LABORATORY TESTING OF FLOW PROPERTIES OF ECOLOGICAL HYDRAULIC FLUID

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Abstract
This work focuses on the experimental evaluation of the ecological hydraulic fluid MOL Biohyd 46, manufactured by Slovnaft. The subject of the investigation was the behaviour of the fluid in terms of flow characteristics at different speeds of a gear pump. Measurements were performed on a laboratory parallel testing device at the Faculty of Engineering, Slovak University of Agriculture in Nitra, during a 50-hour testing cycle. During the laboratory testing, the development of flow rate and flow efficiency was monitored over time, depending on changes in speed. The results confirmed that the ecological hydraulic fluid maintained stable parameters throughout the entire test. The recorded decrease in flow efficiency did not exceed the critical limit, with the most significant drop observed at the lowest speeds. This phenomenon may likely be caused by a change in the fluid's hydrodynamic properties.

Key words: *hydraulic fluid, ecological fluid, gear pump, flow efficiency, laboratory testing.*

INTRODUCTION
In the current era, as global attention increasingly focuses on sustainable development and environmental protection, there is growing pressure on all industries, including hydraulic systems, to switch to more ecological alternatives. Ecological fluids, often referred to as biodegradable, represent a significant part of this effort, especially in areas where leakage and environmental contamination may occur, such as in agriculture, construction, or the transport sector.
Hydraulic fluids are a key element of hydraulic systems, which are an integral part of many machines and equipment. These systems enable the transmission of energy and power between individual components, while the quality and properties of the fluid used fundamentally affect the efficiency, reliability, and lifespan of the system. However, traditional hydraulic fluids often use petrochemical components that are harmful to the environment. Therefore, ecological fluids are becoming an increasingly important alternative, as they have the ability of biodegradability and a lower environmental impact in case of leakage *(Müller-Zermini, Gaule, 2013)*.
The development and testing of ecological hydraulic fluids represent a significant research trend, as ecological alternatives must demonstrate their ability to replace traditional fluids without compromising technical parameters such as viscosity, flow efficiency, wear resistance, lubricating properties, and others. For example, in standardized tests, such as Vickers Pump tests or similar pump tests, fluid degradation during operation under extreme conditions, including high pressures and temperatures, is monitored. These tests provide valuable information on how the fluid reacts to stress and whether it maintains its properties during long-term use *(Tkáč et al., 2021)*.
This work deals with laboratory tests of an ecological hydraulic fluid from Slovnaft, which is designed as a universal ecological replacement for traditional hydraulic fluids. Testing will be carried out based on flow efficiency tests using a gear pump, which represents a simulation of real operating conditions in which hydraulic fluids are commonly used. This work has the potential to contribute to the search for sustainable solutions in the field of hydraulic systems and will provide useful data for further improvement of ecological fluids, thereby helping the transition to greener and more sustainable technology.

MATERIALS AND METHODS
This chapter provides a detailed description of the equipment used, test methods, and the method of evaluating the results within the framework of laboratory tests of a universal ecological hydraulic fluid.

Used Equipment and Devices

For the experimental tests, the Parallel Testing Device SPU TF *(Tkáč et al., 2016)* was used, which enables the simulation of hydraulic system operating conditions. The main elements of the laboratory tests were:

- Test element – Gear pump GHD17R, which ensured the circulation of the fluid in the hydraulic circuit.
- Tested fluid – Experimental tests were performed with the biodegradable hydraulic fluid made from vegetable oils, MOL Biohyd 46, from Slovnaft. Recommended operating temperature range: from -20°C to +45°C.
- Measuring devices – HYDAC:
  - Pressure sensor HDA 4748-H-0400-000 with an accuracy of ≤ ± 0.25%,
  - Flow sensor EVS 3108-H-0060 with an accuracy of ≤ 2%,
  - Temperature sensor ETS 4148-H-006-000 with an accuracy of ≤ ± 0.4%, used for continuous monitoring of test parameters.
- Recording unit – HYDAC HMG 3010 recorded continuous values of pressure, temperature, and flow during the testing phases.
- Control system – A computer with LabView software, used for setting the electric motor speed.

Test Conditions and Measurement Methodology

The testing method is based on the testing approach of the ASTM D 2882 standard *(Johnson, Lewis, 1996)*. The loading pressure produced by the hydraulic circuit will serve to simulate operating conditions, i.e., as if the hydraulic fluid were working in the circuit of real mobile machinery and had to overcome loading forces. The prescribed operating temperature specified by the manufacturer for MOL Biohyd 46 is 45 °C. At the manufacturer's request, we will conduct tests at an elevated temperature of 65 °C, which will allow us to test the fluid under excessive load that the fluid may encounter in mobile machinery operation. Such testing methods can be performed to establish certainty of operation within the prescribed limit value.

