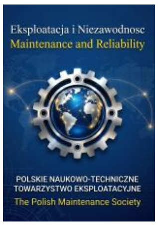

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Investigation of the influence of hydraulic oil temperature on the variable speed fixed displacement piston pump performance

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Abstract

This paper investigates the influence of hydraulic oil temperature on the performance of a piston pump. The primary objective of the study was to determine the variations in volumetric efficiency by developing operational maps under different thermal conditions, system pressures, and rotational speeds. The experiments were conducted on a laboratory test stand equipped with a fixed-displacement piston pump driven by an electric motor. Measurement signals were processed using LabVIEW software, enabling the generation of efficiency maps across a wide operating range. The results highlighted the strong dependence of the pump efficiency on the temperature of the working fluid, particularly at low speeds and elevated pressures. The developed maps provide valuable insights into the operating boundaries of the pump, offering practical guidance for both system design and operational planning. The findings emphasize that temperature-dependent characteristics constitute a crucial source of information for ensuring high efficiency, durability, and reliability of hydraulic systems employing piston pumps.

Keywords: *hydraulic fixed displacement piston pump, volumetric efficiency, temperature-dependent characteristics, variable speed drive, hydraulic oil*

Article citation:
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Highlights

- Piston pump temperature dependent performance over a wide range of speeds and pressures.
- Monitoring and controlling the temperature of oil is essential to ensure process stability.
- Elevated hydraulic oil temperature significantly reduces pump performance.
- Temperature-dependent pump capacity is shown for a wide range of pressures and speeds.

1. Introduction

The physical and chemical properties of the working fluid fundamentally determine the operational reliability and efficiency of hydrostatic systems. As the primary medium for power transmission, the fluid must simultaneously fulfill several additional functions, including lubrication, corrosion protection, heat dissipation, and sealing. These diverse roles impose stringent requirements on their behavior under varying thermal and mechanical conditions. Among the most critical parameters influencing system performance are viscosity and its temperature dependence, which govern the internal friction, leakage, and formation of hydrodynamic lubrication films. The density and the compressibility further affect the dynamic response and stiffness of the hydraulic system, whereas the lubricating capacity of the fluid determines the wear characteristics of the pumps, motors, and control elements.

Equally important are the fluid's resistance to foaming and its ability to release entrained air, as the presence of gas phases leads to cavitation, reduced stiffness, and accelerated degradation of components. Thermal and oxidative stabilities play decisive roles in maintaining long-term fluid integrity and preventing the formation of deposits and acidic by-products that impair system operation. The fluid must also exhibit strong anti-corrosion properties and adequate load-carrying capacity, particularly in high-pressure applications, where surface interactions are severe. In addition, maintaining an appropriate level of cleanliness—typically defined by ISO 4406—is essential, as solid contaminants remain one of the leading causes of hydraulic failures. Finally, the ability to separate water effectively is crucial for preventing corrosion, additive depletion, and the deterioration of lubricating properties.

Collectively, these parameters determine not only the immediate functional characteristics of hydrostatic systems but also their durability, energy efficiency, and operational safety. A comprehensive understanding of fluid properties is indispensable when designing, selecting, and maintaining hydraulic systems intended for demanding industrial applications [1].

In addition to the oil temperature, the ambient temperature is important. Therefore, why pump manufacturers often specify the maximum starting viscosity [2]. It is also worth mentioning the tendency to increase the energy efficiency of systems while reducing their weight. Less oil is associated with a higher thermal load [3].

An important issue is the aging of the hydraulic fluids. It consists of the deterioration of the properties of the oil and its structure under the influence of temperature or pressure. During aging, irreversible chemical processes take place that can prevent further use of oil [4,5]. The aging rate is closely related to the temperature of the hydraulic oil. It is assumed that the temperature of the working liquid during operation should not exceed 55 ÷ 60 °C, because at higher temperatures aging occurs much faster. Moreover, due to miniaturization, the temperature in hydraulic (microhydraulic) systems often reaches values close to 100 degrees Celsius, which necessitates conducting tests at various operating temperatures.

High temperatures reduce viscosity, whereas low temperatures cause it to increase. Both situations can be detrimental to the systems and cause cavitation, performance degradation and failures. Too viscous working fluid increases the flow resistance, which puts a strain on the hydraulic system components. In addition, cold oil causes brittleness, cracking or shrinkage of seals, which negatively affects tightness. Higher temperatures can cause lubrication problems and faster wear of system components due to too low viscosity of the liquid [4]. It should also be noted that temperature-induced changes in the physical properties of the working fluid can significantly influence the pulsation characteristics of positive displacement pumps. The complexity of this phenomenon has been discussed in [5], where it was demonstrated that thermal effects modify the dynamic response of hydraulic pumps in a non-linear and strongly coupled manner.

The appropriate temperature of the hydraulic oil ensures favourable operating conditions for all system components. The papers [8−10] present the issue of monitoring the oil condition in hydraulic systems using appropriate sensors of oil properties (temperature, contamination, etc.). With this knowledge, it was possible to regulate the temperature and analyse the possible unevenness of temperature distribution. Such activities may allow for the development of a system for predicting the life of the oil.

The paper [6] describes the research on the durability of a hydraulic satellite motor powered by rapeseed oil. The tests were conducted on a test bench with a power recuperation system for three constant pressure drops in the motor. Research has shown that the lower the overall efficiency of the motor, the greater the increase in the motor temperature. The paper [7] discusses in detail the influence of different pressure and temperature levels on the increase in oil temperature and the phenomenon of cavitation on a cylindrical slide valve.

