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Investigation of the influence of hydraulic oil temperature on the variable-speed pump performance

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Highlights

- Temperature-dependent pump capacity is shown for a wide range of pressures and speeds.
- Testing and controlling the temperature of the working medium ensures a stable process.
- Too high hydraulic oil temperature negatively affects the hydraulic pump performance.
- The dependence of the flow rate on speed and temperature enables diagnose the pump.

Abstract

This paper describes investigation on the influence of hydraulic oil temperature on the performance of a hydraulic pump. The aim of the research is to determine changes in volumetric efficiency of the pump in the form of maps of operation at different temperatures of the hydraulic oil, in conditions of variable speed and pressure. The described tests were carried out on an experimental stand with a hydraulic fixed-displacement gear pump controlled by a servo motor. Based on the signals from the sensors processed with the LabVIEW program, maps of the hydraulic pump operation were drown in a wide range of speeds and temperatures. The paper presents the results of the research and based on this the conclusions regarding the main aim of the research and others that were observed during the measurements were presented. The most important conclusion from the study shows that the temperature-dependent characteristics provide users with a significant amount of information such as operating conditions that will ensure a high level of efficiency.

Keywords

hydraulic pump, volumetric efficiency, temperature-dependent characteristics, variable speed drive, hydraulic oil.

1. Introduction

Nowadays, industrial machines are more and more advanced. They use various electronic, pneumatic or hydraulic systems. In processes where high power and accuracy are required, hydraulic systems are used. The most important part of such systems is the hydraulic pump, which ensures the proper flow of the working medium. Tsankov et al. [16] paid attention to gear pumps manufacturability – such as ease of manufacture, a wide range of design, hydraulic parameters and relatively low cost. Due to their popularity, gear pumps are used in various industries, such as metal forming, transport machines, positioning systems, lifting systems or presses. Hydraulic pumps and the drives used with them should be adapted to work in various conditions and different places. Regardless of them, the pump should always offer the greatest possible efficiency, because its parameters affect the performance of the entire machine. For this reason, systems equipped with a hydraulic gear pump are more and more often the subject of experimental tests and simulations. Unfortunately, manufacturers of hydraulic pumps provide only limited operating parameters or characteristics for selected rotational speeds of motors. Sometimes it even happens that the data from the directories differ by up to 25% from the reality [19]. This has a significant impact on the real behaviour of the machine and may cause it to malfunction. Proper knowledge of the correct operating parameters of the pump can bring measurable benefits in the form of the possibility of its diagnosis and the expected wear time. This is especially important when estimating the durability of aviation hydraulic drives, where any failure can cause a catastrophe [17]. Another important example of proper diagnostics of hydraulic systems are machines with related redundancy with ensuring the safety of a continuous flow of materials, in which the delivery of materials is carried out continuously (24 hours a day). It is necessary to ensure the collection and transport of the material at a strictly defined time and in the required quantity. It is a system in which the presence of a failure poses a threat to human life and environmental degradation [6].

Numerical calculations can be used to predict the behaviour of hydraulic systems. Unfortunately, they are burdened with errors resulting from simplifications and assumptions, which is why experimental research, and its proper interpretation are so important [14]. In order

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to increase the effectiveness of the methods of predicting the life and wear of hydraulic drives to be more effective, several parameters of their operation should be taken into account. Apart from variable load conditions or different speeds of the motors driving the pumps, it is worth considering the influence of the operating oil temperature. In all hydraulic systems, oil heats up in the same way – by friction. In classic hydraulic systems, the flow is often controlled using throttling, which also significantly affects the temperature of hydraulic oil. In closed-circuit hydraulic systems, small tanks are installed to leakage compensation, which results in a smaller amount of liquid in the system and faster heating of it. In open-circuit systems, larger tanks are used to reduce oil heating. Despite this, long-term operation of the hydraulic system consequently causes the oil to heat up as a result of friction, and the only way to maintain a constant temperature is to use a cooler. Besides, the temperature of the oil can be influenced by the outside temperature. Machines using hydraulic systems are found in non-air-conditioned warehouses, workshops or technological halls. There are also mobile systems used in construction machinery or the mining industry, where temperatures can be high. As temperature increases, oil viscosity decreases, and the properties change at the same time. It is important to know these changes because the task of the working medium is not only to transfer energy, but also to lubricate or even cool the system moving elements through heat dissipation [9]. It is very well visible in the study of the influence of temperature on the force that can be transmitted by hydraulic shock absorbers. Increasing the speed reduces the available force and the range of motion of the absorber, which results in less energy dissipation [4]. The change in the viscosity of the liquid affects the values of the transmitted torques, pressure drops, flow rate losses, and thus power [5]. For this reason, the technical specification of a given product should be carefully read when the hydraulic system is designed. It seems like a truism, but gear pump manufacturers typically show characteristics only for one (less often several) selected operating temperatures without displaying the entire range, so it is advantageous to know the map of the hydraulic pump operation under specific conditions for a given application. Rydberg [9] and Tkáč [12] described the research on hydraulic oils and they were found, that the type and manner of using the working medium used has a significant impact on the performance of the hydraulic pump.

