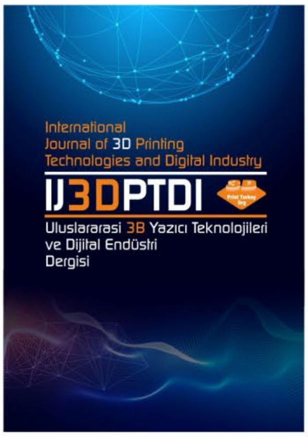

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A NEW SPECIFIC CARBON FOOTPRINT (SCF) THEORY OF FLOW RATE AND ENERGY CONSUMPTION VARIATIONS OF AN INDUSTRIAL INTERNAL GEAR PUMP

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ABSTRACT

Pumps in fuel oil systems are mechanical equipment used for the transfer of liquid fluid from one place to another. In particular, pumps are required to transfer the maximum flow rate in the transfer units in minimum time. They consume a very high amount of energy for this transfer. In this research, research studies were carried out to ensure the transfer of the highest possible amount of fuel oil by consuming energy at optimal rates. In this experimental study, the energy consumption and flow rate were measured across a range of engine speeds (100-700 RPM) and varying gear lengths (90-100 mm). According to the findings, energy consumption reached ideal levels at 600 RPM engine speed. In addition, it was determined that the lowest CO_2 emission was obtained in the range of 600-700 RPM and by using long gear length. In addition, it is observed that the effect of gear length on energy efficiency is significant and energy consumption decreases as the gear length gets shorter. The results show that minimum energy consumption can be obtained with maximum flow rate at 609 RPM engine speed and 100 mm gear length. The ANOVA analysis used in the study reveals that the flow rate changes are 98% related to the engine speed, while the gear length is 78% effective in CO_2 emission reduction. This research provides an important contribution to energy efficiency and carbon emission reduction in industrial applications. This study provides an innovative method that can be used to achieve energy saving and environmental sustainability goals and makes valuable contributions to the literature on optimizing internal gear pump designs.

Keywords: Carbon Footprint, Energy Efficiency, Energy Consumption, Internal Gear Pump.

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1. INTRODUCTION

Pumps are machines that can use electrical energy for fluid transfer through a mechanical transfer system. It is a part of a transfer system used to transport all kinds of fluids from one place to a desired different place and to control the amount of flow (flow rate) [1]. The rapid filling or emptying of tanks is one of the most important factors directly affecting the performance of these systems. However, it is not enough to perform this process quickly. It is also very important to work with minimum energy consumption during this transfer process. In other words, the system must both work fast and provide energy efficiency. Thus, performance can be kept at the highest level while reducing costs [2-3].

Technically, "energy efficiency" means using fewer energy inputs while maintaining the same level of economic activity or service, whereas "energy conservation" is a broader concept that includes reducing consumption through behavioral change or reduced economic activity. In practice, it is difficult to distinguish between these two concepts and the terms are often used interchangeably [4]. Energy efficiency means producing the same amount of goods and services using less energy or producing more goods and services with the same amount of energy. When this is achieved, businesses can gain competitive advantage both locally and internationally [5].

Among the machines that consume electricity, pumps are one of the highest energy consumers with a share of 20%. Therefore, the appropriate use of pump systems and energy efficiency has become an important issue. Although improvements in pump efficiency are limited, it has been determined that up to 30% energy savings can be achieved with proper design and optimization of pump systems [6]. Design parameters in pumps have a direct impact on efficiency and energy consumption; these parameters affect pump performance and energy consumption [7]. At the same time, the use of highly efficient pumps alone is not sufficient for a pumping system to operate at maximum efficiency. Efficient operation of pumping systems depends not only on the design of the pump, but also on the correct design of the entire system and favorable operating conditions. In an incorrectly designed or incorrectly installed system, even the most efficient pump cannot perform as expected and can become inefficient [8]. Therefore, it should not be forgotten that system design and installation play an important role in energy efficiency as well as design parameters.

