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Microfiltration of industrial oils as a method for reducing the amount of waste oils

Wojciech Sawczuk[1*], Sławomir Kołodziejski[2]

[1] Institute of Transport, Faculty of Civil and Transport Engineering, Poznan University of Technology, ul. Piotrowo 3, 60-965 Poznań, Poland
[2] Doctoral School of Poznan University of Technology, ul. Piotrowo 3, 61-138 Poznań, Poland
* Corresponding author's e-mail: wojciech.sawczuk@put.poznan.pl

ABSTRACT

Used industrial oils are among the most frequently generated petroleum-based wastes in Poland, posing a threat to the natural environment. Oil changes in vehicles or industrial machinery generate significant amounts of this waste. According to regulations, used oil must be properly disposed of. One method of reusing oil is its microfiltration. The first objective of the article was to present the methodology for testing oil compliance with standards for cleanliness classes. The second objective was to present the results of oil testing using portable oil microfiltration stations and to demonstrate that repeated microfiltration extends the service life of oil before the next replacement. The article shows that by applying microfiltration, the kinematic viscosity of the oil decreased by 1.5 cSt after 480 hours of operation, whereas without microfiltration the viscosity decreased by 3.5 cSt. The oil cleanliness class, according to NAS 1638, with microfiltration remained stable at 7–8, while without microfiltration the class rapidly increased from 7 to 12.

Keywords: used oil, oil microfiltration, oil cleanliness class, kinematic viscosity.

INTRODUCTION

Membrane separation is a common method used to purify liquids from contaminants. According to study [3], filtration techniques are applied depending on pore (opening) diameter, such as microfiltration, ultrafiltration, nanofiltration, reverse osmosis, and gas separation. On the basis of studies [23, 25], it has been found that in the case of industrial oils, microfiltration is a sufficient method to purify the oil to the required cleanliness class.

However, in the case of oil spills into the sea during maritime transport, it is necessary to precede microfiltration with biological treatment and finally apply membrane distillation [19]. This is due to environmental contamination and the negative impact on animals.

Another example of microfiltration application is the purification of the water contaminated with crude oil during hydraulic fracturing and horizontal drilling in rock formations in the extraction of oil and gas from shale [24]. In these processes, microfiltration is also used together with electrocoagulation and membrane distillation.

The issue of reusing industrial oils receives the least attention, as periodic oil replacement is generally assumed, and the used oil is designated for disposal in accordance with national or European regulations.

Waste oils, both industrial and vehicle-derived, belong to the category of hazardous waste [18]. The Regulation of the Minister of Economy of October 5th 2015 on the detailed method of handling waste oils precisely defines the procedures for managing waste oils. According to the regulations, used oil should be collected in dedicated oil containers and transferred for collection and disposal by licensed companies [25]. In the field of waste oils, additional legal acts apply, including:

a) The Waste Act of December 14th 2012, which defines, among other things, the principles for handling hazardous waste and the obligation to transfer it to authorized entities,

b) The Environmental Protection Law Act of April 27th 2001, which specifies the scope of liability for environmental damage caused by improper handling,
c) The Regulation of the Minister of Climate of January 2nd 2020 on the waste catalogue, which classifies used oils as hazardous waste with specific codes, e.g., 13 01 01* for hydraulic oils, 13 02 05* for engine and gear oils, and 13 01 10* for mineral oils,
d) The Criminal Code Act of June 6th 1997, in which Articles 182 and 183 define criminal sanctions for illegal storage and disposal of hazardous waste,
e) The SENT system (Electronic Transport Supervision System), a Polish teleinformation system of the National Revenue Administration designed to monitor the transport of sensitive goods, such as fuels, alcohol, tobacco, selected wastes, and cereals.

The listed legal acts constitute the guidelines and procedures for the entities generating used oils, covering proper disposal from the source of generation, through collection and transport, to final treatment understood as recycling. Owing to appropriate procedures, detailed control at each stage of waste oil management is possible [20].

METHODS OF WASTE OIL RECYCLING

In the field of waste oils, various recycling techniques can be applied to remove solid contaminants and water in order to reuse the oil. These techniques include:
a) chemical separation,
b) hydroprocessing,
c) vacuum distillation,
d) membrane separation,
e) bioremediation,
f) thermolysis,
g) catalytic treatment.