Many of the research conducted do not take into account the change in temperature of the working fluid. Some papers contain tests of systems only for specific temperatures of the working medium with a difference up to a dozen or so Celsius degrees. Tsankov et al. [16] presented the characteristics of the pump for several selected temperatures of the oil with one operational speed of the pump. Voicu et al. [18] performed tests on the characteristics assuming a constant temperature of the working medium but did not present them at other temperatures. The efficiency research of the fixed-displacement gear pump operating in bidirectional mode in closed circuit controlled by a servomotor, are presented in [19, 20] however without temperature level changes. The use of this drive allows to absorb flow drops caused by e.g. leaks. This phenomenon is also subject to many studies, even in the case of hydraulic systems in which water is the working medium [1]. Stawiński et al. [10] presented the system which compensate the leakages of the pump basing on experimental determined flow characteristics of the pump for different operational speeds (hence different oil flows from the pump). Tests were conducted without research of different temperatures influences. Similar studies were carried out by Pascal et al. [7], where the influence of the temperature of the working medium was not investigated either. There are also papers presenting simulations of such phenomena with appropriate mathematical descriptions. Szwemin et al. [11] presented an example of an oil flow simulation in a gear pump, which was compared with the results of the experiment at a constant temperature of hydraulic oil. The authors concluded that the analysing the flow inside the pump is a difficult process based only on experiment. Another examples are the pumps efficiency tests for different output flows generated by variable pump displacement [8] operating in closed circuit and change of the gear pump speed [15]. The pump characteristics under different environmental conditions were investigated. The results of their tests show research at constant temperatures of the working medium. In turn, the studies shown by Ketelsen et al. in [2] and Zecchi et al. in [21], by simulation and experimentation, the influence of the temperature of the working medium on the pressure and flow values obtained was examined, but also for a few selected temperature values.

All the papers confirms that tests of hydraulic pumps in a wide range of parameters are necessary for the correct design of hydraulic systems with the highest efficiency and also shows a decrease of pump efficiency with increasing temperature of the working medium. In this paper the studies of influence of temperature, operating pressure and rotational pump speed on pump efficiency are presented. These are studies not available in nowadays literature. It must be underlined that tests were carried for the wide range of both pressure and speed and temperature. The paper also confirms that the studies of gear pump efficiency considering three above operation parameters are important for proper operation of hydraulic systems with variable speed pumps. The research carried out and the results discussed in this paper complement the lack of available research papers.

This paper is organized as follows. Chapter 2 contains detailed information on the test stand and the method of conducting the research. The method of processing measurement data and their conversion is also shown. Section 3 shows the experimental test results as the maps of the hydraulic pump operation, presenting the relationship between pressure, volumetric efficiency and temperature, measured in different pump speeds. The last Chapter 4 contains an analysis of the results as well as conclusions and observations from the conducted research.

2. Methodology

The measurements were carried out on a laboratory test stand, which is described in detail below. The technical specification of the subassemblies is given, and the measurement program is presented. The research methodology and the scope of the tested parameters are described, as well as the process of processing measurement data. The conversion of measurement data into volumetric efficiency was also mentioned in order to better present the research results.

2.1. Laboratory test stand

The electro-hydraulic laboratory test stand for the testing of pumps and valves is shown in Fig. 1. This stand was the subject of research in previous studies carried out by Kosucki et al. [3], where pressure valves were tested. The modernization of this stand, consisting in the expansion of the control and measurement program and the installation of the temperature sensor, allowed for further scientific research. The hydraulic scheme of the test stand is shown in Fig. 2.

The tested element is the PGP505 fixed-displacement gear pump (1) driven by the AC synchronous motor with the permanent magnet SEW-EURODRIVE CFM90S4 (2) fed by the frequency inverter SEW-Eurodrive Movidrive MDS60A0055 (3). The use of this type of drive makes it possible to test a hydraulic pump for a wide range of speeds. The rotational speed of the pump is measured by a resolver installed on the motor shaft. The frequency inverter is connected to the measurement and control device (MCD) via the appropriate outputs and inputs. The gear pump ports are connected to the system and the hydraulic oil reservoir by flexible hoses to isolate the vibrations. The rest of the system, connected with rigid steel pipes, is equipped with control and measuring components. These include the GFM-30 flow meter (4) and HBP P8AP pressure transducer (6). The Pt100 HTFB2 resistance temperature sensor with the TP9237 temperature transducer (7) was used to measure temperature of the hydraulic oil in the hydraulic tank, which was placed near suction line of the pump. The load adjuster in the system is the WZPSE6 proportional valve with the ZELPRO Controllable current amplifier type 20RE10E (5). In order to reach the set pressure, the DSL081 valve (10) must be

