Vol. 47, No. 4 (2025) 663-672, DOI: 10.24874/ti.1942.04.25.09

Tribology in Industry

www.tribology.rs

RESEARCH

Tribological Aspects of Operation of Hydraulic Fluids

Zdenko Tkáč[a], Daniel Skladaný[a], Martin Nagy[a,*], Ján Kosiba[a], Liudmyla Hanushchak-Yefimenko[b], Tetiana Bukoros[b], Martin Eššeс[c], Marek Halenár[a]

[a]Institute of Agricultural Engineering, Transport and Bioenergetics, Faculty of Engineering, Slovak University of Agriculture in Nitra, Tr. A. Hlinku 2, 949 76 Nitra, Slovakia,
[b]Faculty Economics and Business, Kyiv National University of Technologies and Design, Mala Shyianovska St, 2, Kyiv, 01011, Ukraine,
[c]Jaguar Land Rover, Horné lúky 4540/1, 949 01 Lužianky-Nitra, Slovakia.

Keywords:

Synthetic hydraulic oil
Hydraulic gear pump
Total acid number
Kinematic viscosity
Purity code
Additive elements

* Corresponding author:

Martin Nagy
E-mail: xnagym@uniag.sk

Received: 28 April 2025
Revised: 12 July 2025
Accepted: 13 September 2025

A B S T R A C T

This paper deals with the effect of a synthetic oil based on synthetic esters on a QHD 17R hydraulic gear pump with a geometric volume of 17 cm³, intended for use with mineral oil, during a 500-hour lifetime test. Changes in kinematic viscosity (a decrease of 1.9% at 40°C and 3.9% at 100°C), total acid number (an increase of 2.6%), ISO 4406 purity code (a change from 23/21/17 to 18/16/13), and the morphology of wear particles were observed and analysed to assess the influence of long-term workload on the hydraulic gear pump. Apart from changes of tribological properties, presence of unwanted particles in oil was evaluated. These particles occurred because of internal wear of the hydraulic gear pump and other hydraulic components. Amount of Copper in hydraulic oil increased by 308% to 0.49 mg·kg⁻¹ and amount of Tin increased by 167% to 3.61 mg·kg⁻¹. Metallic particles emitted this way can produce more wear, as they behave as additional abrasive particles flowing in the hydraulic medium. Although these particles did not immediately reduce the machine's efficiency during the test, their long-term accumulation may accelerate internal wear and lead to reduced flow performance over time.

1. INTRODUCTION

Hydraulic gear pumps are widely used hydraulic transducers either with external or internal gear configuration. The external gear pump has the characteristics of a simple structure, easy fabrication, low cost, small size, good pollution resistance, and self-suction capacity; consequently, it has been widely used in the industrial field [1].

In the present day, these pumps are becoming less common, as piston hydraulic transducers represent better alternatives with wider pressure ranges and flow efficiencies, without unwanted pulsations of hydraulic flow, as teeth of gear wheels fit one between others. However, in some fields, such as agriculture, these pumps still have their place since their production cost is lower.

To maintain the performance of any hydraulic transducer, it is necessary to use an appropriate hydraulic fluid. This ensures the transducer is properly lubricated, protected by a thin layer of fluid between moving metallic parts moving one by one, cooled and insulated form atmospheric air and humidity. For this reason, it is not recommended to use synthetic oil in cooperation with hydraulic gear pump intended to be used with mineral oil. In order to verify the condition of hydraulic fluids during use, users often monitor basic parameters such as viscosity, clarity, presence of particles or sludge, and signs of oxidation or acidification. Such evaluation helps to identify degradation of the fluid before it causes malfunction or wear.

The four states of gear pump include normal state, wear and tear, pitting fault, and snaggletooth fault [2]. Normal state can be prolonged by using correct working modes and high-quality hydraulic fluid, so the transducer is protected from turning into fault states.

Mineral hydraulic oils are the most popular choice by users of hydraulic devices, since they are less expensive than plant-based or synthetic alternatives. At present, the fluids used in most hydraulic systems are hydraulic oils of the HV quality class (according to EN-ISO 6743-4) [3]. They consist of mineral base oil and various improvers, such as oxidation and corrosion inhibitors, viscosity improvers and anti-wear additives [4]. Hence, their origin is petroleum – they are formulated from base petroleum stocks with about 10 – 25% additives. These additives consist of antioxidants and metal deactivators, detergents, dispersants, corrosion inhibitors, rust inhibitors, amongst others [5,6].

On the other hand, synthetic oil, that we used in experiment, has chemically produced base, and this way, manufacturers can adjust it to various needs. Synthetic oils generally have lower coefficient of friction, which can potentially lead to better efficiency and energy saving. This is because lower friction reduces energy losses in the contact zones between moving components, resulting in less heat generation and improved mechanical efficiency. Detergent properties are another benefit, leading to cleaner inward of system. Another benefit is that synthetic oils can be produced as biodegradable. Their disadvantages are that they are not compatible with some materials (e.g. rubber) and they evaporate – some synthetic oil´s vapours could be toxic. Emulsification – creating mixture of oil and water can also lead to corrosion in system. On top of this list, we can nominate it´s cost, as the biggest disadvantage.