The first recycling method involves the use of chemical separators to separate water and contaminants from waste oil [1, 2]. This process neutralizes aromatic hydrocarbons and other harmful substances. The second method is hydroprocessing, which uses hydrogen to remove contaminants from waste oil and includes hydrotreating, hydrocracking, and hydroconversion. This method enables the production of high-quality base oils [14, 23].

Vacuum distillation is a separation process in which oil components are separated into fractions based on their boiling points. Under vacuum conditions, the process can be conducted at lower temperatures, minimizing the risk of thermal degradation of oil [6, 15]. These methods use various solvents to remove contaminants from used oil. For example, polar solvents differentiate between oil components, enabling their selective removal [19].

Membrane separation is one of the most popular and effective methods of contaminant removal. Different membrane types (microfiltration, ultrafiltration, nanofiltration) can be used to remove particles, water, and other impurities. Membrane techniques differ in membrane materials and pore diameters [8, 16].

Bioremediation uses microorganisms to decompose contaminants in used oil. It is an environmentally friendly process that can complement other recycling methods [9, 13].

Thermolysis involves oil decomposition at high temperature, often in an oxygen-free atmosphere, producing gases, oils, and solid residues. This process is effective for treating the oil containing difficult-to-remove contaminants [10, 17].

The use of catalysts allows more efficient removal of contaminants from used oil. Catalysts support the chemical reactions that remove sulfur, nitrogen, and other harmful substances [24].

Among all the listed waste oil recycling methods, oil separation via microfiltration is the fastest and simplest method of removing contaminants and water. Portable oil microfiltration units are available on the market, along with filters capable of retaining contaminants larger than 1 μm [12]. For industrial oils such as hydraulic oils, microfiltration is sufficient for oil purification and reuse. Another advantage of this method is that the diversity of microfiltration units allows oil purification directly at the place of use, i.e., in the facilities operating hydraulic machinery and vehicles. There is no need to transport used oil to storage or recycling companies.

The first objective of this article was to present a methodology for testing oil compliance with ISO, SAE, and NAS cleanliness standards. The second objective is to present test results obtained using portable oil microfiltration units and to demonstrate that repeated microfiltration can extend oil service life until the next replacement.

The proposed method for testing and microfiltration of oil is widely known. The authors of the article pointed out that microfiltration under industrial conditions is very often performed without prior oil testing, based only on the appearance of oil and the amount of contaminants remaining after microfiltration.

RESEARCH METHODOLOGY

The research object was HV46 hydraulic oil. Before the main tests, the oil cleanliness class and kinematic viscosity were verified in accordance with the methodology described in [7, 12]. The condition of hydraulic oil is currently defined by its cleanliness class according to ISO 4406, SAE AS 4059, and NAS 1638 standards. ISO 4406 currently replaces SAE AS 4059 and NAS 1638; however, ISO 4406 provides three cleanliness class values for contaminants larger than 4 µm, 6 µm, and 14 µm, while NAS 1638 provides a single class value from 0 to 12. HV46 oil was filled into the hydraulic system of a Liebherr 566 wheel loader. Oil cleanliness testing was performed using a portable laboratory OPComII Portable Oil Lab PPCO 300-1000 by ArgoHytos. A portable laboratory for measuring the oil cleanliness class enables testing of all industrial oils (hydraulic, engine, gear oils, and others, as well as fuels). The view of the research object together with the portable laboratory is presented in Figures 1 and 2.

a) b)

Figure 1. View of the oil in a plastic container used in the experiments [5] and the OPComII Portable Oil Lab PPCO 300–1000 portable laboratory by ArgoHytos [11]

a)

Figure 2. View of: a) the Liebherr 566 wheel loader used in the experiments, b) oil cleanliness class testing using an ArgoHytos analyzer

The tests were conducted in accordance with the principles of an active experiment [4, 21], with deliberately defined and modified boundary conditions and observation of system response to changes in input parameters. The variable parameter was oil operating time. Every 160 operating hours, the oil was tested for cleanliness class and kinematic viscosity. The tests were conducted for up to 480 operating hours.