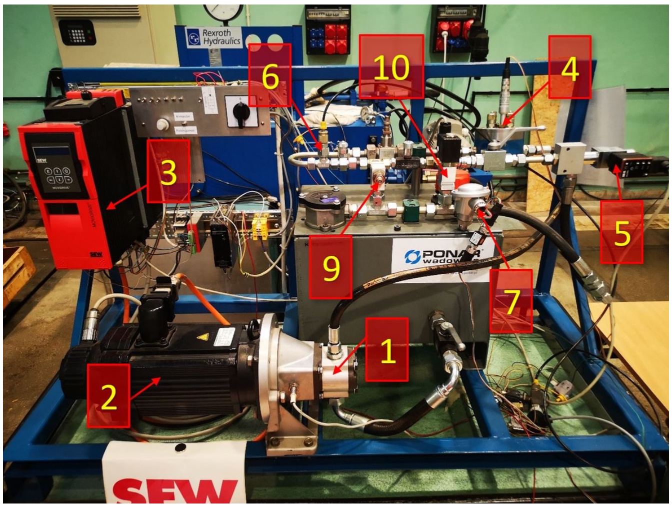


Fig. 1. Electro-hydraulic laboratory stand

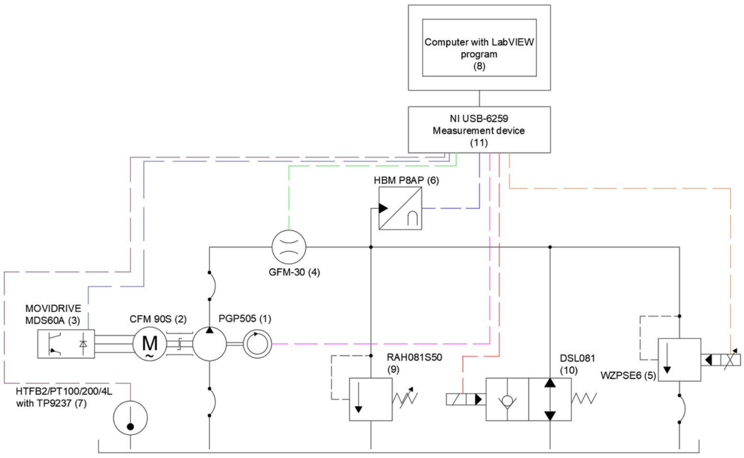


Fig. 2. Hydraulic scheme of the laboratory stand

switched. If the proportional valve is set to 100% close, the relief valve RAH081S50 (9) will open. The list of all components with their operating parameters is presented in Table 1.

Before starting the measurements, certain ranges of temperature, pressure, flow and rotational speed values were assumed to be ex-

Table 2. The maximum ranges of parameters that can be obtained on a laboratory stand

Ranges of laboratory stand parameters			
Temperature	Pressure	Speed	Flow
[°C]	[MPa]	[rpm]	[lpm]
23 - 90	0 - 21	0 - 3000	0 - 15

amined in order to obtain as much key information as possible. The values of the ranges of temperatures, pressures and flows presented in Table 2 result from the maximum and minimum values that were achieved during all measurement series.

2.2. The principle of operation of the LabVIEW program

In order to process the signals from the measuring sensors, it was necessary to properly configure the inputs and outputs in the measurement and control device NI 6259. LabVIEW software has many features that make this process much easier.

Fig. 3 shows the 'Diagram block' of the measurement program developed in LabView software allowing control of the valve operation and motor speed and measurement of important values. The program was built to enable the generation and setting of the assumed signal controlling the engine speed in the range of 0-3000 rpm and the assumed pressure control signal in the range of 0-21 MPa. The program also included blocks responsible for measuring signals from transducers, respectively pressure, flow rate, engine speed and temperature of the working liquid. All measured and control signals were, after appropriate conversion to their units, displayed on charts and simultaneously saved in a csv file.

2.3. Measurement method

In accordance with the assumed goal of determining pump operation maps, it was necessary to plan an appropriate measurement process so that it would not take much time and be accurate. Due to rapid heating of the hydraulic oil and the lack of a cooler in the hydraulic system, the series of measurements were carried out at greater intervals, maintaining the same environmental conditions. Each of the measurement series started with low hydraulic oil temperatures – a temperature about 23 degrees Celsius.

The load in the system was generated using the WZPSE6 proportional valve operating during the DSL081 valve was actuated. The amplifier controlling the WZPSE6 valve was controlled by a voltage in the range of 0-10 V, which came from the measurement and control card. In order to determine the appropriate characteristic, the valve control voltage had to be gradually increased. A range of 0-9 V in 1 V steps was assumed. In practice, this made it possible to reach the pressure of up to 18 MPa.

The pump rotational speed was set by voltage signal in the range of 0-10 V, proportional to assumed speed. This signal from the MCD was the input function to the servo drive. The pump rotational speed range recommended by the manufacturer (above 500 rpm) was tested. In order to investigate the influence of oil temperature on the leakage occurring in the hydraulic pump, measurements were also made for lower speeds, from 100 rpm to 500 rpm. The speed range

Table 1. Parameters of system components

No.	Component	Parameters
1	Pump PGP505 A0050CQ2D2NE3EB1	5 cm^3/rev, 500 - 4000 rpm
2	Motor CFM90S/BR/TF/RH1M/SB50	400 V AC, max. 3000 rpm
3	Frequency inverter MOVIDRIVE MDS60A0055-5A3-4-00	5,5 kW
4	Flow meter GFM-30 3143-03-35.00	0,2 – 30 lpm, accuracy ±0,5%
5	Proportional valve WZPSE6 with ZELPRO-20RE10E	60 lpm, max. 21 MPa
6	Pressure transducer HBM P8AP	max. 50 MPa, accuracy ±0,3%
7	Temperature sensor PT100 TiTEC HTFB2/PT100/200/4L with transducer Ifm electronic TP9237	−50 - 400°C, class A
8	Computer with LabVIEW software	Lenovo Ideapad Y530 with NI LabVIEW 2015 SP1
9	Relief valve RAH081S50	max. 35,5 MPa, max. 75,8 lpm
10	Solenoid valve DSL081	max. 25 MPa
11	NI USB-6259 DAQ Device	16-bit, max. 1.25 MS/s