The aim of this study is to investigate how a synthetic hydraulic oil affects the performance, wear, and internal cleanliness of a gear pump originally designed for mineral oil. Since synthetic hydraulic oils can be environmentally friendly, unlike mineral oils, we want to prove that they can be used as a replacement for mineral oils in hydraulic pumps intended to be used with mineral oils. Another benefit is that standard mineral oils have generally lower viscosity index, meaning under higher temperatures they are more likely to behave less efficiently. This work can thus contribute to finding new, environmentally acceptable solutions. Unlike previous works that focused on short-term compatibility tests, this study evaluates real degradation and wear behavior after 500 hours of continuous operation. The added value of this work lies in connecting fluid condition monitoring with actual mechanical effects on the pump system under realistic working conditions.

2. THEORETICAL BASES

In our research, we investigated four crucial quantities and their changes during lifetime test of synthetic oil in cooperation with hydraulic pump intended to be used with mineral oils.

Total Acid Number describes amount of KOH (potassium hydroxide) needed to neutralize one gram of hydraulic fluid. This value is used to evaluate degradation of hydraulic fluid, since increase of acid number is a result of oxidation of hydraulic fluid.

Acid number and Base number are fundamental measures of oil condition, these being routinely used to monitor relative changes in acidity or reserve alkalinity, respectively, of new and in-service oils [7]. It is important to point out, that initial acid number is not important for judging oil´s degradation, only it´s change matters. According to standards ASTM D943 [8] and ISO 4263 [9], hydraulic fluid is considered degraded when change of acid number is bigger than 2 KOH/g.

Kinematic viscosity is one of the most important physical parameters of hydraulic fluid, as it directly affects flow characteristics.

The lifetime of hydraulic fluids is significantly affected by their physical properties, particularly kinematic viscosity [10]. Viscosity plays an important role in liquid dynamics, as it determines the fluid's resistance to flow. In hydraulic systems, a high-viscosity fluid increases friction and energy loss, whereas a low-viscosity fluid can lead to excessive leakage. Since viscosity is highly dependent on temperature and pressure, fluctuations in these factors directly impact the performance of hydraulic oils [11]. Kinematic viscosity (ν) is used when normalizing dynamic viscosity (μ) to the fluid density (ρ) and is expressed as [12]:

$$\nu = \frac{\mu}{\rho} \qquad (1)$$

Where:

ν = kinematic viscosity [$m^2 \cdot s^{-1}$]
μ = dynamic viscosity [Pa·s]
ρ = density [$kg \cdot m^3$]

This property can be understood as a measure of how effectively a fluid transfers momentum per unit volume. Fluids with high kinematic viscosity exhibit superior momentum transport capabilities, making highly viscous or low-density liquids especially effective in applications where efficient momentum transfer is required [13].

Currently, the main methods for measuring liquid viscosity are the capillary flow method, vibrating wire method, oscillating disk method, oscillating quartz crystal method, falling body method, and rotating cylinder method. These measurements are relatively accurate under atmospheric conditions [11].

Oil in the hydraulic system is mostly mixed oil, and its density data is inaccurate, which further increases the uncertainty of dynamic viscosity data. [11]

Purity code as described in ISO 4406-2021 [14], relates to number of particles of various sizes in hydraulic oil.

The standard specifies a method for determining the code that defines the concentration of solid particles present in a hydraulic fluid system. The purity code applies to both particle counter and microscope-based measurements and is represented by three numbers separated by slashes. The first number expresses the quantity of particles smaller than 4 μm, the second number corresponds to particles smaller than 6 μm, and the last number counts particles smaller than 14 μm. Additionally, the standard includes a reference table correlating particle quantity and size with the assigned code, guidelines for conformity declaration, and a graphical depiction of the purity classification.

Additive element tracking analysis is used to determine presence of various chemical elements, in this case atomic emission spectrometry was used. This way, it is possible to evaluate presence and amounts of any chemical particles in hydraulic fluid, as well as observe their changes, which may lead to changes in oil´s performance.

Particles present in hydraulic oil have at least one of three origins. Evans (2010) [15] divides origin of elements in hydraulic oil into these categories:

- Wear metals – occurs in oil as a result of wear of hydraulic components and describe machine´s health.
- Oil additives – particles are part of oil´s composition, and their changes describe oil´s health
- Contaminants – these particles got into the oil from outside, as dust, dirt, or form coolant leaks, during maintenance or during machine´s operation.