The tests were performed twice: first without microfiltration, with oil tested every 160 hours; then the oil was replaced with new oil, and the oil was cleaned every 160 hours using a portable Kleenoil MS2+MM5 microfiltration unit, as shown in Figure 3. Figure 4 presents the preparation of the Ostwald–Pinkiewicz capillary for kinematic viscosity measurement. The capillary constant was 0.2736.

Microfiltration was performed four times. In both test cases (with and without microfiltration), the first filtration was conducted on new oil to achieve the recommended cleanliness class of

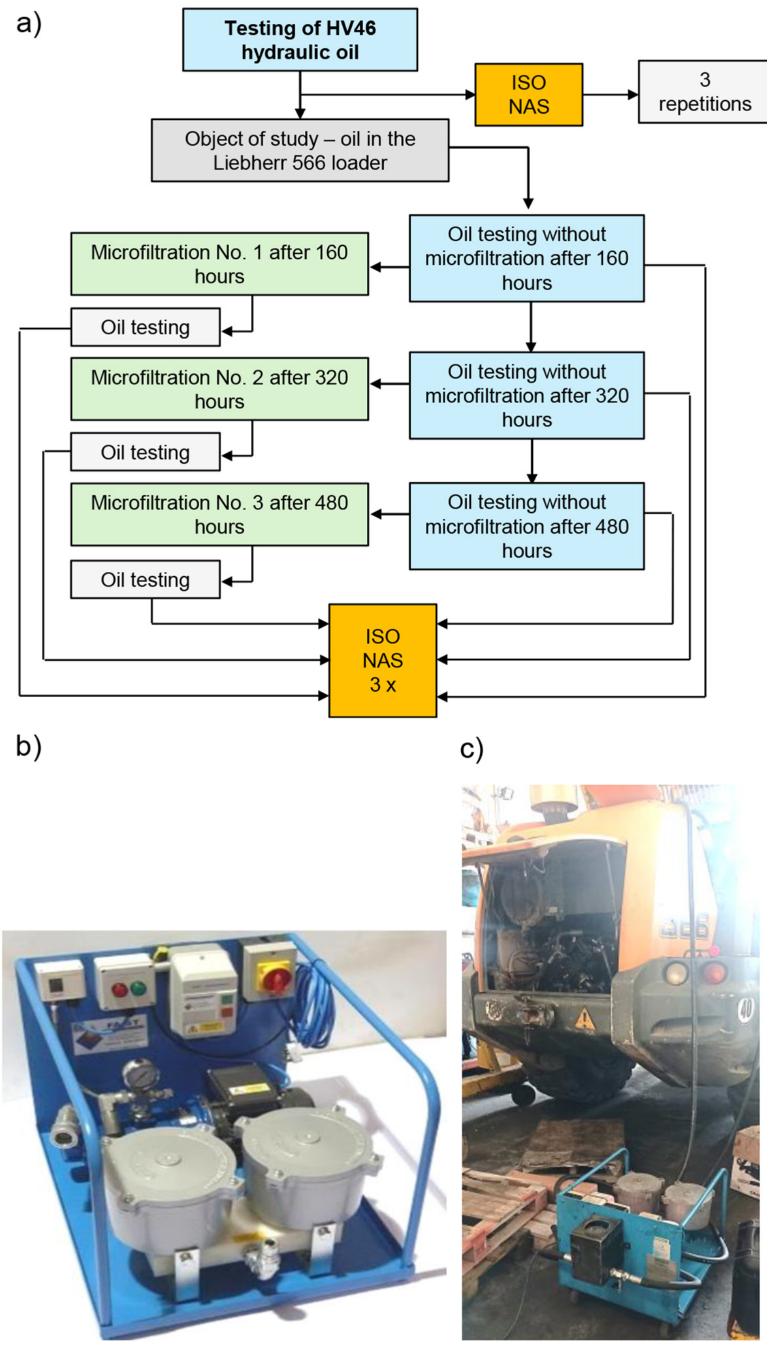

Figure 3. View of: a) Block diagram of oil testing and microfiltration, b) the portable Kleenoil MS2+MM5 unit with a capacity of 600 L/h, c) the Liebherr 566 wheel loader during the microfiltration process

