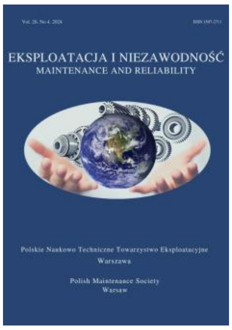

Eksploatacja i Niezawodnosc – Maintenance and Reliability

Volume 26 (2024), Issue 4

journal homepage: http://www.ein.org.pl

Article citation info:
Novaković B, Djordjević L, Đurđev M, Radovanović L, Zuber N, Desnica E, Bakator M, Effect of changes in hydraulic parameters and tank capacity of the hydraulic press system on the heating of the hydraulic oil, Eksploatacja i Niezawodnosc – Maintenance and Reliability 2024: 26(4) http://doi.org/10.17531/ein/190826

Effect of changes in hydraulic parameters and tank capacity of the hydraulic press system on the heating of the hydraulic oil

Indexed by: Web of Science Group

Borivoj Zoran Novaković[a,*], Luka Djordjević[a], Mića Đurđev[a], Ljiljana Radovanović[a], Ninoslav Zuber[b], Eleonora Desnica[a], Mihalj Bakator[a]

[a] Mechanical Engineering, Technical faculty "Mihajlo Pupin", University of Novi Sad, Serbia
[b] Mechanical Engineering, Faculty of Technical Science, University of Novi Sad, Serbia

Highlights

- Influence of altering hydraulic parameters on the temperature of ISO HM VG 46 hydraulic mineral oil.
- Analysis of the quality of hydraulic mineral oil ISO HM VG 46.
- The impact of varying input parameters such as flow rate, kinematic viscosity, and pressure on the thermal characteristics of the system.

Abstract

This study examines the influence of altering hydraulic parameters on the temperature of ISO HM VG 46 hydraulic mineral oil. Hydraulic mineral oils find extensive application in industrial power transmission systems, where precise temperature control is crucial for achieving optimal performance and prolonging system lifespan. Variations in hydraulic parameters, encompassing flow rate, pressure, and viscosity, can significantly impact the thermal characteristics of hydraulic oil. In this research, experimental studies were carried out to study the influence of changing hydraulic parameters on the temperature of hydraulic mineral oil. Experiments were performed on a hydraulic press, where different working conditions were simulated. The quality of hydraulic fluid is considered, according to all research, to be the most influential factor in ensuring the reliable operation of hydraulic systems.

Keywords
hydraulic, parameters, oil, temperature, viscosity, reliability.

1. Introduction

One of the key aspects in the development of hydraulic drives is achieving optimal operation of the hydraulic system that powers the machine, all with the goal of improving the efficiency of the hydraulic system by reducing energy losses and controlling the heating of hydraulic oil. Regarding temperature changes within a hydraulic fluid, the case most encountered is fluid heating rather than cooling. Elevating the temperature of the fluid, namely hydraulic oil, occurs as a consequence of the dissipation of hydraulic energy within the hydraulic system's components. The primary aim is to ensure that the working fluid reaches the minimum viscosity levels demanded by the system components during operation, which serves as a fundamental motivation for these efforts. Research studies investigate the changes in the kinematic viscosity of relevant types of nano lubricants, as demonstrated in the papers [1, 5, 14, 26]. Manring [18] provided a detailed empirical representation of defining the most important parameters of hydraulic fluid, namely viscosity, and density. As Shababi et al. highlight in their paper [25], temperature and the presence of nanoparticles significantly influence the change in kinematic

(*) Corresponding author.
E-mail addresses: B. Novaković (ORCID: 0000-0003-2816-3584) borivoj.novakovic@tfzr.rs, L. Djordjević (ORCID: 0000-0003-4578-9060) luka.djordjevic@tfzr.rs, M. Đurđev (ORCID: 0000-0002-1825-2754) micadjurjev@gmail.com, L. Radovanović (ORCID: 0000-0002-5234-4820) ljiljana.radovanovic@tfzr.rs, N. Zuber (ORCID: 0000-0003-0843-2732) zuber@uns.ac.rs, E. Desnica (ORCID: 0000-0002-4724-5764) eleonora.desnica@gmail.com, M. Bakator (ORCID: 0000-0001-8540-2460) mihaljbakator@gmail.com,

viscosity. The paper [27] describes the close connection between the occurrence of cavitation in hydraulic systems and an increase in the temperature of the hydraulic fluid, which can have catastrophic consequences for the system components and affects the system's reliable and efficient operation. In low, and medium pressure stationary hydraulic systems, the recommended operating temperature, measured at the tank, is approximately 40–50 °C. However, in systems operating at higher pressures (exceeding 400 bar), the average system temperature can be elevated by approximately 10–20 °C [4]. The temperature of the hydraulic fluid should not surpass 90 °C (maximum range of 100–120 °C) at any location within the system [11].More detailed effects of cavitation on the system and fluid heating are described in papers [15, 35]. Every fluid change within the system must be followed because it performs critical functions such as energy transfer, heat transfer, corrosion prevention, and component wear [12]. The change in temperature affects the parameters of the system, especially through the viscosity of the oil, because by increasing the temperature of the fluid, the viscosity decreases, which can affect increased leaks within the system components, drop in flow, poorer lubrication, and poorer cooling of the system [23, 29]. Based on the analysis of available data and previous research, a notable gap in the literature regarding the investigation of the influence of changes in hydraulic parameters and tank capacity on the heating of hydraulic oil in hydraulic systems has been identified. This study contributes to filling this gap by identifying specific effects of parameter alterations on the thermal characteristics of hydraulic oil, thus providing relevant insights for enhancing the efficiency of hydraulic systems.

When it comes to hydraulic systems with high pressures, such as hydraulic presses, one of the main problems is leaks that occur in components after a certain period of exploitation. Some of the main reasons for this are non-ideal geometries of the internal components themselves, the reason for this is wear, while another reason can be cited as inadequate oil, i.e., oil with reduced performance compared to the required one, more or less in all components there are leaks [19, 30]. Increased leaks in the system can cause a greater drop in flow reaching high pressure, decreasing volumetric efficiency. Leaks inside the hydraulic pumps are described in the papers [20, 22, 34]. In addition to the control components and drive components, pumps and leaks can also occur on excellent elements, which in the case of hydraulic presses are represented by cylinders. Leaks in cylinders were described by Jin et al. [13]. Detailed analysis of hydraulic oil leakage inside the cylinder are also described in the papers [6–8, 33]. The temperature of the fluid is certainly one of the main reasons for increased leaks in hydraulic systems, as described in the paper [17].All the listed leaks affect the temperature of the working fluid in the system, so it is crucial to design the reservoir in which the hydraulic oil is located. Under design, the size of the tank is also considered as a parameter that affects the even distribution of heat, however, the tanks must be adapted to the space and the economic aspect, so the tanks must not be oversized. A larger reservoir can allow the oil to stay in the system longer, resulting in better oil cooling as it passes through the various system components. Suppose the tank's surface is well-designed and made of material that conducts heat well. In that case, the larger surface area can improve the dispersion of heat from the oil to the environment, thus reducing the overall temperature of the oil. Oversizing the reservoir of hydraulic systems can cause aeration inside them, which is described in the paper [9]. Also, in the paper [31], the main factors influencing the quality of hydraulic oil on the performance of executive elements, in this case, construction machines, were presented. One of the main reasons for examining the geometry and structure of the system is to determine the appropriate system for cooling the hydraulic fluid in the tanks based on the calculations. In the paper [16], experimental investigations and comparative analyzes were carried out while installing a new cooler on the hydraulic system, where the appropriate thermo-characteristics were shown. From the aspect of modern methods of regulating technical systems, according to research from 2021, oil analysis is considered one of the most important analyses in diagnosing the system's state, in addition to vibration diagnostics, ultrasound, and thermography shown in Fig. 1.