Additives are divided into four groups characterizing their main role in hydraulic oils, according to Pabsetti (2023) [16]:

1. Surface protective additives
    a. Anti wear agents
    b. Extreme pressure additives
    c. Corrosion inhibitors
    d. Detergents
    e. Dispersants
2. Performance additives
    a. Viscosity index improvers
    b. Friction modifiers
    c. Pour point depressants
3. Lubricant protective additives
    a. Antifoaming agents
    b. Antioxidants
4. Nanoparticles

Surface protective additives reduce friction and protect surface against undesirable impacts of hydraulic oil on hydraulic components.

Detergents serve as the foundation for the so-called base number, the alkalinity reserve of motor oils, which neutralises corrosive acids and keeps surfaces free of deposits. Typically, they are chemical substances made of calcium and magnesium [16].

Surface protective additives protect hydraulic circuit as well as oil: Sulphur is also found in many additives, including anti-wear, antioxidant, extreme pressure, corrosion inhibitor and metal deactivator additives [15].
Phosphorus is a non-metal and is found in many additives. These include: anti-wear, antioxidant, extreme pressure, corrosion inhibitor, friction modifiers, metal deactivator and biocide chemicals [15].

The addition of metallic nanoparticles such as Fe, Pd, Ni, etc. has also been found to improve tribological properties. Through comparative investigations, it has been discovered that metal oxides with useful lubricating features include ZnO, TiO_2, and ZrO_2 [16].

Performance additives are added to hydraulic oil to improve its viscosity and friction properties, thus increasing mechanical and flow efficiency in hydraulic devices.

In the range of 0.1% and 1.5%, phosphoric acid esters, high molecular weight organic phosphorus, organic fatty acids, amines, amides, and imides are added to lubricants that are intended to act as friction modifiers [16,17].

Even more complex chemicals and nanoparticles are being investigated: Alumina (Al_2O_3) and hexagonal boron nitride (hBN) nanoparticles were examined by Abdullah et al. [18,16] with results, that they noticeably reduce friction coefficients.

Lubricant protective additives serve as substances protecting hydraulic oil itself against degradation.

They serve to prevent oil form foaming, as silicon: Silicon is part of a chemical added to oils to stop them foaming so silicon can be an additive [15], or to prevent them from oxidation: Antioxidants are present in almost all lubricating oils and greases; examples include aromatic amines, hindered phenols, and zinc dialkyldithiophosphates [16].

The biggest hazard to the proper functioning, durability, and reliability of hydraulic systems is posed by the presence of contaminants in the oil (cleanliness of the oil). A deterioration in other oil properties, including viscosity, viscosity index, and increased acid number, does not cause major risks [4].

Although gear pumps are typically designed for use with mineral oils, increasing environmental and performance demands are encouraging the use of synthetic biodegradable alternatives. This research investigates how such a substitution affects pump wear and fluid condition during long-term operation. The impact was evaluated based on the quantity and type of abrasion particles in the fluid, which reflect internal component wear [7].

3. MATERIAL AND METHODS

Hydraulic pump used for this experiment was QHD 17 R gear pump with geometric volume 17 cm3. This type of pump is commonly used in agricultural devices and use in cooperation with hydraulic fluid of better environmentally friendly properties, than mineral oils would be beneficial.

Hydraulic oil used during this experiment was based on synthetic esters (HEES) with ability to biodegrade.

Testing device used for experimental part of this research is situated at Slovak University of Agriculture in Nitra and consist of two separate hydraulic circuits connected with mechanical binding, powered by electric motor. This device was for the sake of this experiment adjusted to configuration with only one circuit, containing following hydraulic components: Hydraulic tank, hydraulic gear pump, pressure safety valve, mechanical pressure valve for loading, filter, cooler and sensors, HYDAC HDA sensor for measuring pressure, HYDAC ETS sensor for measuring temperature and HYDAC EVS sensor for measuring flow of the fluid.

Table 1. Parameters of hydraulic components used in testing circuit.

Hydraulic tank [m³]	0.120
Hydraulic gear pump [cm³]	17
Pressure safety valve [MPa]	22
Pressure valve for loading [MPa]	20
Filter [μm]	10
HYDAC HDA [MPa]	-0,1 – 40
HYDAC ETS [°C]	-25 – 100
HYDAC EVS [$dm^3 \cdot min^{-1}$]	6 – 60
Cooler set to [°C]	85

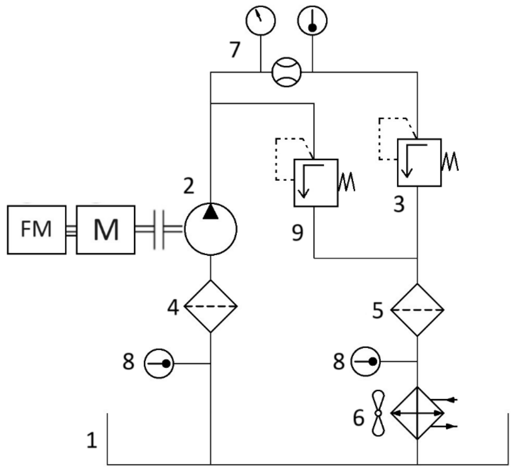

Fig. 1. Hydraulic scheme of testing device. (1. Tank, 2. hydraulic gear pump, 3. pressure valve set to 20 MPa, 4. entrance filter, 5. fine filter 20 μm, 6. cooler, 7. measurement devices for pressure, flow and temperature HYDAC, 8. thermometers, 9. safety valve set to 22 MPa).