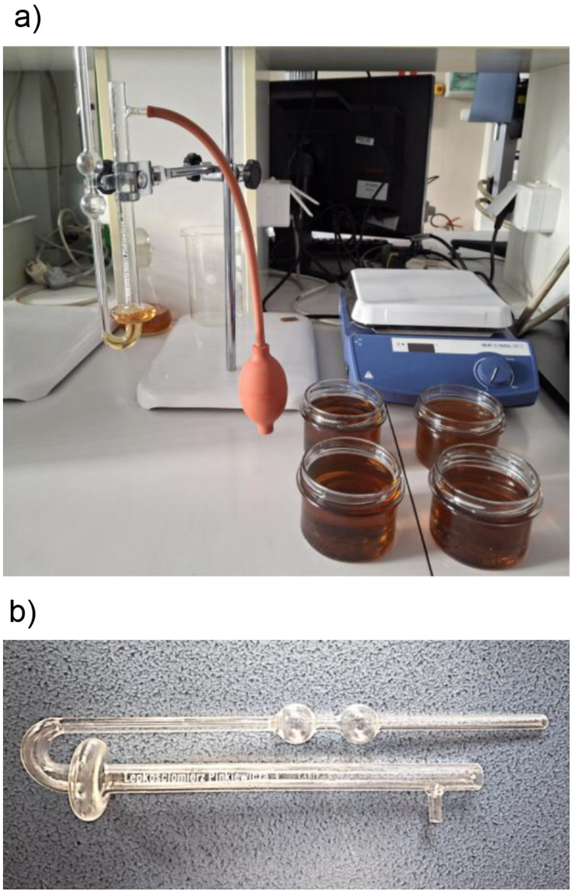

Figure 4. View of: a) preparation of the capillary for kinematic viscosity measurement, b) Ostwald–Pinkiewicz capillary with a constant k = 0.2736

NAS 7 [12], corresponding to ISO 19/15/12 or 18/16/13. For oil prepared in this manner, testing started after 160 hours of loader operation and continued up to 480 hours, corresponding to half of the oil service interval before replacement. Kinematic viscosity was determined according to the ISO VG 46 quality class in compliance with ISO 11158-HV.

ANALYSIS OF RESEARCH RESULTS

Figure 5 presents the relationship between kinematic viscosity expressed in cSt (mm²/s) for eight oil samples taken from the systems without and with microfiltration. Measurements were performed at 40 °C.

When analyzing the graphs shown in Figure 5, it was found that periodic oil cleaning every 160 hours in the loader slows down the oil degradation process, as evidenced by a smaller decrease in its kinematic viscosity after 480 hours of operation. In the microfiltered system, viscosity decreased from 48 mm²/s to 46.5 mm²/s (a decrease of 1.5 cSt), whereas in the system without microfiltration, viscosity decreased from 48 mm²/s to 44.5 mm²/s (a decrease of 3.5 cSt).

On the basis of the conducted tests and the allowable kinematic viscosity range for HV46 hydraulic oil (41.4–50.6 cSt), linear regression models [22] were used to estimate the operating time until oil replacement at the limiting viscosity of 41.4 cSt. The results are presented in Table 1 and Figure 6.

On the basis of the analysis of the results presented in Table 1 and Figure 6, the experimental findings indicate that the system equipped with microfiltration extends the oil service life by approximately 2.3 times compared to the system without microfiltration, up to the limiting kinematic viscosity value of 41.4 cSt. The estimated operating times were obtained using linear regression models based on experimental data collected up to a system operating time of 480 hours.

On the basis of the experimental results and a review of the relevant literature, it was concluded that, despite the maintenance intervals specified in the machine technical documentation, the hydraulic oil replacement interval depends on three key factors: a decrease in kinematic viscosity below the critical value, an increase in the total acid number (TAN), and the concentration of contaminants as well as water content in the oil. Contaminants and water are removed through microfiltration, while an increased acid number does not significantly affect the corrosive aggressiveness of the oil due to its anti-corrosion properties, as reported in the literature. Consequently, it was determined that only the decrease in kinematic viscosity governs the timing of hydraulic oil replacement.

