The improvement of the total efficiency of the gerotor orbital hydraulic motor

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In this study, the efficiency of the low speed high torque gerotor hydraulic motor for mobile hydraulic was investigated. A gerotor with the floating outer ring is rarely described in literature. The purpose of this paper was to analyse the influence of the size of the holes in the valve plate on the total efficiency of the gerotor. A very high total efficiency was obtained with the hole size of Φ6,3 mm. In that case, the total efficiency was on average 5 % higher in comparison to the initial hole size of Φ5,5 mm. Some tribological tests have been performed. We investigated relationship between surface roughness, contact force and friction. The minimum friction was 0,077.

Keywords: Mobile Hydraulics, Hydraulic Motor, Efficiency
Target audience: Mobile Hydraulics

1 Introduction

In this paper, the results of the measurement of low speed high torque orbital hydraulic motor are presented. The rapid development of the hydraulic components in the last few years has contributed many novelties, innovations and improvements in hydraulics. One of the groups of hydraulic component is hydraulic motor group. Hydraulic motors convert hydraulic energy into the mechanical energy. The most crucial measure of performance of the hydraulic motor is the total efficiency. There are many factors, which influence the hydraulic motor performance. They are related to hydraulic, tribological, material and other challenges. The performance of the hydraulic motor depends on the construction parameters as well. A gear pair has the largest influence on performance, whereas other parameters are also very important. We investigated the influence of the size of the holes in the valve plate. The holes are important for inlet and outlet flow of the fluid. Fluid takes care of the relative movement of the gear pair and lubrication of the main parts of the hydraulic motor. Within research, we found out that the diameter of the holes in the valve plate influences hydraulic motor performance significantly. With the right choice of hole diameter, we can raise the total efficiency on average around 5 %. The paper is structured as follows. In the introduction is described an objective and the purpose of the research. Section 2 presents the theoretical framework of the conducted research. Hydraulic gerotor motor was described as well as procedure for the determination of the volumetric, mechanical-hydraulic and total efficiency. Furthermore, the calculation of the gerotor's derived displacement volume is proposed according to the international standard ISO 8426. Methodology is described in section 3. A test rig of the experiment is shown in section 4. The Results are presented in section 5 and conclusions are summarized in section 6. In the last two sections, there is a list of references and a nomenclature explanation.

1.1 Literature review

There are many factors, which influence the performance of the gerotor. The viscosity, viscosity index, high-shear viscosity, piezo viscosity and shear stability of prototype fluids have been characterized in the research of fluid properties influence on the total efficiency of low speed high torque hydraulic motors [1]. In literature, there exists very little scientific papers, which deal with hydraulic gerotor motor with the floating outer ring. Usually the classical orbital hydraulic motor with inner rotor and gerotor's housing are analysed. In the past few decades, many designs have been disclosed in relative patents, but many of them were not feasible for actual motor production. A kind of deep analysis of multiple performance attributes and structural design of the gerotor motor has been extensively investigated through multi-objective optimization design of the gerotor motor [2]. Pressure distribution within gerotor and some other physical quantities were analysed through a CFD model for orbital gerotor motor [3]. A CFD analysis helps us to understand the physics of gerotor's operation and enable us a rapid development of new hydraulic motors [4]. The total efficiency is very much related to losses. Experimental and torque losses in gerotor were investigated in case of hydrostatic machines which represent complex fluid dynamic systems due to intricate and partially unknown dynamics [5]. Some losses are related to tribological behaviour. The most important are friction [6] and wear [7, 8]. Regarding rotational speed, there are two types of hydraulic motors. A low speed hydraulic motor does not exceed the rotational speed of 250 min^{-1}. On the other hand, a high speed hydraulic motor reaches rotational speed higher than 250 min^{-1}. A difference between the above mentioned group is shown in Figure 1 [9]. The low speed hydraulic motors achieve a higher total efficiency when they rotate relatively slowly (Figure 1, line 1). The total efficiency of the high speed hydraulic motor increases in case of the rising rotational speed (Figure 1, line 2).