In addition to the mentioned methods of diagnosing the condition of various technical systems, including hydraulic systems there are also modern approaches to system condition assessment that support the overall maintenance of the tested system, through combinations of fault tree analysis, fuzzy logic, expert systems, and graphical methods [36]. Due to complex conditions and non-linearity during tests and failure occurrences, methods such as deep learning can greatly increase the productivity of maintenance of hydraulic systems [32]. In hydraulic systems, reliability analysis is one of the foundations upon which an appropriate maintenance approach is based. Elements such as pumps, motors, and cylinders are mostly analyzed [2, 3, 10, 21, 28], but it is undeniable that the fluid within the system represents the most influential factor for the reliable operation of the system.

This study aims to investigate the impact of altering hydraulic parameters and tank capacity on the heating of hydraulic oil within a hydraulic press system, with the overarching objective of enhancing the understanding of thermal dynamics in hydraulic systems for improved operational efficiency and reliability. Through experimental studies and empirical modeling, this research endeavors to elucidate the specific effects of parameter variations on the thermal behavior of hydraulic oil, thereby facilitating informed decisions in system design and maintenance practices to optimize performance and longevity.

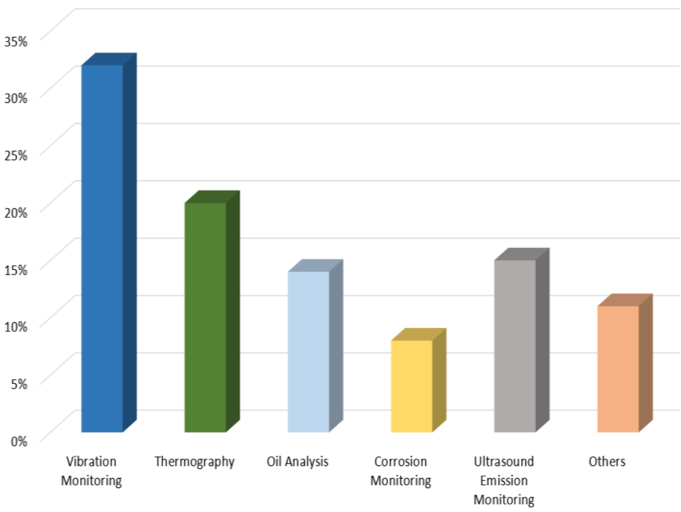

Fig 1. Research carried out on the market on the application of diagnostics in the analysis of the work of technical systems [37]

2. MATERIALS AND METHODS

2.1. Diagnostic tool utilization in hydraulic press system analysis

Devices for monitoring hydraulic fluid parameters, specifically hydraulic oil, were employed. Instruments for testing oil quality, such as the presence of solid microparticles and water in the oil, as well as a device for testing the kinematic viscosity of the oil, were used. The application of this type of diagnostics represents the initial phase for designing the behavior of the fluid in the hydraulic system under different operating parameters and the construction of the system itself. The initial results and values obtained were implemented into appropriate empirical models for defining the potential behavior of hydraulic fluid under various conditions.

The operating parameters of the hydraulic press are as follows:

- Flow: $Q = 40 \frac{l}{min}$,
- Pressure: $p = 250\ bar^{*}$,
- Hydraulic mineral oil HM VG 32, density: $\rho = 835 \frac{kg}{m^3}$

* $1\ bar = 10^5\ Pa$ - the metric unit "bar" was utilized in practice instead of the SI unit "Pascal" in the study, reflecting its application within practical contexts

2.2. Impact of filtration process on hydraulic oil parameters

The testing was conducted in two phases, with the first phase examining the oil found in the hydraulic press system and the second phase focusing on assessing the hydraulic oil's behavior following the filtration process.

In Table 1, the results of the tested ISO HM VG 32 oil before the filtration process are presented.

Table 1. Results of the tested oil ISO HM VG 32 before the filtration process

Description and sample identification	ISO HM VG 32 hydraulic oil			
Characteristics	Units	Methods	Results obtained	Oil purity requirements according to standard ISO 4406-05
Oil purity	ISO cod	ISO 4406-05	20/19/18	18/16/14 (axial-piston pump, valves)
Relative humidity	ISO cod	ISO 4406-05	81 %	30-80 %
Kinematic viscosity	mm^2/s	ISO 3104	29,950	32 (ISO HM VG 32)

Kinematic viscosity, as the most important parameter of oil, has allowable limits for deviation from the ideal state. According to ISO standard 3448, the minimum allowable limit of kinematic viscosity for ISO VG 32 oil is 28.8, while the upper limit of viscosity for this type of oil is 35.2.

In Table 2, the results after the filtration process on hydraulic mineral oil are presented.

Table 2. Results of the tested oil ISO HM VG 32 after the filtration process.

Description and sample identification	**ISO HM VG 32 hydraulic oil**			
Characteristics	Units	Methods	Results obtained	Oil purity requirements according to standard ISO 4406-05
Oil purity	ISO cod	ISO 4406-05	18/17/15	18/16/14 (axial-piston pump, valves)
Relative humidity	ISO cod	ISO 4406-05	63 %	30-80 %
Kinematic viscosity	mm^2/s	ISO 3104	31,200	32 (ISO HM VG 32)

The filtration process can never fully restore the oil to its original factory condition.

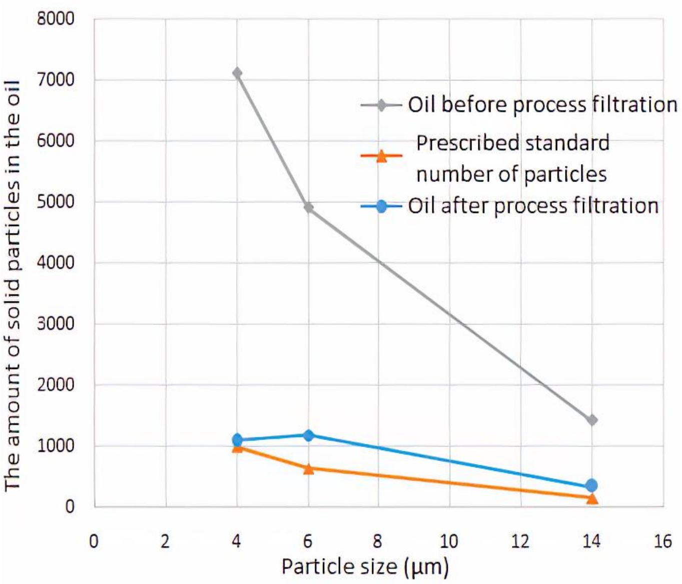

Fig. 2. The presence of solid particles before and after the filtration process.