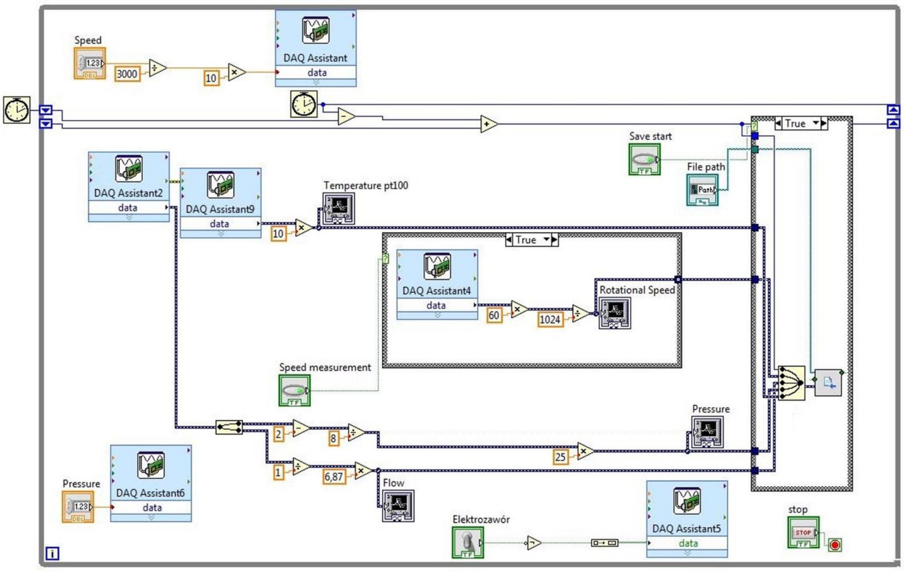


Fig. 3. 'Diagram block' – measurement program

between 1000 rpm and 3000 rpm was performed with a step of 200 rpm, while below 1000 rpm, the tests were carried out with a step of 100 rpm. The measurement was also carried out at a speed of 1500 rpm due to the fact that it is one of the most frequently used rotational speeds in hydraulic pumps.

Measurement of flow, pressure and temperature was continuous with the sampling frequency dependent on the frequency of the MCD. The values of these parameters were saved in appropriate files and then processed. All series of measurements, for each tested hydraulic pump speed, were carried out until the maximum oil temperature resulting from the system load was reached. The maximum achieved temperature was over 90 degrees Celsius.

2.4. Hydraulic pump volumetric efficiency

Based on the measurements of the hydraulic pump, the volumetric efficiency of the pump can be determined by the following equation (1), where Q – output flow rate [m^3/s], V_G – geometrical volume of hydraulic pump [m^3], and ω – angular speed of hydraulic pump [rad/s] [11, 13]:

$$\eta_v = \frac{Q}{V_G \cdot \omega} \cdot 100\,[\%] \tag{1}$$

2.5. Processing of measurement data

The received .csv files containing the measurement data were processed in the Gnuplot software. The processing of the measurement data began with the removal of noise from the signal generated by the movement of the proportional valve. Noise removal was carried out by detecting points significantly deviating from most of the measurement points, thus obtaining a number of measurement points very close to each other. The measurements carried out with the method described above meant that for one value of pressure, flow and temperature, there were several dozen measuring points with small deviations.

In order to further process the measurement data, a function of the Gnuplot program called dgrid3d was used. During the measurements, the steps between the given values of the oil temperature was not constant and amounted to approximately 2-3 degrees Celsius. Function dgrid3d enables non-grid to grid data mapping. The most important of the parameters is the norm parameter that controls the weight ratio – each measurement point is weighted inversely by its distance from the grid point raised to the norm power. This function is a simple low pass filter that converts scattered data to a grid data set. The flow values were computed as weighted averages of the scattered measurement points. The 'norm' parameter was selected on the basis of all measuring points after the noise removal process. In the case of low speeds of the hydraulic pump, these points were more widely scattered in space at some points of the measurement in relation to the neighbour-