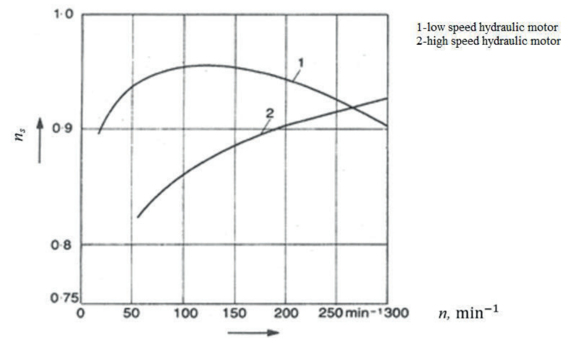

Figure 1: The total efficiency of low and high speed hydraulic motor.

Nowadays, there are many different types of hydraulic motors. Gear, vane, axial piston and radial piston hydraulic motor. Geroller and gerotor are two special types of gear hydraulic motors. Our scientific paper deals with the gerotor, which has two special characteristics. It is a low speed hydraulic motor with high torque capability. In literature, it is often abbreviated as LSHT ("low speed high torque"). Other precendences and limitations are listed in Table 1.

Precendences:	• relatively simple construction compared to other types of hydraulic motors
	• high torque
	• low speed
	• self-braking ability
	• relatively small and light
	• relatively cheap
Limitations	• friction
	• wear
	• low sealing ability of lobes between the inner rotor and outer ring
	• low total efficiency

Table 1: Precendence and limitations of the hydraulic gerotor motor.

2 Hydraulic gerotor motor with the floating outer ring

The hydraulic gerotor motor with the floating outer ring, its design, and principle of operation are presented in this section. At the end of the section we will introduce the procedure of displacement volume and efficiency determination for such a type of hydraulic motor.

2.1 Design and principle of operation of the gerotor

Gerotor has a mass of around 20 kg. Its working pressure is up to 35 MPa. The hydraulic gerotor motor consists of thirty different parts. The maximum diameter is Φ174 mm, whereas the maximum dimension represents the length of the gerotor – it is 250 mm (Figure 2).

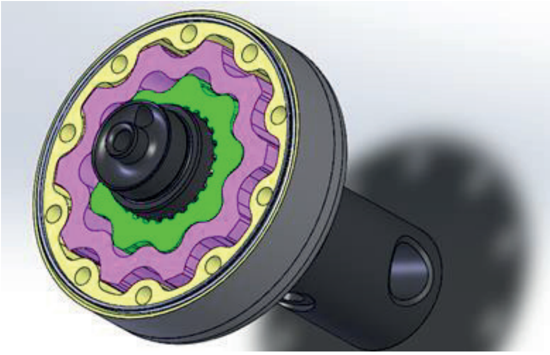

Figure 2: The hydraulic gerotor motor design (Φ174 mm × 250 mm).

There are four very important parts according to the functionality of the gerotor. The most influential elements of the hydraulic motor regarding principle of operation are: 1-the inner rotor, 2-the outer ring, 3-the gerotor housing and 4-the valve plate (Figure 3).

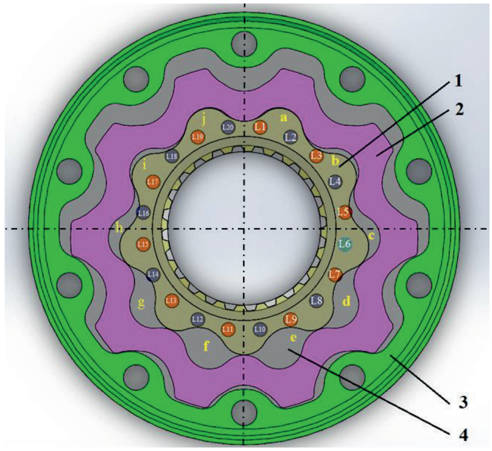

Figure 3: Four basic parts of the hydraulic motor (Φ 174 mm).

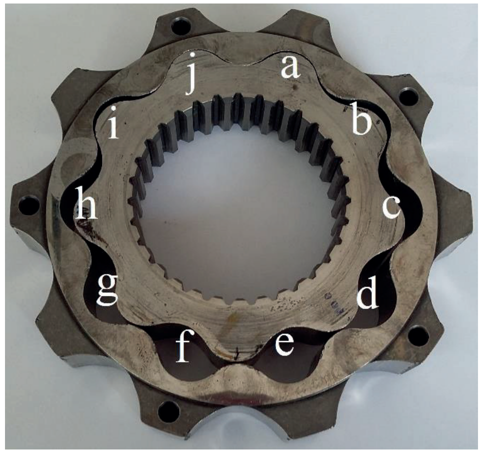

Figure 4: Lobes.

