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Experimental investigation of the performance and energy consumption efficiency of elliptical gear hydraulic pump and evaluation by Taguchi method

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A R T I C L E I N F O

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A B S T R A C T

This study presents an approach based on the Taguchi method to evaluate the energy consumption performance of spur and elliptical gear hydraulic pumps. Output flow is one of the essential indicators of gear pump performance. Taguchi L8 experimental design with two factors and mixed level design was applied to determine the gear pump performances. Rotational speed (200, 600, 1000 and 1400 rpm) and pump type (spur and elliptical) is selected as experimental parameters. Thus, the effect of the rotational speed of an elliptical gear pump on the gear pump flow and energy consumption performance is experimentally analyzed. The results of the analysis showed that the elliptical gear pump delivered approximately 120 % higher volumetric flow rate. In terms of pressure performance, the elliptical gear pump showed an advantage of around 87 %, providing higher pressure, especially at low speeds. In terms of energy consumption, the elliptical gear pump has been experimentally proven to consume approximately 145 % less energy at low speeds. It is also found that there is less temperature difference in the hydraulic fluid during operation of the elliptical gear pump. In addition, the elliptical gear pump exhibited a similar behavior tendency under high-loads as in the partia-loaded case.Elliptical gear pump can be said to be a new type of volumetric pump, which is better than the commonly used spur gear pump, especially in terms of output flow and energy consumption performance.

1. Introduction

The hydraulic pump is the power component of the hydraulic system. The performance of the hydraulic pump directly affects the performance and reliability of the hydraulic system [1]. The gear pump is the most commonly used positive displacement hydraulic component in the hydraulic drive system. The commonly used of gear pumps in both industrial and mobile applications creates the need to improve the efficiency of hydraulic drives [2]. Therefore, the researchers fabricated pumps with different tooth profiles and gears. A simple technique has been developed to find geometrical models of helical and cylindrical gear rotors of gear pumps [3–5]. Pumps with an asymmetric gear profile are known to reduce both pump size and flow fluctuation [6–8]. Numerical simulations were used to find a way to reduce the pressure and flow fluctuation of the circular internal gear and external gear pump [9–14].

External gear pumps continue to be widely used in fluid power applications. Research based on improving the efficiency and performance of external gear pumps remains important. Li Yulong et al. [15] used simulation method to analyze the get hold of between trapped oil pressure and gear dynamics in external gear pumps. Xu Gaohuan et al. [16] propose a fluid mechanics and solid mechanics simulation methodology to analyze the coupling dynamics of volumetric pumps between fluids and the transmission system. Mitov, A. et al. [17] carried out a numerical study to obtain the main characteristics of the pump flow obtained at different speeds of the external gear pump by computational fluid dynamics modeling. The effect of parameters such as rotational speed, operating pressure, fluid structure and fluid temperature distribution on the spur gear pump has been investigated in various studies [18–20].

The above research shows that the fluid structure interaction of hydraulic pump type is an important research direction. Currently, research on volumetric external gear pumps is mainly focused on the study of trapped fluid. In recent years, more studies have been carried out on the pump performance of the tooth effects of the gear pump. Pawar et al. [21] researched the effects of gear tooth surface roughness on pump efficiency. Tang et al. [22] investigated the effect of root stress on the pump performance due to the contact between the gears during

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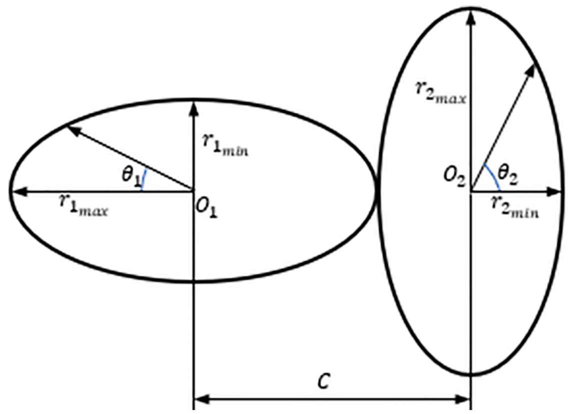

Fig. 1. Two identical ellipses.

gear pump operation. Guo and Chen [23] improved the design of the pump gear profile using optimization methods to improve the performance of the gear pump. Dhote et al. [24] conducted a study to check the effect of gear pump casing and gear on gear pump performance due to wear. Also, in the next stage of the study, they used the Taguchi method to find the most effective parameter on the performance of the gear pump.

The Taguchi method is often used as the first step in an optimization process where the factors studied in the experiment are used as design variables to optimize a system or a process [25]. Studies on multi-objective optimization for parameter design to improve gear profiles have been published [26,27]. According to Taguchi, the aim of parameter design is to obtain the factor levels that give the best results for the product or process under study. The control factor and the noise factor are two types of factors in parameter design. Taguchi experimental designs use orthogonal arrays (OA), which are specially constructed tables. In the OA table, each column corresponds to a factor and each row to the value of the input process parameter in the experiments. In the Taguchi method for determining the level of control factor that characterizes the performance against these factors, the objective function values are converted into signal-to-noise (S/N) ratio, i.e. the desired signal-to-noise ratio for an undesired random noise value that indicates the experimental data quality characteristics, and then analyzed [24]. In determining the parameters that affect pump performance and energy consumption, the Taguchi analysis method has emerged as an effective, controlled and efficient way to study energy consumption efficiency [28].

Today, attention is focused on improving energy consumption efficiency, even a relatively small fraction of which becomes very important for any technology [29–31]. Therefore, the question arises as to how to select the gear set to reduce gear pump energy consumption. For this reason, 6 % of R&D studies are directed towards energy saving of pumps [32]. This data shows that energy savings have become inevitable for the sector. The true meaning of energy savings is that the same amount of goods and services can be produced with less energy or more goods and services can be produced with the same amount of energy. Fluid transfer of the pump with minimum energy consumption, maximum flow rate and minimum time is crucial in terms of energy saving.Therefore, design changes in pumps directly affect efficiency and energy consumption results [33–35]. For this reason, elliptical gears are used in this article to improve the working conditions of external gear hydraulic pumps, increase energy efficiency and protect the environment.

Although there are studies on mathematical modeling, design principles and manufacturing techniques of elliptical gears [36,37], there is a lack of research focusing on practical applications in the field of external gear hydraulic pumps [35,38]. In particular, no study has been found on the energy efficiency of elliptical gear pumps. Therefore, this study is intended to fill this gap by investigating the performance characteristics of elliptical gear hydraulic pumps at different operating speeds and under different loads and contribute to the literature, especially in terms of energy efficiency. Therefore, a modern experimental setup equipped with a programmable logic control system (PLC) was designed and data were collected. A performance verification was carried out by comparing spur and elliptical gear pumps with the same module and number of teeth. For this purpose, a two-factor Taguchi L8 experimental design and a mixed level design were applied.

2. Material and methods

2.1. Elliptical gear design and manufacturing parameters

A curve, called an ellipse, is a curve obtained by cutting obliquely into the base of objects such as cylinders or cones and enclosing surfaces. From two points called foci, the geometric location of points whose sum is constant and whose major axis is equal is called elliptical coordinates (Fig. 1). The polar equation of elliptic curves is calculated by the following equations [39].

The polar equation of the ellipse is obtained by Eq. (1).

$$R_k = \frac{P_k}{1 - e_k \cos(k\phi)} \quad P_k,\ e_k \in \mathbb{R} \ \ k = 1, 2, \ldots, r \tag{1}$$

where R is the real numbers, P_k is the semi-lateral rectum, ∅ is the radius

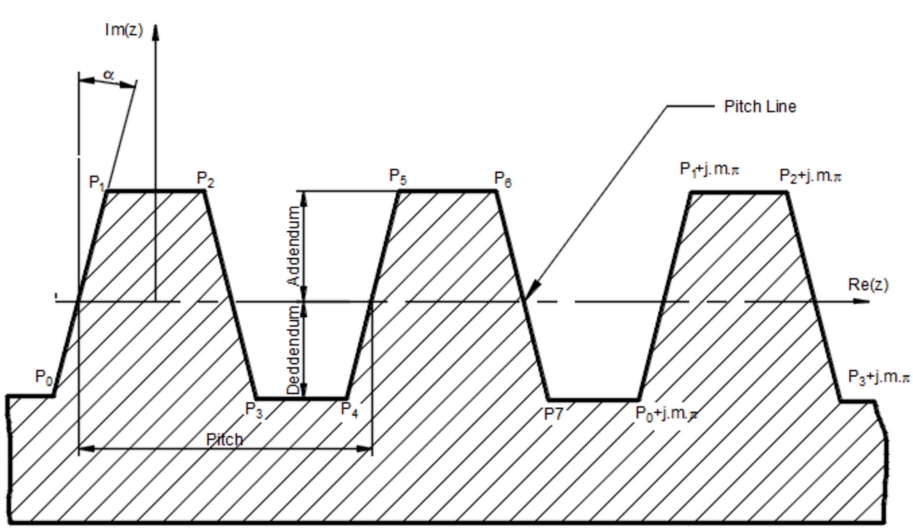

Fig. 2. Reference profile of the rack cutter.

change angle and e_k is the eccentricity value. e_k value is calculated by Eq. (2).

$$e_k = \frac{\sqrt{a^2 - b^2}}{a} \tag{2}$$

here, a is the semi-major axis of the ellipse and b is the semi-minor axis of the ellipse. On the other hand, P_k is calculated by Eq. (3).

$$P_k = a(1 - e_k^2) \tag{3}$$

Within the scope of this study, the gear manufacturing and the gear type cutter profile were designed only by the involute method (Fig. 2).