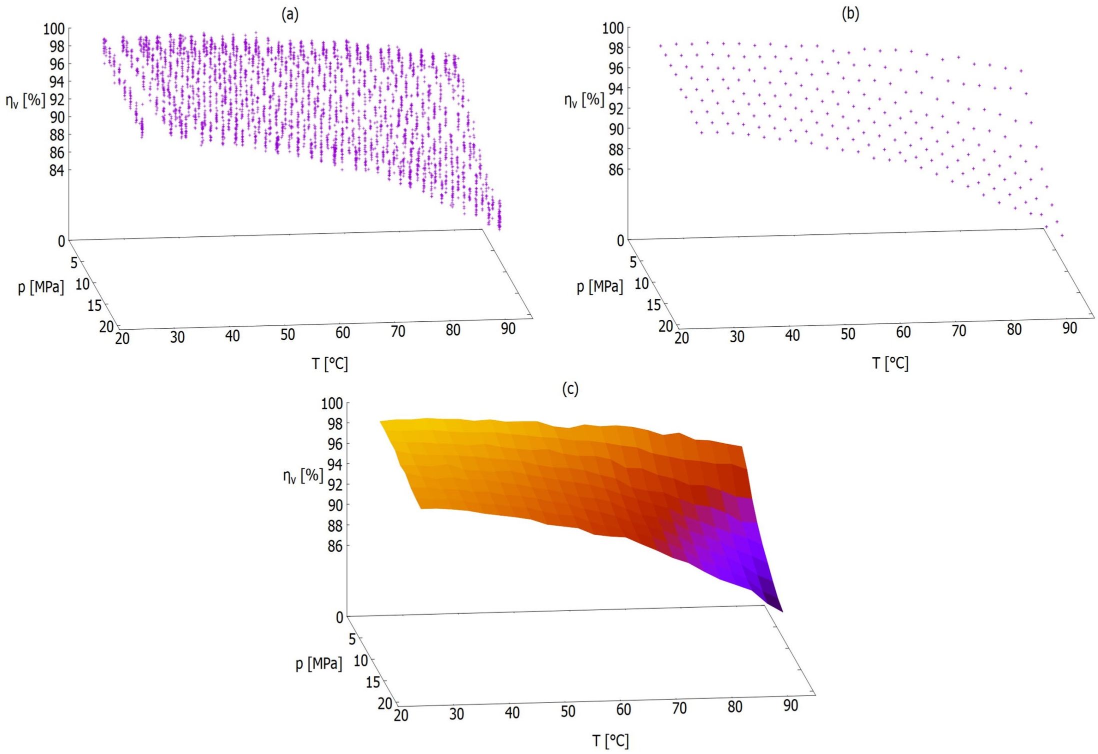


Fig. 4. Sample map of measurement points from the Gnuplot software: (a) after noise reduction, (b) after dgrid3d function, (c) after data processing

ing points, which meant flow fluctuations during the measurement and was the main criterion for selecting the 'norm' parameter. These fluctuations were not observed at high speeds. The larger the value of 'norm', the less effect of more distant data points. Accordingly, for low speeds (below 600 rpm), a large value of the parameter 'norm' was assumed to be 5, except for the speed of 200 rpm, where the parameter was set to 8. For a speed of 600 rpm and above, the 'norm' parameter was 3. Using low values for the parameter smoothed the volumetric efficiency map, therefore at low speeds a higher value was used to show flow fluctuations.

Fig. 4a shows the measurement data after the noise has been removed. Then this data should be processed using the dgrid3d function to get the grid data set. The set of data prepared in this way made it possible to create a surface presenting a map of the pump's operation. The last stage of data processing is to create a surface between the set of points shown in Fig. 4b. The result of the described activities is the map of volumetric efficiency shown in Fig. 4c.

3. Results

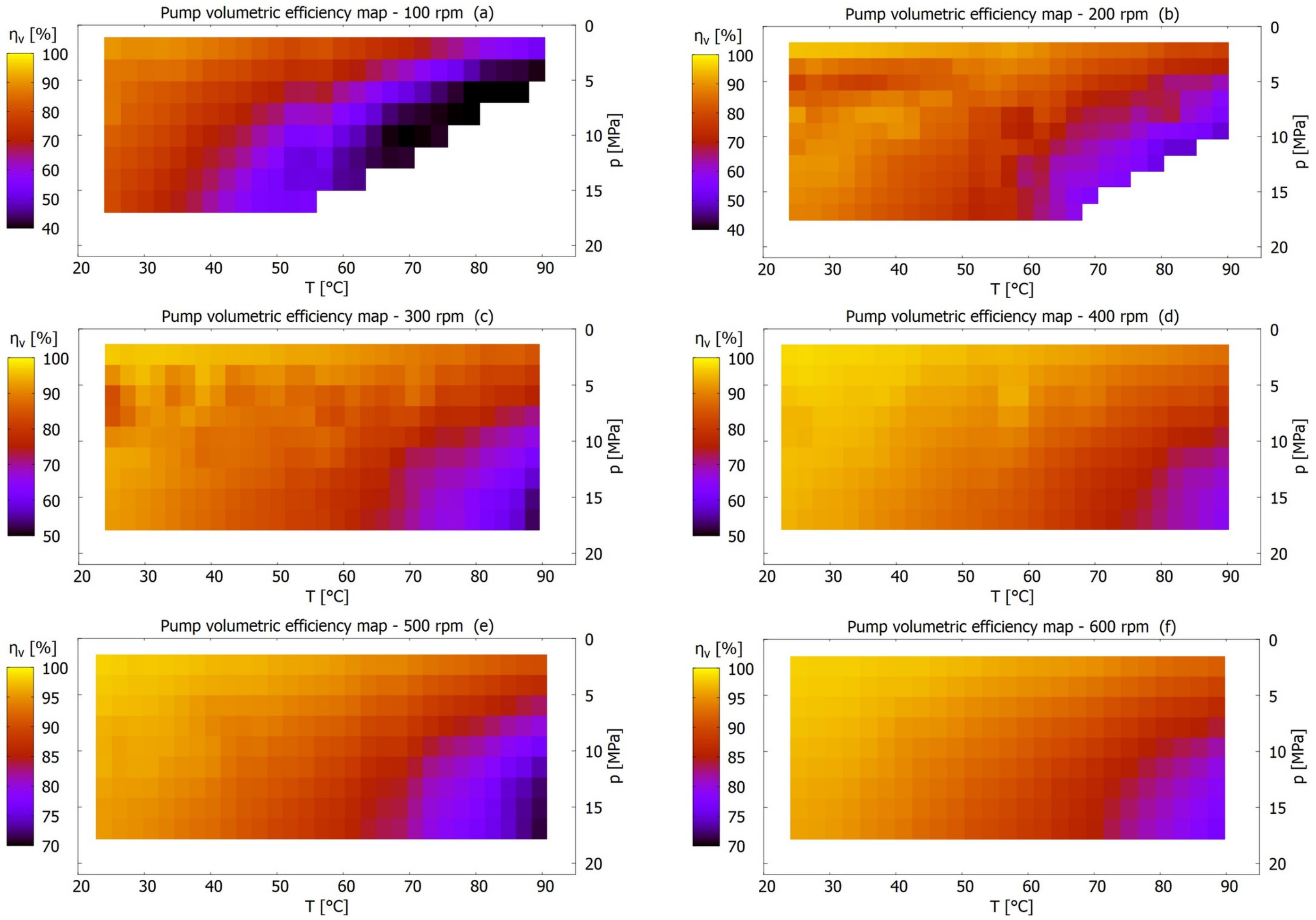
Based on the previously described methods, a series of measurements were made for 21 different rotational speeds of the hydraulic pump. This paper presents all results of the experiment to show the most important differences and conclusions. To make it easier to see changes in the hydraulic pump efficiency map they are shown in 2D view. The following symbols have been used in the graphs presented in Fig. 5: volumetric efficiency η_v [%], hydraulic oil temperature T [°C] and pressure p [MPa].