The outer ring has 10 teeth, whereas the inner rotor has 9 teeth and. They together constitute 10 lobes, which are designated with the small letters on Figure 3 and Figure 4. On Figure 3 we can recognize twenty holes, which are part of valve plate. The first hole has the mark L1, and the last one L20. Odd numbers represent holes which are connected with the high pressure zone, and even numbers represent holes which are linked to the low pressure zone. As operators, we can change low and high pressure zone with the control valve. A main function of the gerotor housing is the limitation of motion of the outer ring.

2.2 Gerotor displacement volume (ISO 8426)

In theory, there are two kinds of displacement volumes. The first one is the theoretical VG and the second one is the derived displacement volume VI. The difference between them is that the derived displacement volume considers the real production tolerances. The estimated deviation between VG and VI was 2-3 % [10]. Gerotor displacement volume is very important information that helps us to determine the volumetric and hydraulic-mechanical efficiency of the hydraulic motor. There exist three methods of determination of derived displacement volume [9]: a) Measurement of displacement volume with the two reservoirs; b) Toet-method; c) Method regarding ISO 8426. Due to international accepted standard, we decided to use the third method. The above mentioned standard ISO 8426 [11] proposes the measurement of volume flow rate with different pressure differences, whereas the speed of shaft of the hydraulic motor is the constant value. We have to determine the volume flow rate for $\Delta p = 0$. We can do this graphically either with the help of the method of least squares as it is shown in equation 1.

$$V_i = \left\{ \left(\frac{1}{k} \sum_{i=1}^{k} Q_i \right) - \left[\frac{\frac{1}{k}\sum_{i=1}^{k}(\Delta p_i Q_i) - \frac{1}{k^2}\left(\sum_{i=1}^{k}\Delta p_i\right)\left(\sum_{i=1}^{k} Q_i\right)}{\left(\frac{1}{k}\sum_{i=1}^{k}\Delta p_i{}^2\right) - \left(\frac{1}{k}\sum_{i=1}^{k}\Delta p_i\right)^2} \right] \left(\frac{1}{k} \sum_{i=1}^{k} \Delta p_i \right) \right\} \frac{1}{n} \tag{1}$$

2.3 Gerotor efficiency

In reality, there are many kind of losses. Volumetric losses include external volumetric losses, internal volumetric losses, losses due to compressibility, losses due to incomplete filing. Hydraulic-mechanical losses represent viscosity friction, friction losses due to turbulent flows, due to pressure differences. The most important fact related to energy consumption of the hydraulic component is efficiency. It represents the ratio between the useful output to the total input, in energy terms. According to hydraulic gerotor motor there are three different types of efficiency:

- total efficiency,
- volumetric efficiency,
- hydraulic-mechanical efficiency.

It's not possible that any of these efficiencies would be greater than 100 % in real applications.

A conversion of hydraulic energy into mechanical energy is the main purpose of the hydraulic motor. Hydraulic energy (equation 2) is a function of volume flow rate and pressure difference, whereas mechanical energy (equation 3) depends on rotational speed and torque.

$$E_h = Q_1 \cdot (p_1 - p_2) \tag{2}$$

$$E_m = 2 \cdot \pi \cdot n \cdot M \tag{3}$$

The total efficiency of the hydraulic motor is ratio between input hydraulic energy and output mechanical energy as it is shown in equation 4.

$$\eta_t = \frac{2 \cdot \pi \cdot n \cdot M}{Q_1 \cdot (p_1 - p_2)} \tag{4}$$

If we would like to determine volumetric and hydraulic-mechanical efficiency, we have to have information about the derivate displacement volume of hydraulic motor. Volumetric efficiency of the hydraulic motor is a function of rotational speed, derivate displacement volume, and volumetric input flow rate into the hydraulic motor (equation 5).

$$\eta_v = \frac{n \cdot V_i}{Q_1} \tag{5}$$

Hydraulic-mechanical efficiency of the hydraulic motor depends on effective torque, pressure difference and derivate displacement volume of the hydraulic motor (equation 6).

$$\eta_{hm} = \frac{M \cdot 2\pi}{(p_1 - p_2) \cdot V_i} \tag{6}$$

3 Methodology

According to the previous research activities, we decided to observe hydraulic motor operation in eighteenth different measured points, which are stated in the Table 2. We chose two different rotational speeds: 15 min^{-1}, 17 min^{-1} and nine different pressure differences: 16 MPa, 17 MPa, 18 MPa, 19 MPa, 20 MPa, 21 MPa, 22 MPa, 23 MPa, and 24 MPa. Within the wide set of the measurement activities we took into account recommendations and guidelines from different international standards, whereas we would like to emphasise the importance of the international standard ISO 8426 [11] as well as other standards which are related to different types of hydraulic motor efficiency. Our main purpose was to determine hydraulic motor displacement volume and total, volumetric, and hydraulic-mechanical efficiency of the investigated hydraulic motor.