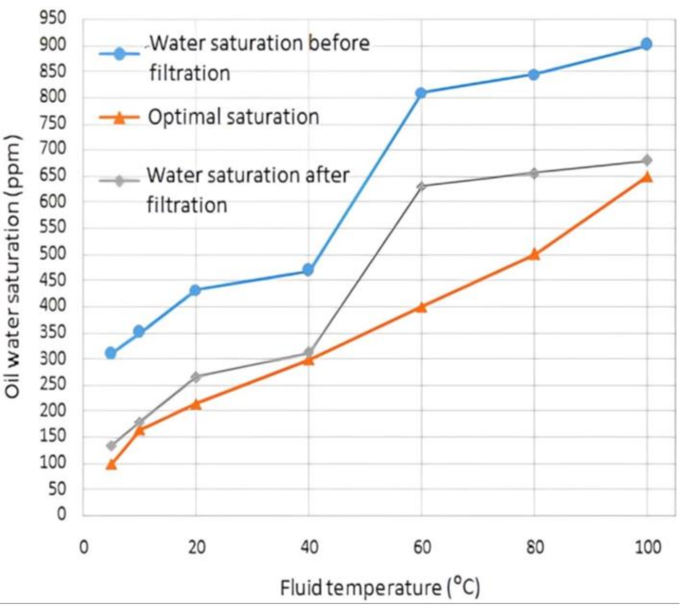

Fig. 3. Water saturation in hydraulic oil ISO HM VG 32.

However, it can significantly improve the condition of used oil and bring it to an optimal state for the smooth operation of hydraulic system components. Filtered oil certainly performs better and more efficiently in a high-pressure and load-bearing system, which will be examined during the operation. On Fig. 2, the presence of solid particles is depicted before and after the conducted filtration process.

The diagram in Fig. 3 represents the depiction of water presence within hydraulic oil.

2.3. Designing reservoirs for optimal heat management

The research is set up to be conducted under several defined operating conditions, all of which are related to the capacity of the reservoir installed in the hydraulic press system. Several initial conditions have been established to project the behavior of the working fluid temperature, the volume of the hydraulic press system's reservoir being 80 dm^3, 120 dm^3, 160 dm^3, 240 dm^3, and 280 dm^3. Another variable pertains to the pressure drop occurring in the system, within the ranges of 10 bar, 12 bar, 18 bar, 25 bar, and 28 bar. The third variable in the research concerns clearance leaks, ranging from 0,2 l/min; 0,45 l/min; 0,5 l/min; 0,65 l/min; 0,85 l/min. The fourth and final variable pertains to heat exchange with the surroundings, ranging from 30 %; 40 %; 50 %; 55 %; 60 %.

2.4. Defining parameters for hydraulic system thermal analysis

Savić described the heating of the working fluid in his book [24], with the equation (1):

$$\Delta T = \frac{t}{V_R \cdot c_p \cdot \rho} \cdot \Delta P_g \cdot ED \cdot \{1 - k\}, \tag{1}$$

while he defined the heating of the working fluid when changing the volume of the reservoir with the equation (2):

$$\Delta T_s = \frac{\Delta P_g \cdot ED \cdot \{1 - k\}}{c_p \cdot \rho} \cdot \frac{1}{V_R}, \tag{2}$$

The increase in the working fluid temperature during one working hour of the hydraulic system is represented by the equation (3):

$$\Delta T_x = \frac{ED \cdot \{1 - k\}}{V_R \cdot c_p \cdot \rho} \cdot \Delta P_g \tag{3}$$

3. RESULTS AND DISCUSSION

By setting all the initial conditions of the observed system and its working fluid, temperature changes within the hydraulic press system were examined under various operating parameters. Based on the established empirical equations, the results are presented in diagrams for three specified conditions, namely, three reservoirs of different capacities (as mentioned in the materials and methods section).

In Fig. 4, the influence of changing the reservoir volume on the heating of the hydraulic working fluid is shown.

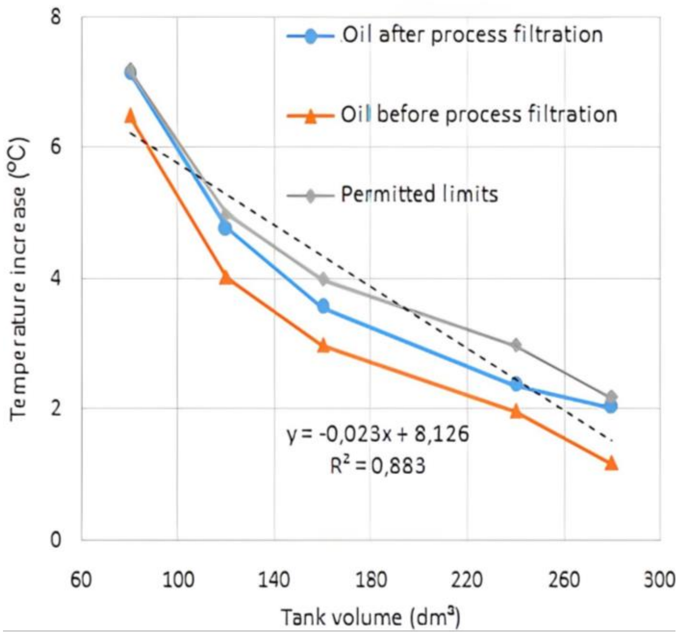

Fig. 4. The influence of changing the reservoir volume on the heating of the working fluid.

The first step in the research and the basis for further examination of the heating of the working fluid is to investigate the impact of changing the reservoir volume installed on the hydraulic press on the fluid's heating. According to the diagram in Fig. 4, it is established that, for the standard capacities considered for this system, the oil in the smallest reservoir variant of 80 dm^3 to the largest variant, a reservoir of 240 dm^3, heats up by approximately 27 % under normal operating conditions for the hydraulic press, referring to the oil tested before the filtration process. However, the oil heats up by around 24 % after the filtration process when changing the reservoir volume, but it still complies with the required heating limits. This proportion demonstrates the significant influence of the reservoir volume on the potential heating of the hydraulic working fluid in the press system.

In the diagrams shown in Figs. 5, 6, 7, 8, and 9, the influence of pressure drop in the hydraulic press system on the potential increase in the working fluid's temperature is presented.

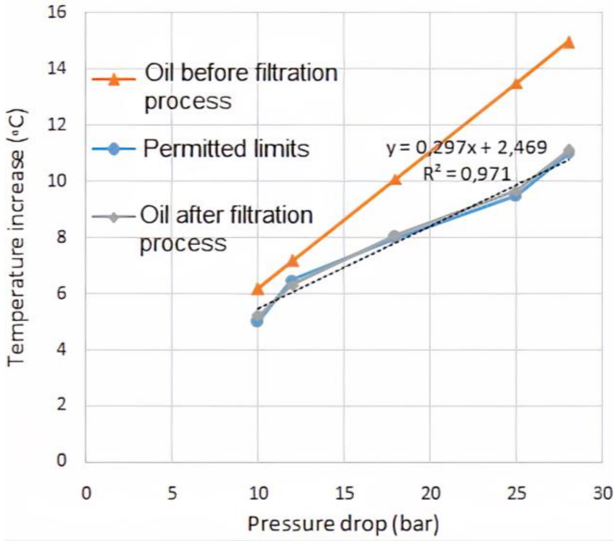

Fig. 5. The increase in temperature within the hydraulic system due to a pressure drop for a reservoir with a capacity of 80 dm^3

