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ENERGY EFFICIENCY ANALYSIS IN MOBILE HYDRAULICS

ANALIZA ENERGETSKE UČINKOVITOSTI V MOBILNI HIDRAVLIKI

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Abstract

The primary purpose of this paper is to estimate possible energy and cost savings in the optimization of mobile hydraulics. A gerotor is a low-speed, high-torque hydraulic motor, which is very rarely described in the literature and often use in mobile hydraulics. In this paper, the total efficiency of the hydraulic motor was investigated. The influence of the size of the holes in the valve plate on the total efficiency of the gerotor was analysed. The total efficiency is the most important and prominent information about the energy conversion of hydraulic components, such as hydraulic motors and pumps. The operation of a gerotor is briefly described as well as some equations for the determination of displacement and efficiency. The results show that there is a correlation between the size of holes in the valve plate and the total efficiency of the gerotor. Furthermore, a very high total efficiency was obtained with the hole size of Φ6.3 mm. In that case, the total efficiency was on average 16.1% higher in comparison to the total efficiency when the hole size was Φ5.5 mm. It plays a significant role in possible reductions in energy cost. Energy analysis and cost estimation were conducted.

Povzetek

Glavni namen raziskave je bil oceniti energetske in stroškovne prihranke, ki so posledica optimizacije v mobilni hidravliki. Gerotor je počasno vrteč hidravlični motor za premagovanje velikih momentov.

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Takšen hidravlični motor je redko opisan v literaturi, ampak pogosto uporabljen v praksi. V prispevku je raziskana možnost povečanja skupnega izkoristka takšnega hidravličnega motorja zaradi spreminjanja velikosti lukenj v ventilski plošči. Skupni izkoristek je merilo, kako učinkovita je pretvorba hidravlične energije v mehansko delo. V prispevku je predstavljeno delovanje hidravličnega motorja in postopek določitve skupnega izkoristka. Rezultati so pokazali, da velikost lukenj pomembno vpliva na skupni izkoristek. Pri velikosti lukenj Φ6.3 mm je bil skupni izkoristek kar 16.1% večji kot pri velikosti lukenj Φ5.5 mm. To je pomembo dejstvo, ki nas je spodbudilo, da smo opravili energetsko analizo in ocenili možne prihranke, ki bi jih lahko dosegli.

1 INTRODUCTION

Energy efficiency is specified by the European Union (EU) as a key driver of the transition toward a low-carbon society, *[1]*. The Republic of Slovenia follows the European legislation related to the new rules in the energy market, *[2]*. A new energy concept in Slovenia was proposed *[3]*, *[4]*. Energy technology is one of the most critical topics in mobile hydraulics, where energy savings play a critical role in cost reduction. The rapid development of mobile hydraulics in recent years has contributed many innovations and improvements in the field. One of the groups of hydraulic components is the hydraulic motor group. Hydraulic motors convert hydraulic energy into mechanical energy. The most crucial measure of performance of a hydraulic motor is the total efficiency. In this paper, the results of the measurement of a slow rotation orbital hydraulic motor are presented. There are many factors that influence the hydraulic motor's performance. The influence of the size of the holes in the valve plate was investigated. The holes are essential to the 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. In the research, we have determined 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 16.1%. The above-described hydraulic motor has a large carbon footprint; consequently, care must be taken to continuously develop reductions in energy demand.

The paper is structured as follows: in the introduction, the objective and the purpose of the research are described. Section 2 covers the literature review. More details of the hydraulic gerotor motor are described in Section 3. The methodology is explained in Section 4. The results are presented in Section 5. In Section 6 key findings of the research are summarized. At the end is a list of references and a nomenclature explanation.

2 LITERATURE REVIEW

In the relevant literature, there are few scientific papers that deal with hydraulic gerotor motors with a floating outer ring. There are many factors that 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 the influence of fluid properties on the total efficiency of low-speed, high torque hydraulic motors, *[5]*. A significant influence on the total efficiency of hydraulic motor or pump is the geometry of the gear pair, *[6]*, *[7]*, *[8]*. 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, *[9]*. Pressure distribution within a gerotor and some other physical quantities were analysed through a CFD model for an orbital gerotor motor, *[10].* A CFD analysis aids in understanding the physics of a gerotor's operation and enables the rapid development of new hydraulic motors, *[11].* The total efficiency is very much related to losses. Experimental and torque losses in gerotors were investigated in the case of hydrostatic machines, which are complex fluid dynamic systems due to their intricate and partially unknown dynamics, *[12].* Some losses are related to tribological behaviour. The most important are friction, *[13]*, and wear, *[14]*, *[15].*