#	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Rotational speed *n*,	15	15	15	15	15	15	15	15	15
Pressure difference *Δp*, MPa	16	17	18	19	20	21	22	23	24
#	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Rotational speed *n*,	17	17	17	17	17	17	17	17	17
Pressure difference *Δp*, MPa	16	17	18	19	20	21	22	23	24

Table 2: List of eighteen selected measured points.

The ambient temperature was 25 °C, whereas the fluid's temperature was 60 °C. One set of the measurements represents 18 measurements points with the one specific hole diameter in valve plate – for example, Φ5,9 mm. For the testing of one set of the measurements we spent around four hours. Two hours for the preparation and measuring installation, and additional two hours for determination of physical quantities, which are represented in equations for hydraulic motor efficiency. All measurements were accomplished in the laboratory for fluid power and controls at the Faculty of Mechanical Engineering, University of Ljubljana. The uncertainty analysis was done according to the international standard JCGM 100:2008-BIMP [12]. International standard ISO 8426 addresses three classes of measurement accuracy: A, B and C. In the Table 3 are permissible systematic measuring instruments errors for each class.

Parameter	**Permissible systematic measuring instrument errors for each class of measurement accuracy**		
	A	**B**	**C**
Rotational frequency (%)	± 0,5	± 1	± 2
Flow rate (%)	± 0,5	± 1,5	± 2,5
Pressure, MPa gauge where *p* < 0,15	± 0,001	±0,003	± 0,005
Pressure, MPa gauge where *p* ≥ 0,15	± 0,05	± 0,15	± 0,25
Test fluid temperature (°C)	± 0,5	± 1	± 2

Table 3: Permissible systematic measuring instrument errors [11].

Within measurement, we were able to ensure the following errors for desired physical quantities: Pressure difference: ± 0,05 MPa, Rotational speed: ± 0,1 min^{-1}, Fluid Temperature: ± 1 °C. The original diameter of holes in the valve plate was Φ5,5 mm (Figure 5). It was the first set of the measurements. Every additional set had 0,2 mm incremental increase in hole diameter. The maximal hole diameter was Φ7,1 mm (Figure 6).

Figure 5: The minimal hole size (Φ5,5 mm) in the valve plate (Φ174 mm × 15 mm).

Figure 6: The desired maximal hole size (Φ7,1 mm) in the valve plate (Φ174 mm × 15 mm).

To conclude, hole diameter in the valve plate was the only parameter which was being changed. As an objective function we selected the total efficiency of hydraulic gerotor motor. As it was mentioned in the first part of paper, hydraulic motor consists of some very important elements. Friction in contacts (Figure 7) represents losses which lead to lower hydraulic-mechanical efficiency and consequently lower total efficiency. In the second part of research we did some basic tribological tests. Relationship between contact force F (14 N, 40 N, 114 N), surface roughness Ra (0,05 μm and 0,2 μm) and friction was investigated.

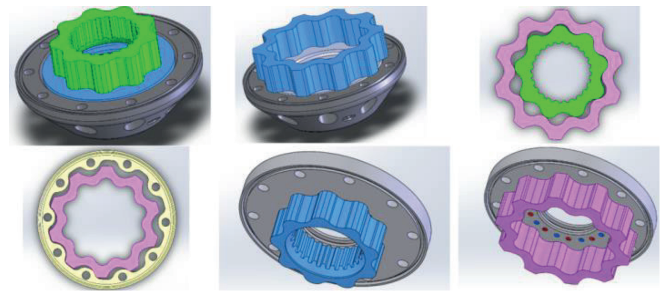

Figure 7: Tribological pairs of the main gerotor's parts.