The second objective of the study was to determine the cleanliness class of the collected oil samples obtained from two hydraulic systems (with and without microfiltration) after viscosity testing, in accordance with the ISO 4406:99 and NAS 1638 standards. The oil cleanliness results obtained using the ArgoHytos portable oil condition laboratory (Figure 1b) are presented in Table 2 and Figure 7. Kinematic viscosity and cleanliness class measurements were preceded by testing of fresh oil and its filtration to ISO Class 18/16/13, which is equivalent to NAS Class 7.

On the basis of the analysis of the data presented in Table 2 and Figure 7, the experimental

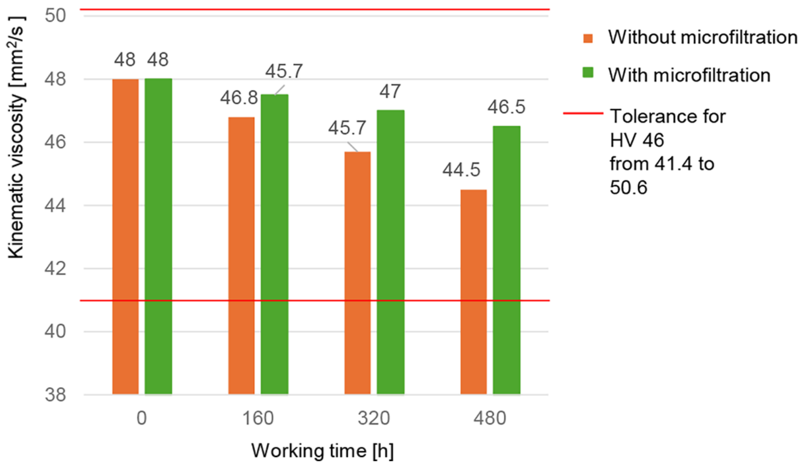

Figure 5. Relationship between kinematic viscosity and hydraulic system operating time, as well as the type of hydraulic installation (without and with microfiltration), at an oil temperature of 40 °C

Table 1. Estimated operating time until oil replacement at the limiting kinematic viscosity

Hydraulic system type	Regression model	Estimated time to replacement
Without microfiltration	$Y_{without\ MF} = -7.3 \cdot 10^{-3}\ x + 47.99$	902 h
With microfiltration	$Y_{with\ MF} = -3.1 \cdot 10^{-3}\ x + 48$	2129 h

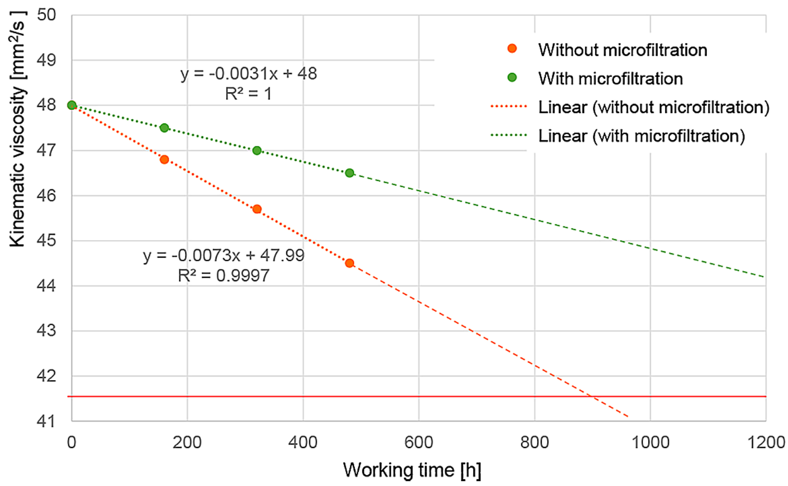

Figure 6. Relationship between kinematic viscosity, expressed in mm²/s, and operating time, based on modeling the operating hours required to reach the limiting viscosity of 41.4 mm²/s

results indicate that the application of microfiltration after 160 operating hours of the wheel loader maintains the oil cleanliness class at NAS Class 7 up to 320 operating hours. Additional 160 hours of operation resulted in an increase by one NAS class to Class 8. This one-class increase is attributed to the fact that, in each case, microfiltration was carried out for 8 hours after the completion of loader operation. If the oil separation time were extended by, for example, 2 additional hours, it is likely that the cleanliness class could be reduced again to NAS Class 7. This aspect will be the subject of further research by the authors.