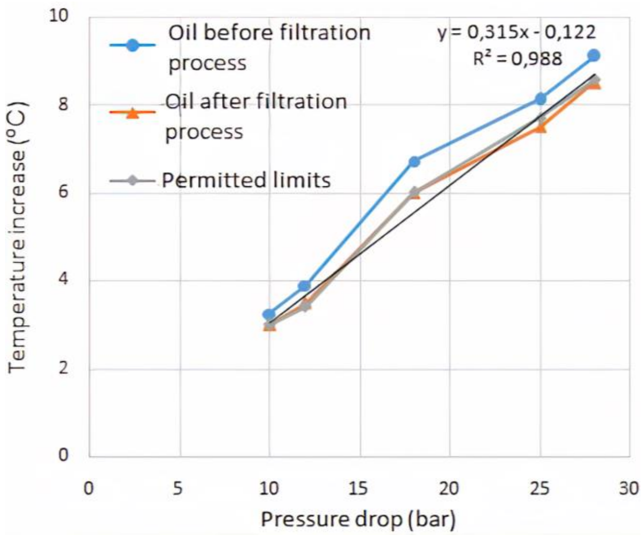

Fig. 6. The increase in temperature within the hydraulic system due to a pressure drop for a reservoir with a capacity of 120 dm^3

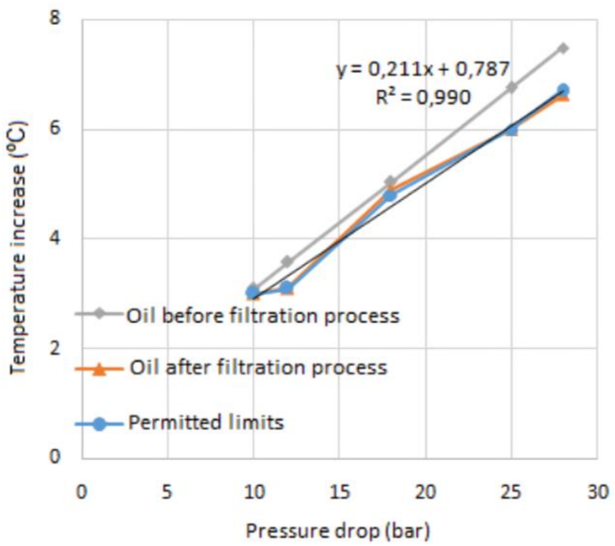

Fig. 7. The increase in temperature within the hydraulic system due to a pressure drop for a reservoir with a capacity of 160 dm^3

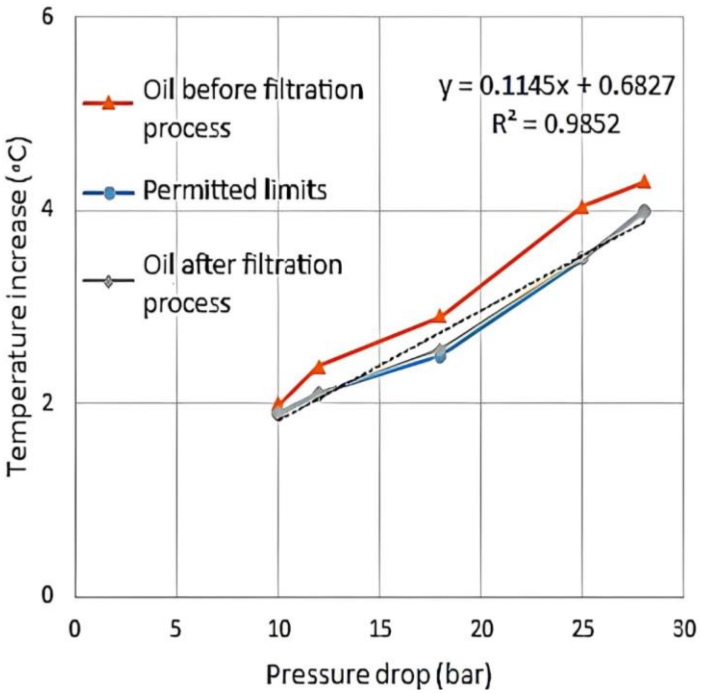

Fig. 8. The increase in temperature within the hydraulic system due to a pressure drop for a reservoir with a capacity of 240 dm^3

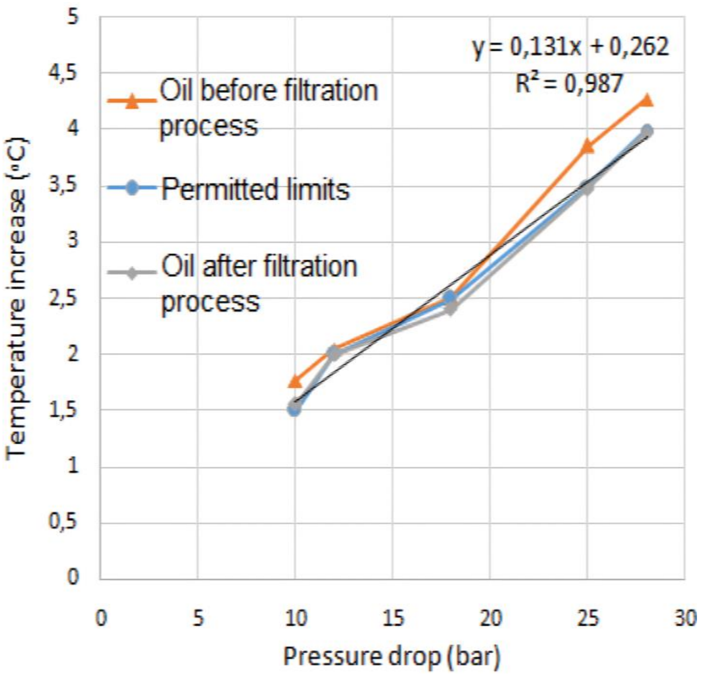

Fig. 9. The increase in temperature within the hydraulic system due to a pressure drop for a reservoir with a capacity of 280 dm^3

From the displayed diagrams, it can be concluded that the impact of pressure drop on fluid heating is highly significant within the hydraulic press system. When considering the reservoirs within the shown range, the difference in the heating of the working fluid between the smallest and largest reservoir falls within a percentage range of about 27 %, representing a substantial risk to the operation and function of the system components. If we examine the oil after the filtration process, the difference range is slightly smaller, around 18 %.

In Figs. 10, 11, 12, 13, 14, diagrams of the temperature increase of the working fluid due to specific oil leakage through clearances in system components are presented.

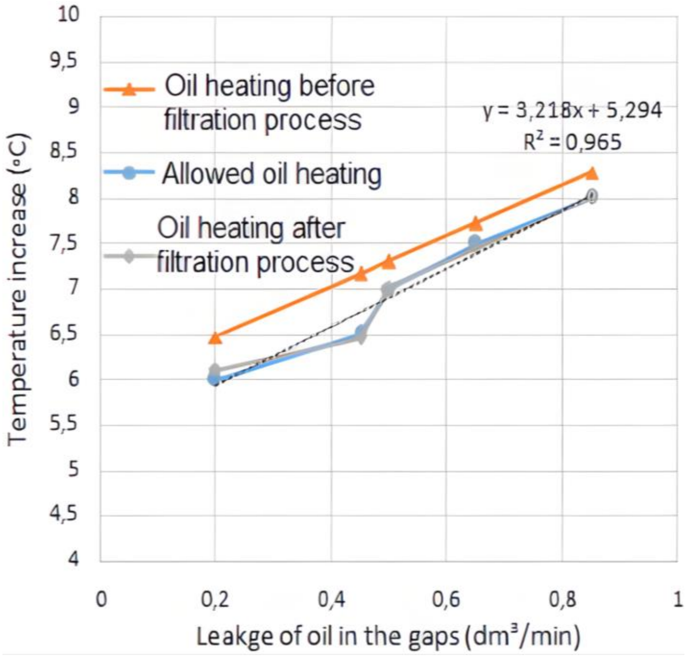

Fig. 10. The increase in temperature due to leakage through clearances for the case of an 80 dm^3 reservoir.