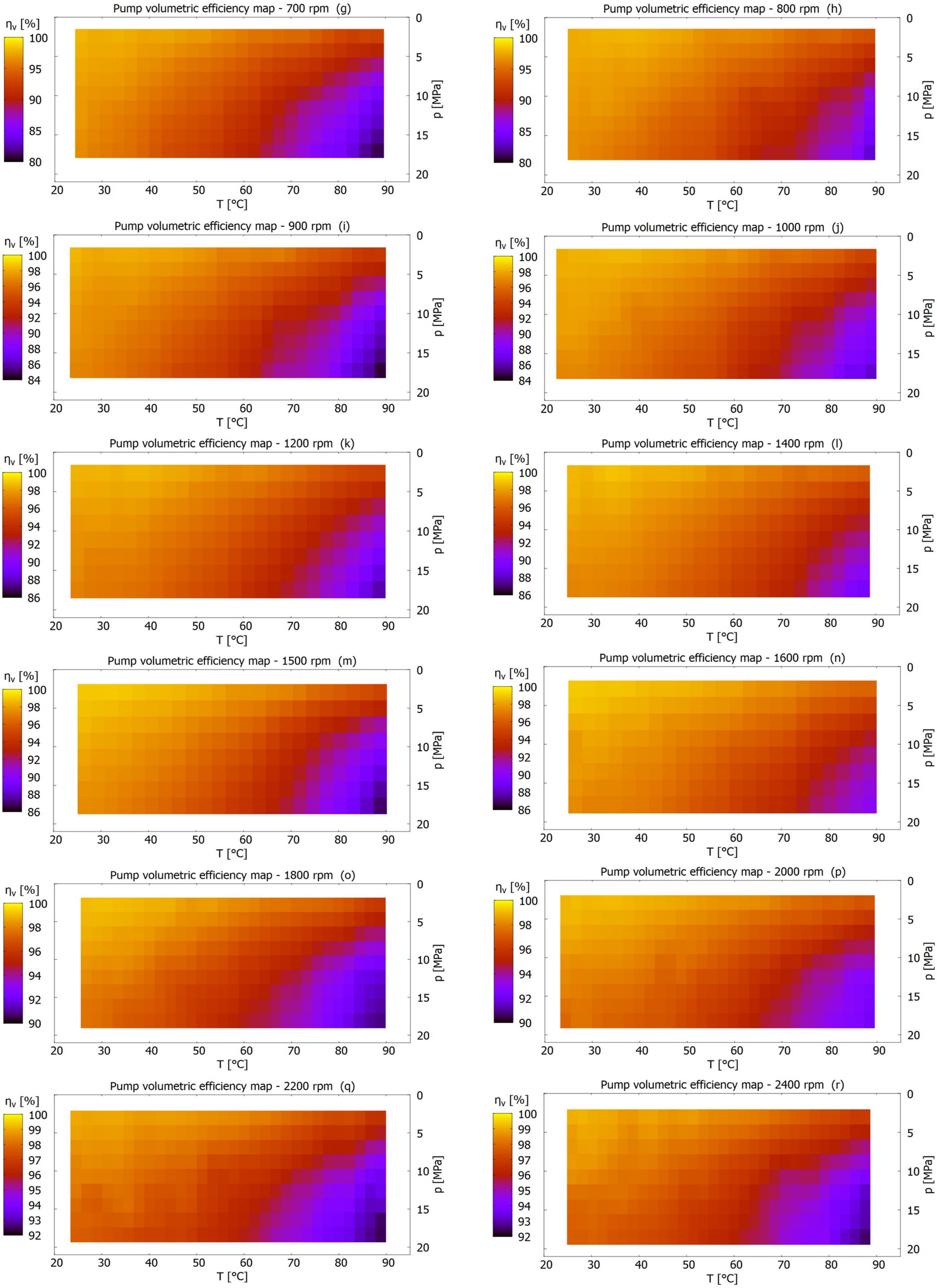
The maps of volumetric efficiency presented in Fig. 5 are similar, therefore a table was created showing the maximum and minimum values of volumetric efficiency for a pressure of about 17 MPa. This pressure was chosen as the pressure most commonly used in hydraulic actuators. Additionally, the maximum pressure values obtained for each speed are presented. The results are shown in Table 3 below and also in Fig. 6. The obtained data allow to determine the range of efficiency depending on temperature for variable speeds at constant pump load, what is important both for designing and operation of hydraulic systems with variable speed pumps. In Fig. 6, the minimum speed recommended by the pump manufacturer is indicated by the dashed line. It is worth noting that at low temperatures the pump works with high efficiency, even below this speed (about 89%). However, performance drops significantly as the temperature rises. An important aspect is also the fact that as the temperature rises and the viscosity of the oil decreases, the leakage at the pump increases, which makes it impossible to obtain higher pressures.