According to the ISO 4406 standard, the concentration of contaminants larger than 4 μm and 6 μm remained at similar levels (19–18) and (15–16), respectively. In contrast, the concentration of contaminants larger than 14 μm decreased from levels of 12–13 to 11, indicating high efficiency in removing the largest-diameter particles.

Table 2. Results of oil cleanliness class measurements using the ArgoHytos portable laboratory according to ISO 4406 and NAS 1638

Operating time (hours)	Without microfiltration			
	Particle size (diameter)			NAS
	ISO 4 um	ISO 6 um	ISO 14 um	
0	19	15	12	7
160	19	17	13	9
320	22	18	14	10
480	23	21	15	12
Operating time (hours)	With microfiltration			
	Particle size (diameter)			NAS
	ISO 4 um	ISO 6 um	ISO 14 um	
0	19	15	12	7
160	18	16	13	7
320	18	14	11	7
480	19	16	11	8

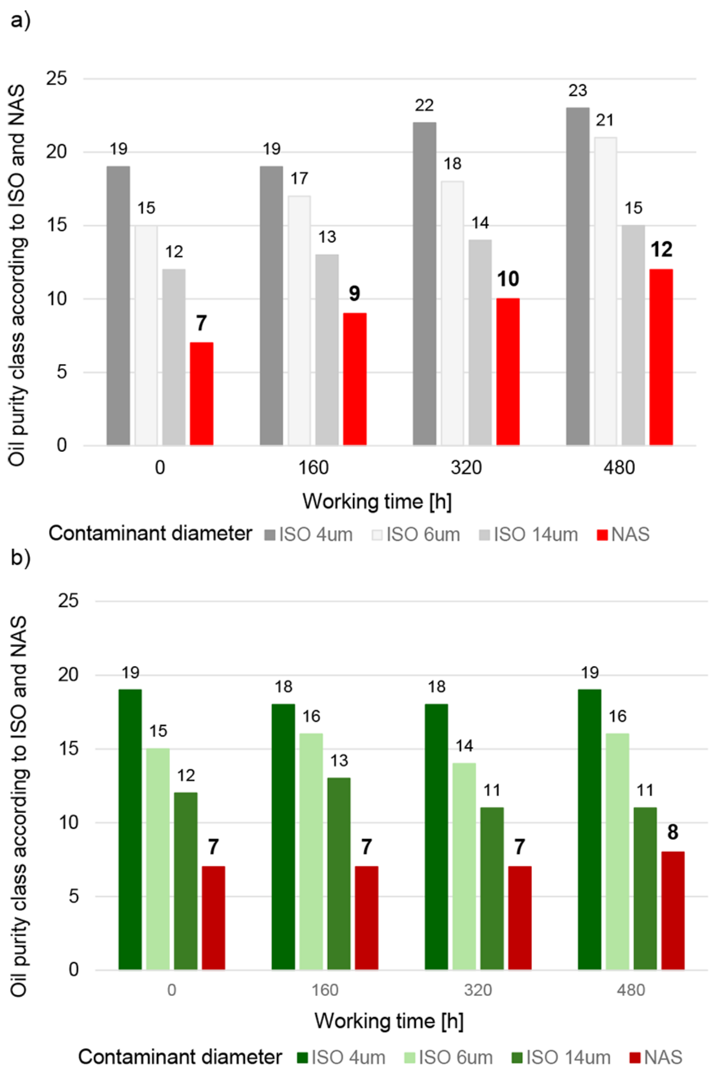

Figure 7. Hydraulic oil cleanliness class according to the ISO 4406:99 and NAS 1638 standards as a function of time and hydraulic system type: (a) without microfiltration, (b) with microfiltration

The hydraulic system without additional microfiltration exhibited a continuous increase in oil cleanliness class during operation, and after 320 operating hours the oil became out of specification, requiring immediate purification. In this case, the increased level of contaminants contributes directly to accelerated wear of interacting components within the hydraulic system.