Many papers have presented models for predicting temperature, which can result in better control performance. In [8], a model of precise temperature prediction in hydraulic closed circuits is discussed. The theory was confirmed experimentally, while the research was aimed at increasing the efficiency of the system while ensuring a safe temperature level.

The paper [9] describes the influence of different temperatures and pressures on the performance of the hydraulic elements and the entire system. Article [10] discusses the effect of temperature on the performance of a fixed displacement gear hydraulic pump when operating at different speeds and pressure levels. The research aimed to prepare maps of hydraulic oil operation, that allow for the quick determination of pump efficiency at a given temperature. In [11], the hydraulic system with an electro-hydraulic valve (EHSV) is tested, the advantage of which is the possibility of precise control. In this paper, the static and dynamic performance of a linear hydraulic system under different operating conditions was investigated. It was found that an increase in temperature increased the power requirement to reach a specific pressure. In [12], simulations and experiments performed to determine the effect of high temperatures on the distribution of the pressure and velocity fields are presented. As the temperature increases, the flow resistance decreases, and the flow velocity increases, which unfortunately creates the suitable conditions for cavitation. In [13], a numerical model is presented that allows the simulation of the internal flow field for the pump. The effect of different temperatures on the quality of the power flow was tested. Optimum flow performance at the pump can only be achieved with the correct specific oil temperature. In the case of temperature changes, cavitation in the field flow can increase. [14] discusses the mathematical simulation of the effect of temperature on the pressure drop across the pump suction line. In addition, the effect of the oil flow rate on the pressure drop at the pump was determined. It has been observed that with increasing temperature, the oil is more susceptible to flow losses and less susceptible to pressure losses. In addition, the paper addresses the issue of cavitation, which can lead to deterioration of the performance of hydraulic components. In [15], the authors simulated the effect of oil temperature change on the control performance of an electrohydraulic servo valve. The temperature changes significantly affect the control characteristics of the valve. The efficiency of this component can significantly change the efficiency of the entire hydraulic system. That's why ensuring the highest possible stability and reliability of the valve is so important. Paper [16] discusses the issues related to optimizing the performance of the hydraulic system by selecting the exact position of traditional hydraulic actuators. The influence of changes in dynamic and kinematic viscosity and oil density on the exact position of ordinary, typical hydraulic cylinders was investigated.

The paper [17] describes research on the influence of viscosity on the characteristics of selected elements of hydraulic systems. It was noticed that as the viscosity increased, the efficiency of the pump increased, because of the fewer leaks in the pump casing.

The paper [18] also discusses the effect of the viscosity of hydraulic oils on the proportional valve for the rice transplanter based on the PID control algorithm. A viscosity-aware adjustment algorithm was developed to control the rice planting depth of the rice planter using different hydraulic oils at various temperatures. The proposed system can control the pressure on the proportional valve, therefore it can control the displacement of the actuator. Without considering the viscosity, the planting depth could not be controlled.

The paper [19] presents issues related to temperature distribution in the case of an axial piston hydraulic pump. This distribution concerned the oil layer of a pair of valve plates in such a pump. The effect of the change in the angle of inclination of the control disc and the working pressures on the temperature of this layer was investigated. The test results show that the temperature of the layer increases with the operating pressure and the angle of inclination.

Numerous publications discuss the study of temperatures in hard environmental conditions. The paper [20] discusses the issue of the efficiency of direct driven hydraulic drives (DDH) operated in cold environments (below 0 °C). The system efficiency was determined by two types of hydraulic oils: conventional multigrade and special, high-performance oils. In addition, different speeds and payloads were tested under various environmental conditions. It was shown that after using a special oil, performance improved.

The hydraulic motors' operation under thermal shock conditions, when cold motors were powered by hot oil, is described in [21]. The paper presents tests of a properly and incorrectly functioning satellite motor during start-up under thermal shock conditions. The influence of the decrease in pressure on the increase in the engine temperature was determined. Using a satellite motor as an example, a method for determining the correct operation of motors was developed, using changes in the measured parameters (inlet pressure and temperature of motor components).

A review of the available literature clearly indicates that comprehensive testing of hydraulic pumps across a wide range of operating parameters is essential for the proper design of high-efficiency hydraulic systems. Existing studies consistently report a reduction in pump efficiency with increasing temperature of the working fluid. However, the simultaneous influence of temperature, operating pressure, and rotational speed remains insufficiently explored. The present work addresses this gap by investigating the combined effect of these three parameters on the volumetric efficiency of a piston pump. It should be emphasized that the experiments were conducted over an extensive range of pressures, rotational speeds, and fluid temperatures, which are rarely documented in contemporary research. The findings presented herein demonstrate the relevance of such multidimensional analyses, particularly for hydraulic systems employing variable-speed pumps. Consequently, the results contribute to filling a noticeable gap in the current state of knowledge.

The structure of the paper is as follows: Chapter 2 provides a detailed description of the experimental test stand and the methodology used to conduct measurements, including the procedures for processing and converting the recorded data. Chapter 3 presents the experimental results in the form of operational maps of the hydraulic pump, illustrating the relationships between the pressure, volumetric efficiency, and temperature at various pump speeds. Finally, Chapter 4 offers a comprehensive analysis and discussion of the results obtained.

2. Methodology

The experimental investigations were conducted on a laboratory test stand, the detailed description of which is provided in the following section. The technical specifications of the individual components are presented together with the measurement program implemented during the study. The research methodology, including the scope of the examined operating parameters, is discussed, along with the procedures used for processing and validating the recorded measurement data. Additionally, the method applied to convert the raw measurement signals into volumetric efficiency values is outlined, ensuring a clear and consistent basis for the presentation and interpretation of the experimental results.