The tooth flanks of rack and pinion cutters consist of two angular and symmetrical connections that form a force angle (α) with respect to the principal axes of the two-dimensional coordinate system. In the two-dimensional coordinate system, the coordinates of the corners of the cutter are defined by complex numbers (Eqs. (4)–(6)).

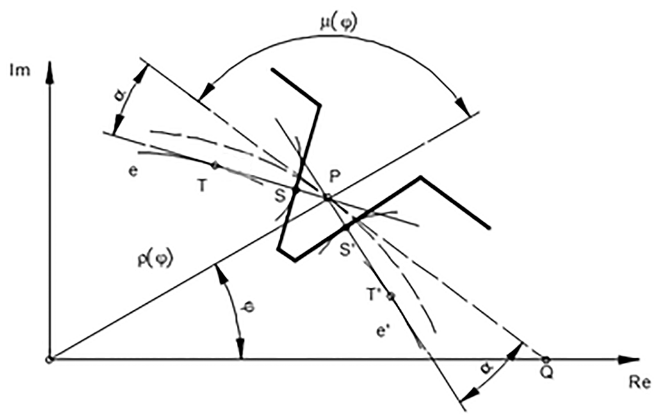

Fig. 3. Section ellipse where the cutter is rolling.

$$\left.\begin{aligned} P_0 &= m\left(h_1 - i\left(\frac{\pi}{4} + h_1\tan(\alpha)\right) \right) \\ P_1 &= m\left(-h_2 - i\left(\frac{\pi}{4} - h_2\tan(\alpha)\right) \right) \\ P_2 &= m\left(-h_2 + i\left(\frac{\pi}{4} - h_2\tan(\alpha)\right) \right) \\ P_3 &= m\left(h_2 + i\left(\frac{\pi}{4} - h_2\tan(\alpha)\right) \right) \end{aligned}\right\} \tag{4}$$

in the equations $i^2 = -1$ is taken. The step connection of the cutter is mapped to the complex axis and is neglected in the drawing, which is considered as a standard tool. The complex coordinates of the corner s of the rack forming the rack cutter are obtained by Eq. (5).

$$P_s = P_{s-4} + im\pi \tag{5}$$

where $s = 4, 5, 6......, 4Z - 1$ is the total number of teeth of the basic shear bar.

In order to design the elliptical gear according to the Involute method in a Computer Aided Design (CAD) environment, the ellipse content was obtained using the equations listed below.

The arc length of the ellipse is calculated by Eq. (6).

$$s_t = \int_0^t \sqrt{a^2\sin(x)^2 + b^2\cos(x)^2 dx} \tag{6}$$

The coordinates of the ellipse are determined by Eq. (7) and Eq. (8).

$$x(t) = a\cos(t) + \frac{as_t\sin(t)}{\sqrt{a^2\sin(t)^2 + b^2\cos(t)^2}} \tag{7}$$

$$y(t) = b\sin(t) - \frac{bs_t\cos(t)}{\sqrt{a^2\sin(t)^2 + b^2\cos(t)^2}} \tag{8}$$

The evolution of the ellipse drawn using these equations in the CAD environment is given in Fig. 3. The main curved profile curves of the teeth can be determined by the regular profile numbers of the teeth of the rack cutter. The normal lines intersect the tangent line at the point of

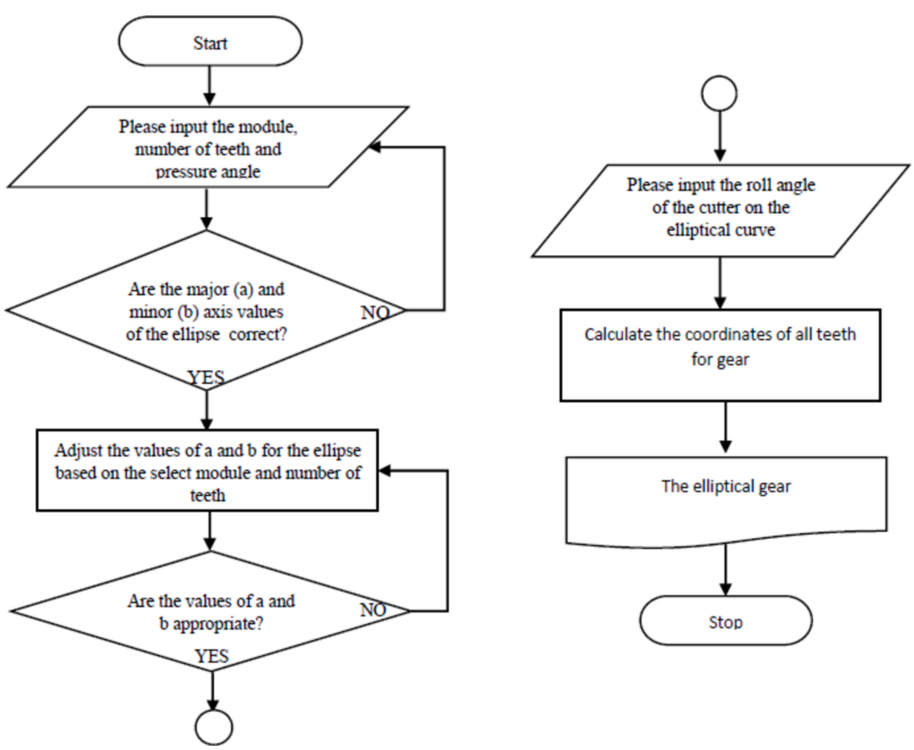

Fig. 4. Flowchart of the code flowchart of the elliptical gear design program flowchart.

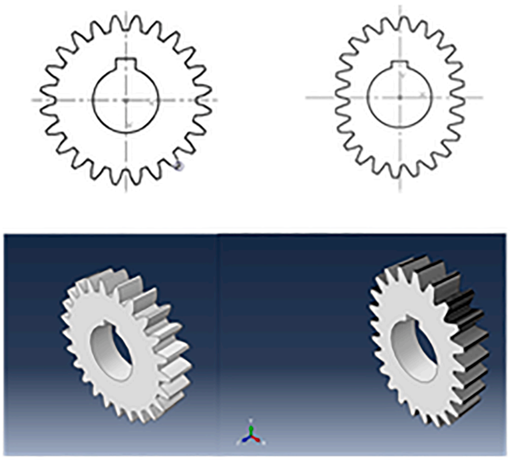

Fig. 5. 2D and 3D design of spur gear and elliptical gear.

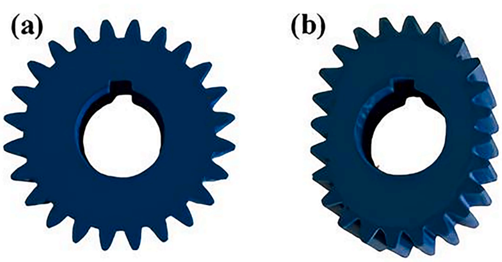

Fig. 6. (a) Manufactured spur gear and (b) Elliptical gear.

contact.

After the 90^0 arc profiles of elliptical gears are obtained by this method in CAD systems; the elliptical gear wheel can be obtained using standard design commands such as move, rotate, copy and mirror [39].

$$w = \left(t_s - I\int_0^{\psi} \sqrt{\rho^2 + \left(\frac{\partial}{\partial\varphi}\rho\right)^2}\, d\varphi \right) e^{(I\mu)} + \rho e^{(I\psi)} \tag{9}$$

The inclination angle of the tangential line is calculated by Eq. (10).

$$\mu = \psi + \frac{\pi}{2} + \theta \tag{10}$$

The angle between the radius vector and the tangent line is determined by Eq. (11).

$$\theta = \arctan\left(\frac{\rho}{\frac{\partial}{\partial\varphi}\rho}\right) \tag{11}$$

The modulus of the gear is calculated by Eq. (12).

$$m = \frac{\int_0^{\frac{\pi}{k}} \sqrt{R^2 + \left(\frac{\partial}{\partial\varphi}R\right)^2}\, d\varphi}{\xi\pi} \tag{12}$$

According to the equations given above, the flowchart of the elliptical gear design program, which is written according to the involute method, is given in Fig. 4.

