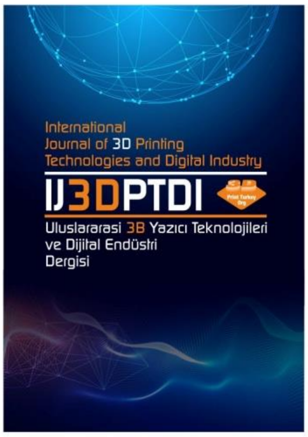


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# THE TAGUCHI AND RSM BASED OPTIMIZATION OF ENERGY CONSUMPTION ON INTERNAL GEAR PUMPS

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## ABSTRACT

Internal gear pumps are used in a variety of applications for the transfer of many different types of liquids like fuel, oil and food in both the industry and daily life. The R & D studies for the efficiency of pumps carried out worldwide account for 6% of the total, and thus energy savings of 303 trillion BTU can be achieved annually. With minimum energy consumption, high rates of energy savings will be ensured by transferring maximum amount of fuel. For this purpose, firstly a detailed literature review was made, and then industrial pump manufacturers and scientific studies were investigated. As a result of that, a new type of internal gear pair design ,which has not been manufactured so far in the industry, has been proposed. In the new pump, the effects of tooth length and the changes in the number of revolutions on flow, power and SEC results were studied. Thus, it will be possible to compare energy expenditure and flow rate with the other pumps developed. By using Response Surface Method (RSM), “Taguchi Method” and “Anova Variance Analysis”, optimum speed and tooth length were determined as 700 RPM for speed and 85 mm for tooth length by taking SEC S/N graph into account. In this way, pump production with optimum flow rate and energy consumption amount in the industry was produced, and the energy consumption value was decreased during the fuel transfer from 156,1 Wh/m3 to 92,0 Wh/m3.In addition, the change in the flow rate was found to be the most effective parameter in the 83% rate change.

**Keywords:** Internal Gear Pump, Specific Energy Consumption (SEC), Taguchi Methods, Response Surface Method (RSM).

## 1. INTRODUCTION

Uncontrolled energy consumption is deemed to be one of the most serious issues of modern life. Due to the limited resources, priority should be given to energy-saving, and after all, these fuels cause significant environmental pollution [1-2]. However, the meaning of energy-saving does not mean less energy consumption. It means 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. Organizations capable of achieving this target increase their competitive power in both national and international areas. All around the World, energy needs have emerged in a total of four different areas, including industry, transport, housing and commerce (Figure 1.), [3]. The highest energy consumption is 51% in industry and 27% in transport. The perpetual increase in the energy consumption in the world production and the insufficient supply of new energy sources have led to a significant increase in energy costs in the past decade [4]. As a global concept, it covers significant elements of many engineering fields and practices for a sustainable production [5]. Adoption of sustainable production practices allows companies to increase their economic and environmental performance. To reduce the energy consumption of machine tools and to investigate the measures to be taken to realize clean production, it is of great importance in the processing processes where a large amount of energy is consumed [6].

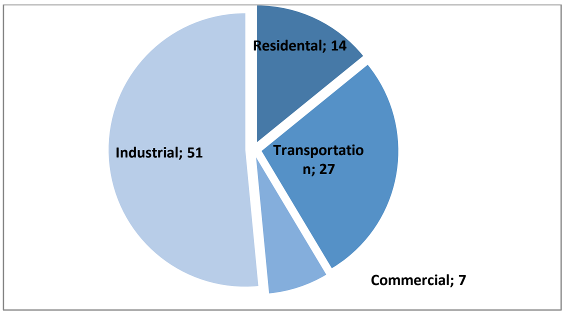


**Figure 1.** Energy consumption areas and rates in the world [3]

In the report prepared on energy and dollar savings, 6% of the most effective R & D studies accounts for the optimization of the pumps (Figure 2). While R & D activities for pumps cost 1370 billion dollars, energy savings of 303 trillion BTU can be achieved through those researches [7]. Thus, the transfer of the pump with minimum energy consumption at the maximum flow rate in the minimum time bears vital importance for the conservation of energy across the world. Certain studies are available in the literature aimed at optimizing pumps.