2.1. Test stand

The electro-hydraulic laboratory test stand used for the variable speed fixed displacement (VSFD) piston pump testing is presented in Figure 2. This facility has previously served as the basis for the experimental investigations presented in [22], where the estimation method of the pressure level in the hydraulic drive with an actuator fed by a VSFD piston pump was developed. Subsequent modernization of the stand—including an extension of the control and data-acquisition system as well as the installation of an additional temperature sensor—enabled the continuation and expansion of research activities. The hydraulic schematic of the test stand is shown in Figure 1. and contains only the elements necessary to obtain flow characteristics of the piston pump operating as VSFD pump. The tested fixed displacement bidirectional piston pump XPi 12 Hydro Leduc (3) is driven by the asynchronous motor MS 100L3-4 (2) fed by frequency converter Yaskawa CIMR-UC4E0014AAA (1). The applied drive system enables the testing of the hydraulic pump over a broad range of rotational speeds. Pump speed is monitored using an incremental encoder (B) mounted directly on the motor shaft, while the frequency converter communicates with the measurement and control device (MCD) NI USB 6434 (A) through dedicated input and output channels. The pump ports are connected to the hydraulic circuit and the oil reservoir via flexible hoses to minimize the transmission of vibrations. The remaining sections of the system, assembled using rigid steel piping, incorporate the necessary control and measurement instrumentation. These include the Hydrotechnik MultiEpc 100 pressure transducers (C) and QG 110 flowmeter (D). The temperature of the hydraulic oil in the reservoir, located near the pump suction line, was measured using a type J thermocouple (E). The system loading is regulated by the WZPSE6 proportional valve controlled by a ZELPRO 20RE10E current amplifier (5). When the proportional valve is fully closed, the Ponar A-VMP-PIB-12-SP relief valve (4) opens to protect the system from damage. A complete list of the components and their operating parameters is provided in Table 1.

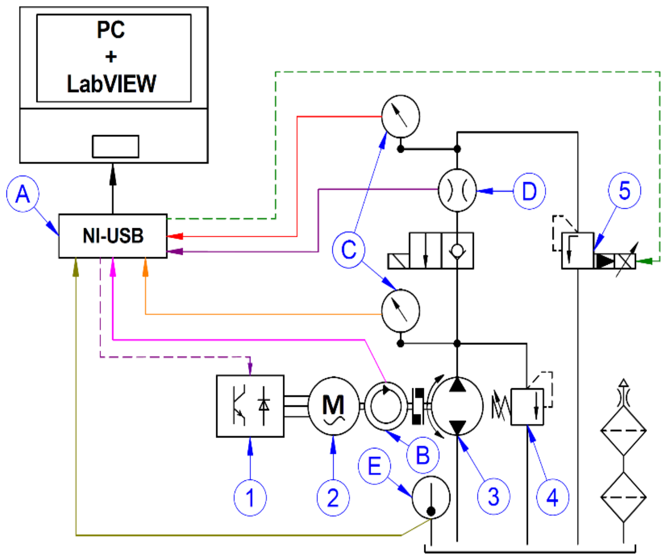


Figure1. Hydraulic scheme of the test stand. List of elements according to Table 1.

Table 1. List of components of the test stand.

No.	Component	Parameters
1	Frequency converter Yaskawa CIMR-UC4E0014AAA	400 V, 14A, 0–400 Hz
2	Electric motor MS100L3-4 B5	400 V, 4 kW, 1430 rpm
3	Pump:Hydro Leduc XPi 12 0523820	12 cm^3/rev, 38 MPa, 0–3150 rpm, -25–80°C
4	Relief valve Ponar A-VMP-PIB-12-SP	35 MPa, 70 lpm
5	Proportional valve WZPSE6 with ZELPRO-20RE10E	21 MPa, 60 lpm
A	MCD: NI USB 6434	16 AI, 2 AO, 24 DIO USB
B	Incremental encoder GI331.0224135	5000 imp/rev, TTL 5V
C	Pressure transducers Hydrotechnik MultiEpc 100	0–40 MPa, Acc: ±0,2%
D	Flowmeter HySense QG 110 3185-03-S-35.030	0,2–30 lpm, Acc: ±0,7%.
E	Type J thermocouple	-210–760°C, Acc: ±0,75%

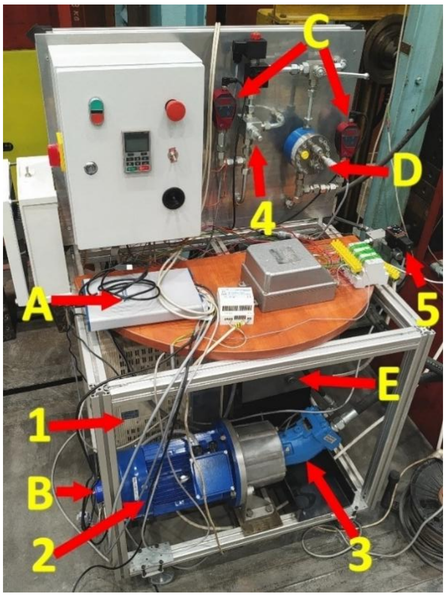


Figure 2. Electro-hydraulic test stand. List of elements according to Table 1.

2.2. Measurement method

Prior to conducting the measurements, predefined ranges of temperature, pressure, flow rate, and rotational speed were established to ensure that the experiment captured the most relevant operational characteristics of the VSFD piston pump. The ranges of temperatures, pressures, and flow rates summarized in Table 2. correspond to the minimum and maximum values recorded across all measurement series, thereby reflecting the full spectrum of conditions achieved during the experimental campaign.