The software, whose program flow chart is given, runs on CAD program. This has made elliptical gear design easy and fast. 2D and 3D drawings of the gears drawn in CAD environment are shown in Fig. 5.

2.2. Material selection and manufacturing of hydraulic pump gears

In the material selection of gear pairs used for hydraulic gear pumps, factors such as mechanical properties, chemical resistance, temperature resistance and application requirements need to be considered. For this reason, the best choice for the durability and performance of gear wheels is ABS filament with an elasticity of 2250 MPa, a Poisson's ratio of 0.35 and a specific mass of 1.05 g/cm^3. Therefore, the gear pairs of the hydraulic pump were produced by additive manufacturing method using ABS filament. During the production phase, the print bed temperature was 105 °C, the layer height was 0.1 mm, 0.02 mm shrinkage for ABS filament was taken into account and the gears were manufactured with full fill ratio. Measures such as heated print bed, sealed print area, low layer height, high filler density and control of ambient temperature minimized the tendency of ABS filament to warping and shrinkage and ensured high accuracy in gear rotor production. The manufactured spur gear and elliptical gear are shown in Fig. 6.

2.3. Hydraulic gear pump design and manufacturing

In the first stage of the design and manufacturing process of the hydraulic gear pump, the pump components were designed using a CAD program. After transferring these models to the CAM environment, G codes were derived and fabricated from St37 steel material on a CNC milling machine. St37 steel: It has a chemical composition of 0.09 % C, 0.01 % Cr, 0.02 % Ni, 0.16 % Si, 0.92 % Mn, 0.01 % Mo, less than 0.02 % P, less than 0.05 % S and the rest Fe. In addition, the mechanical properties of this steel yield strength is more than 235 MPa and tensile strength is 360-510Mpa.

Gland connections with a fluid inlet diameter of 18NPT and outlet diameter of 14NPT were used. Two gasket channels with a diameter of 4 mm were drilled into the pump body and sealing was ensured by using a suitable gasket. The casing and cover of the pump are housed with bearings for the rotor shaft and the counter gear. Fig. 7 is an image of the completed pump body and components.

2.4. Experimental setup

In this study, a laboratory experimental setup was developed to compare the performance of elliptical gear and spur gear pump with respect to each other. The developed experimental setup consists of two subsystems: hydraulic and PLC system. The schematic drawing of this experimental setup is shown in Fig. 8.

The hydraulic system consists of a hydraulic tank with a volume of 14L, gear pump (spur/elliptical), hydraulic equipment to ensure proper operation of the pump. The pumps are driven by a three-phase asynchronous motor with a power of 1.1Kw. A speed controller is used that allows us to change the speed of the electric motor. Flow meter, pressure sensor and temperature sensor are connected to the discharge line of the gear pump respectively (as can be seen in Fig. 9). In this way, it is possible to measure the volumetric flow rate, operating pressure and temperature of the fluid in different operating modes of the pump. A return filter group with sufficient nominal flow rate is connected to the return line to prevent additional pressure load.

As seen in Fig. 8, the other sub-component of the system is the PLC unit consisting of Siemens 1215C CPU and SM1231 analog module. Two transducers are used in these sensors for flow rate, pressure and fluid temperature values. These transducers convert physical quantity (pressure and temperature) into a voltage at their output. Since the flowmeter is gear type, the converter is a frequency counter. The frequency counter output signal is in the form of voltage pulses fed to the input of the PLC. This requires the processing of the signal to be converted into a flow rate of mL/s. It is realized by a specially created command where signal pulses are imported and processed by a loop counter. The measured flow rate signal sampling time is one second and is defined as a counter. The output signal of the flow meter is connected to the CPU input of the PLC

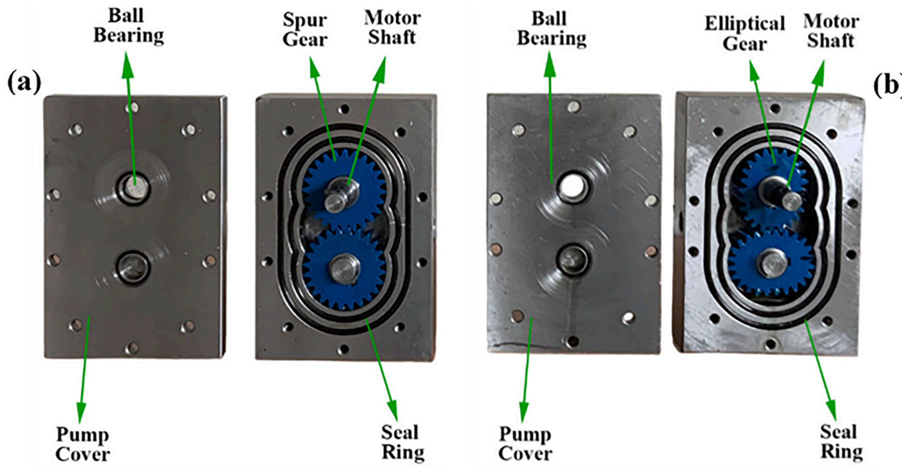

Fig. 7. (a) Hydraulic pump with cylindrical spur gear pair (b) Hydraulic pump with elliptical gear pair after manufacturing and assembly.

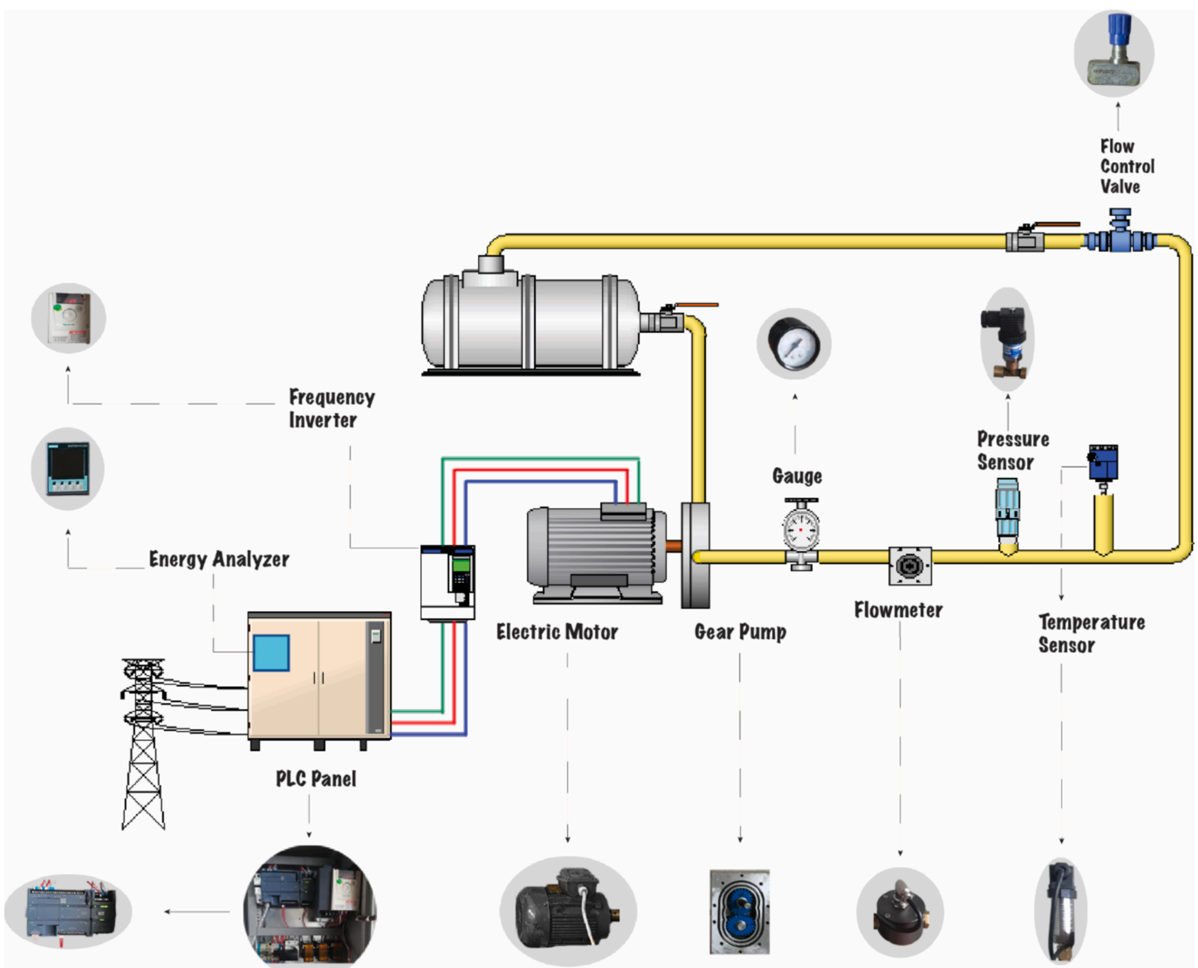

Fig. 8. Schematic of the hydraulic gear pump test bench.

unit, while the output signals of the pressure and temperature sensors are connected to the analog module input (AI). An energy analyzer was also connected to the system to compare the energy efficiency of spur and eliptical gear pumps. All earthing and enclosure terminals are connected to a common point. The connections in the system are made with shielded cables. The parameters of the components used are presented in Table 1.