Pumps are inefficient systems that cause the loss of approximately 40% of energy inputs. Optimization of these systems can be achieved through strategies such as correction of misconfigured pump systems, replacement of old and high maintenance cost systems and detection of damaged pumps. Such improvements can lead to significant energy savings in motorized pump systems, which account for approximately 25% of energy consumption in the manufacturing sector [9].

In the study conducted by Bae et al., the rotor profile was optimized using automatic design methods and multiple calculation programs, taking into account fuel efficiency and low torque demands. During the design process, various parametric analyses and calculations were performed to obtain the ideal rotor profile. The prototypes were subjected to performance tests and the calculated torque values were compared with experimental data.

The results show that the calculated torque values show high agreement with the experimental data, and this agreement reveals the accuracy of the design and simulation processes. This result proved that the rotor design was successful in achieving the efficiency and performance targets. [10]. In his study, Akhan achieved significant energy savings by using frequency inverter in variable flow fan and pump systems. In the study, thanks to the use of frequency inverter, the efficiency of the systems was optimized and energy consumption was reduced by 60% [11].

The highly efficient P/M internal gear pump rotors developed by Sasaki and his team are called Megafloid rotors and respond to the demands for fuel consumption reduction and hydraulic power increase in the automotive industry. These rotors are equipped with an innovative tooth profile and offer a discharge volume of 10% or more compared to conventional rotors of the same size. Thanks to these features, the pumps can be produced in smaller sizes and operate with lower torque, resulting in significant improvements in fuel efficiency. Megafloid rotors are widely used, especially in automotive engine oil pumps, contributing to energy efficiency targets in the industry [12]. In their study, Öztürk and Küçük developed a new gear pump design to optimize energy consumption. This design, obtained by using the Fundamental Motion Analysis method, aims to provide maximum flow rate with low energy consumption during fuel transfer. In the study, the effects of engine speed and gear design on energy consumption were investigated and it was determined that energy consumption was minimized especially in the 500-600 RPM range. In the experiments, it is predicted that 3506 kWh energy saving can be achieved annually with the newly developed spur gear pump design.[2]. In their study, Özürk et al. present an experimental investigation on the optimization of energy consumption of internal gear pumps using Taguchi and Response Surface Method (RSM). In the study, the effects of the pump design parameters of tooth length and motor speed on flow rate, power consumption and specific energy consumption (SEC) were investigated. The optimum motor speed was determined as 700 RPM and tooth length as 85 mm, and energy consumption was reduced by 41% from 156.1 Wh/m³ to 92.0 Wh/m³ with the new pump design. The effect of flow rate change on energy consumption was found to be 83% [13]. Artificial Neural Networks, RSM, and Taguchi techniques are frequently used in various fields and diverse industrial applications due to their robust sensing and optimization capability [14-17]. In a study conducted by the American Hydraulic Institute, 20% of the energy consumed in developed countries is consumed by pumps. It is explained that 30% of this energy can be saved with a good system design and selection of suitable pumps [18].

The need for energy in the world has emerged in four different areas: industry, transport, housing and trade. The highest energy consumption is realized in industry with 51% and in transport with 27% (Figure 1). Energy consumption in production worldwide has been increasing continuously for the last 20 years and it is predicted that it will be in a continuous increase for the next 20 years (Figure 2). The limited availability of energy resources has led to a continuous increase in energy costs [19].

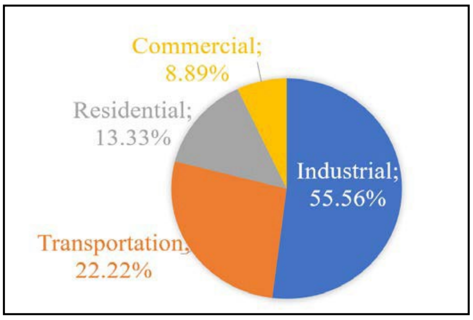

Figure 1. Energy consumption areas in the world [19].