4 Test rig

The test rig of the experiment consisted of sixteen different hydraulic components (Figure 8), whereas we would like to describe just the most important parts. The experiment was carried out by (1)-the electromotor and (2)-variable displacement pump. The tested hydraulic motor is denoted with the number (3). We used (7)-pressure reduction valve and (8)-pressure relief valve. Five different physical quantities have been measured. We applied (12)-volume flow rate meter, (13)-torque sensor, (14)-rotational speed sensor, (15)-pressure sensor and (16)-temperature sensor. If we would like to determine different kind of efficiencies of the hydraulic motor, we have to measure the physical units properly in sense of location of sensors. We would like to emphasize that on the inlet flow side we have to measure flow rate (Q_1) and pressure (p_1). On the other hand, outlet pressure (p_2) is absolutely essential, because the pressure difference of the inlet and outlet flow of the hydraulic motor is very important.

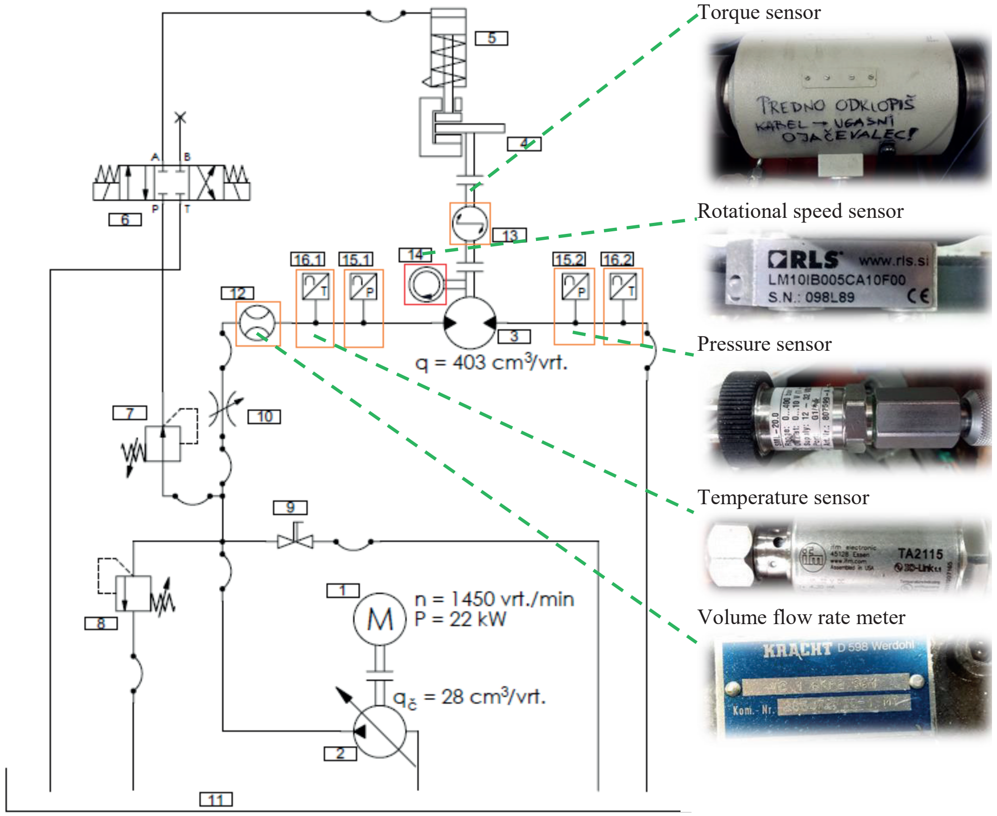

Figure 8: Test rig of the experiment.

5 Results and discussion

The result of research is presented in three sections. In the first section is presented the influence of the size of the holes in the valve plate on efficiency. In the second section is the result of tribological investigation. In the third part is introduced the uncertainty analysis.