The purpose of the study was to determine volumetric efficiency under conditions of varying motor speed, changing system pressure and varying hydraulic oil temperature. The initial oil temperature on the stand was 25°C. The maximum temperature reached was over 80°C. The oil used in the study was L-HL46 with a viscosity index VI=101. The t-v diagram is presented in Figure 3.

Table 2. Ranges of parameters that can be obtained on the stand.

Temperature	Pressure	Speed	Flow rate
[°C]	[MPa]	[rpm]	[lpm]
25 – 80	0 – 16	0 – 1500	0 – 18

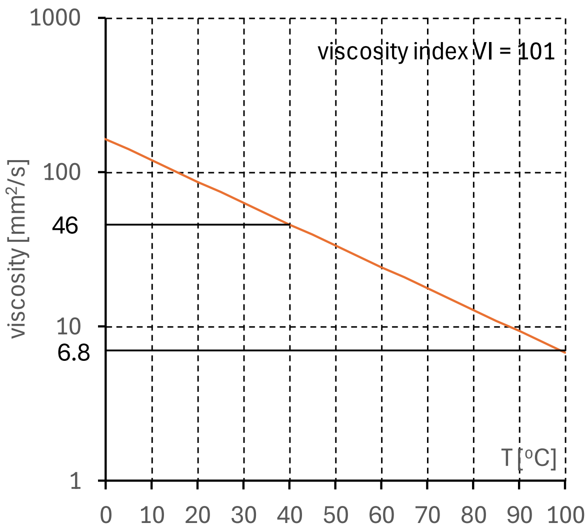


Figure 3. v-t diagram for oil L-HL46.

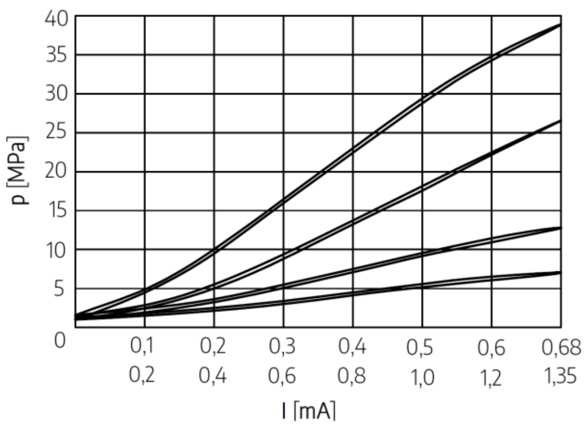


Figure 4. Characteristics of the proportional valve WZPSE6 (Ponar Wadowice).

For a given oil temperature, a series of measurements was taken – one measurement series for one motor speed, ranging from 0 to 1500 rpm, increased by 150 rpm. The rotational speed of the pump shaft was controlled by a voltage signal in the range of 0–10 V, proportional to the desired speed. This signal, generated by the MCD, served as the input command for the frequency converter. During each measurement series, the setting of a proportional valve was changed, which was controlled using a voltage signal in the range of 0 – 10 V in 1 V steps at 5-second intervals. To protect the system with which the drive unit cooperates, the pressure valve is set to an opening pressure of 14 MPa. The pressure in a line, in addition to temperature (viscosity) and flow rate, also depends on the current (0-0.68 A), proportional to the voltage control signal. An example performance curve of the valve used is shown in Figure 4. Therefore, the system pressure could have been slightly above 16 MPa, but the pressure valve was fully open, so the flow rate was unreliable. Therefore, 14 MPa was assumed as the pump's maximum operating pressure.

2.3. The principle of operation of the LabVIEW program

The program controlling the stand was developed using LabVIEW software. Figure 5 shows a view of the “Block Diagram” window for controlling the proportional valve and motor speed and reading the data from sensors. Pressure, flow rate and temperature measurements were continuously taken with a sampling rate of 100 measurements per 1 second.