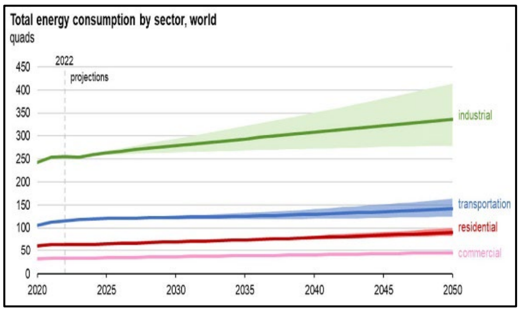

Figure 2. Total energy consumption by sector, World [19].

The concepts of sustainable production and energy efficiency are of great importance in modern engineering practice. Studies in these fields aim to save energy, optimize resource use and reduce environmental impacts in production processes. In particular, life cycle assessment and resource efficiency strategies in manufacturing processes are widely applied to increase environmental and economic sustainability in production [20-22].

Strategies to improve energy efficiency and optimise resource use increase production efficiency by reducing energy intensity in industrial processes. In this way, businesses reduce their carbon footprint while at the same time reducing costs [22].

Carbon footprint is one of the most widely used indicators to measure climate impacts today. Since its introduction in public relations, various stakeholders have continued their efforts to reduce their carbon footprint and communicate this to customers and other interested parties. Carbon footprinting is a component of life cycle assessment (LCA) that focuses solely on greenhouse gas emissions. LCA is guided by ISO 14040-44:2006 standards, while carbon footprint calculations are performed according to ISO 14067:2018 standard [23].

In this study, experimental design methods using RSM (Response Surface Method) will be applied for the design and optimization of energy consumption and energy efficiency. In this way, it is aimed to develop an ideal pump to increase sustainability.

2. MATERIAL AND METHOD

In the calculation of active power in 3-phase electric motors, it is calculated with parameters such as the energy load (I) measured with an ammeter and the voltage value (V) of the motor. For three-phase motors, this power consumption is calculated in kW using energy power conversion equations. The generally used equation is converted into kW power consumption with the equation (Equation 1). I=Energy load measured by ammeter (A), Cos σ=Power Factor (Induction Motor; 0,85) [8, 24,25].

$$\boldsymbol{P\ total} = \sqrt{3}.V.I.Cos\ \sigma \tag{1}$$

Carbon footprint is a measure of the total emissions of carbon dioxide (CO_2) and other greenhouse gases released directly or indirectly into the atmosphere by individuals, businesses or products. These emissions can come from a variety of sources, such as the burning of fossil fuels, deforestation and agricultural activities. The carbon footprint is usually expressed in terms of carbon dioxide equivalents (CO_{2e}), which provides a combined measure of the impacts of different greenhouse gases on the climate. According to a report published by

Defra, based on 2023 data, the emission factor for natural gas is 0.202 kg CO_{2e} per kilowatt-hour (kWh), while the emission factor for coal used in electricity generation is 0.33 kg CO_{2e} per kilowatt- hour. However, after taking into account all production types and related processes, the average emission factor is considered to be 0.48 kg CO_{2e} per kilowatt-hour (Equation 2) [26,27].

$$CF_{(t)}\,(CO_2) = 0.48 \times \sum_{k=1}^{\Delta t} kWh \qquad (2)$$

The Surface Method (RSM) has been used to determine the optimal machining conditions of extruded aluminum parts. Developed in 1951 by Box and Wilson, RSM provides fast and sequential results for the improvement, optimization and modelling of complex processes in industrial experiments [28]. This method designs a series of experiments with the aim of obtaining optimal results by analyzing the interactions between various independent variables and one or more response variables [29,30]. When the linear function of the independent variable closely matches the response of the system, the approximation is modelled using a first-order equation [31]. In this research study, the selection of the gear length and the number of revolutions required to provide the most ideal fuel oil transfer during this process while ensuring minimum energy consumption was carried out using the RSM method.

Table 1. RSM Experiment Design.