3 HYDRAULIC MOTOR - GEROTOR

The hydraulic gerotor motor consists of thirty different parts. The maximum diameter is Φ174 mm, whereas the maximum dimension is the length of the gerotor (250 mm). It has a mass of around 20 kg. Its working pressure is up to 350 bar. The inner rotor has 9 teeth, and the outer ring has 10 teeth (Figure 1a). They together constitute 10 lobes. On Figure 1b, there are twenty holes, which are part of the valve plate. The first hole has the mark L1 and the last one L20. Odd numbers represent holes that are connected with the high-pressure zone, and even numbers represent holes that are linked to the low-pressure zone. As operators, we can change the low and high-pressure zones with the control valve.

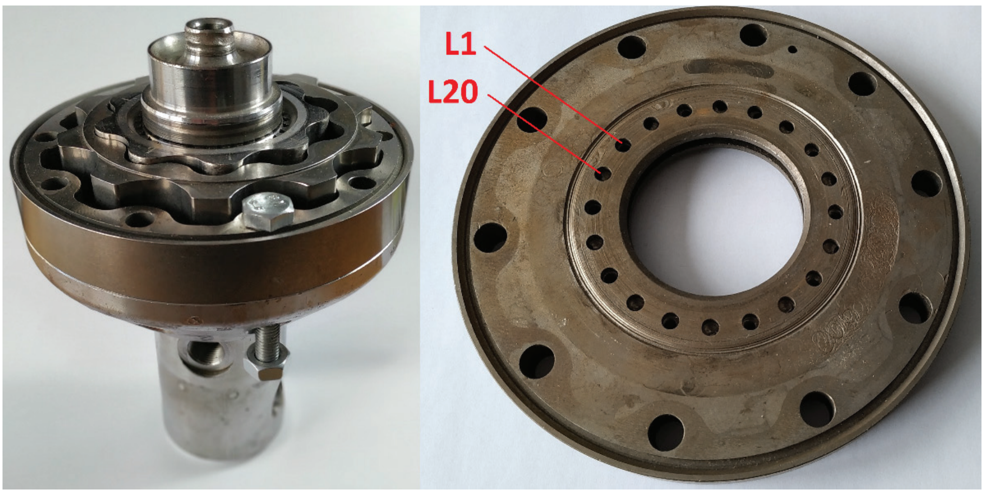

Figure 1: *(a) Gerotor Hydraulic motor (Φ174 mm × 250 mm), (b) valve plate (Φ174 mm × 15 mm)*

Gerotor displacement volume is essential information that helps determine the volumetric and the hydraulic-mechanical efficiency of the hydraulic motor. Standard ISO 8426, *[16]*, proposes the measurement of volume flow rate with different pressure differences, whereas the speed of the shaft of the hydraulic motor is a constant value. We have to determine the volume flow rate for $\Delta p = 0$. This can be done graphically with the help of the method of least squares, as shown in Equation 3.1.

$$V_i = \left\{ \left(\frac{1}{k} \sum_{i=1}^{k} Q_i \right) - \left[\frac{\frac{1}{k} \sum_{i=1}^{k} (\Delta p_i Q_i) - \frac{1}{k^2} \left(\sum_{i=1}^{k} \Delta p_i \right) \left(\sum_{i=1}^{k} Q_i \right)}{\left(\frac{1}{k} \sum_{i=1}^{k} \Delta p_i^{\,2} \right) - \left(\frac{1}{k} \sum_{i=1}^{k} \Delta p_i \right)^2} \right] \left(\frac{1}{k} \sum_{i=1}^{k} \Delta p_i \right) \right\} \frac{1}{n} \tag{3.1}$$

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. The total efficiency of the hydraulic motor is the ratio between output mechanical energy ($P_{izst,HM}$) and input hydraulic energy ($P_{vst,HM}$) as shown in Equation 3.2.

$$\eta_{s,\,HM} = \frac{P_{izst,\,HM}}{P_{vst,\,HM}} \tag{3.2}$$

Mechanical energy ($P_{izst,HM}$) is dependent on rotational speed (n_{HM}) and torque (M_{HM}) as shown in Equation 3.3.