ENVIRONMENTAL COST OF HYDRAULIC OIL

An analysis of the operation and maintenance documentation (DTR) of various construction and road machines indicates a wide range of hydraulic oil replacement intervals, e.g. every 500, 1.000, or even 5.000 operating hours, in the absence of periodic microfiltration. Such a large variation results from differing operating conditions of hydraulic systems and machine operation under low, medium, or high load. It should be emphasized that, due to the increasing awareness of both machine manufacturers and users regarding microfiltration, technical operation and maintenance documentation or maintenance system documentation (e.g., for Palfinger HDS cranes) increasingly includes the requirements stating that, prior to filling the hydraulic system, the oil cleanliness class according to ISO 4406 should be 17/15/12, corresponding to NAS Class 6 (very clean oil suitable for systems operating up to 32 MPa), with oil replacement specified every 1.000 operating hours or once per year.

On the basis of the fee rates for used oil specified in the Notice of the Minister of Climate and Environment of July 28th 2024 on environmental usage fee rates for 2025, as well as disposal fees

Table 3. Calculation of the costs of purchasing and replacing hydraulic oil in a representative construction machine equipped with a 200-L reservoir, in relation to the purchase and maintenance costs of an oil microfiltration unit

Parameter	Item	Value	Unit
Conventional approach to hydraulic oil replacement in accordance with the machine operation and maintenance documentation (DTR)	Purchase of new HV 46 oil	10	PLN/L
	Cost of filling a 200 L reservoir	2000	PLN/L
			-
	Oil replacement interval	4	months until oil replacement
	Machine operation for 8 hours per day	2	months until oil replacement
	Number of oil replacements per year (8 h/day)	3	replacements/year
	Number of oil replacements per year (16 h/day)	6	replacements/year
	Oil disposal cost	1	PLN/L
	Disposal cost for 3 oil replacements	600	PLN/year
	Disposal cost for 6 oil replacements	1200	PLN/year
	Environmental fee	69.09	PLN/year
	Total annual cost for 8 hours of operation per day	**6669.09**	PLN/year
	Total annual cost for 16 hours of operation per day	**13269.09**	PLN/year
Costs associated with the application of an oil microfiltration unit (MF) Item	Cost of filling a 200 L reservoir	2000	PLN
	Purchase cost of the microfiltration unit	14000	PLN
	Cost of microfiltration filters	400	PLN
	Assumption: threefold extension of oil service life through microfiltration – 3000 h		
	Number of oil replacements per year (8 h/day)	1	replacements/year
	Number of oil replacements per year (16 h/day)	2	replacements/year
	Disposal cost for 1 oil replacement	200	PLN/year
	Disposal cost for 2 oil replacements	400	PLN/year
	Environmental fee	69.09	PLN/year
Cost including MF unit purchase	Total annual cost for 8 hours of operation per day	16 669.09	PLN/year
	Total annual cost for 16 hours of operation per day	19 269.09	PLN/year
Cost excluding the purchase of the microfiltration (MF) unit	Total annual cost for 8 hours of operation per day	**2 669.09**	PLN/year
	Total annual cost for 16 hours of operation per day	**5 269.09**	PLN/year

Table 4. Comparison of the costs of purchasing and disposing of waste oils under the conventional hydraulic oil maintenance approach in accordance with the machine operation and maintenance documentation (DTR) and with the application of a microfiltration unit

<table>
<tr><td colspan="3">Annual cost of hydraulic oil purchase and disposal</td></tr>
<tr><td></td><td>Operation of the oil for 8 hours per day</td><td>Operation of the oil for 16 hours per day</td></tr>
<tr><td>Without microfiltration</td><td>6669.09 PLN</td><td>13269.09 PLN</td></tr>
<tr><td>With microfiltration</td><td>2 669.09 PLN</td><td>5 269.09 PLN</td></tr>
<tr><td rowspan="2">DIFFERENCE</td><td>4000.00 PLN</td><td>8000.00 PLN</td></tr>
<tr><td colspan="2">60%</td></tr>
<tr><td colspan="3">Annual amount of generated waste</td></tr>
<tr><td>Without microfiltration</td><td>600 l</td><td>1200 l</td></tr>
<tr><td>With microfiltration</td><td>200 l</td><td>400 l</td></tr>
<tr><td rowspan="2">DIFFERENCE</td><td>400 l</td><td>800 l</td></tr>
<tr><td colspan="2">approx. 66%</td></tr>
</table>

for waste oil, the maintenance cost of a single construction machine equipped with a hydraulic system and a 200-liter hydraulic reservoir was estimated. Table 3 presents the maintenance costs of a construction machine under the conventional hydraulic oil replacement approach, compared with the costs associated with the purchase and use of a unit for periodic hydraulic oil microfiltration.