RPM	Length (mm)	StdOrder	RunOrder	Blocks	PtType
100	100	1	1	1	1
200	100	2	2	1	1
300	100	3	3	1	1
400	100	4	4	1	1
500	100	5	5	1	1
600	100	6	6	1	1
700	100	7	7	1	1
100	90	8	8	1	1
200	90	9	9	1	1
300	90	10	10	1	1
400	90	11	11	1	1
500	90	12	12	1	1
600	90	13	13	1	1
700	90	14	14	1	1

While the speed change in the range of 100-700 RPM was determined as the parameter level, the gear length of 90-100 mm was selected as the second parameter. The pump body and gear were manufactured by turning on a lathe according to the technical drawing dimensions. Table 1 shows the RSM experiment design.

The thrust gear pump used in the experiments and the IPT Fuel Oil test system where the tests were performed are shown in Figure 3. Within the scope of university - industry cooperation, all experiments were carried out with the support of the R&D unit of the factory and all results were reported and then the necessary statistical analysis was carried out.

Figure 3. Pump efficiency test unit.

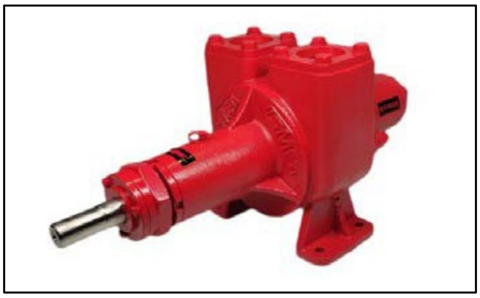

Figure 4. Internal gear pump

3. EXPERIMENTAL FINDINGS

All test results performed according to the experimental design are presented in Table 2.

Table 2. Experiment Results.

Volume (Lt)	Power (W)	SEC (kW/lt)	SCF (CO_2)
108	1140	94.74	45.5
226	1980	114.14	54.8
326	2620	124.43	59.7
440	3340	131.74	63.2
560	4220	132.70	63.7
600	5070	118.34	56.8
660	5700	115.79	55.6
89	865	102.89	49.4
188	1520	123.68	59.4
280	2150	130,23	62.5
390	2540	153.54	73.7
480	2880	166.67	80.0
560	3200	175.00	84.0
600	3600	166.67	80.0

Specific energy consumption values are considered as an important indicator in determining the ideal energy consumption. As a result of the analyses, it was observed that the ideal energy consumption value was reached at 600 RPM. In instantaneous current changes, it has been determined that a significant reduction in energy consumption is achieved by reducing the gear length. In particular, the instantaneous power consumption was reduced from 5.7 kW to 3.6 kW. The lowest CO_2 emission results were obtained in the 600-700 RPM ranges with the use of gears between 200-300 mm in length. Similar results were obtained in the studies conducted in the literature [32,33]. However, it is considered that these ranges may not always be a suitable choice due to the low amount of flow rate required at lowspeed ranges. Figure 5 shows the SCF (Stress Concentration Factor) and Figure 6 shows the Probability Plot graph showing the accuracy of the values obtained for the volume results. It can be stated that the results obtained are within the lower and upper limit value range and the experiments are completed within the desired confidence interval.

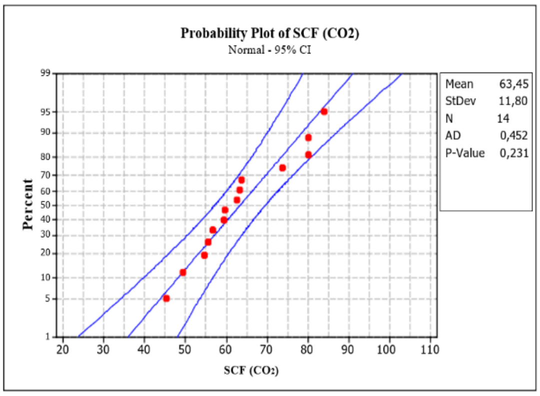

Figure 5. Probability Plot of SCF (CO_2) Results.