Flow experiments were carried out with Opet Fullmono HD 10 oil with a density of 0.877 kg/lt and a kinematic viscosity of 35 cSt at 40 °C.

During the tests, rotational speeds, operating times, fluid temperature and whether the pumps are under load or not are taken into consideration as operating conditions. Under these conditions, the gear material (ABS filament) showed mechanical and thermal durability. Details of the operating conditions of the elliptical gear and spur gear

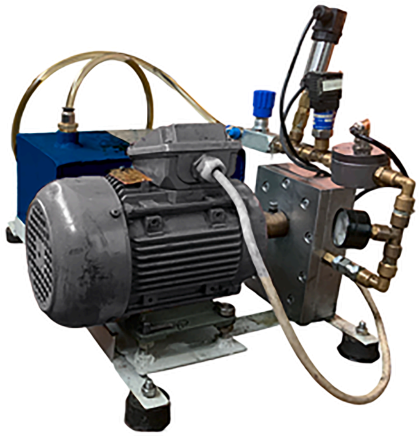

Fig. 9. Closed loop test bench.

Table 1
System components.

Component	Model	Parameters
Tank	Custom design	V = 14L
Electric Motor	WAT Electric Motor	P_{EM} = 1.1 kW n = 3000 rpm
Spur Gear	Custom design	m = 2 z = 24 b = 20
Eliptical Gear	Custom design	m = 2 z = 24 b = 20
Checkvalves	Mirox	Δp_{max} = 2 Mpa
Return Filter Group	Hydrex	η = 25 µm
Flow control valve	HYFC-08	Q_{max} = 25 L/min Δp_{max} = 35 Mpa ΔT = -30 °C – 80 °C
Frequency Inverter	ATV12HU22M2X	U = 380 V P = 2.2 kW
Flow Meter	WatSeasor OFZAT04	Oval Gear type Q = 0.5–20 L/min Δp_{max} = 50 MPa
Pressure Sensor	BCT 22	Δp = 0–1.6 MPa U_{out} = 0–10 V
Temprature Sensor	QDL80A	ΔT = -50 °C-200 °C U_{out} = 0–10 V
Controller	Simatic S7-1200 PLC	CPU 1215C
DAQ Device	Simatic S7-1200 PLC Signal Modules	SM 1231 analog input modules
Energy Analyzer	SENTRON, measuring device	PAC 3200

Table 2
Suitable operating conditions for elliptical and spur gear pump.

Test parameter	Parameter value	Gear material parameter (ABS)
Speed (rpm)	200 – 600 – 1000 – 1400	Suitable (ABS: resistant to low/medium rotational speeds)
Under part-load (kPa)	0–150	Suitable
Under high-load (kPa)	150 – 400	Limited (ABS: not suitable for higher pressure)
Oil temprature (°C)	20 – 40	Suitable (ABS: resistant up to 90–100 °C)
Short/Long Operating time (min)	10 – 60	Suitable (ABS: sufficient for intermittent operating)
Experimental area	Laboratory	Suitable
Fluid type	Hydraulic oil 10 W	Suitable (ABS: resistant to hydraulic oil)

pumps during the tests and the suitability of the gear material are given in Table 2.

2.5. Data collection and processing

The data obtained at different speeds of both spur and elliptical gear pumps were used in the PLC unit and a measurement program was developed with ladder diagram modeling in the TIA Portal V16 software environment. Besides parameterization and adjustment of the Analog Digital converter (ADC) channels through the developed ladder diagram (Fig. 10), the user interface allows real-time monitoring of the scaled values of the parameters and their records are generated. It is possible to change the sampling rate, number of samples, timeout, etc. The output signal of the pressure transducer is a voltage in the range 0–10 V, corresponding to a pressure range of 0–16 bar and the output signal of the temperature transducer is a voltage in the temperature range −50 °C-200 °C. The signal conversion takes place in the software environment based on the PLC manufacturer of linear characteristics.

During the operation of each pump, both hydraulic parameters such as flow rate, pressure and fluid temperature and all electrical parameters such as voltage, current and input power are recorded by the control system.

While calculating the energy consumption in this study, firstly, the average current indices were recorded by the energy analyzer using current transformers connected to the inverter inputs and the input power was determined during the operation of each pump.

Thus, a correlation between the total amount of power and the amount of fluid transferred is proposed (Eq. (13)). As a result, the energy consumption efficiency of each pump can be calculated based on the input and output values [29,32].

$$Energy\ consumption = \frac{Energy\ used}{Pumped\ volume} \tag{13}$$

In addition, to find the input power of each pump, the power consumed by the electric motors and the power required by the motor at different speeds with the help of the inverter can be calculated with Eq. (14) [29,32]. In the equation, V is voltage, I is current and φ is the phase angle.

$$P = \sqrt{3}VI\cos(\varphi) \tag{14}$$

This systematic and controlled method has enabled a precise evaluation of the pump performance at different speeds. The experiments of both hydraulic pumps were carried out with the same experimental setup and under the same experimental conditions.

2.6. Theoretical and experimental comparison of spur gear pump

In the theoretical calculation of the flow values realized at different operating frequencies of the spur gear pump, Eq. (15)-(16) [40] were taken into consideration. In Eq. (15), Q represents the flow rate of the gear pump, z the number of teeth, S the tooth gap area, m the gear modulus, n the motor speed and η_v the volumetric efficiency (85 %-95 %). In Eq. (16), D_a represents the tooth top diameter and D_f represents the tooth bottom diameter.

$$Q = \frac{2.z.S.m.n.\eta_v.60}{10^6} \tag{15}$$

$$S = \frac{D_a^2 - D_f^2}{4.2.z}\pi \tag{16}$$

The theoretically calculated flow rate and experimental data results are shown in Fig. 11. As can be seen from the figure, despite small deviations, the experimental flow rate results and the theoretical results are in agreement with each other. Therefore, it was concluded that the developed experimental setup was capable of measuring accurate values. It is accepted that these small deviations due to possible

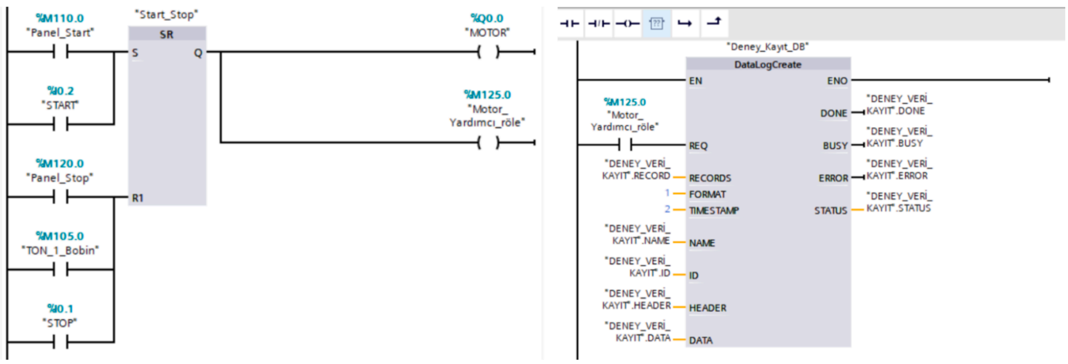

Fig. 10. PLC ladder diagram of the data collection and processing.

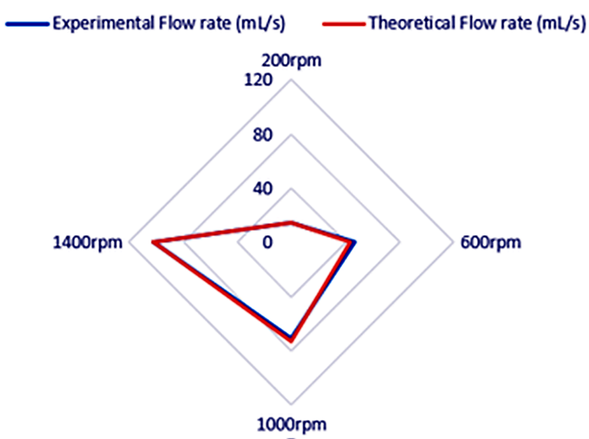

Fig. 11. Experimental and theoretical comparison of spur gear pump.