The measurement phase will take place at a loading pressure of 0 MPa, i.e., without load. The significance of testing hydraulic fluid at zero load *(0 MPa)* is an important method for evaluating the basic properties of the fluid and the pump under free flow conditions. This type of test provides reference values for comparison with tests performed under higher pressures and allows for a better understanding of the system's mechanical properties *(Kosiba et al., 2023)*. One of the main reasons for testing at zero load is to monitor the pure work of the pump without pressure resistance. In this mode, the hydraulic fluid moves only due to the mechanical energy supplied by the pump, without additional resistance caused by back pressure.

Tab. 1 Test Conditions

Parameter	Working phase	Measuring phase
Rotational speed	1800 min^{-1}	500 – 2500 min^{-1}
Load pressure	20 MPa	0 MPa
Inlet temperature	65 °C	
Duration	50 hours	10 s every 12.5 h

Evaluation of the Test:

- Flow rate recording depending on RPM for 10 seconds at 12.5-hour intervals. Measured values range from 500 to 2500 RPM, increasing by 500 RPM, with a 10-second measurement at each value.
- The maximum permissible decrease in fluid flow rate is 3.75% throughout the entire measurement.

Methods of Evaluating Results

The following statistical methods were used to process the results:

- Descriptive statistics – for calculating average flow rate values.

- Regression analysis – application of polynomial trendlines to express the relationship between pump speed and flow efficiency.
- Standard deviation *(STDEV)* – analysed the stability of the flow rate in individual measurements *(Freund, 2010)*.
- Z-score – a method for identifying outliers in the data. It represents the measure of how many standard deviations a specific value differs from the mean of a given distribution *(Moore et al., 2012)*.

Data were processed using MS Excel software, where they were visualized using trend graphs.

Procedure for Evaluating Results

First, in the statistical processing of the data, we identified and excluded outliers using the Z-score method.

Subsequently, we processed the data such that we had arithmetic means from each 10-second measurement with outliers removed, and from these means, we determined the average standard deviations for data dispersion analysis.

If a trend of increasing dispersion appeared during the 50 hours of testing, it could indicate wear of the gear pump or other undesirable changes in the hydraulic system. In that case, this phenomenon would need further investigation, as the Z-score method would eliminate these extreme values, and further results of the hydraulic fluid testing might no longer be relevant.

RESULTS AND DISCUSSION

The next step was to evaluate the average flow data at given speeds. This was applied to the entire range of speeds and measurement times. Following this step, a graph showing the trend of flow rate decrease across the entire measured speed spectrum was created.

Tab. 2 Average flow rate values *(Q)* and their corresponding standard deviations *(σ)*

Duration	0 h		12.5 h		25 h		37.5 h		50 h	
Rpm	Q	σ	Q	σ	Q	σ	Q	σ	Q	σ
[min⁻¹]	[dm³min⁻¹]									
500	8.676	0.10	8.602	0.08	8.617	0.11	8.533	0.10	8.470	0.10
1000	17.357	0.65	17.359	0.06	17.322	0.05	17.177	0.04	17.206	0.06
1500	26.120	0.88	26.147	0.07	26.111	0.06	24.446	0.09	25.971	0.09
2000	34.890	0.74	34.935	0.07	34.828	0.10	34.747	0.09	34.849	0.11
2500	43.344	0.62	43.318	0.22	43.248	0.11	42.981	0.28	43.091	0.31

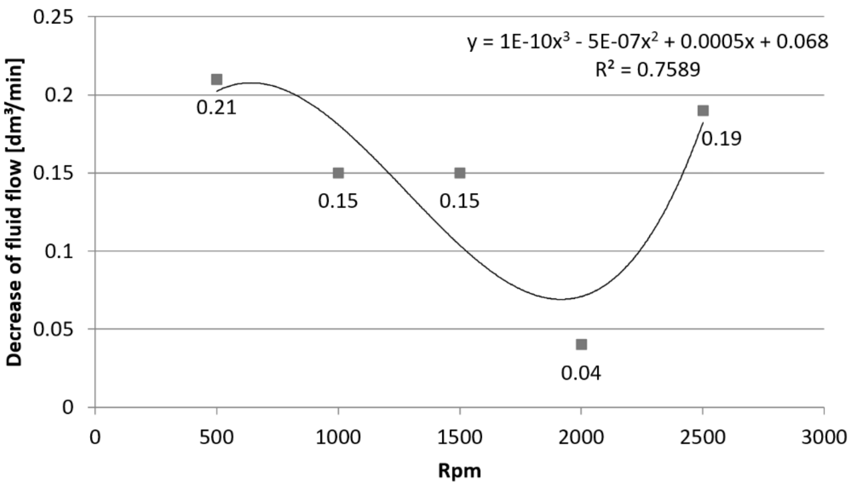

Fig. 1 Flow Rate Decrease after 50 Hours of Hydraulic Fluid Loading

The graph in Fig. 1 illustrates the flow rate decrease over 0 to 50 operating hours. The highest flow rate decrease was observed at 500 RPM, reaching 0.21 dm^3min^{-1}.
However, the flow rate alone doesn't indicate the system's suitability *(Rundo, 2017)*. It's necessary to calculate the flow efficiency, which considers more factors, namely the geometric volume of the pump and its speed, for all flow rate values from Table 2.