$$P_{izst,\,HM} = 2 \cdot \pi \cdot n_{HM} \cdot M_{HM} \tag{3.3}$$

Hydraulic energy ($P_{vst,HM}$) is defined by flow rate ($Q_{vst,HM}$) and the pressure difference between inlet pressure ($p_{vst,HM}$) and outlet pressure ($p_{izst,HM}$); see Equation 3.4.

$$P_{vst,\,HM} = Q_{vst,\,HM} \cdot \left(p_{vst,\,HM} - p_{izst,\,HM} \right) \tag{3.4}$$

Considering Equations 3.2, 3.3, and 3.4, we get Equation 3.5.

$$\eta_{s,\,HM} = \frac{2 \cdot \pi \cdot n_{HM} \cdot M_{HM}}{Q_{vst,\,HM} \cdot \left(p_{vst,\,HM} - p_{izst,\,HM} \right)} \tag{3.5}$$

In a very similar way, we can calculate the hydraulic-mechanical efficiency as shown in Equation 3.6.

$$\eta_{hm,HM} = \frac{M_{HM} \cdot 2\pi}{\left(p_{vst,HM} - p_{izst,HM} \right) \cdot V_{HM}} \tag{3.6}$$

The volumetric efficiency of the hydraulic motor is defined by rotational speed (n_{HM}), displacement (q_{HM}), and flow rate ($Q_{vst,HM}$); see Equation 3.7.

$$\eta_{v,\,HM} = \frac{n_{\mathrm{HM}} \cdot V_{\mathrm{HM}}}{Q_{vst,\,HM}} \tag{3.7}$$

In general, the total efficiency is the result of multiplication of the hydraulic-mechanical efficiency and the volumetric efficiency (Equation 3.8).

$$\eta_{s,\,HM} = \eta_{hm,HM} \cdot \eta_{v,\,HM} \tag{3.8}$$

4 METHODOLOGY

Within the research, the influence of the size of the holes in the valve plate on the hydraulic motor characteristics was investigated. According to the previous research activities, we decided to observe a hydraulic motor at a rotational speed of 15 min^{-1} and at three different pressure differences: 160 bar, 200 bar, and 240 bar. Within the broad set of the measurement activities, we took into account recommendations and guidelines from different international standards; we would like to emphasise the importance of the international standard ISO 8426, *[16]*, as well as other standards which are related to different types of the hydraulic motor efficiency. Our main purpose was to determine hydraulic motor displacement volume and total, volumetric, and the hydraulic-mechanical efficiency of the investigated hydraulic motor. The original diameter of holes in the valve plate was Φ5.5 mm (Scenario 0). Holes were later increased to Φ6.3 mm (Scenario 1) and Φ6.9 mm (Scenario 2).

Energy efficiency analysis was made according to the data, downloaded from the Statistical Office of Slovenia. A price for business consumers was calculated based on the price average for 2017, *[17].* It was €0.075/kWh in Slovenia.

5 RESULTS

5.1 The total efficiency

The most important results of the research activities are presented in Figure 2, which shows a relationship between the total efficiency and size of the holes in the valve plate. Different colours represent different hole sizes (different scenarios). There is pressure difference (range: from 160 bar to 240 bar) on the x-axis and the total efficiency (range: 0%-45 %) on the y-axis. The height of a column represents a value of the total efficiency in a specific measured point. The greater the height of the column, the greater the total efficiency of the hydraulic gerotor motor. The highest total efficiency was obtained in Scenario 1 (hole: Φ6.3 mm) and the lowest in Scenario 2 (hole: Φ6.9 mm). In other words, 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 total efficiency.