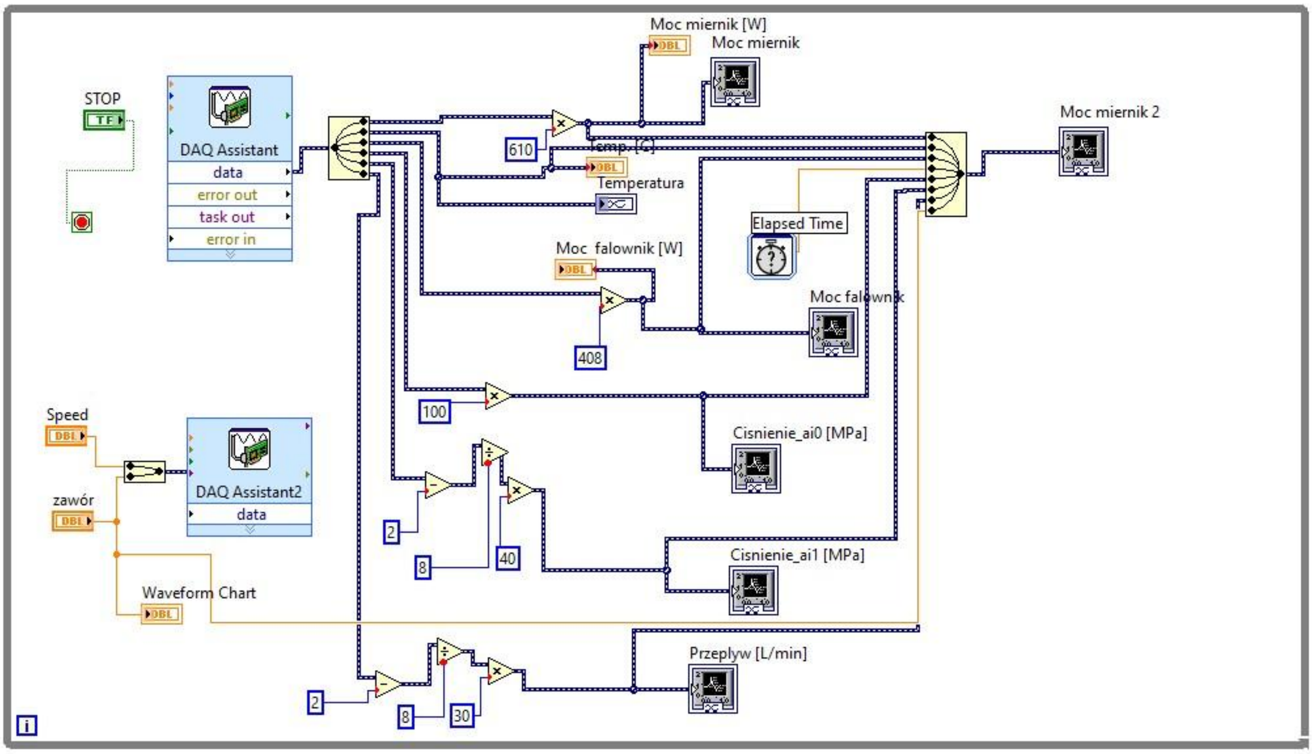


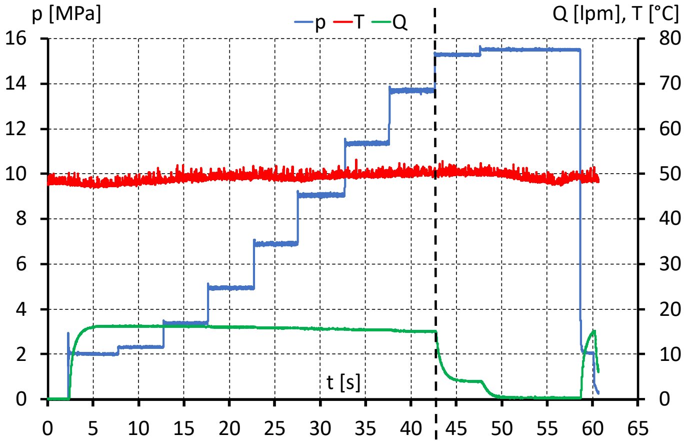
Figure 5. Control and measuring program in LabVIEW.

The obtained data was collected in the form of .csv files, containing readings from sensors and control signals. An example of the graph of pressure waveforms over time is presented in Figure 5a. The dashed line indicates the maximum pressure considered during the volumetric efficiency tests of the tested pump. After processing, the averages of measured values for every pressure level are calculated and are the basis for flow characteristics preparation (Figure 5b) and further calculations.

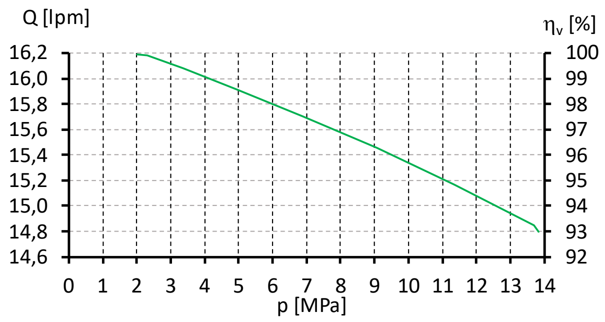
The theoretical flow rate values were determined for each set motor speed using formula (1), where: Q_p [m^3/s] and Q_{pt} [m^3/s] are respectively a total flow rate of the pump (measured) and the theoretical flow rate of the pump (calculated according to equation 1), q_p [m^3/rad] is the displacement (data from the catalogue), ω [rad/s] is an angular velocity of the pump drive shaft (measured). Based on the measurements of the hydraulic pump, the volumetric efficiency of the pump η_v can be determined by equation (2):

$$Q_p = q_p \cdot \omega \cdot \eta_{vp} = Q_{pt} \cdot \eta_{vp} \quad (1)$$

$$\eta_v = \frac{Q_p}{Q_{pt}} = \frac{Q_p}{q_p \cdot \omega} \tag{2}$$



(a)



(b)

Figure 6. Example graph of pressure-time dependence after signal filtration and the flow characteristic of the pump.

2.4. Processing of measurement data

The acquired *.csv* files containing the measurement data were processed using the Gnuplot software. The initial stage of data processing involved the removal of noise originating from the dynamic operation of the proportional valve. Noise reduction was performed by identifying and eliminating points that significantly deviated from the main cluster of measurements, resulting in a set of closely grouped data points. As a consequence of this procedure, each combination of pressure, flow rate, and temperature was represented by several dozen measurement points exhibiting only minor deviations. During the experiments, the temperature increments of the hydraulic oil were not constant and typically varied by approximately 2 °C.

Further processing of the data was carried out using the *dgrid3d* function in Gnuplot. The *dgrid3d* function enables the transformation of irregularly spaced data into a regular grid. A key parameter in this function is norm, which determines the weighting scheme: each measurement point is weighted inversely to its distance from the grid node raised to the power defined by norm. In practice, this acts as a low-pass filter that converts scattered data into a structured grid. Flow values were calculated as weighted averages of the surrounding measurement points. Figure 6 presents the measurement data after noise reduction. The removal of noise was carried out using the procedure described in [10]. This dataset was subsequently processed using the *dgrid3d* function to obtain a regular grid suitable for surface generation. The resulting grid enabled the construction of a three-dimensional surface representing the pump's operating characteristics. The final stage of data processing involved generating the surface between the grid points.