As electric motor powers hydraulic gear pump, it forces hydraulic fluid to flow through pressure vale, and this way, hydraulic fluid as well as hydraulic gear pump are under stress. Normalized continuous test lasting 500 hours was executed creating massive stress for oil. The test conditions — including the 500 hour duration, 85°C oil temperature, and load pressure — were based on previous internal research on hydraulic systems used in agricultural machinery, combined with practical recommendations for long-term operational stress simulation (e.g., ISO 15380:2023). The aim was to create a stable yet demanding environment representative of typical gear pump workloads in real applications.

With degradation of hydraulic oil, its physical and chemical properties change, and this leads to aggravated cooperation with hydraulic gear pump. Wearing down of hydraulic gear pump emits abrasive particles into the fluid, where we can observe them, after taking samples, using laboratory analysis. Every 125 hours, a sample was extracted for laboratory analysis, for a total of 5 samples. The 500-hour continuous test was conducted once due to the high time and energy demands of the setup. The focus of this study was on capturing long-term wear and degradation trends under controlled conditions. While test repeatability was not part of the current scope, all measurements were performed with high-precision laboratory equipment, and procedures were strictly standardized to ensure reliable results.

Tested oil was standard synthetic hydraulic oil with following parameters:

Table 2. Parameters of hydraulic oil:

Density, [$kg \cdot m^{-3}$]	875
Kinematic viscosity at 40°C, [$mm^2 \cdot s^{-1}$]	64.2
Kinematic viscosity at 100°C, [$mm^2 \cdot s^{-1}$]	10.9
Viscosity index, [-]	162
Freezing point: [°C]	-36
Flash point: [°C]	210

During the experiment, oil was heated up to 85°C.

Formula for calculating the decrease of chemical elements:

$$\Delta A = \frac{A_0 - A_n}{A_0} . 100\ \% \qquad (2)$$

Where:

A_0 – content of chemical elements at 0 hours worked,

A_n – content of chemical elements at n hours worked.

Formula for calculating the increase of chemical elements:

$$\Delta B = \frac{B_n - B_0}{B_0} . 100\ \% \qquad (3)$$

Where:

B_0 – content of chemical elements at 0 hours worked,

B_n – content of chemical elements at n hours worked.

Used measuring instruments and procedures:

- Kinematic viscosity at 40°C and 100°C was measured using a Spectro VISC Q300 viscometer. The instrument has a measurement range of 0.6 to 3000 $mm^2.s^{-1}$ and an operating temperature range of 20°C to 100°C, with a temperature stability of ±0.01°C.
- The cleanliness code according to ISO 4406:2021 was determined using a Hydac CS 1320 device. A 1-liter sample of hydraulic fluid was used for the analysis.
- The acid number of the hydraulic fluid samples was determined using the FluidScan Q1000. This analyzer utilizes an optical system with specific, fixed spectral bands for oil analysis.
- A SPECTROIL Q100 atomic emission spectrometer with a rotating disc electrode was used to determine the concentration of contaminants and additive elements. This instrument can simultaneously analyze up to 31 elements, including wear metals, contaminants, and additives.

4. RESULTS

Hydraulic oil was exposed to pressure load and heat for 500 hours. During an experiment, no signs of damage in hydraulic gear pump, or other hydraulic components were observed, so we ran laboratory analysis. The measurements presented in this section reflect a single test run per time interval. Due to the absence of repeated measurements, error bars (e.g. standard deviation) could not be applied to the graphical results.

4.1 Kinematic viscosity analysis

The measurement of kinematic viscosity was carried out according to ISO 15380:2023 [19], which stipulates that there cannot be a change of more than 20% in the kinematic viscosity value compared to the initial test condition. In Fig. 2, the initial state at the initial 500-hour test at 40 °C was 62.33 $mm^2.s^{-1}$, while based on the ISO 15380:2023 [19] standard, the upper limit value of kinematic viscosity is 74.8 $mm^2.s^{-1}$ and the lower limit value is 49.86 $mm^2.s^{-1}$. After 500 hours of work, the kinematic viscosity had a value of 61.13 $mm^2.s^{-1}$, which, according to the calculation of the decrease determined by analogy with the relationship (*formula 2*), represents a decrease value of 1.9%.