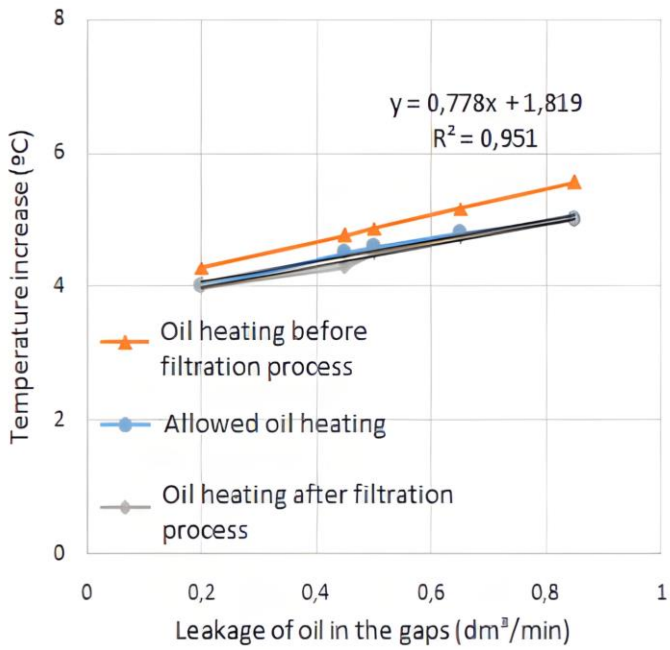

Fig. 11. The increase in temperature due to leakage through clearances for the case of a 120 dm^3 reservoir.

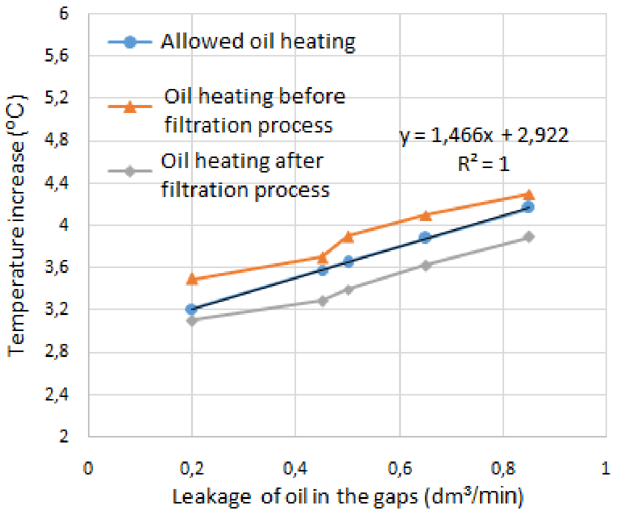

Fig. 12. The increase in temperature due to leakage through clearances for the case of a 160 dm^3 reservoir.

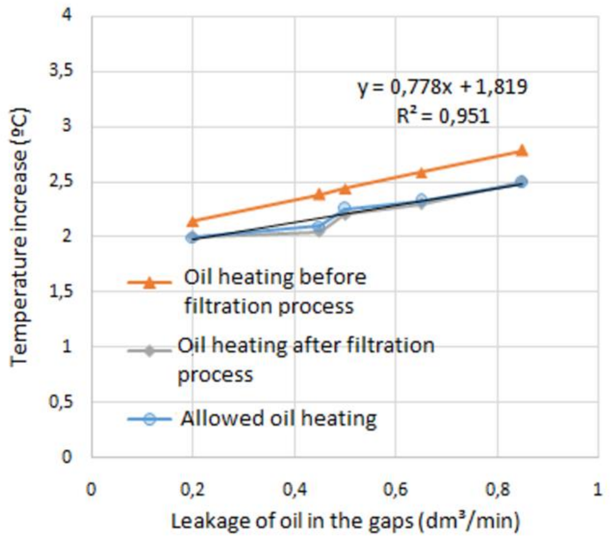

Fig. 13. The increase in temperature due to leakage through clearances for the case of a 240 dm^3 reservoir.

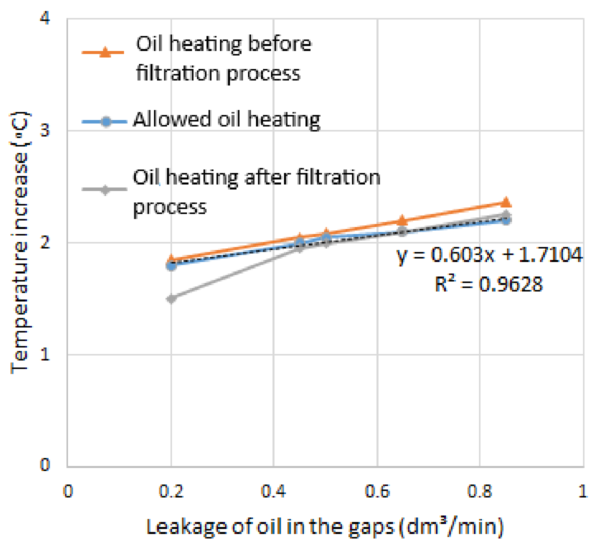

Fig. 14. The increase in temperature due to leakage through clearances for the case of a 280 dm^3 reservoir

In Figs. 15, 16, 17, 18, and 19, diagrams related to the increase in the temperature of the working fluid in the hydraulic press system are shown, considering variations in heat exchange with the surroundings.

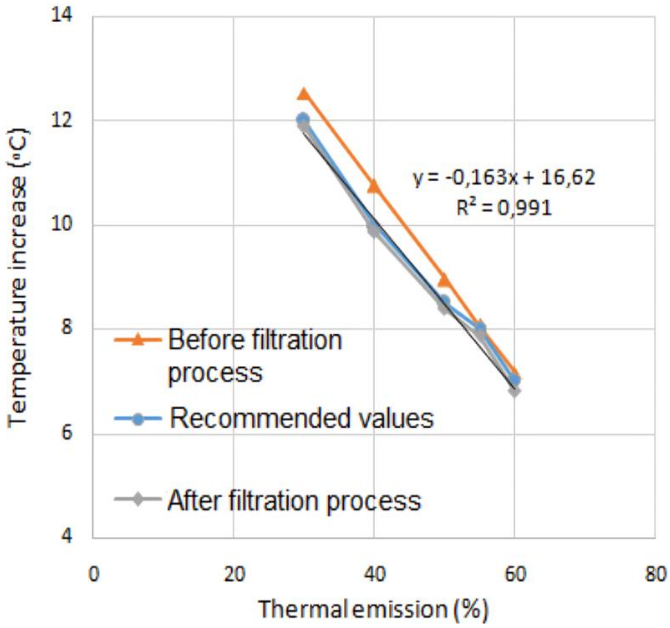

Fig. 15. The increase in the temperature of the hydraulic fluid due to heat exchange for a reservoir with a capacity of 80 dm^3