Tab. 3 Average Flow Efficiency Values of the Gear Pump Across the Entire Measurement Spectrum

Rpm $[min^{-1}]$	Flow efficiency η [%]				
	0 h	**12.5 h**	**25 h**	**37.5 h**	**50 h**
500	95.14	94.32	94.49	93.56	92.88
1000	95.16	95.17	94.97	94.18	94.33
1500	95.47	95.57	95.44	94.81	94.92
2000	95.64	95.77	95.47	95.25	95.53
2500	95.05	95.06	94.85	94.40	94.65

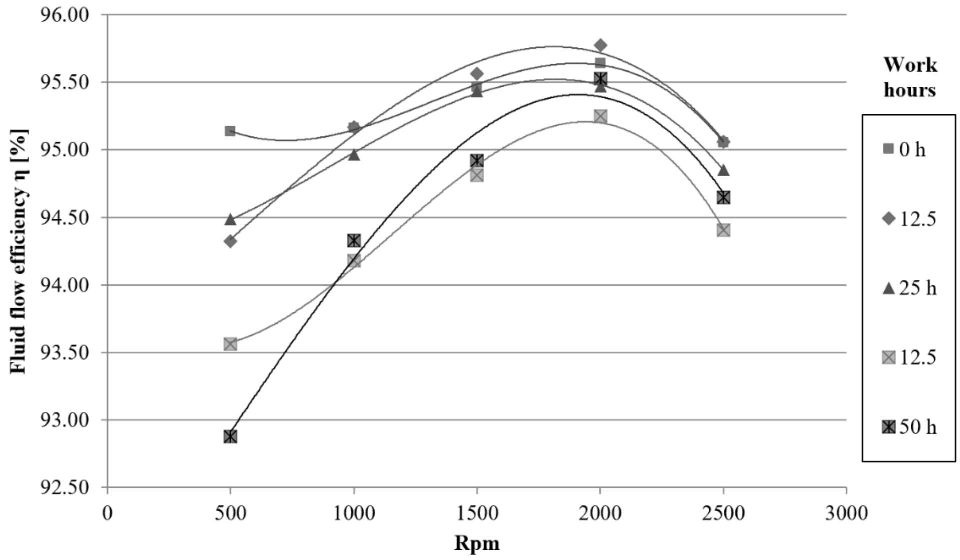

Fig. 2 Graph of Flow Efficiency Trends of the Gear Pump Depending on Speed Across the Entire Measurement Spectrum

Tab. 4 Trend Equations of Flow Efficiency Dependencies on Speed and Coefficient of Determination

Work hours	**Trend of fluid flow efficiency dependent on rpm**	**R²**
0 h	$y = 1E\text{-}10x^3 - 5E\text{-}07x^2 + 0.0005x + 0.068$	0.7589
12,5 h	$y = -3E\text{-}10x^3 + 5E\text{-}07x^2 + 0{,}0014x + 93{,}568$	0.9888
25 h	$y = -4E\text{-}10x^3 + 1E\text{-}06x^2 - 8E\text{-}06x + 94{,}249$	0.9991
37,5 h	$y = -9E\text{-}10x^3 + 3E\text{-}06x^2 - 0{,}0019x + 93{,}874$	0.9933
50 h	$y = -4E\text{-}10x^3 + 6E\text{-}07x^2 + 0{,}0025x + 91{,}593$	0.9794

On Fig. 2, we can observe the trends of flow efficiencies derived from Tab. 3.
For the graphical representation of the trend, a 3rd-order polynomial function was chosen based on the coefficient of determination.
Across all measurement hours, we can observe the same developmental trend:

- Increase in flow efficiency from 500 RPM to 2000 RPM.
- The highest flow efficiency of the gear pump is reached at 2000 RPM.
- After 2000 RPM, we observe a decrease in flow efficiency.
- The flow efficiency changed by a maximum of 2.37% depending on the speed.