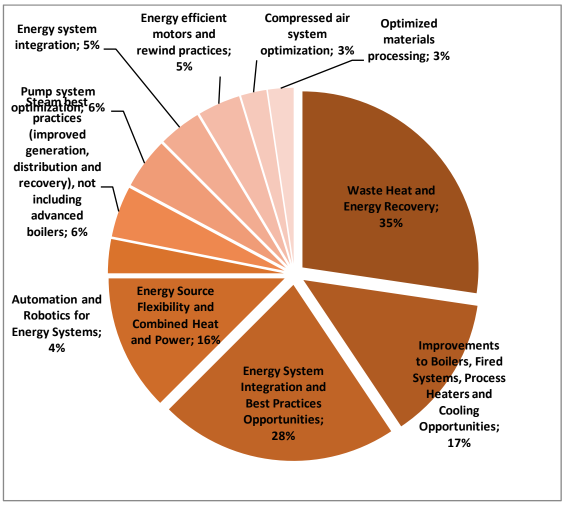


**Figure 2.** Best R & D opportunities for energy saving in trade and process generation [7].

Design changes in pumps directly affect the results of efficiency and energy consumption. Design parameters such as blade number, blade outlet angle and impeller outlet diameter have an effect on pump performance and energy consumption [8]. Regarding gear pump for low power output ORC, an efficiency analysis has been conducted by researchers. Mechanical losses affect the running of the pump at low pressures, whereas volumetric losses at higher pressure have a minor effect [9]. Powder metallurgy (P/M) internal gear pump rotors are widely used in automobiles, particularly for oil pumps. When compared with conventional rotors, it indicates that the newly developed rotors can be made smaller in size and can accomplish lower torque and better fuel efficiency [10]. The most energy effective hydraulic pump drive is searched and the effect of the electric component efficiencies on the system effectiveness is studied. [11].

The oil pump in the diesel engine has a considerable effect on both energy consumption and environmental pollution. In a study, the modelling and simulation of a gear oil pump has been used in a diesel engine, and its fluid flow analysis by a solver has been demonstrated. Increasing thermal efficiency is connected to energy saving and effects on environmental pollution reduction [12]. A study shows a useful approach to the investigation of the effect of oil temperature on the friction torque in various types of hydraulic pumps by making use of a mathematical model. It is determined that, with a rise in oil temperature, the friction torque at a high pump speed declines in a low oil temperature region, but it would not decrease in a high oil temperature region for all the tested pumps. [13].

A new design geometry which can be used at all fuel transfer pump practices has been developed. There exists no noise increase as the bypass system is in operation. This novel design with the same dimensions gains 33% in flow rate and 38% in energy saving [14]. As the safety coefficients and the economic life of the pump are significant criteria in design, minimizing the production cost is a must for the manufacturing industries. Screw diameter, body width, and weight of the gear pump are analyzed so as to optimize the design parameters with the environmental pressure [15]. An equation is put forward to work out the flow rate of a gear pump. The involute curve formula used for the gear design is defined [16].

The various types of displacement pumps are assessed, with the advantages and disadvantages of gear pumps being analyzed [17]. Overall efficiency is improved to an average of 65% by means of a thorough retrofit and repair program, total energy savings of about 4-8 million kWh can be made in the current estimated energy usage of about 12 million kWh per year [18]. Commercial pumps are developed using a test setup [19]. This type of commercial test equipment is used in the development of gear pumps; still, various flow simulations and optimization studies are included in the literature. The response surface method examines the relationship between some input variables and one or more output variables.

The Taguchi method uses a special array called orthogonal arrays. These standard sequences prescribe a way of performing the minimum number of experiments that will give complete information on all factors affecting performance parameters [20-21]. In this study, energy consumption and experimental design which is done by Taguchi and RSM issues will be used for the design and optimization of energy efficiency of gear pumps. Thus, an ideal pump for sustainability will be developed.