Additionally, one extended series of measurements was made for the speed of 1500 rpm. In this case, it started from a lower pressure by opening the DSL081 valve and ended by completely closing the working medium circuit – in effect, the flow was through the RAH081S50 relief valve. The results of these measurements are presented in the form of line graphs for various temperatures, every 5 degrees Celsius in Fig. 7. These curves give very clear guidelines for users of the pumps with the most frequently used speed. The efficiency in this case is still high (over 85%) despite the significant increase in oil temperature. Such tests should be performed by the pump manufacturers and provided with catalogues. From these maps it is possible to read with what efficiency the pump will work at a given oil temperature, and thus with what speed the hydraulic actuator will work. This makes it easier to automate the work cycle and predict machine working times.

4. Discussion and conclusions

The measurement results shown in Fig. 5. contain a lot of important information useful for the user of the hydraulic fixed-displacement pump. Thanks to them, it is possible to predict the behaviour of the




Pump volumetric efficiency map - 700 rpm (g)
Pump volumetric efficiency map - 800 rpm (h)
Pump volumetric efficiency map - 900 rpm (i)
Pump volumetric efficiency map - 1000 rpm (j)
Pump volumetric efficiency map - 1200 rpm (k)
Pump volumetric efficiency map - 1400 rpm (l)
Pump volumetric efficiency map - 1500 rpm (m)
Pump volumetric efficiency map - 1600 rpm (n)
Pump volumetric efficiency map - 1800 rpm (o)
Pump volumetric efficiency map - 2000 rpm (p)
Pump volumetric efficiency map - 2200 rpm (q)
Pump volumetric efficiency map - 2400 rpm (r)
ηv [%]
T [°C]
p [MPa]

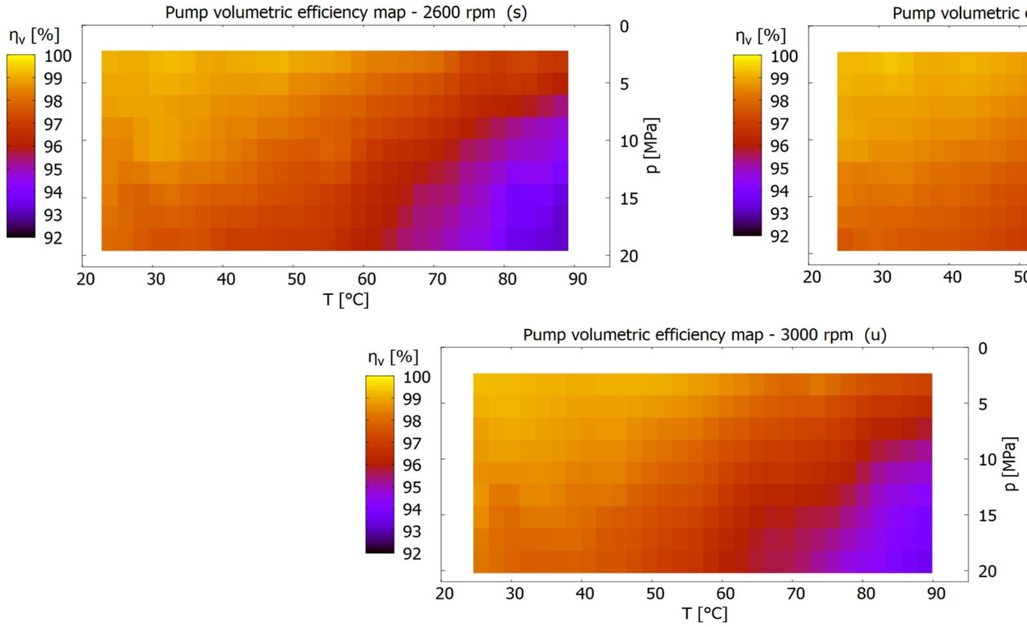


Fig. 5. Volumetric efficiency maps for different speeds

Table 3. Maximum and minimum volumetric efficiencies for various pump speeds at a pressure of 17 MPa