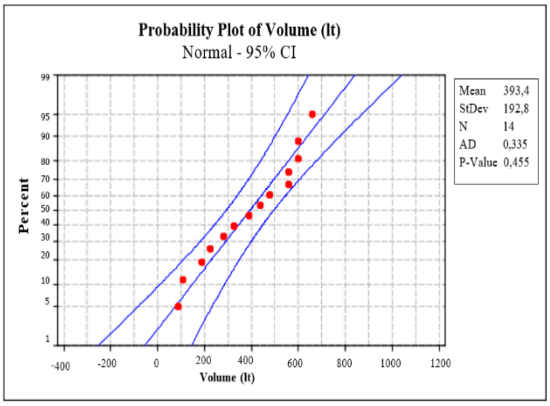

Figure 6. Probability Plot of Volume (Lt) Results.

Figures 7, 8 and 9 show the Surface Plot graphs generated using the Response Surface Methodology (RSM) method.

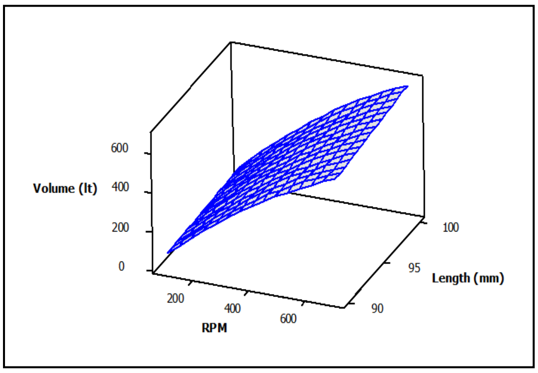

Figure 7. RSM surface plot of volume.

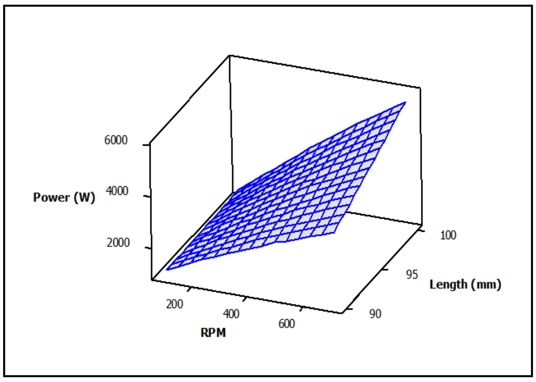

Figure 8. RSM surface plot of power.

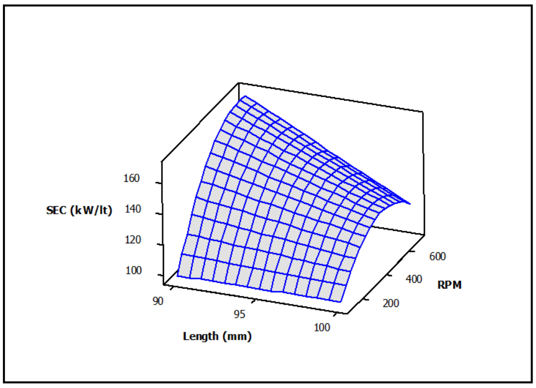

Figure 9. RSM surface plot of SEC.

These graphs provide a clear observation of the effects of level changes in the experimental parameters on the results. It was found that the increase in the number of revolutions has a direct effect on the volume change, but the gear length does not contribute much to this change. In terms of power index change, both gear length and speed change were found to be effective at approximately similar rates. SEC (Specific Energy Consumption) and SCF (Stress Concentration Factor) graphs showed similar results and the maximum value of both parameters was obtained at 400 RPM. This shows the most critical range for both energy consumption and CO_2 emission of the pumps. However, the surface plot graphs for energy consumption and CO_2 emissions exhibit a parallel trend.

The RSM Optimizer results in Figure 10 allowed the determination of the ideal pump operating range. RSM Optimizer is able to evaluate the ideal values of the results according to the order of importance and thus enables the determination of optimum conditions. According to the analyses, it is predicted that maximum flow rate, minimum energy consumption and accordingly minimum CO_2 emission can be obtained by producing at a speed of 609 RPM and a gear length of 100 mm.