## 2. ENERGY CONSUMPTION OF INTERNAL GEAR PUMPS

Industrial internal gear pumps with various geometrical models are used in a large number of different applications [22-23]. The energy consumption and the amount of flow rate which the pumps consume at different engine speeds are given comparatively in Table 1-3.

**Table 1.** Technical specifications of the internal gear pump of Varisco Pump [21].

| RPM | Power (kW) | lpm | lph | SEC (Wh/m³) |
|---|---|---|---|---|
| 600 | 4500 | 707 | 42420 | 106,1 |
| 550 | 5400 | 651 | 39060 | 138,2 |
| 480 | 6000 | 569 | 34140 | 175,7 |
| 400 | 6400 | 476 | 28560 | 224,1 |
| 330 | 6500 | 393 | 23580 | 275,7 |
| 250 | 6300 | 299 | 17940 | 351,2 |
| 190 | 5800 | 228 | 13680 | 424,0 |

When the results are examined, it was observed that the amount of Specific Energy Consumption (SEC) decreases significantly when the engine speed falls. For pumps operating at higher pressures than other pumps, such as the Viking Pump, the difference between those ratios is lower [22].

**Table 2.** Technical specifications of the Viking Pump internal gear pump [22].

| RPM | Power (kW) | lpm | lph | SEC (Wh/m³) |
|---|---|---|---|---|
| 500 | 4700 | 470 | 28200 | 166,7 |
| 400 | 3300 | 360 | 21600 | 152,8 |
| 300 | 2400 | 260 | 15600 | 153,8 |
| 200 | 1900 | 170 | 10200 | 186,3 |
| 100 | 1300 | 80 | 4800 | 270,8 |

**Table 3.** Technical specifications of internal gear pump of IPT fuel company [23].

| RPM | Power (kW) | lpm | lph | SEC (Wh/m³) |
|---|---|---|---|---|
| 600 | 3100 | 550 | 33000 | 93,9 |
| 500 | 2900 | 490 | 29400 | 98,6 |
| 400 | 2700 | 330 | 19800 | 136,4 |
| 300 | 2470 | 250 | 15000 | 164,7 |
| 200 | 2050 | 163 | 9780 | 209,6 |
| 100 | 1300 | 76 | 4560 | 285,1 |

## 3. ENERGY CONSUMPTION IN HELICAL GEAR PUMPS

A study of the optimization of an industrial helical gear pump in energy consumption was carried out by the author. As a result of this research, for the helical gear pumps belonging to different industrial establishments to be able to transfer fuel at the maximum flow rate, the energy consumption they consume has been investigated, and the design geometries of the pumps have been examined [14].

Consequently, 219.44 WH/m3 sec values were obtained from 312.50 Wh/m3 with the help of the new pump developed by making use of benchmarking studies. When all those results are examined, it can be said that helical gear pumps consume more energy than the internal gear pumps.

**Table 4.** Energy consumption variations in helical gear pumps [14].

| Pump Model | lph | Power (kW) | SEC (Wh/m$^3$) |
|---|---|---|---|
| **Z11** | 18.720 | 4.3 | 229.70 |
| **Z 17** | 28.920 | 7.1 | 245.50 |
| **YHL** | 32.400 | 11.0 | 339.50 |
| **SG-1436** | 23.520 | 15.0 | 637.75 |
| **Er-1214** | 24.000 | 7.5 | 312.50 |
| **New Design** | 36.000 | 7.9 | 219.44 |

## 4. MATERIAL AND METHOD

In cooperation with IPT fuel company and within the scope of university-industry collaboration, a joint project aiming at producing a new type of internal gear pump with a new design geometry ,and with less energy consumption, which is capable of transferring fluid at more flow rate has been launched. Within the scope of the study, while the researchers are responsible for the industrial design, Taguchi experiment design and optimization studies, the company has supported the project regarding the material supply and test facilities.