Speed [rpm]	Max. p [MPa]	Max. η_v (Temp.)	Min. η_v (Temp.)
100	16,85	83% (24°C)	55% (55°C)
200	16,90	89% (24°C)	51% (68°C)
300	17,01	92% (24°C)	50% (89°C)
400	17,03	95% (23°C)	63% (90°C)
500	17,08	95% (23°C)	68% (90°C)
600	17,26	96% (24°C)	75% (90°C)
700	17,35	97% (25°C)	78% (89°C)
800	17,46	97% (25°C)	80% (90°C)
900	17,56	97% (24°C)	82% (90°C)
1000	17,60	97% (23°C)	85% (90°C)
1200	17,75	97% (24°C)	87% (90°C)
1400	17,87	97% (24°C)	88% (89°C)
1500	17,94	98% (25°C)	86% (90°C)
1600	18,06	98% (25°C)	90% (90°C)
1800	18,18	98% (25°C)	91% (90°C)
2000	18,27	98% (23°C)	91% (90°C)
2200	18,43	98% (23°C)	92% (90°C)
2400	18,57	98% (25°C)	92% (89°C)
2600	18,71	98% (23°C)	93% (90°C)
2800	18,87	98% (25°C)	93% (90°C)
3000	19,26	98% (25°C)	93% (90°C)

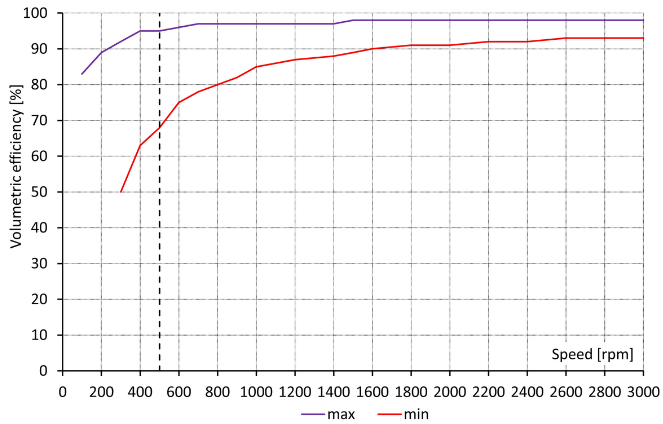


Fig. 6. Volumetric efficiency range for 17 MPa operating pressure

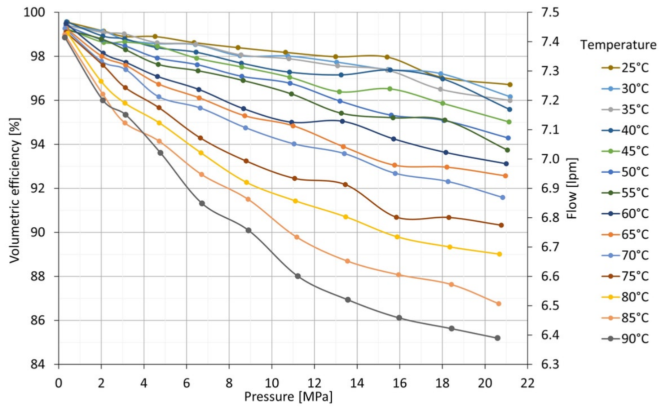


Fig. 7. Volumetric efficiency/flow vs pressure diagram for various temperatures with 1500 rpm

pump under various conditions of temperatures, pressures and flows. On their basis, it is possible to predict the behaviour of actuators and take it into account during their automation or control systems. The developed maps can also be used to diagnose pumps and systems.

When analysing the results, pay attention to the changing range of volumetric efficiency. In accordance with the methodology described in Section 2, first measurements were made for a speed lower than recommended by the manufacturer of the PGP505 hydraulic pump, the results of which are shown in Fig. 5a, b, c, d. For the first two maps of volumetric efficiency (Fig. 5a, b), it is worth paying attention to the lack of experimental results from the full, assumed measuring range. This means that due to increasing leaks in the hydraulic pump it was not possible to reach high pressure at high temperature of the hydraulic oil. As the speed increased, this phenomenon subsided. The volumetric efficiency value for these cases drops even to 40%. This means the obtained flow range is 0.15 to 0.45 lpm. A significant decrease in efficiency is noticeable even at the temperature of 40°C. During the measurement series, flow fluctuations at low pressure were also noticed. For speeds higher that 200 rpm, it was possible to test the entire assumed measuring range. It is worth noting that for the speed of 300 rpm (Fig. 5c) and 400 rpm (Fig. 5d), irregularities appeared even at lower temperatures of the working medium, which confirms the observed effect of flow fluctuations. For these cases, the efficiency drops are as high as 50% for the highest pressure and temperature values.

The results of the hydraulic pump tests from the speed of 500 rpm and above do not include flow fluctuations, and the decrease in volumetric efficiency is smooth and clearly visible. Increasing the speed from 400 rpm to 500 rpm resulted in an increase in the lowest efficiency from 50% to 70%. The minimum volumetric efficiency for the highest values of oil temperature increases with the increase of the rotational speed. The highest level of volumetric efficiency depending on the temperature of the hydraulic oil is observed at speeds higher than 2600 rpm. Up to a temperature of 60°C, a decrease of only 4% is noticeable.

The performed tests confirm that it is important to take into account the temperature of the working medium in hydraulic systems. In order to obtain the highest possible efficiency of the process, care should be taken to cool the hydraulic oil to avoid loss of flow. A solution may be the use of hydraulic oil coolers and flow regulation by changing the speed of the hydraulic pump.

On the other hand, the development of pump efficiency maps facilitates the design of hydraulic systems and the planning of the operation of gear pumps used both in classic drive systems and systems with variable speed pumps. They allow to determine the boundary conditions of use of the studied pumps to the benefit of operating parameters, durability and efficiency of the systems.

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