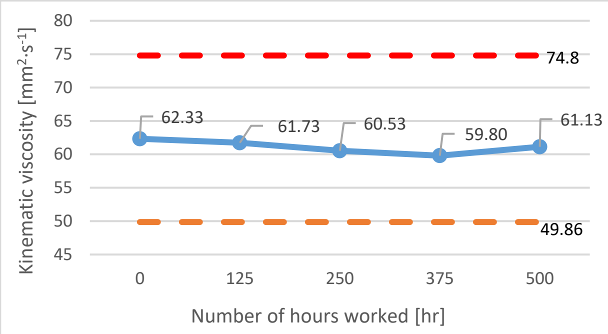

Fig. 2. Graphical dependence of kinematic viscosity at 40° C with respect to the number of hours worked (Upper and lower limit ±20%).

In Fig. 3, the initial state at the initial 500-hour test at 100 °C was 20.59 $mm^2.s^{-1}$, while based on the ISO 15380:2023 [19] standard, the upper limit value of kinematic viscosity is 24.7 $mm^2.s^{-1}$ and the lower limit value is 16.47 $mm^2.s^{-1}$. After 500 hours of work, the kinematic viscosity had a value of 19.79 $mm^2.s^{-1}$, which, according to the calculation of the decrease determined by analogy with the relationship (*formula 2*), represents a decrease value of 3.9%.

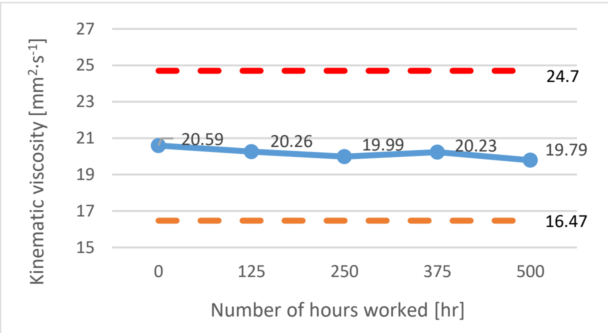

Fig. 3. Graphical dependence of kinematic viscosity at 100° C with respect to the number of hours worked (Upper and lower limit ±20%).

Both values of kinematic viscosity at 40 °C and 100 °C remained well within acceptable ranges according to ISO 15380:2023. This suggests the tested synthetic oil preserved its hydrodynamic properties under thermal and pressure loads. A minor decrease (1.9% at 40 °C and 3.9% at 100 °C) is in line with expectations for high-stability synthetic oils. No abrupt changes were observed, indicating no significant shearing or thermal degradation.

4.2 ISO 4406:2021 Purity code analysis

The evaluation of the purity code of the biodegradable universal liquid is defined by ISO 4406:2021 [14]. Fig. 4 shows the evaluation of the purity code for particles smaller than 4 µm in size compared to the number of hours worked.

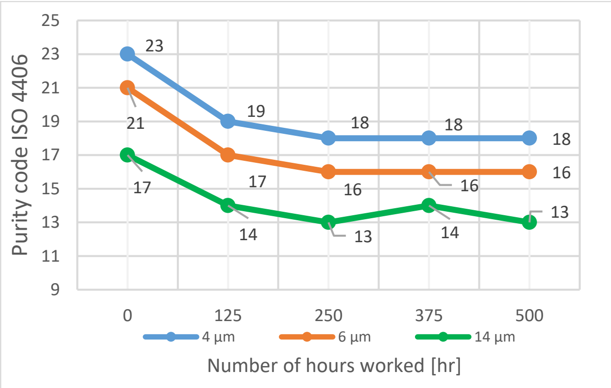

Fig. 4. Biodegradable universal fluid purity code with respect to the number of hours worked.

Considering the ISO 4406:2021 [14] standard, we compared the initial condition at 0 hours worked, the cleanliness code value was 23, then after 500 hours worked, the cleanliness code value decreased to 18. Particles not exceeding 6 µm in size grew as well, at 0 hours worked, the cleanliness code value was 21, then after 500 hours worked, the cleanliness code value decreased to 16. Particles not exceeding 14 changed cleanliness code value form 17, at 0 hours, to 13 at 500 hours worked. It is important to note, that our testing circuit contains 10 µm filter, catching some number of particles not exceeding 14 µm. However, filter was not 100% effective, as we can see from graphical interpretation of purity code. Another issue may be related to the irregular shape of wear particles, which—depending on their orientation—could theoretically pass through filter pores that are otherwise smaller than the particle's nominal size. This phenomenon has been previously described in tribological literature [20]. According to Glaeser (2010), wear particles of non-spherical geometry can exhibit preferential alignment with flow direction, occasionally enabling them to penetrate filter media despite exceeding the nominal filtration threshold.