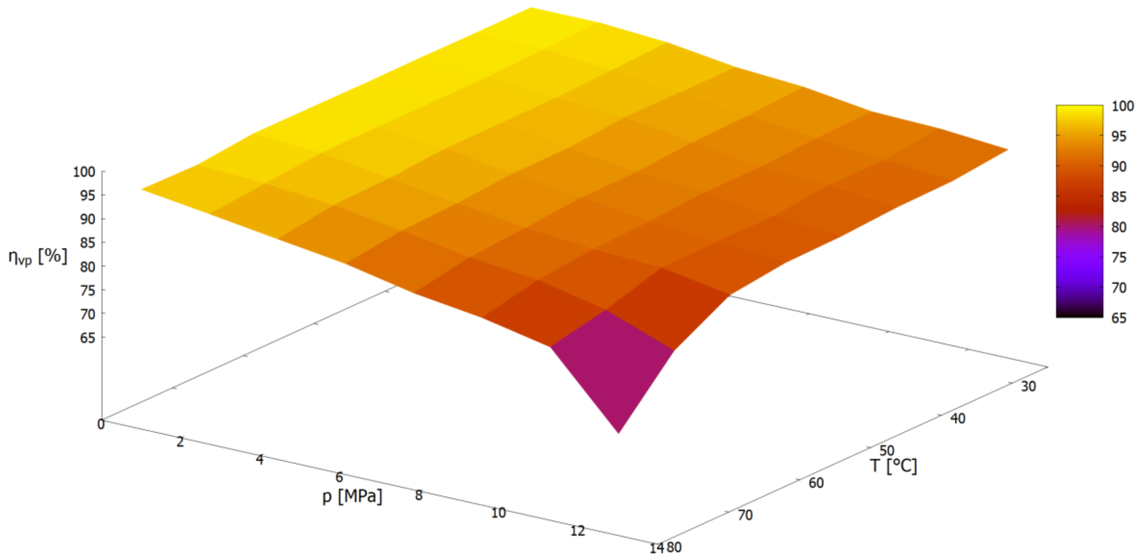


Figure 7. Sample map of measurement points from the Gnuplot software.

From the graph Figure 7, it can be seen that as the pressure increases, the volumetric efficiency begins to decrease, and the same happens when the oil temperature is increased. The worst efficiency of the pump is achieved for the highest values of pressure and oil temperature. The best efficiency, about 98% pump, is achieved at the lowest pressure and the lowest oil temperature. It is worth noting that even for high oil temperatures at low system pressure, the efficiency is about 95%. However, as the pressure increases, the efficiency decreases faster than when the oil temperature is lower.

3. Results

Based on the methodology described in the preceding sections, a comprehensive series of measurements was conducted for 10 distinct rotational speeds of the hydraulic pump shaft. The present paper reports the complete set of experimental results to highlight the most significant trends and conclusions. For improved clarity in interpreting variations within the hydraulic pump efficiency map, the results are additionally presented in a two-dimensional format. The graphs shown in Figure 7 employ the following notation: volumetric efficiency ηv [%], hydraulic oil temperature T [°C], and pressure p [MPa]. The generated maps make it possible to predict the pump's behavior at a given rotational speed, system pressure, and oil temperature. At low speeds (Figure 7a, b, c), the decrease in volumetric efficiency with rising oil temperature is significantly more pronounced than at higher motor speeds. Increasing the rotational speed also raises the minimum efficiency values. At 150 rpm, the lowest efficiency is approximately 20%, whereas at 300 rpm it increases to about 40%. This trend stabilizes at 900 rpm (Figure 7f), where the minimum efficiency reaches approximately 75%, a value that remains similar for higher speeds.

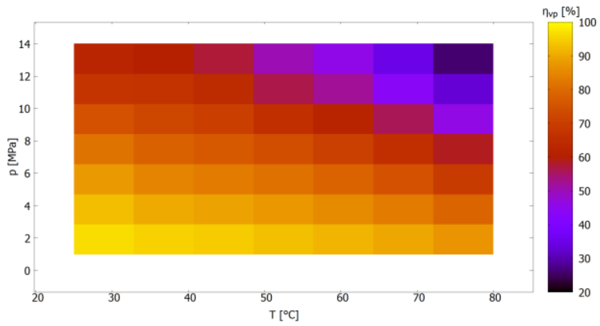
A distinct decline in efficiency becomes evident at a speed of 450 rpm and lower (Figure 7c), while the poorest performance is observed at the lowest tested speed of 150 rpm (Figure 7a). Thus, the rotational speed of n = 450 rpm may be considered the threshold (minimum operating speed for the tested pump) at which a clear drop in efficiency occurs. The results indicate that the pump achieves its highest volumetric efficiencies at an oil temperature of approximately 25 °C and under low system pressures. At higher speeds, the pump maintains high volumetric efficiency even as system pressure and oil temperature increase, whereas at low speeds the efficiency decreases rapidly and sharply under the same conditions.

The volumetric efficiency maps presented in Figure 7 exhibit similar characteristics; therefore, a comparative table was prepared to summarize the maximum and minimum efficiency values at a pressure of approximately 14 MPa. This pressure level was selected because it is commonly used in hydraulic actuators. In addition, the maximum pressure values achieved at each rotational speed are included. These results are compiled in Table 3 and illustrated in Figure 8.