### 4.1. Determination Of Design Geometry

The industrial enterprise exports a pump with outer gear with 8 teeth and inner gear with 6 teeth (Figure 2 - right). It is especially preferred by large masses in countries such as Australia, Mexico and Canada. The design geometry of this gear pump is based on the machining of a two outer gear with a special design bar. As for the inner gear, it was developed as a result of manufacturing and assembly trials . The flow rate and electricity consumption results for different speeds of the pump and 90 mm teeth length are given in Table 3. It can be said that the length of the inner gear came to existence as a result of examining the sample applications in the industry in the 70-100 mm range. In addition, no research has been observed in the literature regarding the selection of this measure. In this study, it was intended to investigate the flow and power consumption results of a gear pair design with 9 teeth outer gear and 7 teeth inner gear (Figure 2 – left). For this purpose, a new gear form has been developed by performing basic motion analysis in Solid Works program. Details of this gear cannot be given due to copyright. Only the assembly design in Figure 2 is allowed to be shared.

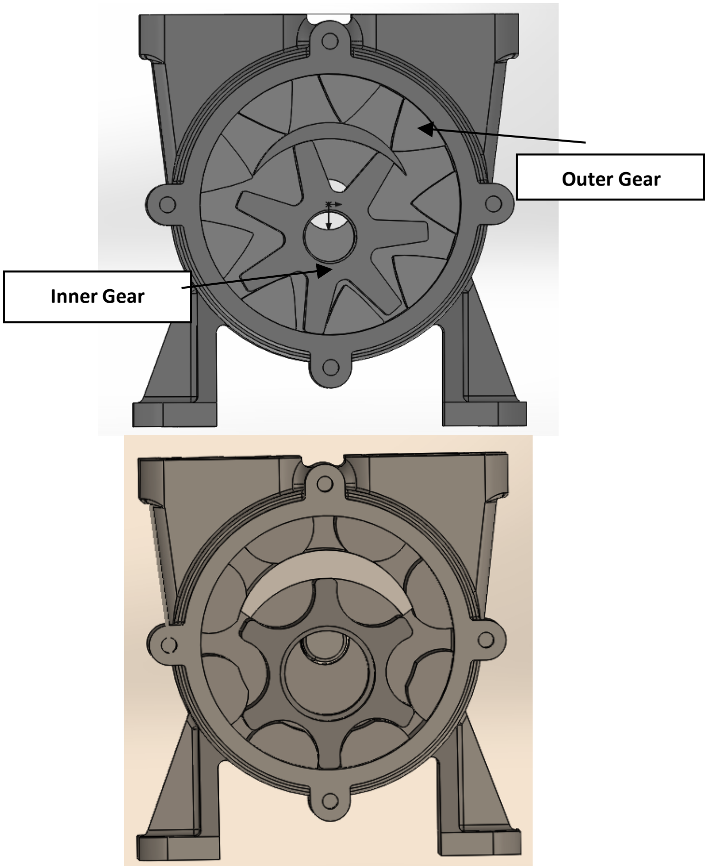


**Figure 2.** New (left) and currently exported (right) design geometry.

### 4.2. Design of Experimental (DOE) via Taguchi Method and Response Surface Method (RSM)

Optimization methods have been developed to determine the effect of parameters used during the processing of the product in the manufacturing sector [24-25]. Experimental design is a powerful statistical method for determining the unknown characteristics of design and production parameters in the experimental process and analyzing and modeling interactions between variables [26-27]. In industrial areas, by using the Taguchi method, product development time for design and production is reduced, and accordingly, the profit ratio of the enterprise can be increased by decreasing the costs [28-29]. Also, the Taguchi method allow for the control of variables caused by uncontrolled factors not considered by traditional experimental design. Taguchi converts objective function values to signal / noise (S / N) ratio to measure performance characteristics of levels of control factors against those factors [30-31]. Additionally, variance analysis is applied to determine the statistical significance of the parameters. The optimum combination of experimental design parameters is determined by using variance analysis and S / N ratio [32-33]. S / N ratios are used in the optimization of control factors. The fact that energy consumption is low and the fuel transferred is of maximum level has great significance from the standpoint of cost, sustainable production, energy conservation and efficiency [14]. In the calculation of S/N ratios, “the nominal value of the characteristic type is best”, “the largest is the best”, “the smallest is the best” methods are used [34]. The objective functions corresponding to those methods are given in Eq.1, Eq.2 and Eq.3, respectively [27,35].