The sharp initial decrease in particle count across all monitored size classes is likely associated with the run-in period of the test rig. During early operation, residual particles from assembly, surface irregularities, and initial friction are typically released into the fluid. These are progressively captured by the filter system. The declining trend confirms the filtration efficiency and stabilization of the wear environment. After this early phase, a plateau suggests a balance between particle generation and removal.

4.3 Acid number analysis ISO 15380:2023

Based on ISO 15380:2023 [19], the maximum increase in acid number is set at TAN = 2 mgKOHg^{-1}. The increase in the acid number value was determined analogously from the relationship (formula 3). Fig. 5 shows the dependence of the acid number TAN and the limit value with respect to the number of hours worked, and after working 500 hours our acid number increased from a value of 1.56 mgKOHg^{-1}, to a value of 1.6 mgKOHg^{-1}, which represents an overall increase of 2.6%.

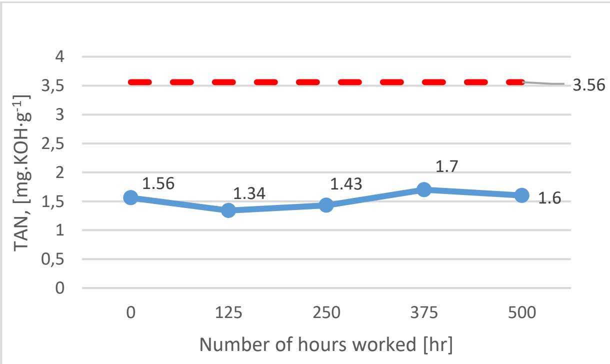

Fig. 5. Acidity number of TAN biodegradable universal liquid with respect to the number of hours worked.

The acid number remained almost constant throughout the test, increasing by only 2.6%, which is far below the degradation threshold set by ISO 15380:2023. This confirms the oxidative stability of the tested fluid. Such low variation suggests the fluid's additive system was capable of neutralizing minor oxidation products without significant breakdown.

4.4 Additive tracking analysis

The laboratory tests of the biodegradable universal liquid were carried out according to the test conditions set out in the methodology of the work. The analysis of the liquid fouling process by atomic emission spectrometry as described in Section 3.1.6 includes the process of monitoring the degradation of the additive elements in the service liquid. In the process of degradation of additive elements, we evaluated the following elements:

- calcium (Ca),
- magnesium (Mg),
- phosphorus (P),
- zinc (Zn).

Table 3 shows the additive content of the universal liquid during the laboratory test. The percentage increase, the decrease in the concentration of the additive elements, is determined based on the formulas 2 and 3.

Table 3. Content of additive elements in universal liquid [mg.kg^{-1}]

Chemical element	Number of hours worked					Δ [%]
	0	125	250	375	500	
Ca	1.72	8.81	6.64	6.53	7.83	+412
Mg	1.18	0.16	1.15	0.5	0.87	-26.27
P	115.95	112.66	108.71	112.05	119.19	+2.8
Zn	0.78	2.47	3.12	3.26	4.13	+429

For calcium (Ca) content, an increase in the chemical element was found after the first 125 hours worked from a value of 1.72 mg.kg-1 to a value of 8.81 mg.kg-1, an increase of ΔB = 412%, which is attributed to the activation of the additive element. Subsequent calcium degradation, the determined rate of additive loss reached a value of 7.83 mg.kg-1 between 125 hours worked from a value of 8.81 mg.kg-1 and 500 hours worked, representing ΔA = 11.8 %. The content of the chemical element magnesium (Mg) showed a decrease in concentration from a value of 1.18 mg.kg-1 to a value of 0.87 mg.kg-1, representing a decrease of ΔA = 26.27%. The concentration of phosphorus (P) recorded a value of 119.19 mg.kg-1 after 500 hours of work, compared to a concentration after 0 hours of work of 115.95 mg.kg-1, an increase in the chemical element of ΔB = 2.8%. The largest increase was observed for zinc (Zn) from a value of 0.78 mg.kg-1 the value rose to 4.13 mg.kg-1 after 500 hours worked, an increase of ΔA = 429%.

The initial spike in calcium content is likely due to additive activation or release from oil reservoirs or surface adsorption sites. Its subsequent slight decline reflects progressive consumption of anti-wear and detergent additives during operation. The stability of phosphorus and zinc levels suggests sustained presence of ZDDP-type additives. The minor magnesium drop may indicate depletion of dispersants or secondary detergents.

4.5 Universal liquid degradation process analysis

In the analysis of the degradation process of the universal liquid, the chemical elements representing the contamination process were monitored. We paid attention to chemical elements in the process of contamination of the liquid: boron (B), barium (Ba), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), potassium (K), molybdenum (Mo), sodium (Na), silicon (Si), tin (Sn), titanium (Ti) and vanadium (V). Table 4 shows the degradation process of the chemical elements representing the contamination of the universal fluid during the laboratory test. The percentage increase, or decrease, in the concentration of the chemical elements is determined based on the formulas 2 and 3.