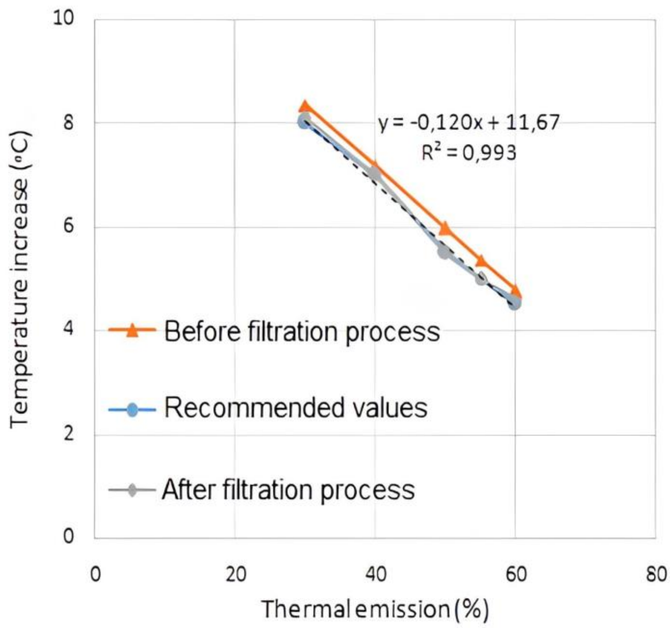

Fig. 16. The increase in the temperature of the hydraulic fluid due to heat exchange for a reservoir with a capacity of 120 dm^3

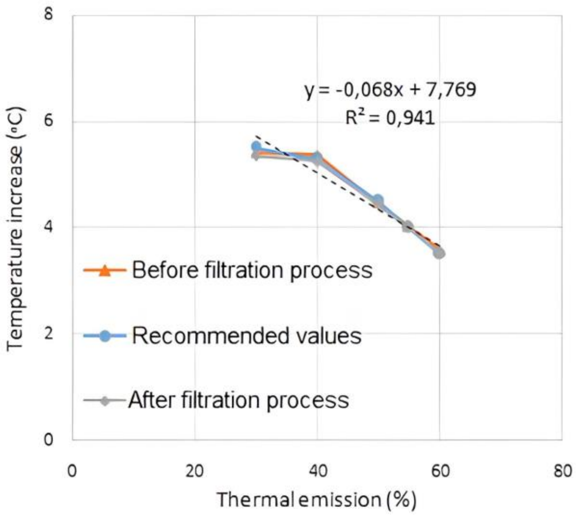

Fig. 17. The increase in the temperature of the hydraulic fluid due to heat exchange for a reservoir with a capacity of 160 dm^3

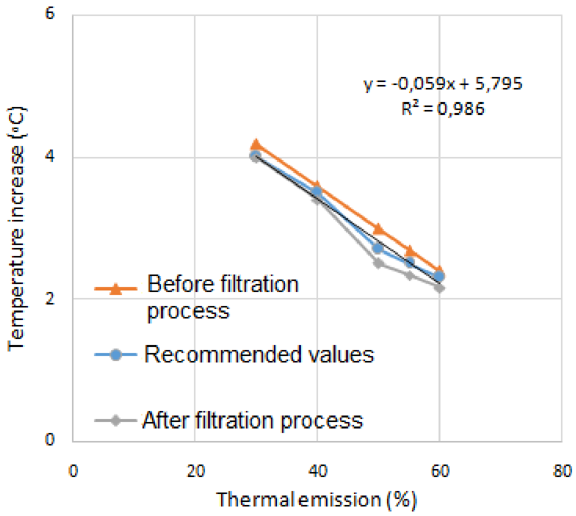

Fig. 18. The increase in the temperature of the hydraulic fluid due to heat exchange for a reservoir with a capacity of 240 dm^3

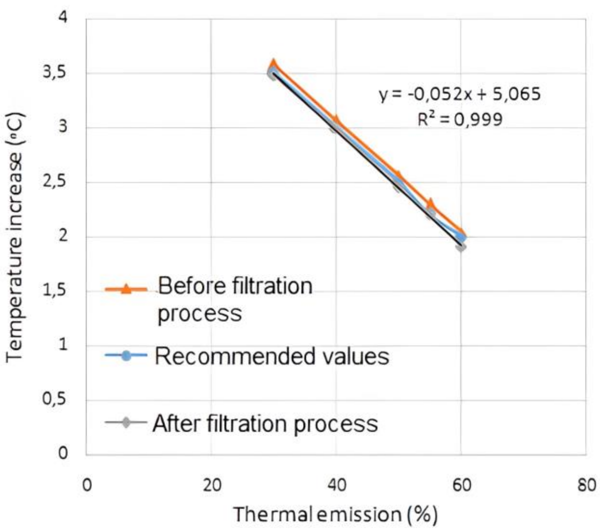

Fig. 19. The increase in the temperature of the hydraulic fluid due to heat exchange for a reservoir with a capacity of 280 dm^3

Based on the displayed diagrams related to the heating of the working fluid due to variations in heat exchange with the surroundings, it can be concluded that this parameter does indeed influence the fluid's heating to varying degrees depending on the reservoir's capacity. In the first scenario, examining the influence of an 80 dm^3 reservoir, the heating percentage ranges from approximately 9 % in the best case to 17 % in the worst case, relative to the normal fluid temperature of around 40 °C. When it comes to a tank of 280 dm^3, the percentage of heating ranges from about 5 % to 10 %, which can be considered satisfactory. Tanks of 240 dm^3 and 160 dm^3 also fall into the satisfactory category in terms of heating the working fluid.

Table 2 displays the influence of changing the reservoir volume on the heating of the working fluid under standard operating conditions for the hydraulic press system.

Table 2. The effect of changing the volume of the tank on the heating of the working fluid in the system - Variable 1.

Variable 1.	Tank volume (dm^3)	80	120	160	240	280
	Temperature increase before filtration process (^{0}C)	7,163	4,775	3,580	2,387	2,046
	Temperature increase after filtration process(^{0}C)	6,156	3,999	2,489	1,995	1,726
	Power loss (kW)	Pressure	Flow		Σ 0,969	
		0,791	0,178			

Table 3 displays the values of the working fluid's heating when changing the pressure within the hydraulic press system.

Table 3. Influence of the pressure change in the system on the heating of the working fluid – Variable 2.

	Tank volume (dm^3)	Pressure drop	Temperature increase before filtration process (^{0}C)	Temperature increase after filtration process (^{0}C)
Variable 2.	80	10	6,187	5,220
		12	7,163	6,321
		18	10,087	8,085
		25	13,498	9,664
		28	14,960	11,097
	120	10	3,801	3,721
		12	3,990	3,675
		18	6,300	6,002
		25	8,100	7,731
		28	9,023	8,202
	160	10	3,094	3,005
		12	3,582	3,420
		18	5,042	4,920
		25	6,749	5,905
		28	7,481	6,371
	240	10	1,997	1,887
		12	2,387	2,107
		18	2,911	2,562
		25	4,050	3,520
		28	4,331	4,017
	280	10	1,768	1,554
		12	2,048	1,996

	Tank volume (dm^3)	Pressure drop	Temperature increase before filtration process (^{0}C)	Temperature increase after filtration process (^{0}C)
		18	2,506	2,402
		25	3,857	3,478
		28	4,274	3,983
	Power losses in the system			
	Pressure		Flow	Σ 0,969
	0,791		0,178	

Table 4 displays the values of the increase in the temperature of the working fluid for various leakages within the components of the system.

