel microfiltration insert on the truck b) view of the tank with the KleenFuel insert with fuel lines [fot. Ł. Kubacki]

Both during the adaptation of the device for microfiltration of engine oil and fuel, kleenoil and kleenfuel filter inserts with a hole diameter of 1 μm were used. This allows for the removal of organic impurities such as oxidation or thermal combustion products, inorganic impurities such as metal particles, and the removal of water by 99.95% [12]. The advantage of microfiltration devices is the possibility of replacing filter inserts without the need to drain the oil. The filter containers are located above the oil tank. The microfiltration application examples in Fig. 4–6 were an attempt to implement large-scale oil and fuel separation in motor vehicles and at gas stations. Despite successful testing, these solutions were not implemented in everyday operation.

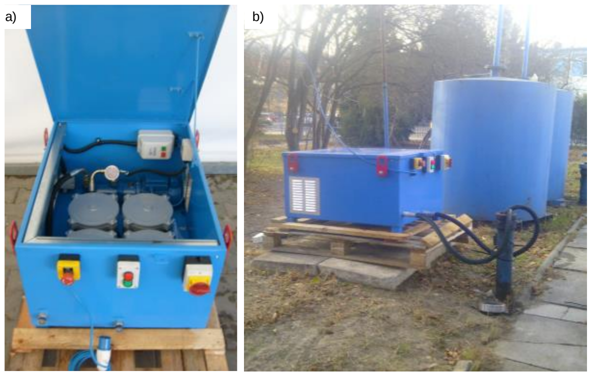

Fig. 6. a) View of the enclosed fuel microfiltration machine at the petrol station with four tanks b) view of the microfiltration device with fuel tanks [fot. Ł. Kubacki]

3. Oil purity class standards

In terms of regulations governing the purity of hydraulic and lubricating oils, the following standards should be indicated:

– ISO 4406
– SAE AS 4059
– NAS 1638
– GOST 17216.

ISO 4406:99 standard was published by Turkish Standards Institute (TSE) under the title: Hydraulic Fluid Power – Fluids – Method for Coding the Level of Particulate Contamination. 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 for reporting the relevant data. NAS 1638 is the American aviation standard, and GOST 17216 is the Russian standard for oil cleanliness. NAS 1638 was replaced by SAE AS 4059 in 2001. Both ISO and SAE standards refer to the number of particles recognized as contamination with a size 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 impurity values (4, 6, and 14 μm) found in 100 ml of the tested oil are selected. For example, hydraulic oil that received a cleanliness class result of 22/20/17 after testing (according to ISO 4406) means that it contained impurities in the number of [2]:

– from 20000 to 40000, about size above 4 μm
– from 5000 to 10000, about size above 6 μm
– from 640 to 1300, about size above 14 μm.

Cleanliness classes according to ISO 4406 standard were correlated with average cleanliness classes according to NAS 1638 standard, which is presented in Table 2. The table additionally presents requirements for various hydraulic system units in terms of oil cleanliness. In the case of finding that the cleanliness class of hydraulic oil is too high for the requirements set by the hydraulic system units and their intended use, it is possible to reduce the oil class thanks to microfiltration. According to the work [8], microfiltration allows for reducing the oil cleanliness by up to 6 classes. This depends on the filtration time and the number of used filter inserts.

Table 2. Hydraulic oil purity classes according to standards ISO 4406 and NAS 1638 [12]

Cleanliness class		Required oil cleanliness class			
ISO 4406	NAS 1638	Pumps and motors	Valves	Bear-ings	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	proportion, mushroom	sliding	cylinders
18/16/13	7				
17/15/12	6			roller	Hydrostatic
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				

4. Research methodology

4.1. Purpose and object of oil research

The aim of the study was to evaluate the ISO, SAE, and NAS cleanliness classes and the relative humidity of three selected new oils contained in a 5-liter plastic container. Achieving the study objective required conducting the study in three stages. The first stage involved testing the new oils, the second stage involved testing the oils after the first microfiltration, and the third stage involved testing the oils after the second microfiltration.