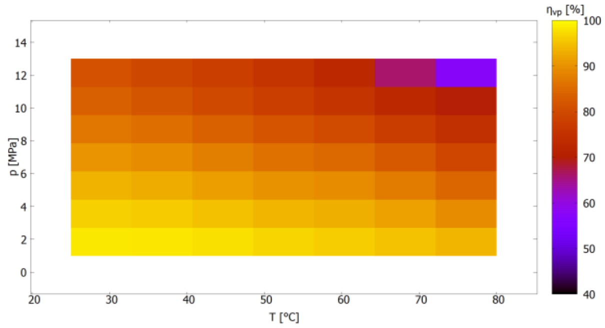
Table 3. Minimum and maximum volumetric efficiency values for each of the tested speeds at maximum pressure in the pump discharge line.

Speed [rpm]	**Max. p [MPa]**	**Max. η_{vp} (Temp.)**	**Min. η_{vp} (Temp.)**
150	14	67% (25°C)	-
300	13.95	83% (25°C)	41% (80°C)
450	14	87% (25°C)	58% (80°C)
600	13.99	91% (25°C)	69% (80°C)
750	13.99	92% (25°C)	70% (80°C)
900	13.99	93% (25°C)	76% (80°C)
1050	13.99	94% (25°C)	76% (80°C)
1200	14	92% (25°C)	85% (80°C)
1350	14	90% (25°C)	77% (80°C)
1500	13.99	88% (25°C)	76% (80°C)

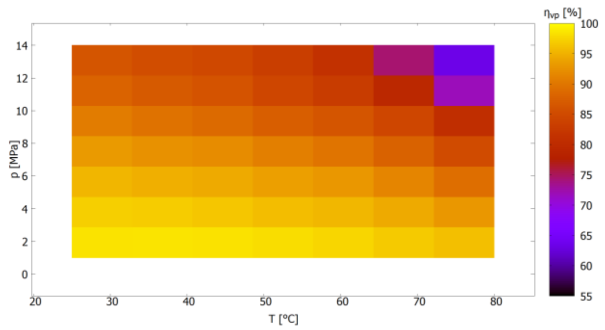
The obtained data make it possible to determine the efficiency range as a function of temperature for variable pump speeds under constant load, which is essential for both the design and operation of hydraulic systems equipped with variable-speed pumps. The manufacturer does not specify the minimum operating speed of this piston pump; however, as illustrated in Figure 7, it can be inferred that the pump should operate at a rotational speed of no less than 600 rpm. It is noteworthy that at low oil temperatures, the pump maintains high efficiency even below the recommended speed, reaching approximately 87%. However, the efficiency decreases markedly as the temperature increases. An important observation is that rising temperature reduces oil viscosity, which in turn increases internal leakage within the pump, ultimately preventing the system from achieving higher pressure levels.