The largest increase was observed for copper (Cu) after 500 hours of work from a value of 0.12 mg.kg^{-1} to a value of 0.49 mg.kg^{-1}, an increase of ΔB = 308%. This was followed by an increase in tin (Sn) from a value of 1.35 mg.kg^{-1} to a value of 3.61 mg.kg^{-1}, ΔB = 167%. A ΔB = 100% increase was observed for the chemical element barium (Ba) as the value increased from an initial 0.02 mg.kg^{-1} to 0.04 mg.kg^{-1}. The last increase was detected for titanium (Ti) by ΔB = 9.6%. In contrast, the largest decrease in concentration was detected for sodium (Na) from a value of 2.4 mg.kg^{-1} to 0.56 mg.kg^{-1}, which represented a decrease of

ΔA = 76.7%. This was followed by a decrease in silicon (Si) ΔA = 75.3% from an initial value of 1.9 mg.kg^{-1} to a value of 0.47 mg.kg^{-1}. Potassium (K) decreased from a value of 0.29 mg.kg^{-1} to a value of 0.13 mg.kg^{-1}, which represents a decrease of ΔA = 55.2%. The smallest decrease in contamination was observed for molybdenum (Mo) ΔA = 7.1%.

Table 4. Content of chemical elements representing contamination of universal [mg.kg^{-1}]

Chemical element	Number of hours worked					Δ [%]
	0	125	250	375	500	
Ba	0.02	0.04	0.02	0.02	0.04	+100
Cu	0.12	0.31	0.38	0.38	0.49	+308
K	0.29	0.04	0.45	0.03	0.13	-55.2
Mo	2.8	2.71	2.72	2.82	2.6	-7.1
Na	2.4	0.2	0.58	0.19	0.56	-76.7
Si	1.9	0	0.36	0.11	0.47	-75.3
Sn	1.35	1.35	2.52	2.25	3.61	+167
Ti	1.25	1.13	1.34	1.2	1.37	+9.6

Among wear metals, copper and tin showed the most pronounced increases, potentially originating from bearings or pump bushings. The significant rise indicates ongoing mechanical interaction, although no visible damage was detected. On the contrary, the drop in sodium and silicon might indicate depletion of contaminants introduced during assembly or initial operation. The trend supports the conclusion that the oil system stabilized after initial wear-in, with no signs of catastrophic failure or uncontrolled degradation.

5. CONCLUSION

During 500 hour lasting normalised lifespan test, we observed slight decrease in oil´s kinematic viscosity at 40 °C and 100 °C. These decreases were mild, what proves oil´s quality. Neither of these changes reached limit intervals set to ±20%.

More important was a change of purity code. Purity code rapidly decreased in first half of experiment, for all sizes of observed particles. In the second half of the experiment, purity code stagnated. In 500 hours it got from 23/21/17 to 18/16/13. This phenomenon could be caused by hydraulic gear pump´s running in in cooperation with new type of hydraulic oil. That is why we observed appearing of more particles polluting fluid in first part of the experiment. In second half, hydraulic gear pump was already run in with new type of hydraulic oil, so it emitted less particles into the fluid, causing purity code´s stagnation. Quality of 10 μm filter also helped to decelerate emission of unwanted particles.

Total acid number overall slightly increased, by 2.6%, although, in the first half of the test, where more particles were emitted, as we prove by purity code, we observed decrease. Only small changes in TAN are also a sign of oil´s quality proving, that this type of synthetic oil can resist oxidation.

Changes in additive elements were caused either by adding elements into the fluid by wear of inner surfaces of hydraulic components – explaining increase in concentrations, or by sedimentation or by getting trapped in filter – explaining decrease in concentrations.

In terms of additive elements, severe increase of calcium occurred during lifetime test. It´s concentration grew rapidly in first quarter of the test from 1.72 to 8.81 mg·kg^{-1}, what makes 412%. This big increase is unrealistic, making us label this measurement as faulty. Calcium could get into the circuit as external contaminant especially from grease used in pipe connections or cooler.

Substantial increases in zinc and copper concentrations suggest wear of internal brass components, such as pump inserts. Although these elements can also originate from additive packages (especially Zinc), the magnitude of the increase implies mechanical degradation as the dominant source under the tested conditions. Copper increased by 308% to concentration 0.49 mg·kg^{-1}.

Tin, used in seals and hydraulic connections, also appeared in the hydraulic oil, increasing by 167% to a concentration of 3.61 mg·kg^{-1}. This represents wear further in the hydraulic circuit, not just on the pump.

Minor fluctuations in other elements, such as phosphorus, were within expected tolerances and likely reflect measurement variability rather than real chemical processes. As phosphorus is a key additive and no phosphorus-based materials are present in the hydraulic components, its concentration remained stable throughout the test.

Acknowledgement

The research that led to these results has received funding from the Visegrad Grants No. 52410187.