Hydraulic oil type HV46, ATF II D oil for automatic gearboxes, and 20W-50 engine oil were used for the tests. The research methodology diagram is presented in Fig. 7.

The choice of the tested oil in a plastic canister resulted from the fact that this type of packaging has the least impact on the phenomenon of evaporation and condensation of water inside during storage and transport. In contrast to metal tanks (barrels), this phenomenon is common, and it is necessary to filter the oil before pouring it into the machine or engine. Especially in a situation where metal tanks are stored without a roof and in warehouses with variable temperature, which depends on the ambient temperature.

4.2. Research method

Hydraulic oil condition tests were performed on the portable analyzer OPComII Portable Oil Lab PPCO 300-1000 by ArgoHytos. The general structure of the analyzer and its view are shown in Fig. 8.

The principle of the analyzer is to shine a laser beam through the flowing oil through a solid particle monitor. 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 the particle size in µm and the number of particles in the oil. Table 3 shows the parameters and values measured by the oil analyzer.

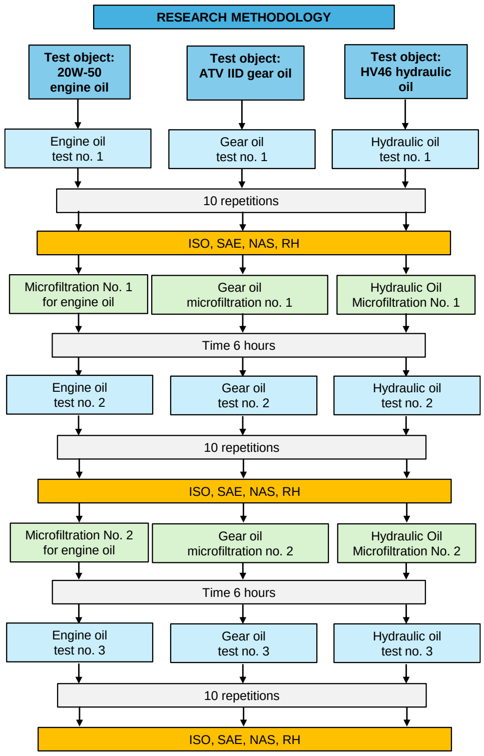

Fig. 7. Oil testing methodology diagram

Table 3. Measured parameters and values of the device OPComII Portable Oil Lab PPCO 300-1000 [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 [12]:

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

After basic tests of new oils from the canister, microfiltration was carried out on the Kleenoil MS2+MM5 device shown in Fig. 2c with two tanks and filter inserts.

5. Results of oil tests

The results of oil tests on a portable oil cleanliness class analyzer are presented in Table 4. The tests were conducted for compliance with ISO, SAE, and NAS standards. Each test was repeated 10 times. Due to the repetition of results within the above-mentioned oil cleanliness classes, only 3 results are presented in Table 4. The only variable value during the oil cleanliness test was relative humidity.

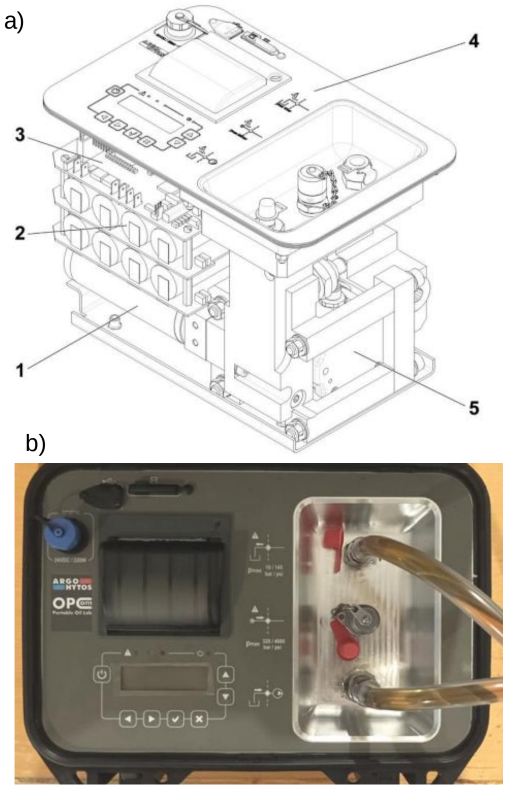

Fig. 8. a) General structure of the oil condition analyzer: 1 – engine with pump and electric gear, 2 – battery, 3 – control electronics, 4 – top side with control panel, 5 – particulate monitor, b) view of the portable oil condition analyzer OPComII Portable Oil Lab PPCO 300-1000 by Argo-Hytos