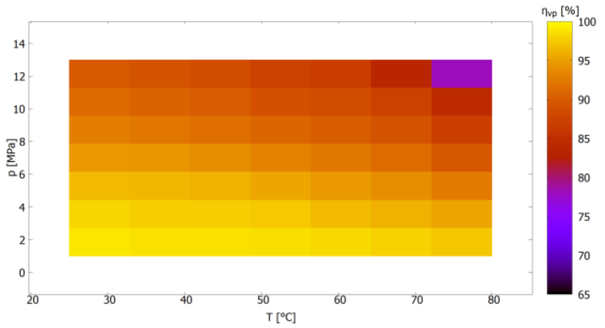
(a) n = 150 rpm



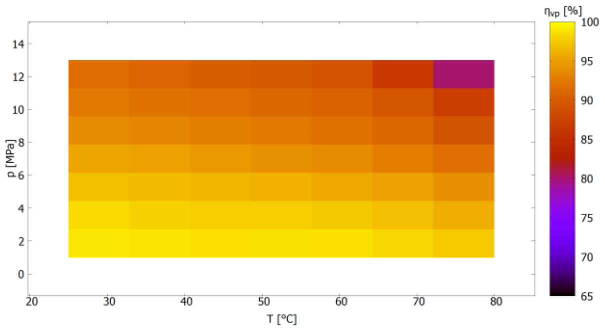
(b) n = 300 rpm



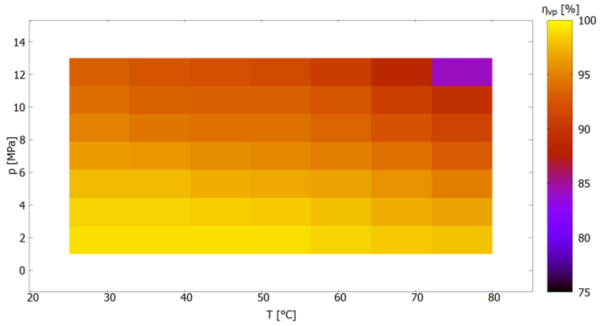
(c) n = 450 rpm



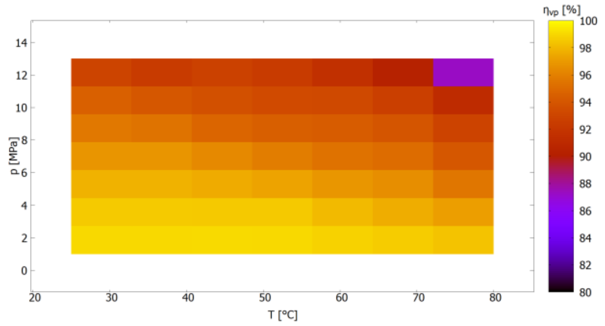
(d) n = 600 rpm



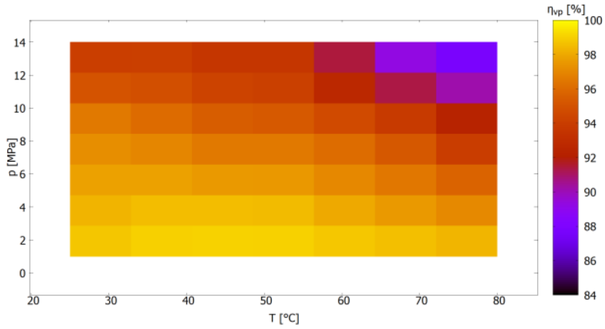
(e) n = 750 rpm



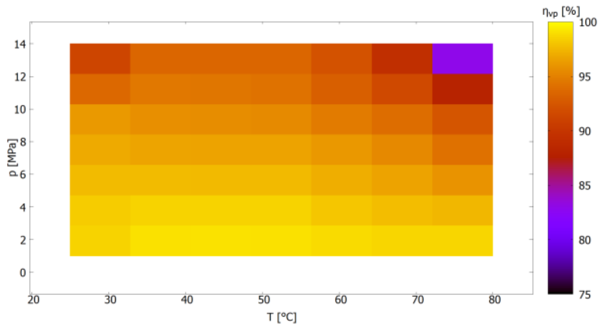
(f) n = 900 rpm



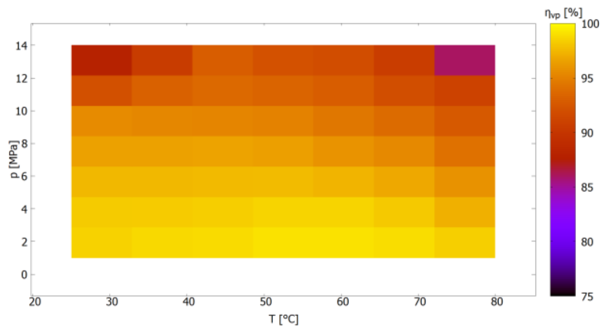
(g) n = 1050 rpm



(h) n = 1200 rpm



(i) n = 1350 rpm



(j) n = 1500 rpm

Figure 8. Volumetric efficiency maps.

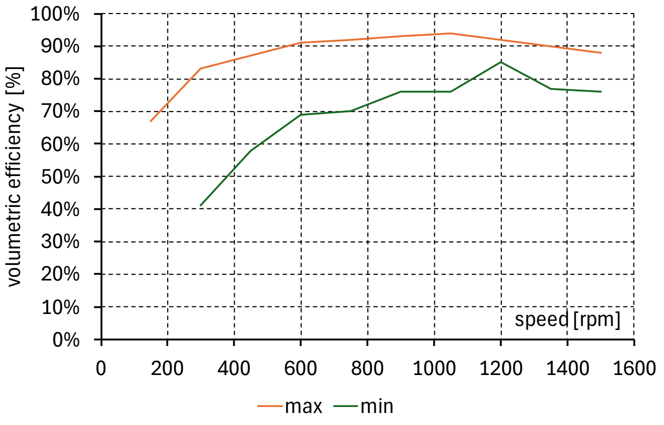


Figure 9. Volumetric efficiency range for 14 MPa operating pressure.

4. Conclusion

This study presents a comprehensive experimental investigation of the volumetric efficiency of a piston pump operating under varying thermal, pressure, and rotational speed conditions. The research addresses a notable gap in existing literature, where the combined influence of these three parameters has not been sufficiently examined. Measurements were conducted across 10 distinct pump speeds using a modernized electro-hydraulic test stand equipped with an extended control and data-acquisition system, including temperature monitoring capabilities. The recorded data were processed using advanced filtering and interpolation techniques, enabling the construction of detailed efficiency maps that illustrate the relationships among temperature, pressure, and volumetric efficiency.

The results demonstrate that pump performance is highly sensitive to the temperature of the working fluid, particularly at low rotational speeds. At elevated temperatures, reduced oil viscosity leads to increased internal leakage, causing significant efficiency losses and limiting the achievable system pressure. Conversely, at higher rotational speeds, the pump maintains substantially higher volumetric efficiency even under increased thermal and pressure loads. The analysis indicates that the most favorable operating conditions occur at oil temperatures around 25 °C and low system pressures. A clear threshold speed of approximately 450–500 rpm was identified, below which efficiency declines rapidly. The conducted tests clearly demonstrate the necessity of accounting for the temperature of the working fluid in hydraulic systems. To maintain the highest possible process efficiency, appropriate measures should be taken to cool the hydraulic oil and thereby prevent flow losses. This can be achieved, for example, through the use of hydraulic oil coolers in combination with flow regulation based on pump speed control.

Furthermore, the development of pump efficiency maps significantly supports both the design of hydraulic systems and the operational planning of piston pumps used in conventional drive systems as well as in variable-speed configurations. These maps make it possible to define the operating boundaries of the investigated pumps, contributing to improved performance, durability, and overall system efficiency.

Although the presented studies provide a comprehensive experimental characterisation of the temperature-dependent volumetric efficiency of a fixed displacement piston pump and demonstrate similarity to tests conducted for constant displacement gear pumps described in [15], further research would be useful to assess the generalizability of the observed trends. This is because gear pumps, vane pumps, and alternative axial piston designs have different leakage paths, compression dynamics, and lubrication mechanisms, which may exhibit different sensitivity to temperature-induced changes in viscosity, bulk modulus, and internal clearances.

Expanded research would support the development of more reliable control and diagnostic strategies for hydraulic systems operating under variable temperature conditions.

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