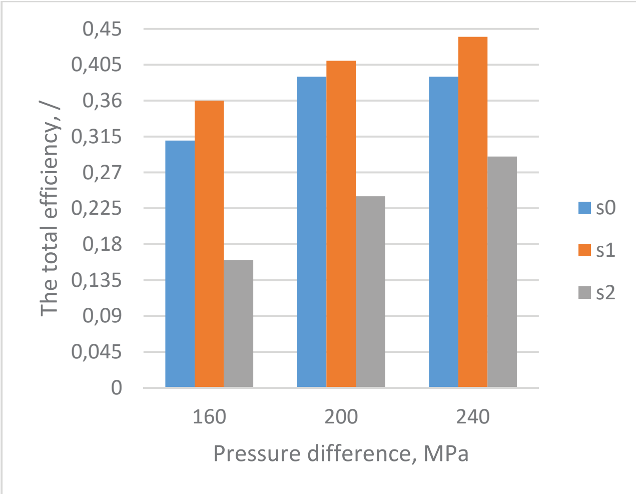

***Figure 2:** The total efficiency of the gerotor (operating point: n = 15 min^{-1})*

5.2 Energy efficiency analysis

Columns in Figure 3 represents cost per year for three different scenarios. As shown, Scenario 1 (in comparison with Scenario 0=initial scenario) leads to a cost reduction from €1544 to €1295 per year for a pressure difference of 160 bar, from €1923 to €1824 per year for a pressure difference of 200 bar, and from €2329 to €2031 per year for a pressure difference of 240 bar. Regarding the calculation, Scenario 2 is worse than scenario 0. There is a cost increase from €1544 to €2291 per year for a pressure difference of 160 bar, from €1923 to €2663 per year for a pressure difference of 200 bar, and from €2329 to €2927 per year for a pressure difference of 240 bar. On average, it is possible to save around €215 per year if optimization is performed wisely.

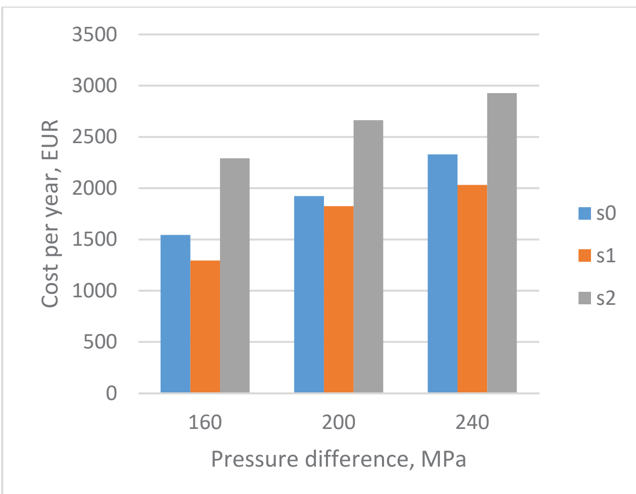

***Figure 3:** Cost per year for three different scenarios*

Cost savings for three different scenarios are presented in Figure 3. In Scenario 1 and a pressure difference of 240 bar, it is possible to reach €299 of saving with Scenario 0. In the worst case, when Scenario 2 was analysed, losses between around €600 and €750 may occur.

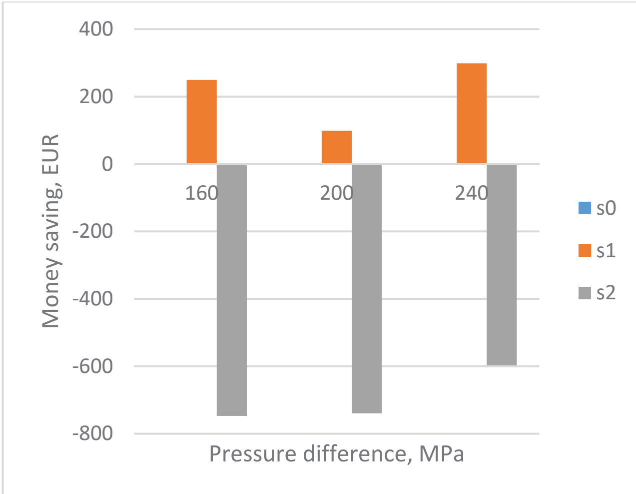

Figure 3: *Money saving for three different scenarios*

6 CONCLUSION

An energy efficiency analysis in mobile hydraulics was discussed in this paper. The conclusion 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;
- Very high total efficiencies were reached with a hole diameter of Φ6.3 mm;
- The highest total efficiency was on average 16.1% higher than the total efficiency of the original hole size. It means that a hydraulic motor with the hole diameter of Φ6.3 mm in the valve plate has on average 16.1% better operation characteristic in every measured point than a hydraulic motor with the hole size of Φ5.5 mm in the valve plate;
- Energy efficiency analysis showed that it is possible to save around €215 per year on average due to optimization.

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Nomenclature

Symbol	Symbol meaning
n	Rotational speed
p	Pressure
Q	Flow rate
M	Torque
V	Displacement
η_T	Flow rate