According to the work [2], relative humidity RH above 70% indicates that water contained in the oil is in a dissolved form. For oils, the permissible relative humidity of the oil is exceeded, and urgent microfiltration of the oil is recommended. The device for testing the oil condition in the generated test reports, already at relative humidity above 50% provides information about a high water level. Figure 9 presents the results of relative humidity tests for new oil (engine, gear, and hydraulic) with the average value and the spread of values from 10 measurements in the form of error bars. For tests related to the oil cleanliness class itself, subsequent repetitions do not result in significant changes. The cleanliness class in subsequent measurements is the same or changes by one class.

Table 4. Canister oil test results wg ISO, SAE and NAS

ISO 4 µm	ISO 6 µm	ISO 14 µm	SAE 4 µm	SAE 6 µm	SAE 14 µm	NAS	RH %
HV46 Hydraulic Oil							
23	21	17	12	12	11	12	52.8
23	21	17	12	12	11	12	52.7
23	21	17	12	12	11	12	52.7
ATV IID Transmission Oil							
22	19	14	12	11	8	11	37.8
22	19	14	12	11	8	11	37.2
22	19	14	12	11	8	11	36.9
20W-50 Engine Oil							
18	17	14	9	8	8	10	36.4
18	17	14	9	8	8	10	35.9
18	17	14	9	8	8	10	34.2

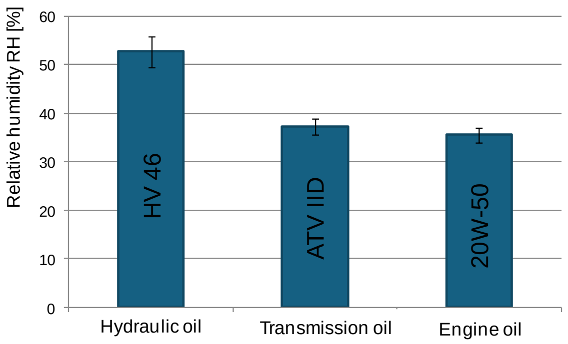

Fig. 9. Relative humidity (RH) test results of the analyzed oils before microfiltration

Based on Fig. 9, it was found that the new engine and transmission oil did not have a relative humidity above 50%, unlike the hydraulic oil. It was also found that the hydraulic oil had the largest dispersion of measurement results as a standard deviation from the mean value (3.17%), while in the case of engine and transmission oil, the standard deviation was 1.60% for 20W-50 oil and 1.62% for ATV IID oil.

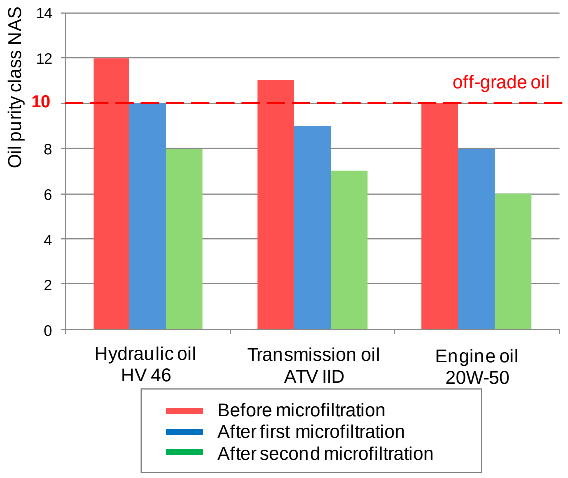

Fig. 10. Results of the NAS purity class test of the analyzed oils after two microfiltrations

After the oil was tested for cleanliness class and relative humidity, two microfiltrations lasting 6 hours were carried out. After each filtration, the cleanliness class and relative humidity were tested with the OPComII Portable Oil Lab PPCO 300-1000 oil analyzer. Figures 10 and 11 show the results of the oil tests (NAS and RH class) after two microfiltrations, the results were related to the first oil test after opening the canisters.