Table 4. The effect of clearance leaks on the increase in the temperature of the working fluid - Variable 3.

	Tank volume (dm^3)	Leakage (dm^3/min)	Temperature increase before filtration process (^{0}C)	Temperature increase after filtration process (^{0}C)
Variable 3.	80	0,2	6,468	6,100
		0,45	7,167	6,455
		0,5	7,306	7,020
		0,65	7,724	7,456
		0,85	8,821	8,001
	120	0,2	4,200	4,001
		0,45	4,420	4,105
		0,5	4,580	4,369
		0,65	5,200	4,520
		0,85	5,801	5,191
	160	0,2	3,490	3,063
		0,45	3,640	3,399
		0,5	3,897	3,311
		0,65	4,100	4,032
		0,85	4,299	3,902
	240	0,2	2,105	1,911
		0,45	2,401	2,050
		0,5	2,489	2,200
		0,65	2,550	3,380
		0,85	2,810	2,498
	280	0,2	1,848	1,505
		0,45	2,048	1,956
		0,5	2,087	1,995
		0,65	2,206	2,100
		0,85	2,365	2,256
	Power losses in the system			
	Pressure		Flow	Σ 0,875
	0,796		0,079	

In Table 5, the temperature values for the heating of the working fluid, specifically variable number 4, are presented.

Table 5. The effect of thermal emission on the increase in temperature of the working fluid - Variable 4.

	Tank volume (dm^3)	Thermal emission (%)	Temperature increase before filtration process (^{0}C)	Temperature increase after filtration process (^{0}C)
Variable 4.	80	30	12,536	11,889
		40	10,745	9,862
		50	8,954	8,400
		55	8,058	7,869
		60	7,163	6,802
	120	30	8,357	8,105
		40	7,163	7.009
		50	5,696	5.510
		55	5,372	5.025
		60	4,775	4,600
	160	30	5.424	5,355
		40	5.372	5,250
		50	4.477	4,451
		55	4.029	4,005
		60	3.582	3,522
	240	30	4,211	3,998
		40	3,797	3,601
		50	3,455	2,655
		55	2,384	2,301
		60	2,215	2,119
	280	30	3,581	3,449
		40	3,070	2,995
		50	2,558	2,490
		0,55	2,302	2,201
		0,60	2,047	1,915
	Power losses in the system			
	Pressure		Flow	Σ 0,969
	0,791		0,178	

4. CONCLUSION

The operation of hydraulic systems relies on hydraulic oil, and its quality is crucial for system reliability. Elevated temperatures, often due to high loads and pressures, can degrade hydraulic fluid quality.

- High temperatures can lead to changes in oil viscosity, affecting system friction and potentially causing malfunctions in hydraulic components.
- Accurate determination of heat exchange coefficients is vital for understanding and managing thermal dynamics in hydraulic systems.
- Leaks within the system can exacerbate overheating by reducing oil volume and impeding effective cooling, highlighting the importance of regular maintenance and leak detection.

The study focuses on the impact of high loads, pressures, pressure changes, component leakage, and related factors on elevated temperatures in hydraulic systems. It specifically examines key variables like pressure differences, leaks, and heat exchange coefficients. Determining accurate heat exchange coefficients is challenging, typically relying on constant values for normal conditions. However, this research establishes an acceptable threshold for this variable.

Pressure and flow variables are relatively easy to examine with diagnostic tools for detecting pressure increases and leaks. Significant leaks result in oil loss, increasing oil usage and preventing sufficient cooling in the reservoir, leading to further heating. This thermal expansion can cause additional leaks and alter oil characteristics, affecting viscosity and system friction.

In the worst case, increased leaks within the system lead to problems in the execution of appropriate functions on the drive and executive elements of the system, causing the entire system not to meet its prescribed characteristics. In hydraulic systems, the reliability of components and the system can be reflected through the volumetric efficiency, which depends on the appropriate pressure and the ratio of the actual to theoretical flow defined for the given system. In hydraulic press systems and their components, if the system is newly constructed, the volumetric efficiency should be between 0.95 and 0.98, i.e., the reliability should be in the range of 95 % to 98 %. For exploited systems, this percentage may go down to 90 % as the lower tolerance limit for reliable and correct operation.

The filtration process of hydraulic mineral oils cannot restore the oil to its factory condition, but it can lead to improved oil characteristics, thereby extending the reliable operational life and durability of the system and its components.

The findings of this study have significant practical implications for the field of hydraulic systems, providing valuable insights into the effects of altering hydraulic parameters and tank capacity on hydraulic oil heating. Engineers and practitioners can utilize these insights to optimize system performance, inform design decisions, and enhance maintenance practices. Furthermore, this study opens avenues for future research in hydraulic systems, particularly in exploring the characterization of thermal dynamics under diverse operating conditions and investigating novel technologies for heat management. By addressing these research directions, future studies can contribute to advancements in hydraulic system design, operation, and maintenance, ultimately driving improvements in efficiency, reliability, and sustainability.

References

1. Alawi O A, Sidik N A C, Xian H W et al. Thermal conductivity and viscosity models of metallic oxides nanofluids. International Journal of Heat and Mass Transfer 2018; 116: 1314–1325, https://doi.org/10.1016/j.ijheatmasstransfer.2017.09.133.
2. Banaszek A. Methodology of flow rate assessment of submerged hydraulic ballast pumps on modern product and chemical tankers with use of neural network methods. Procedia Computer Science 2021; 192: 1894–1903, https://doi.org/10.1016/j.procs.2021.08.195.
3. Banaszek A, Petrovic R. Problem of Non Proportional Flow of Hydraulic Pumps Working with Constant Pressure Regulators in Big Power Multipump Power Pack Unit in Open System. Tehnicki vjesnik - Technical Gazette 2019. doi:10.17559/TV-20161119215558, https://doi.org/10.17559/TV-20161119215558.
4. Bock W. Hydraulic Oils. In Dresel W, Mang T (eds): Lubricants and Lubrication, 1st edition. Wiley: 2017: 345–420, https://doi.org/10.1002/9783527645565.ch11.
5. Esfe M H, Kamyab M H, Afrand M, Amiri M K. Using artificial neural network for investigating of concurrent effects of multi-walled carbon nanotubes and alumina nanoparticles on the viscosity of 10W-40 engine oil. Physica A: Statistical Mechanics and its Applications 2018; 510: 610–624, https://doi.org/10.1016/j.physa.2018.06.029.
6. Goharrizi A Y, Sepehri N. Application of Fast Fourier and Wavelet Transforms Towards Actuator Leakage Diagnosis: A Comparative Study. International Journal of Fluid Power 2013; 14(2): 39–51, https://doi.org/10.1080/14399776.2013.10781074.
7. Goharrizi A Y, Sepehri N. Internal Leakage Detection in Hydraulic Actuators Using Empirical Mode Decomposition and Hilbert Spectrum. IEEE Transactions on Instrumentation and Measurement 2012; 61(2): 368–378, https://doi.org/10.1109/TIM.2011.2161938.
8. Goharrizi A Y, Sepehri N. A Wavelet-Based Approach to Internal Seal Damage Diagnosis in Hydraulic Actuators. IEEE Transactions on Industrial Electronics 2010; 57(5): 1755–1763, https://doi.org/10.1109/TIE.2009.2032198.
9. Gullapalli S, Michael P, Kensler J et al. An Investigation of Hydraulic Fluid Composition and Aeration in an Axial Piston Pump. ASME/BATH 2017 Symposium on Fluid Power and Motion Control, Sarasota, Forida, USA, American Society of Mechanical Engineers: 2017: V001T01A028, https://doi.org/10.1115/FPMC2017-4259.
10. Guo S, Chen J, Lu Y et al. Hydraulic piston pump in civil aircraft: Current status, future directions and critical technologies. Chinese Journal of Aeronautics 2020; 33(1): 16–30, https://doi.org/10.1016/j.cja.2019.01.013.
11. Hodges P. Hydraulic Fluids, Petroleum Consult., Norway. New York, John Wiley Sons: 1996. https://doi.org/10.1016/B978-034067652-3/50022-1
12. Hong S-H, Jeon H-G. Monitoring the Conditions of Hydraulic Oil with Integrated Oil Sensors in Construction Equipment. Lubricants