The gear pump achieved its highest flow efficiency of 95.77% at 2000 RPM after 12.5 hours of operation. The lowest value for the gear pump was 92.88% at 500 RPM after 50 hours of operation, which could be expected based on general knowledge in the field of hydrostatics. Although the flow efficiency changed slightly with increasing speed, we did not observe significant changes.
Subsequently, the percentage decrease in flow efficiency after 50 operating hours was calculated from the values in Tab. 3 according to formula *(1)*:

$$\Delta\eta = \frac{\eta_0 - \eta_x}{\eta_0} * 100\% \qquad (1)$$

where η_0 is the flow efficiency at 0 operating hours and η_x is the flow efficiency after x operating hours.

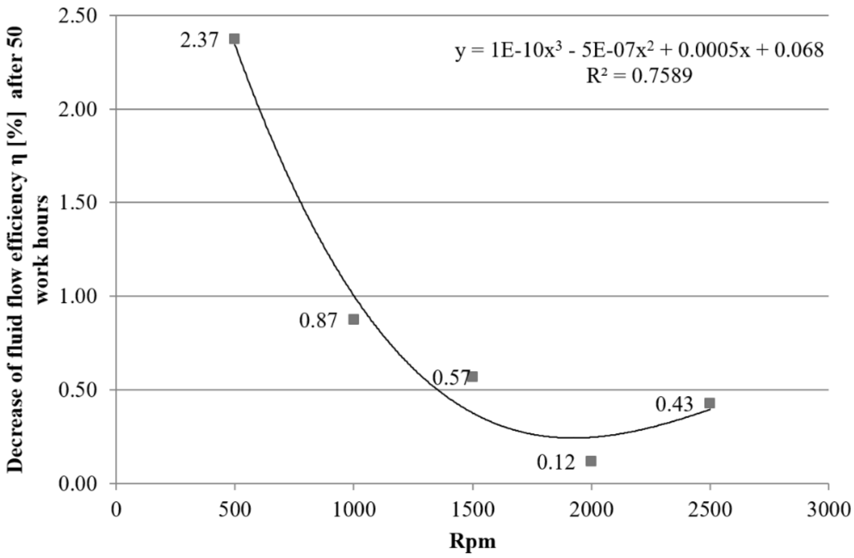

Fig. 3 Decrease in Flow Efficiency After 50 Hours of Hydraulic Fluid Loading

Fig. 3 tracks the decrease in flow efficiency after 50 hours of hydraulic fluid loading. The decrease was calculated from the values at 0 hours and 50 hours at the same speeds. We did not observe a significant decrease in flow efficiency at all speeds, except for the flow efficiency at 500 RPM where the decrease was 2.37%. Under the test conditions according to ASTM D 2882, it was specified that the flow efficiency must not decrease by 3.75%. The gear pump with the tested ecological hydraulic oil met this condition.
The more pronounced decrease observed at 500 RPM could have resulted from fluid degradation. One of the most significant factors affecting its behaviour is viscosity, which can change due to operation and fluid aging *(Michalides et al., 2023)*. During testing, there was a decrease in flow efficiency at 500 RPM after 50 hours of operation, while at higher speeds, this decrease was minimal. This phenomenon can be explained by the fact that at lower speeds, the flow of hydraulic fluid is slower, and since it is dependent on its viscosity, it can manifest as greater resistance in the hydraulic system. Conversely, at higher speeds, the flow dynamics are more pronounced and partially eliminate the influence of changed viscosity, which explains why the efficiency decrease at higher speeds was negligible.

CONCLUSIONS

The aim of this work was to experimentally test the universal ecological hydraulic fluid MOL Biohyd 46 from Slovnaft and evaluate its flow characteristics under given operating conditions. Testing was carried out on a laboratory test circuit, where fluid parameters were analysed at various speeds of a gear pump, with measurements taking place at time intervals up to a total duration of 50 hours. With the manufacturer's consent, we loaded the tested fluid at an increased operating temperature of 65 °C. The operating temperature specified by the manufacturer is 45 °C.
The results showed that the flow properties of the fluid remained stable throughout the entire testing, despite the increased loading temperature stated by the manufacturer. The flow efficiency values did not show significant deviations, with only a minimal decrease in efficiency identified within the experimental conditions. The highest decrease in efficiency was recorded at the lowest speeds *(500 min⁻¹)*, due

to a greater influence of viscosity given that the fluid flow rate is lower, which results in increased resistance in the hydraulic system. However, this change was minimal and still within the norm. Conversely, at higher speeds, the fluid behaved consistently, with minimal flow losses.
During the testing, no significant signs of fluid degradation, foam, or air inclusions were recorded, confirming its suitability for long-term use in hydraulic circuits.
The tested ecological hydraulic oil met the requirements according to ASTM D 2882 for conventional hydraulic oils, from which it can be concluded that it is suitable for use while simultaneously having a reduced negative impact on the environment. The results of this work can thus serve as a starting point for further studies focusing on ecological hydraulic fluids and their wider implementation in industrial practice.

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