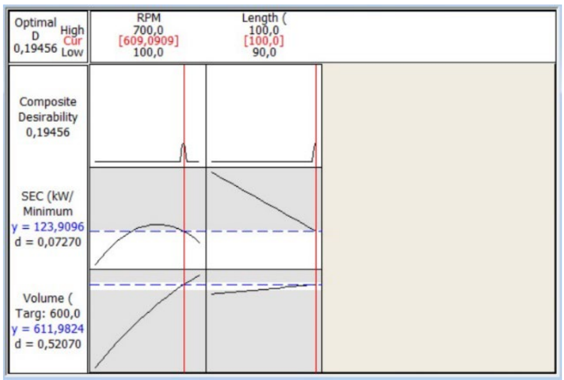

Figure 10. RSM Optimizer.

Table 3 shows the ANOVA results which provide information about the effect rates of the experimental design parameter on the results [34]. When these results are taken into consideration, volume changes are 98% related to the number of revolutions. In other words, a change in gear size for flow rate change does not have a significant effect. In the instantaneous power consumption, it can be said that a contribution of almost 50% - 50% is provided. In other words, it has been observed that reducing the gear size reduces energy consumption at a very high rate. According to these results, it is determined that the gear size is 78% effective in CO_2 emission reduction studies.

3.1 ANOVA Results and Evaluation

In Table 3, ANOVA (Analysis of Variance) results showing the effects of the experimental design parameters on the results are given.

According to these results, it is determined that 98% of the volume changes are related to the speed. This shows that a change in gear size does not have a significant effect in terms of flow rate change [35]. On the other hand, speed and gear size have an effect on instantaneous power consumption by approximately 50%-50%. This shows that reducing the gear size leads to a significant reduction in energy consumption. In CO_2 emission reduction studies, it has been determined that the gear size is 78% effective in line with these results. These findings show that optimizing the gear size is critical for energy efficiency and environmental impacts [36].

Table 3. ANOVA results.

	Source	DF	Seq SS	Adj SS	Adj MS	F	P	% Effect
Volume (L)	RPM	6	474353	474353	79059	435.24	0	98.1
	Length (mm)	1	7921	7921	7921	43.61	0.001	1.6
	Error	6	1090	1090	182			
	Total	13	483363	483363				
Power (W)	RPM	6	20396496	20396496	3399416	12.72	0.003	47.1
	Length (mm)	1	3822088	3822088	3822088	14.3	0.009	52.9
	Error	6	1603225	1603225	267204			
	Total	13	25821809					
SCF (CO_2)	RPM	6	931.06	931.06	155.18	3.07	0.099	21.3
	Length (mm)	1	574.3	574.3	574.3	11.36	0.015	78.7
	Error	6	303.39	303.39	50.57			
	Total	13	1808.76					

4. RESULTS

In this study, the effects of different engine speeds (100-700 RPM) and gear lengths (90-100 mm) on the flow rate and energy consumption of an industrial internal gear pump were investigated. According to the findings, it was found that the energy consumption reached ideal levels at 600 RPM engine speed and the lowest CO_2 emission was obtained in this speed range. The effect of gear length on energy consumption is remarkable and significant reductions in energy consumption are achieved with decreasing gear length. In particular, it was observed that the instantaneous power consumption was reduced from 5.7 kW to 3.6 kW. These findings indicate that gear size is a crucial parameter for optimizing the system in terms of energy efficiency.

In addition, according to the results of ANOVA analyses, it was determined that the flow rate variations were related to engine speed by 98% and gear length was effective in reducing CO_2 emissions by 78%. These results show that optimizing the engine speed and gear length provides significant contributions in terms of energy efficiency and environmental sustainability.

As a result of the experimental studies, maximum flow rate and minimum energy consumption were obtained at 609 RPM motor speed and 100 mm gear length. This study presents an innovative approach to improve energy efficiency and reduce carbon footprint in the design of internal gear pump systems. The findings of the study provide an important guide to save energy and minimize environmental impacts in industrial applications.

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