Nominal is the best: $\frac{S}{N} = 10\log\left(\frac{\bar{y}}{S_{\bar{y}}^2}\right)$ (1)

The biggest is the best: $\frac{S}{N} = -10\log\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}$ (2)

The smallest is the best: $\frac{S}{N} = -10\log\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}$ (3)

This new gear design of the pump at 400 - 900 RPM speed of the motor shaft and inner gear length in the range of 70-90 mm in the measurement changes of the effects on flow and energy consumption values were investigated. By analyzing 6 different motor rotation cycles (400, 500, 600, 700, 800 and 900) and three different inner gear length (70, 85 and 90) on the test apparatus, Taguchi L18 mixed (61 x 31) factorial fractional design of experiment (DOE) was used to examine the effects on flow and energy consumption results (Table 5.).

**Table 5.** Taguchi L18 mixed (61 x 31) factorial fractional design of experiment (DOE)).

| | $P_1$ | $P_2$ | $P_3$ | $P_4$ | $P_5$ | $P_6$ | $P_7$ | $P_8$ | $P_9$ | $P_{10}$ | $P_{11}$ | $P_{12}$ | $P_{13}$ | $P_{14}$ | $P_{15}$ | $P_{16}$ | $P_{17}$ | $P_{18}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $L_1$ | 1 | 1 | 1 | 2 | 2 | 2 | 3 | 3 | 3 | 4 | 4 | 4 | 5 | 5 | 5 | 6 | 6 | 6 |
| $L_2$ | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| $L_1$ (RPM) | 400 | 400 | 400 | 500 | 500 | 500 | 600 | 600 | 600 | 700 | 700 | 700 | 800 | 800 | 800 | 900 | 900 | 900 |
| $L_2$ (mm) | 70 | 85 | 100 | 70 | 85 | 100 | 70 | 85 | 100 | 70 | 85 | 100 | 70 | 85 | 100 | 70 | 85 | 100 |

Response the Surface Method is a statistical method developed by Box and Wilson in 1951 [36, 37] response to surface method; defined as a method in which statistical and mathematical techniques are used together for the development and optimization of processes. The response surface method is used to determine the relationship between the experimental strategies, the response of the system and the independent variables that influence it. It also includes empirical modeling techniques and optimization techniques for finding the levels in which the process variables show the desired effect in the response of the system. [37]. In this method, the DOE generated for the Taguchi Method can be used. The results can be examined by comparison with it.

### 4.3. Energy, Power, Flow and Efficiency Calculation Theory in Pumps

Some empirical formulas are defined for the flow rate, power, energy consumption and efficiency calculations of pump applications. These formulae can be used to determine the nominal pump size for a specific application [36]. In these equations, output flow (Q), input torque (M), input power: (P) calculations can be made (Equation 4-6).

$$Q = \frac{Vg.n.nv}{20.\pi.nm} \quad (4)$$

$$M = \frac{Vg.\Delta p}{20.\pi.nm} \quad (5)$$

$$P = \frac{Q.\Delta p}{600.nt} \quad (6)$$

Equations for the calculation of different properties (output flow (Q), input power: (P), pressure (p)) are also used in the theoretical calculations of pumps [39]. The design calculations for pumps are based on the parameters that follow. It is also necessary After all, allowing for different efficiencies is necessary. The formulas below describe the different relationships.