Table 3
Test factors and levels.

Parameters	Symbol	Level 1	Level 2	Level 3	Level 4
Revolution (rpm)	A	200	600	1000	1400
Hydraulic Pump	B	SG	EG		

SG: Spur Gear, EG: Elliptical Gear.

manufacturing and assembly errors can be ignored. Thus, the experimental setup designed and manufactured within the scope of the study is within acceptable limits.

2.7. *The Taguchi method of experimental design*

In this study, Taguchi L8 (4^1x2^1) orthogonal experimental design with two factors and mixed level design was applied to determine the hydraulic pump performance. The number 8 indicates that 8 trials are required. The array can operate up to 2 factors at 4 levels each. Pump performance conditions were determined by considering the calculated signal-to-noise ratios (S/N). In order to achieve higher efficiency, the "bigger is better" approach was followed for flow and pressure in the calculation of signal-to-noise ratios, while the "smaller is better" approach was taken into account in the calculation of energy consumption. The parameters used in the experimental study and their levels are presented in Table 3.

The symbols A and B in Table 3 are used to denote the rotational speed (rpm) and pump type parameters, respectively. In addition, rotational speed is presented with four levels while pump type is presented with two levels.

3. Results and Discussion

Volumetric flow rate measurements, operating pressures, temperature changes and energy consumption data of the spur gear and elliptical gear pumps tested in the experimental setup at different speeds and under different loads are presented and evaluated. Prior to the experiments, the experimental setup was run for ten minutes without data acquisition in order to increase the precision of the measurements and eliminate possible errors.

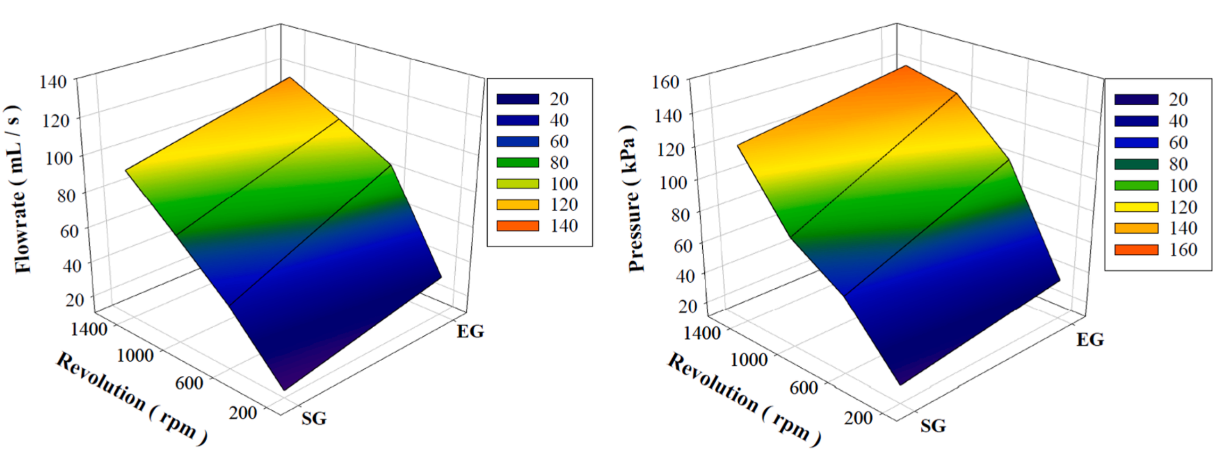

Fig. 12. Flow rate and pressure performance of spur gear and elliptical gear hydraulic pump.

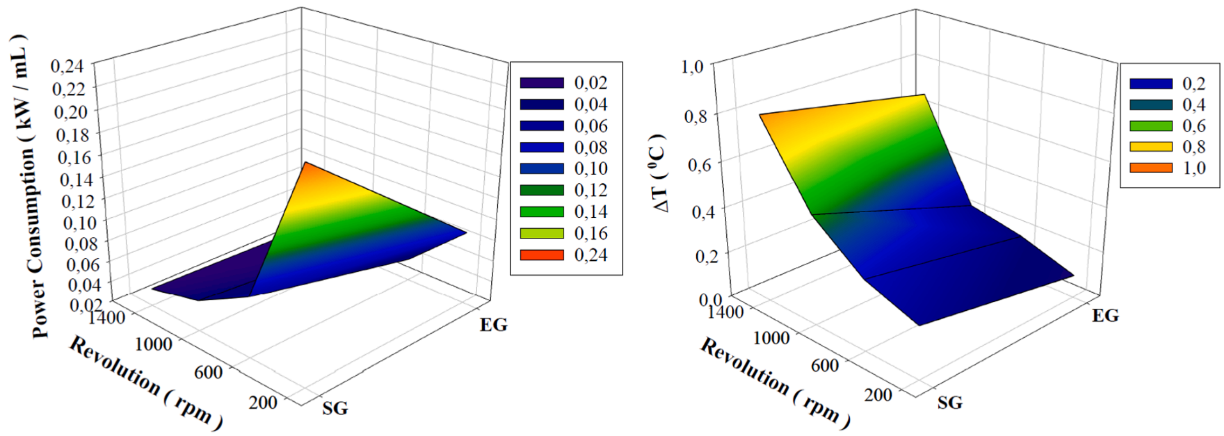

Fig. 13. Energy consumption and temprature difference of spur and eliptical gear hydraulic pump.

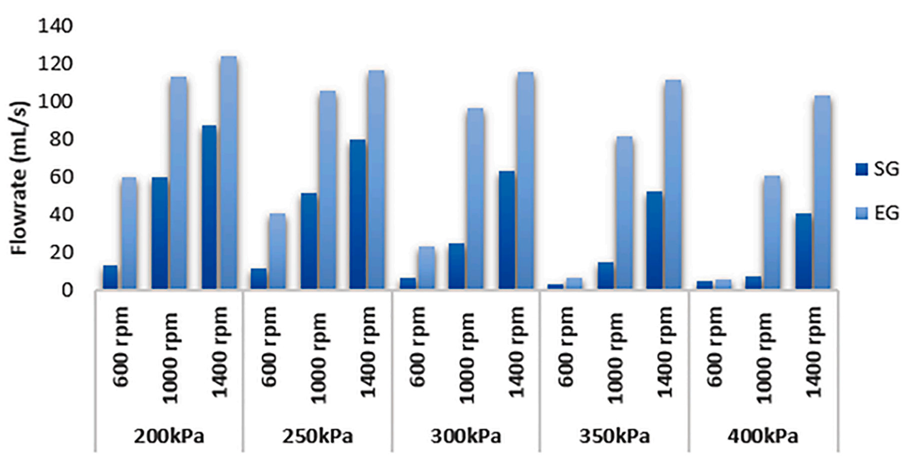

Fig. 14. Flow performance of spur and elliptical gear hydraulic pumps under high loads.

3.1. Experimental results

3.1.1. Experimental analysis of spur gear and elliptical gear hydraulic pumps under part-loads

The effect of gear type parameter on flow rate and pressure is shown graphically in Fig. 12. When the pumps tested at four different speeds were examined, it was observed that the elliptical gear pump transported larger amounts of liquid more effectively than the spur gear pump. At 200 rpm, the elliptical gear pump moves about twice as much liquid as the spur gear pump. When the speed was increased from 200 rpm to 600 rpm, although the amount of liquid transport of both pumps increased, the elliptical gear pump transported approximately 85 % more liquid than the spur gear pump. When the speed was increased from 600 rpm to 1000 rpm, the elliptical gear pump transported about 45 % more liquid. At 1400 rpm, it was observed that it transported approximately 20 % more liquid.

When all speeds are analyzed, it is concluded that the elliptical gear pump has a very high liquid carrying capacity for each speed and is efficient as can be seen from the performance graph shown in Fig. 12. However, the low speed range of the elliptical gear pump tested in this study was found to be more efficient.

Due to their high flow capacity and efficient performance, elliptical gears should be preferred in industrial applications where low speeds are required. This provides the flexibility to work in different conditions in a variety of industries. Also, for fast rotating machines or applications, elliptical gears are thought to be more ideal solution providers than spur gears.

When the graph given in Fig. 12 is examined, it is observed that the spur gear pump shows linear pressure increase while the elliptical pump shows non-linear pressure increase depending on the speed value. It is observed that the elliptical hydraulic pump exhibits approximately 120 % performance at 200 rpm compared to the spur gear pump. However, when increased from 200 rpm to 600 rpm, the pressure of the elliptical gear hydraulic pump increased by about 50 % compared to the previous cycle, while the spur gear pump increased by about 30 %. In addition, as a result of the examination between 1400 rpm, it was found that the spur gear pump performed about 3 % higher than the elliptical gear pump.