2022; 10(11): 278, https://doi.org/10.3390/lubricants10110278.
13. Jin Y, Shan C, Wu Y et al. Fault Diagnosis of Hydraulic Seal Wear and Internal Leakage Using Wavelets and Wavelet Neural Network. IEEE Transactions on Instrumentation and Measurement 2019; 68(4): 1026–1034, https://doi.org/10.1109/TIM.2018.2863418.
14. Kotia A, Rajkhowa P, Rao G S, Ghosh S K. Thermophysical and tribological properties of nanolubricants: A review. Heat and mass transfer 2018; 54: 3493–3508, https://doi.org/10.1007/s00231-018-2351-1.
15. Lind S J, Phillips T N. The influence of viscoelasticity on the collapse of cavitation bubbles near a rigid boundary. Theoretical and Computational Fluid Dynamics 2012; 26(1–4): 245–277, https://doi.org/10.1007/s00162-011-0227-9.
16. Liu S, Tu A, Mo X et al. Experimental study and comparative performance analysis on thermal-hydraulic characteristic of a novel longitudinal flow oil cooler. Applied Thermal Engineering 2021; 199: 117567, https://doi.org/10.1016/j.applthermaleng.2021.117567.
17. Mahankar P S, Dhoble A S. Review of hydraulic seal failures due to effect of medium to high temperature. Engineering Failure Analysis 2021; 127: 105552, https://doi.org/10.1016/j.engfailanal.2021.105552.
18. Manring N D, Fales R C. Hydraulic control systems. John Wiley & Sons: 2019. https://doi.org/10.1002/9781119418528
19. Mondal M K, Manna N K, Saha R. Study of leakage flow through a spool valve under blocked-actuator port condition—Simulation and experiment. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science 2014; 228(8): 1405–1417, https://doi.org/10.1177/0954406213507702.
20. Novaković B, Radovanović L, Zuber N et al. Analysis of the influence of hydraulic fluid quality on external gear pump performance. Eksploatacja i Niezawodność – Maintenance and Reliability 2022; 24(2): 260–268, https://doi.org/10.17531/ein.2022.2.7.
21. Osiński P, Deptuła A, Partyka M A. Hydraulic Tests of the PZ0 Gear Micropump and the Importance Rank of Its Design and Operating Parameters. Energies 2022; 15(9): 3068, https://doi.org/10.3390/en15093068.
22. Ritucci A L, Frizziero L, Liverani A. Maintainability Approach: Hydraulic Pump with External Gears Explored with Design for Disassembly and Augmented Reality. Applied Sciences 2021; 11(2): 666, https://doi.org/10.3390/app11020666.
23. Rydberg K-E. Hydraulic fluid properties and their impact on energy efficiency. Linköping University Electronic Press: 2013: 447–453. https://doi.org/10.3384/ecp1392a44
24. Savić V. Uljna hidraulika 4 deo 2. Novi Sad, IKOS Novi Sad: .
25. Shababi K, Firouzi M, Fakhar A. An experimental study on rheological behavior of SAE50 engine oil: Effects of temperature and hybrid nano-materials composed of 20 vol% MWCNTs and 80 vol% TiO2. Journal of Thermal Analysis and Calorimetry 2018; 131(3): 2311–2320, https://doi.org/10.1007/s10973-017-6693-6.
26. Sharma G, Kotia A, Ghosh S K et al. Kinematic viscosity prediction of nanolubricants employed in heavy earth moving machinery using machine learning techniques. International Journal of Precision Engineering and Manufacturing 2020; 21: 1921–1932, https://doi.org/10.1007/s12541-020-00379-9.
27. Shen W, Zhang J, Sun Y et al. Effect of cavitation bubble collapse on hydraulic oil temperature. Journal of Central South University 2016; 23(7): 1657–1668, https://doi.org/10.1007/s11771-016-3220-z.
28. Śliwiński P. The influence of pressure drop on the working volume of a hydraulic motor. Eksploatacja i Niezawodność – Maintenance and Reliability 2022; 24(4): 747–757, https://doi.org/10.17531/ein.2022.4.15.
29. Stawiński Ł, Kosucki A, Cebulak M et al. Investigation of the influence of hydraulic oil temperature on the variable-speed pump performance. Eksploatacja i Niezawodność – Maintenance and Reliability 2022; 24(2): 289–296, https://doi.org/10.17531/ein.2022.2.10.
30. Strmčnik E, Majdič F. Comparison of leakage level in water and oil hydraulics. Advances in Mechanical Engineering 2017; 9(11): 168781401773772, https://doi.org/10.1177/1687814017737723.
31. Sun Y, Wang P. Main Influencing Factors of Hydraulic Oil Performance for Construction Machinery. IOP Conference Series: Materials Science and Engineering 2019; 677(2): 022129, https://doi.org/10.1088/1757-899X/677/2/022129.
32. Xue L, Jiang H, Zhao Y et al. Fault diagnosis of wet clutch control system of tractor hydrostatic power split continuously variable transmission. Computers and Electronics in Agriculture 2022; 194: 106778, https://doi.org/10.1016/j.compag.2022.106778.
33. Yao Z, Tang J, Rui T, Duan J. A time–frequency analysis based internal leakage detection method for hydraulic actuators. Advances in Mechanical Engineering 2017; 9(1): 168781401668505, https://doi.org/10.1177/1687814016685058.
34. Zhao X, Vacca A. Numerical analysis of theoretical flow in external gear machines. Mechanism and Machine Theory 2017; 108: 41–56,

https://doi.org/10.1016/j.mechmachtheory.2016.10.010.

35. Zhou J, Vacca A, Casoli P. A novel approach for predicting the operation of external gear pumps under cavitating conditions. Simulation Modelling Practice and Theory 2014; 45: 35–49, https://doi.org/10.1016/j.simpat.2014.03.009.
36. Zhu Y, Wu Q, Tang S et al. Intelligent Fault Diagnosis Methods for Hydraulic Piston Pumps: A Review. Journal of Marine Science and Engineering 2023; 11(8): 1609, https://doi.org/10.3390/jmse11081609.
37. Market Research Report. 2022: 343.