5.1 Influence of the size of the holes in the valve plate on efficiency

The results of the research are presented in Figure 9, which show a relationship between pressure difference, size of the holes in the valve plate and total efficiency. Different colours represent different holes' size. There is pressure difference (range: from 160 bar to 240 bar) on the y-axis and total efficiency (range: 0 % – 45 %) on the x-axis. The length of a row represents a value of the total efficiency in a specific measured point. The longer the length of the row, the greater the total efficiency of the hydraulic gerotor motor. In the case of rotational speed 15 min^{-1}, the initial total efficiency of gerotor with the valve plate with the diameter Φ5,5 mm was 30,7 %. The highest total efficiency was 36,2 %, returning an 18 % higher total efficiency compared to the initial state. The highest total efficiency was obtained with the hole diameter of Φ6,3 mm. The additional increase of the hole diameter had a negative influence on the gerotor characteristics - total efficiency dropped down dramatically. For example, the total efficiency of the gerotor with the valve plate with hole diameter Φ7,1 mm was just 11,4 %. There exists almost the same trend for every set of pressure differences. In general, we found out that the total efficiency increases with the increase of pressure differences if we observe the total efficiency of one specific hole diameter. For example, the total efficiency values for hole diameter of Φ6,7 mm were increasing in the following way: 20,5 %, 24,3 %, 26,5 %, 29,5 %, 32,0 %, 33,3 %, 35,1 %, 35,5 %, 36,2 %. When we accomplished the measurement of the gerotor with rotational speed 17 min^{-1} (Figure 9), we found out that there exist similarities with the results of gerotor with rotational speed 15 min^{-1}. If we look at the results in the second case, we can find out that gerotor has a slightly lower total efficiency. There exists the increasing and the decreasing trend of total efficiency within every set of measurements. If we focus on the total efficiency in both cases (n = 15 min^{-1}, n = 17 min^{-1}), we can see that the total efficiency was higher in case of slightly larger holes. In the initial state, total efficiency was relatively low. When we enlarged hole diameter from Φ5,5 mm to Φ6,3 mm, the hydraulic motor reached the maximum total efficiency in a few sets of meausurements. Additional escalation of the hole diameter led to lower total efficiency. In some cases, the holes are so big that the hydraulic motor couldn't operate.

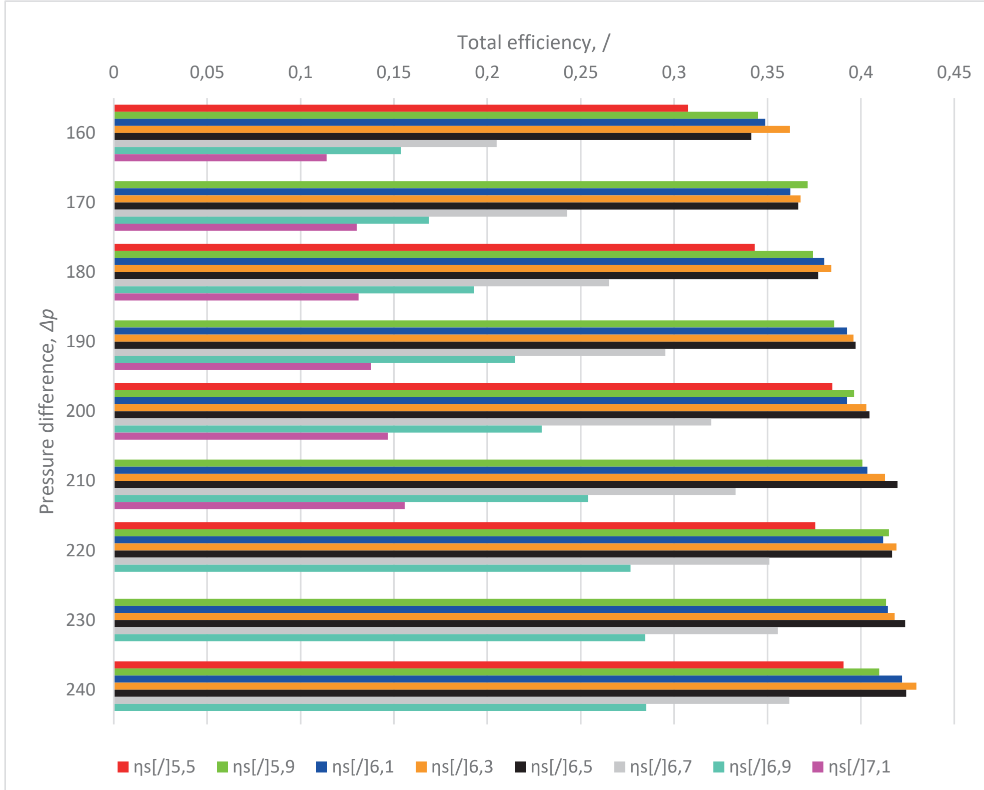

Figure 9: Total efficiency of the gerotor (operating point: n = 17 min^{-1}).

To summarize, we found out that a hole diameter of Φ6,3 mm is the most appropriate size of holes in the valve plate regarding total efficiency of the hydraulic gerotor motor. In this case, the total efficiency is around 5 % higher on average.