The calculation of the costs of purchasing and disposing of hydraulic oil, based on a single machine (vehicle) equipped with a hydraulic system and a 200-liter reservoir, as presented in Table 3 for both the conventional maintenance approach in accordance with the machine maintenance documentation and the alternative approach using a microfiltration unit, enabled the estimation of savings in oil purchase costs and the reduction of generated waste oil. Assuming that the machine (vehicle) operates only 8 hours per day, the investment in a portable microfiltration MF unit is reimbursed after approximately two years, whereas for an operating time of 16 hours per day, the microfiltration unit pays back within one year. Table 4 presents a final summary of the savings in oil purchase and the reduction in generated waste oil.

On the basis of the comparative data presented in Table 4, from a cost perspective, the application of a microfiltration unit reduces the operating costs of a hydraulic system by approximately 60% solely in terms of oil purchase and disposal, compared to the conventional approach of periodic oil replacement in accordance with the machine operation and maintenance documentation (DTR). It should be emphasized that, in practice, the savings related to oil purchase may be even higher, as the present study assumed, based on experimental results, that microfiltration extends oil service life to three replacement intervals. However, manufacturers of oil separation units and filtration systems declare that microfiltration may extend oil service life without replacement by four or even five times.

For such an approach to be feasible, continuous monitoring of hydraulic oil kinematic viscosity is required. Furthermore, it was concluded that, in addition to reducing the oil purchase and replacement costs, microfiltration contributes to extending the service life of hydraulic components such as pumps, directional control valves, actuators, and valves, due to the continuous removal of contaminants and water from the hydraulic system.

An analysis of oil replacement and disposal costs in relation to the purchase of a microfiltration unit, based on a single vehicle equipped with a hydraulic system and a 200-liter reservoir, indicates that the investment in a microfiltration device is recovered after approximately two years when the construction machine operates 8 hours per day, or after one year when operating 16 hours per day. From an environmental perspective, in terms of the amount of generated waste oil, microfiltration reduces the volume of oil sent for disposal by more than 60%.

CONCLUSIONS

On the basis on the conducted research on a wheel loader with periodic oil microfiltration, the following conclusions were drawn:

1. The service life of the oil until the next replacement is more than twice as long compared to periodic oil replacement, while maintaining the required kinematic viscosity. Further studies will be repeated, as filter cartridge suppliers declare that the filtered oil can be reused up to four times before replacement.
2. Oil microfiltration slows down the aging and degradation process of hydraulic oil until the lower limit of kinematic viscosity is reached.
3. Oil microfiltration must be accompanied by periodic measurements of kinematic viscosity. Without viscosity monitoring, the oil may meet the cleanliness class requirements according to the ISO or NAS standards, while no longer providing the required lubricating properties.
4. Depending on the frequency of application, microfiltration reduces the amount of generated waste oil by a factor of 2 to 4.
5. The purchase of a microfiltration unit reduces oil purchase and disposal costs by approximately 60%, compared to the conventional approach based on oil replacement intervals specified in the technical documentation of vehicles or machinery.
6. From a global environmental perspective, the use of portable microfiltration units enables oil purification at the place of use, thereby reducing the number of oil transports to storage facilities and subsequent recycling or disposal sites.

The directions for the authors' future work include conducting additional research on the impact of hydraulic oil microfiltration on the abrasive wear of hydraulic system components. In this regard, the authors plan to examine the wear of such assemblies as the spool in the hydraulic control valve housing and the pistons of an axial piston pump. These two assemblies of the hydraulic system are responsible for the oil flow, i.e., the output capacity of the hydraulic pump.

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