REFERENCES

[1] G. Li, L. Zhang, and W. Han, "Profile design and displacement analysis of the low pulsating gear pump," *Advances in Mechanical Engineering*, vol. 10, no. 3, Mar. 2018, doi: 10.1177/1687814018767003.

[2] Y. Lu and Z. Huang, "A new hybrid model of sparsity empirical wavelet transform and adaptive dynamic least squares support vector machine for fault diagnosis of gear pump," *Advances in Mechanical Engineering*, vol. 12, no. 5, May 2014, doi: 10.1177/1687814020922047.

[3] EN ISO 6743-4 Lubricants, industrial oils and related products (class L) – Classification – Part 4: Family H (Hydraulic systems), 2015.

[4] K. Baczewski and P. Szczawiński, "Investigation of the process of ageing of hydraulic oil during its use," *The Archives of Automotive Engineering/ Archiwum Motoryzacji*, vol. 73, no. 3, Sep. 2016, doi: 10.14669/am.vol73.art1.

[5] E. Aluyor, and M. Ori-jesu, "Mudiakeoghene. Biodegradation of mineral oils–A review," *African Journal of Biotechnology*, vol. 8, no. 6. 915–920, Jan. 2009.

[6] A. M. Farrington and J. M. Slater, "Monitoring of engine oil degradation by voltammetric methods utilizing disposable solid wire microelectrodes," *The Analyst*, vol. 122, no. 6, pp. 593–596, Jan. 1997, doi: 10.1039/a608022g.

[7] C. Winterfield and V. De Voort, "Automated acid and base number Determination of Mineral-Based Lubricants by Fourier Transform Infrared Spectroscopy: Commercial Laboratory Evaluation," *SLAS TECHNOLOGY*, vol. 19, no. 6, pp. 577–586, Oct. 2014, doi: 10.1177/2211068214551825.

[8] ASTM D943, Standard Test Method for Oxidation Characteristics of Inhibited Mineral Oils, 1999

[9] ISO 4263, Petroleum and related products — Determination of the ageing behaviour of inhibited oils and fluids using the TOST test, 2015

[10] J. Kosiba, Z. Tkáč, J. Jablonický, G. Čurgaliová, J. Tulík, and M. Halenár, "Laboratory Test of a Gear Hydraulic Pump during the Application of an Environmentally Friendly Hydraulic Fluid with Constant Pressure and Temperature," *Lubricants*, vol. 12, no. 9, p. 304, Aug. 2024, doi: 10.3390/lubricants12090304.

[11] S. Liu, C. Xu, T. Liu, and Y. Cai, "Designing of a double-cylinder viscometer for high-pressure liquids," *Measurement and Control*, vol. 53, no. 7–8, pp. 1482–1492, Aug. 2020, doi: 10.1177/0020294020944958.

[12] C. D. Neveu, R. Sondjaja, T. Stöhr, and N. J. Iroff, "Lubricant and fuel additives based on polyalkylmethacrylates," in *Elsevier eBooks*, 2012, pp. 453–478. doi: 10.1016/b978-0-444-53349-4.00277-6.

[13] B.E. Rapp, "Chapter 9 – Fluids," in B. E. Rapp (Ed.), in Microfluidics: Modelling, Mechanics and Mathematics, Elsevier, 2016, pp. 243–263. doi: 10.1016/b978-1-4557-3141-1.50009-5.

[14] ISO 4406-2021 Hydraulic fluid power – Fluids - Method for coding the level of contamination by solid particles, 2021.

[15] J.S. Evans, "Where does all that metal come from?" in Technical Bulletin, Wear check Africa, Set point group, 01/2010.

[16] P. Pabsetti *et al.*, "Performance of hydraulic oils and its additives in fluid power system: A review," *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 1161, no. 1, p. 012009, Apr. 2023, doi: 10.1088/1755-1315/1161/1/012009.

[17] D. Puhan, „Lubricant and Lubricant Additives," in Tribology in Materials and Manufacturing - Wear, Friction and Lubrication. in *IntechOpen eBooks*, 2020, doi: 10.5772/intechopen.93830.

[18] M. I. H. C. Abdullah, M. F. Abdollah, H. Amiruddin, N. Tamaldin, and N. R. M. Nuri, "Effect of HBN/AL2O3 nanoparticle additives on the tribological performance of engine oil," *Jurnal Teknologi*, vol. 66, no. 3, Feb. 2014, doi: 10.11113/jt.v66.2685.

[19] ISO 15380:2023 Lubricants, industrial oils and related products (class L) — Family H (Hydraulic systems) — Specifications for hydraulic fluids in categories HETG, HEPG, HEES and HEPR, 2023

[20] J. Vižintin, M. Kalin, K. Dohda, and S. Jahanmir, *Tribology of Mechanical Systems: A Guide to Present and Future Technologies*. ASME Press, 2004. doi: 10.1115/1.802094.