In particular, it is observed that the elliptical gear pump performs better in the low speed range. In the light of these data, it can be said that the elliptical gear pump will generally be suitable for operation at higher pressures at lower speeds. Therefore, it is concluded that the elliptical gear pump is advantageous in terms of pressure performance.

To compare the energy efficiency of two pumps, factors such as energy consumption and flow performance are taken into account. In this context, when the energy consumption graph given in Fig. 13 is examined, it is seen that the spur gear hydraulic pump consumes approximately 140 % more energy than the elliptical gear pump at 200 rpm. By increasing the pump speed from 200 rpm to 600 rpm, it was determined that the spur gear hydraulic pump consumed approximately 85 % more energy compared to the elliptical gear pump. At 1000 rpm, the spur gear pump consumed about 36 % more energy. At 1400 rpm, both gear pumps consume almost the same amount of energy, although the elliptical gear pump is known to move more fluid.

When the energy consumption and flow rate performance of the spur gear pump are analyzed, it can be said that at low speeds, the spur gear pump loses pump efficiency compared to the elliptical gear pump.

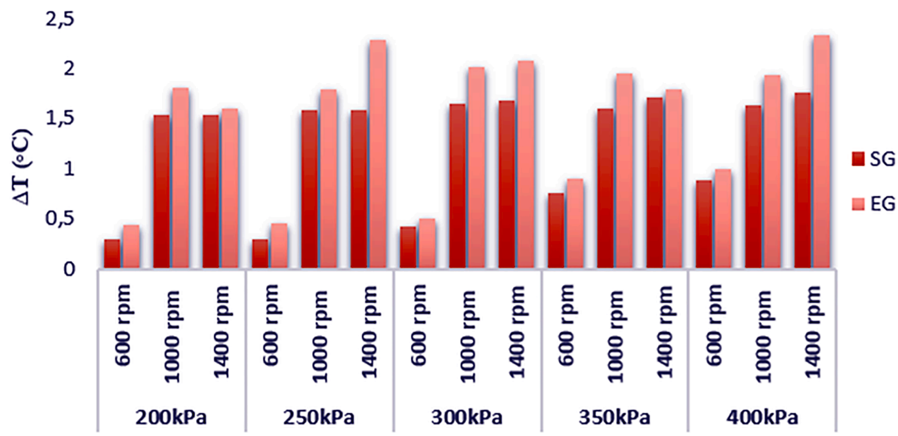

Fig. 15. Temperature difference between spur and elliptical gear hydraulic pumps under high loads.

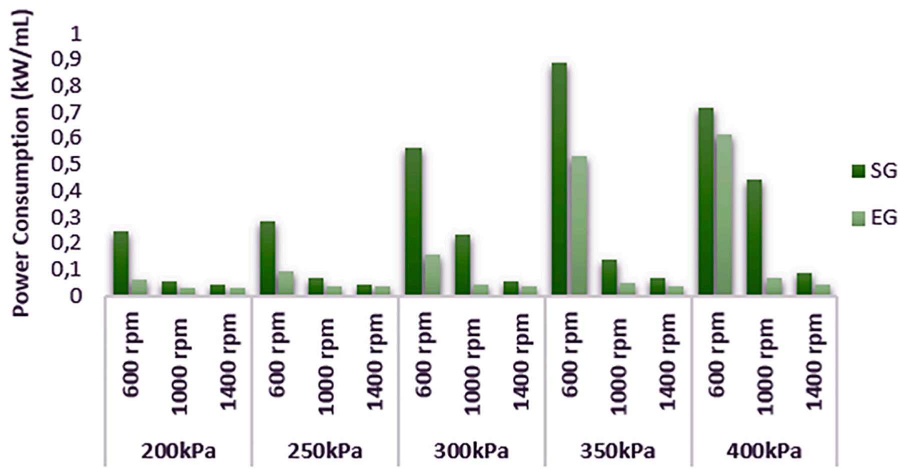

Fig. 16. Energy consumption performance of spur and elliptical gear hydraulic pumps under high loads.

Table 4
Experimental results and S/N ratios.

Exp. No	Control factors: A (rpm)	B (Hyd. Pump Type)	Q (mL/s)	P (kPa)	Δ T (°C)	EC (kW/mL)	S/N ratio Q (mL/s)	S/N ratio P (kPa)	S/N ratio Δ T (°C)	S/N ratio EC (kW/mL)
1	200	SG	14	21	0.23	0.212	22.92	26.44	12.77	13.47
2	200	EG	32	36	0.10	0.089	30.10	31.13	20.00	21.01
3	600	SG	45	59	0.31	0.077	33.06	35.42	10.17	22.27
4	600	EG	85	101	0.18	0.041	38.59	40.09	14.89	27.74
5	1000	SG	70	80	0.48	0.049	36.90	38.06	6.38	26.20
6	1000	EG	101	132	0.23	0.036	40.09	42.41	12.77	28.87
7	1400	SG	94	123	0.81	0.037	39.46	41.80	1.83	28.64
8	1400	EG	116	140	0.67	0.033	41.29	42.92	3.48	29.63

EG: elliptical gear, SG: spur gear Q: flowrate, P: pressure, ΔT: temperature difference, EC: energy consumption.

Table 5
S/N and significance response tables for flowrate and pressure.

Level	Q (mL/s) Revolution (rpm)	Q (mL/s) Hydraulic Pump	Level	P (kPa) Revolution (rpm)	P (kPa) Hydraulic Pump
	A	B		A	B
1	26.51	33.09	1	28.79	35.43
2	35.83	**37.52**	2	37.75	**39.14**
3	38.49		3	40.24	
4	**40.38**		4	**42.36**	
Delta	13.86	4.43	Delta	13.58	3.71
Rank	1	2	Rank	1	2

Because when both the flow rate and energy consumption of the pumps at low speeds are compared, it is understood from the graphs that the spur gear pump carries less liquid and has more energy consumption capacity. In addition, when the energy consumption and flow performance of the elliptical gear pump are analyzed, it is seen that the flow performance increases with increasing energy consumption. However, when the energy consumption of both pumps is analyzed according to flow rate performance, it is seen that the elliptical gear pump is more efficient.

As can be seen from the graph obtained in Fig. 13, it is observed that there is a lower amount of temperature difference in the liquid pumped by the elliptical gear hydraulic pump compared to the spur gear

Table 6
S/N and significance response tables for temperature change and energy consumption rate.

Level	Δ T (°C)		Level	EC (kW/mL)	
	Revolution (rpm)	Hydraulic Pump		Revolution (rpm)	Hydraulic Pump
	A	B		A	B
1	**16.38**	7.79	1	17.24	22.64
2	12.53	**12.79**	2	25.01	**26.82**
3	9.58		3	27.54	
4	2.65		4	**29.13**	
Delta	13.73	4.99	Delta	11.89	4.17
Rank	1	2	Rank	1	2

hydraulic pumps at the same speeds. In the examinations of the hydraulic pumps at 200 rpm and 600 rpm, a temperature difference of approximately 130 % more occurs in the spur gear hydraulic pump compared to the elliptical gear pump, while more than twice the temperature difference occurs at 1000 rpm and 1400 rpm. As a result of these examinations, it can be seen from the graph that elliptical gear pumps tend to heat up less in general.

3.1.2. *Experimental analysis of spur gear and elliptical gear hydraulic pumps under high-loads*

When the pumps are tested at high speeds and under five different loads, it is observed that the elliptical gear pump transports larger quantities of liquid more efficiently than the spur gear pump even under high loads.

It is seen that the elliptical gear pump transports on average about

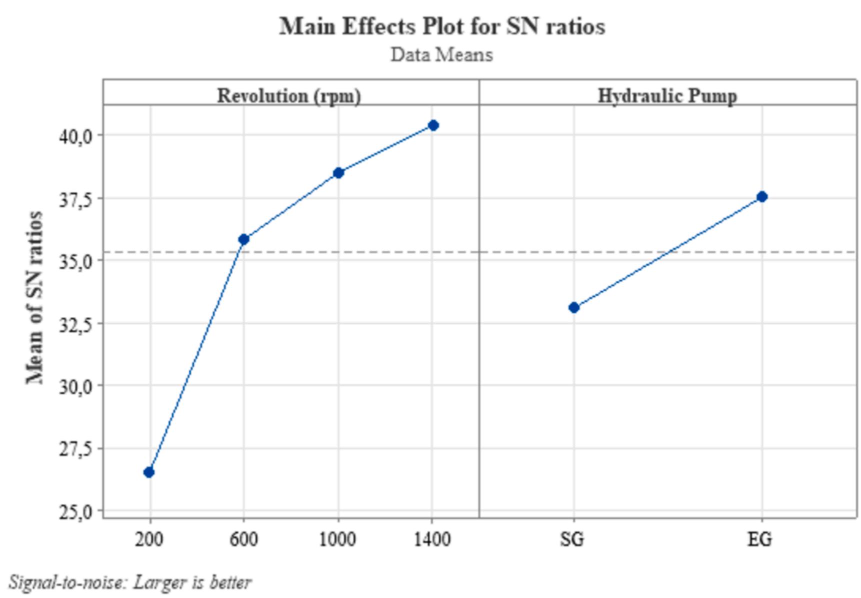

Fig. 17. Hydraulic pump parameter effects on average S/N ratio for flow rate.