5.2 Tribological investigation

Tribological tests have been done with the tribometer TE77. We used a stainless steel AISI 440C. The result (Figure 10) shows that the surface roughness has very important influence on friction. The minimum friction was obtained by surface roughness Ra = 0,05 μm and maximum contact force F = 112 N. It was 0,077. It has been proven that the surface with higher roughness causes higher friction. Red bars are on average 16 % higher than blue bars. We found out that friction is dependent on contacts force. Higher contact force means lower friction.

Friction by contact force 112 N was always lower than friction by contact force 40 N or 14 N for the same surface roughness. Future investigation are going to be dedicated to friction and wear analysis of different lubricants such as water and ionic liquid.

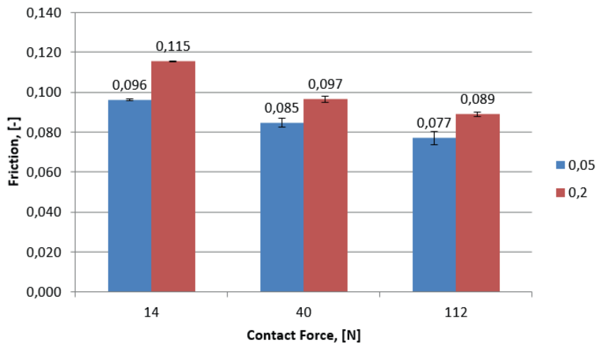

Figure 10: Coefficient of friction of stainless steel AISI 440C.

5.3 Uncertainty analysis

The uncertainty analysis gave us information about the confidence in the results. Within the study, we measured 5 physical quantities: pressure, flow rate, torque, rotational speed, and temperature. Briefly, we would like to present the uncertainty analysis for the first four physical units. The expanded uncertainty analysis was done by assuming triangular and rectangular distribution and a coverage factor = 2 (Table 4).

	Rectangular distribution [%]	Triangular distribution [%]
Pressure	1,50	1,06
Flow rate	1,73	1,22
Torque	2,02	1,43
Rotational speed	1,73	1,22

Table 4: Expanded uncertanty analysis.

6 Conclusion

A research of the hydraulic gerotor motor efficiency with the floating outer ring is presented in this paper. The findings of this study can be summarized as follows: The diameter of holes in the valve plate influences the total efficiency of the hydraulic gerotor motor. For each set of the measurements exists an optimal diameter of holes. Very high total efficiencies were reached with holes' diameter being Φ6,3 mm in most cases. The highest total efficiency was on average 5 % higher than the total efficiency of the original hole size. It means that a hydraulic motor with the hole diameter Φ6,3 mm in the valve plate has on average 5 % better operation characteristic in every measured point than a hydraulic motor with the hole size Φ5,5 mm in the valve plate. We can conclude that we would be able to optimize the gerotor's operation with some simple mechanical operation. With drilling we can make hole diameter larger to raise the total efficiency of the gerotor around 5 % on average. This happens if the diameter of holes in the valve plate is Φ6,3 mm. According to the tribological prospective we found out that surface roughness and contact force play very important role regarding friction. The lowest friction was 0,077, it occourred when surface roughness was $Ra = 0{,}05$ µm and contact force was 112 N. The results and research findings present a very important contribution to science. Hydraulic gerotor motors with the floating outer ring were very rarely discussed in scientific papers. There is a lack of such analysis in literature. An influence of hole diameter in the valve plate on the total efficiency of hydraulic gerotor motors represents novelty and original insight in the gerotor's group of hydraulic motors.

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8 Nomenclature

Variable	*Description*	*Unit*
i	Index	[-]
k	Number of samples	[-]
n	Rotational speed	[min^{-1}]
p_1	Pressure at the inlet port of hydraulic motor	[bar]
p_2	Pressure at the outlet port of hydraulic motor	[bar]
E_h	Hydraulic energy	[-]
E_m	Mechanical energy	[-]
M	Torque	[Nm]
Q_1	Volume flow rate at the inlet port of hydraulic motor	[m^3s^{-1}]
V_g	Geometric displacement volume	[m^3]
V_i	Derived displacement volume	[m^3]
Δp	Pressure difference	[bar]
η_{hm}	Hydraulic-mechanical efficiency	[-]
η_v	Volumetric-efficiency	[-]
η_t	Total efficiency	[-]