Analyzing the results of the tests presented in Fig. 10 and Fig. 11, it was found that after the first microfiltration lasting 6 hours, the cleanliness of the gear oil and engine oil was reduced by two NAS classes, which, according to Table 2, made the oil clean and suitable for use. In the case of hydraulic oil, the NAS class was reduced from 12 to 10 and required another microfiltration. The second microfiltration, which lasted 6 hours, allowed for a further reduction (by 2 classes) of oil cleanliness. In terms of relative humidity, each microfiltration on the portable Kleenoil MS2+MM5 device reduced the RH value with a standard error of 2.5% for hydraulic oil and about 1% for gear oil and engine oil.

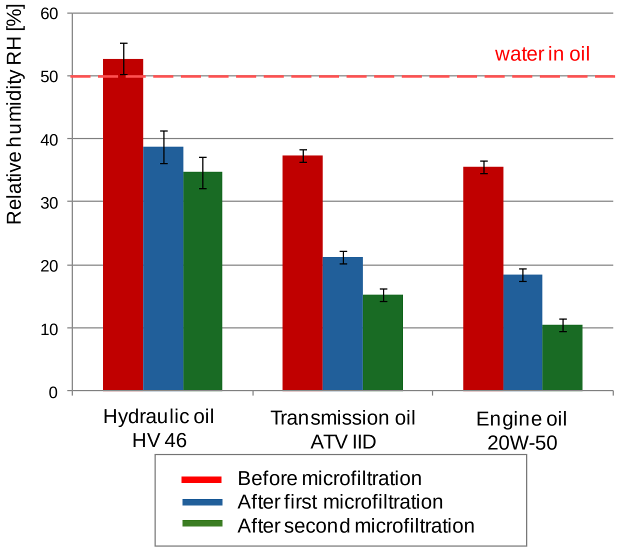

Fig. 11. The results of the relative humidity (RH) test of the analyzed oils after two microfiltrations

Analyzing the authors' research, they concluded that, in field conditions, oil microfiltration at portable stations should be conducted concurrently with oil testing for solid contaminants and water. Assessing the degree of filter contamination (filter elements) in the Kleenoil MS2+MM5 machine does not allow for classifying the oil into a given cleanliness class according to current standards. The authors believe that oil microfiltration should be conducted concurrently with oil testing.

5. Conclusions

The main advantage of using membranes in separation processes is simple operation. This is a technology that generates little waste and is more environmentally friendly compared to other separation methods. It is also economically viable due to the lower amount of energy used. The conducted literature study in the field of microfiltration and the authors' research allow for the formulation of the following conclusions:

a) 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.
b) The use of portable oil microfiltration devices together with an oil condition analyzer allows for the oil cleaning process to be carried out to the required cleanliness class. The microfiltration time will depend on the current cleanliness class of the oil.
c) The new oil tested was out of class (12 NAS class for HV46 oil, 11 NAS class for ATV, and 10 class for 20W-50) and requires microfiltration before flooding the hydraulic system, transmission, or combustion engine, which was confirmed by the authors.
d) New oil from manufacturers may be off-grade due to long distribution and storage periods. The purity class may rise to the level of off-grade. It is recommended to test the purity class before pouring the oil.
e) One-time microfiltration of hydraulic oil lasting about 6 hours allows for the oil cleanliness to be reduced by two NAS classes.

Acknowledgements

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Nomenclature

ATF	automatic transmission fluid
cSt	centistokes
EC	electrocoagulation
GOST	Gosudarstwiennyj Standard
HV	high viscosity
ISO	International Organization for Standarization
MD	membrane distillation
MF	microfiltration
NAS	National Aerospace Standard
UF	ultrafiltration
RH	Relative Humidity
SAE AS	Society of Automotive Engineers Aerospace

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