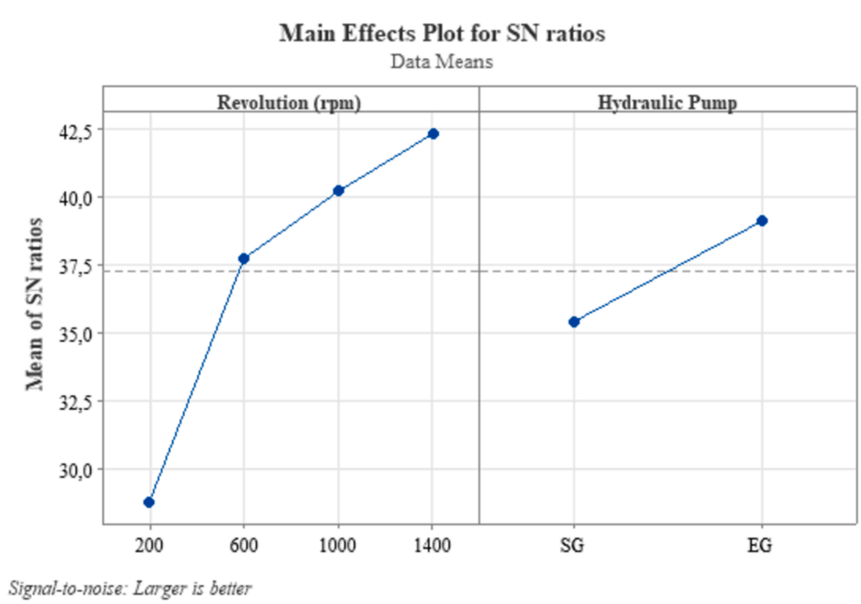

Fig. 18. Hydraulic pump parameter effects on average S/N ratio for pressure.

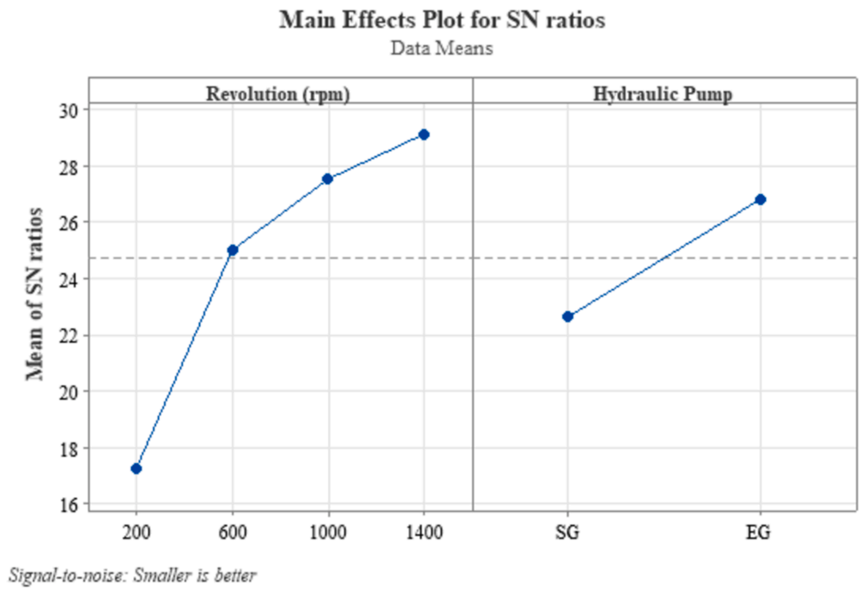

Fig. 19. Hydraulic pump parameter effects on average S/N ratio for energy consumption.

Table 7
Equations for prediction of flow rate, pressure and energy consumption.

Flow rate (mL / s)	
SG (linear)	Flow rate (mL/s) = 2.45 + 0.06663 Rev (rpm)
EG (linear)	Flow rate (mL/s) = 30.20 + 0.06663 Rev (rpm)
R-sq = 95.16 %	
SG (quadratic)	Flow rate (mL/s) = -13.02 + 0.1229 Rev (rpm) – 0.000035 Rev (rpm)ˆ2
EG (quadratic)	Flow rate (mL/s) = 14.73 + 0.1229 Rev (rpm) – 0.000035 Rev (rpm) ˆ2
R-sq = 98 %	
Pressure (kPa)	
SG (linear)	Pressure (kPa) = 3.8 + 0.0838 Rev (rpm)
EG (linear)	Pressure (kPa) = 35.3 + 0.0838 Rev (rpm)
R-sq = 93.57 %	
SG (quadratic)	Pressure (kPa) = -14.1 + 0.1488 Rev (rpm) – 0.000041 Rev (rpm)ˆ2
EG (quadratic)	Pressure (kPa) = 17.4 + 0.1488 Rev (rpm) – 0.000041 Rev (rpm)ˆ2
R-sq = 96 %	
Energy Consumption (kW/mL)	
SG (linear)	Energy consumption (kW/mL) = 0.1663—0.000091 Rev (rpm)
EG (linear)	Energy consumption (kW/mL) = 0.1223—0.000091 Rev (rpm)
R-sq = 67 %	
SG (quadratic)	Energy consumption (kW/mL) = 0.2241 – 0.000301 Rev (rpm) + 0.000000 Rev (rpm)ˆ2
EG (quadratic)	Energy consumption (kW/mL) = 0.1801 – 0.000301 Rev (rpm) + 0.000000 Rev (rpm)ˆ2
R-sq = 81 %	

three times more liquid than the spur gear pump at 600 rpm and 1000 rpm, while this is about twice as much at 1400 rpm. At 600 rpm, it is seen that the elliptical gear pump is significantly superior to the spur gear pump when the load value acting on the pumps is low, but as the load value increases, it is observed that the liquid carrying capacity of both pumps approaches each other. However, it is seen that the opposite is realized at 1000 rpm and 1400 rpm. When all loads are evaluated, it is concluded that the ellipse gear pump is efficient as can be seen from the performance graph shown in Fig. 14. This can offer ideal solutions for different sectors operating in the industrial field.

As can be seen from the graph obtained in Fig. 15, it is observed that under the same speed and the same loads, almost similar temperature difference occurs in the liquid pumped by spur gear and elliptical gear hydraulic pumps. Under all loads, it is seen that there is a very small temperature difference at 600 rpm compared to other speeds. At the same time, although it is seen that the temperature of both pumps increases linearly with linear load increase at 600 rpm, it is not possible to say this at other speeds. As a result of these examinations, it can be seen from the graph that elliptical gear pumps tend to heat up more than straight gear pumps under load.

The energy consumption of elliptical gear and spur gear pumps under high loads is expressed in Fig. 16. When the graph given in Fig. 16 is analyzed, energy consumption increases as the load applied on the pumps increases. With the linear increase in the load applied to the pumps, the elliptical gear pump exhibits a linear behavior while the spur gear pump exhibits a non-linear behavior. The energy consumption of the elliptical gear pump under load at low speed is significantly lower than the energy consumption of the spur gear pump under load. However, as the speed increases, the energy consumption values of the pumps approach each other. Although the energy consumption of the pumps are close to each other at high speeds, the energy consumption of the elliptical gear pump is more preferable than the spur gear pump. As can be seen from the graph shown in Fig. 16, it is concluded that the elliptical gear pump is advantageous in terms of energy consumption performance.

3.2. Analysis of the signal-to-noise (S/N) ratio of hydraulic pumps

Table 4 shows the S/N ratios and output variable (flow rate, pressure, temperature and energy consumption) results obtained by Taguchi L8 (mixed level) experimental design on the hydraulic pump. Taguchi significance response table was used to determine the most effective control factors among rotational speed and pump type control factors for optimum levels of flow rate, pressure, temperature and energy consumption performance characteristics. Table 5 and Table 6 present the S/N significance response table and show which pump type is most effective. When Table 5 is examined, it is seen that the elliptical gear hydraulic pump, which is one of the hydraulic pump types, is quite effective in flow and pressure significance response values compared to the spur gear pump. When Table 6 is examined, it is seen that the elliptical gear hydraulic pump is effective on the fluid temperature change at low speeds. In terms of energy consumption, it is seen that the elliptical gear hydraulic pump has an advantage over the spur gear hydraulic pump even at high speeds.

When evaluating the S/N ratios and experimental analyses obtained with Taguchi L8 experimental design, S/N ratio graphs were obtained by selecting the highest flow rate and pressure and the smallest energy consumption value (Figs. 17-19). When these results are evaluated, the flow rate is normally directly proportional to both parameters. Changing the pump shaft rotation speed and pump type causes the flow rate to increase. Although the energy consumption (kW/mL) was found to be inversely proportional to the experimental parameters, it was determined that the shaft rotation speed increase would not show the same inverse ratio. According to these results, it is determined that pump type is the most important factor in flow rate, pressure and energy consumption. Thus, it is determined that the elliptical gear pump is more efficient than the spur gear pump among the pumps with the same number of teeth and modulus.

3.3. Regression analysis of hydraulic pumps

Regression analysis is applied for modeling and analysis when there is a relationship between a dependent variable and one or more independent variables. In this study, regression analysis is used to calculate the equations for predicting the flow rate, pressure and energy consumption of the pump. The equation predictions were formulated as a first order model due to the comparison of the spur gear pump with the elliptical gear pump. Table 7 shows the estimated linear equations for the output parameters. The R^2 values found through the linear regression model equations were 95.16 % for flow rate, 93.57 % for pressure and 67 % for energy consumption value.

The comparison of the predicted values in the second order regression model with the experimental results is shown in Figs. 20-22. A very good correlation was found between the predicted values and the experimental results. In the equations performed with the second order

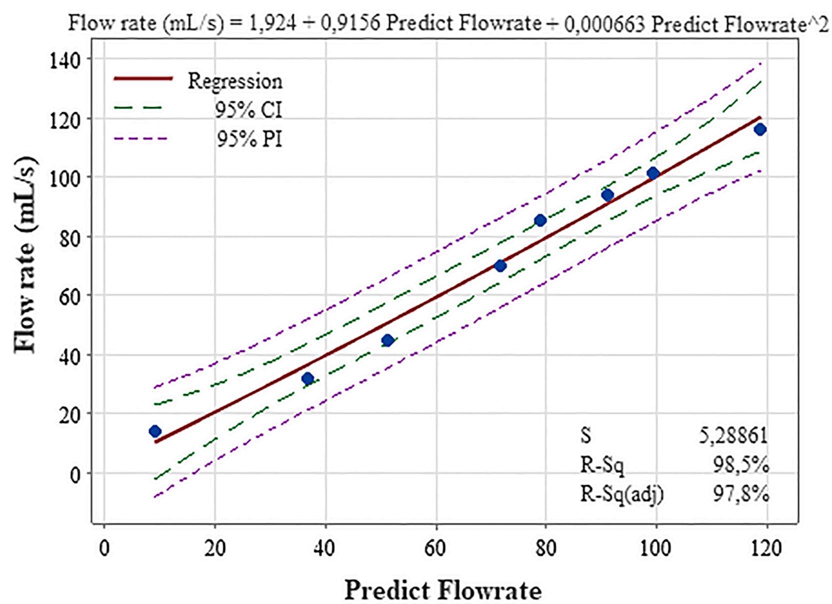

Fig. 20. Quadratic regression model compared with experimental results for flowrate.

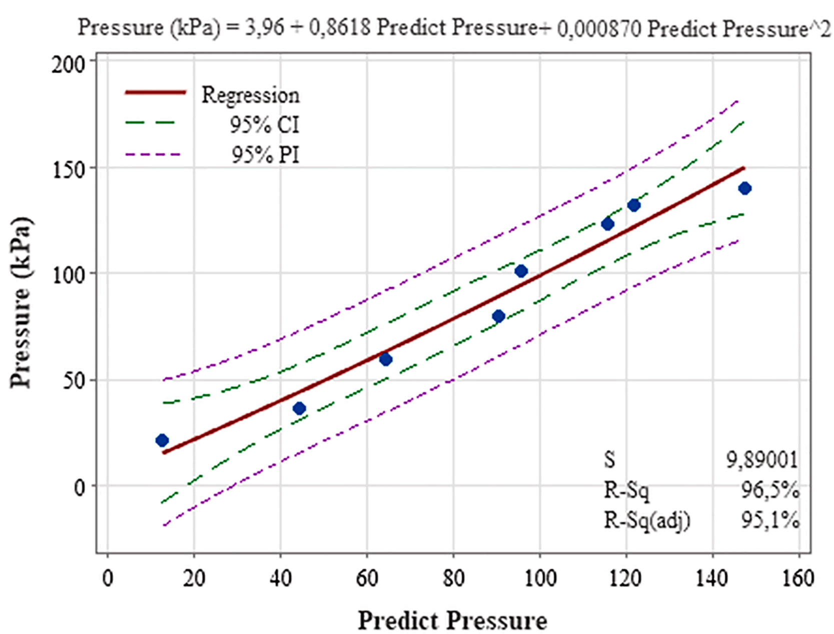

Fig. 21. Quadratic regression model compared with experimental results for pressure.

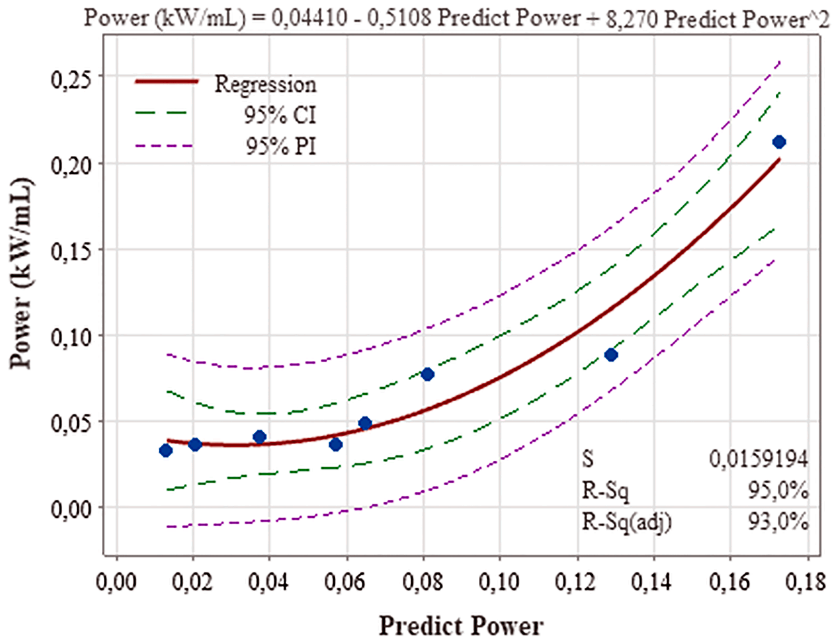

Fig. 22. Quadratic regression model compared with experimental results for energy consumption.

regression model, R^2 values were determined as 98 % for flow rate, 96 % for pressure and 81 % for energy consumption value. The fact that the prediction values obtained with the quadratic regression model are better than those obtained with the linear regression model reveals that the quadratic regression model is successful in predicting flow, pressure and energy consumption.

4. Conclusions

The ever-increasing costs of energy supply have made energy conservation a necessity. Considering that the need for energy consumption in industry is much higher than in other areas and that the use of pumps in industry is widespread, the importance of the research can be easily understood. This paper aims to investigate the effects of flow processes in an external gear pump on performance and energy consumption efficiency. For this reason, spur gears with well-known technical specifications and elliptical gears with not so well-known technical specifications were used in these pumps. An experimental setup has been developed that allows us to successfully measure the variables needed. An analysis based on the Taguchi method was carried out to evaluate the energy consumption performance of gear hydraulic pumps by comparing the experimental results.

- When the flow, pressure, and energy consumption performance effects of external gear (spur and elliptical) hydraulic pumps subjected to motor shaft speed operation were evaluated by Taguchi method, it was seen that the elliptical gear pump gave good results.
- It was found that the flow rate of the elliptical gear hydraulic pump was about 120 % higher at low speeds and about 46 % higher at high speeds compared to the values of the spur gear pump.
- The pressure value of the elliptical gear hydraulic pump is more than twice as high at low speeds compared to the values of the spur gear pump, while it performs the same as the spur gear pump at high speeds.
- It was observed that spur gear hydraulic pumps consume approximately 140 % more energy at low speeds than elliptical gear hydraulic pumps and have the same energy consumption at high speeds.
- It can be said that the elliptical gear pump has a considerably higher liquid carrying capacity for each speed, is suitable for operation at higher pressures at lower speeds and tends to heat up less in general.
- It is observed that elliptical gear pumps maintain their overall performance tendency even under high loads
- In the light of these data, it can be said that the elliptical gear pump shows a very high performance in terms of energy efficiency.

As a result, when making a choice between spur gear and elliptical gear hydraulic pumps, factors such as application requirements, energy efficiency and performance should be considered.

CRediT authorship contribution statement

Mithat Yanikören: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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