$$Q = V.n.\frac{nv}{100000} \tag{7}$$

$$p = M.\frac{nhm}{1,59.V} \tag{8}$$

$$P = \frac{p.Q}{6.nt} \tag{9}$$

In this study, mean current indices (PI (A)) were first determined by using current transformers that were connected to inventor inputs while calculating power. Thus, with the help of the inventor, when the engine is operated in different speed numbers, the total amount of power required can be obtained by using the energy – power conversion equation (Equation 10).), [39]. Moreover, a correlation was proposed between the total amount of power and the amount of fuel transferred (Equation 11), [40].

$$P = \sqrt{3}\, V\, I\, \mathrm{Cos}\, \alpha \tag{10}$$

$$(SEC) = \frac{\text{Energy Used}}{\text{Pumped Volume}} \tag{11}$$

**4.4. Test Mechanism Designs And Measurements**

Flow rate changes are calculated by flow transmitter, emote field-mount Coriolis transmitter and programmable logic controller (PLC) with MVD technology for multiple variables (Figure 3.). Micro Motion 1700/2700 field-mount transmitters are powered by MVD Technology and designed for compact integral fixing, or to easily attach to a wall or pipe stand. These transmitters feature a rugged Class I, Division 1 / Zone 1 having an optional local operator interface which is designed to make flowmeter access easy. Flowmeter commissioning is simple and clear-cut with practically no special programming needs. Process matters can be easily identified and resolved with built-in, easy access to diagnostics now including Plant Web alerts with Foundation Field bus.


**Figure 3.** Flow Transmitter & Controller.

Flow transmitter & controller IPT is installed in the test setup of the fuel company. Thus, quality control of all pumps and meters produced can be carried out in this test scheme (Figure 4.). The flow change of the pumps produced with different design features within the scope of joint research has been measured in it.

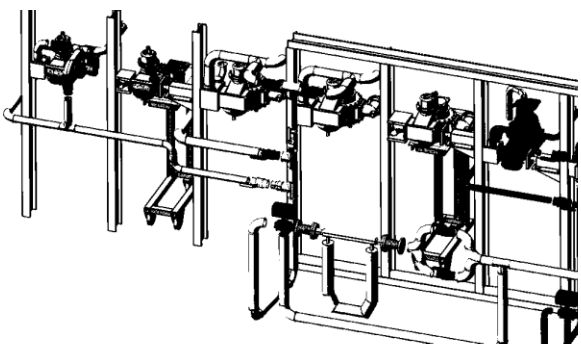

**Figure 4.** IPT flow measurement test setup for fuel pumps and meters

## 5. RESULTS AND DISCUSSION

### 5.1. Specific Energy Consumption (SEC) and Flow Results (lpm)

The values of flow and flow Index were measured by applying the parameters and levels determined in Taguchi experimental design. Total power consumption values were calculated using energy–power conversion equations. In addition to these results, Figure 6 was created, with the resultant of the calculations of the SEC changes made.

**Table 6.** Results Obtained In Test Setup.

| DOE | lpm | $P_{total}$ (kW) | SEC (Wh/m³) |
|---|---|---|---|
| 1 | 327 | 2350 | 119,8 |
| 2 | 412 | 2950 | 119,3 |
| 3 | 491 | 3390 | 115,1 |
| 4 | 551 | 3710 | 112,2 |
| 5 | 601 | 4120 | 114,3 |
| 6 | 649 | 4530 | 116,3 |
| 7 | 385 | 2660 | 115,2 |
| 8 | 487 | 2843 | 97,3 |
| 9 | 549 | 3281 | 99,6 |
| 10 | 641 | 3539 | 92,0 |
| 11 | 669 | 4160 | 103,6 |
| 12 | 691 | 4610 | 111,2 |
| 13 | 442 | 3340 | 125,9 |
| 14 | 559 | 4220 | 125,8 |
| 15 | 603 | 5100 | 141,0 |
| 16 | 665 | 5730 | 143,6 |
| 17 | 701 | 6310 | 150,0 |
| 18 | 723 | 6770 | 156,1 |

The effect of variations in flow on Ptotal (kW) and SEC results was studied by using the scatter chart in the Minitap program (Figure 5.). The distribution has not shown a linear result. The most probable cause of this is thought to be the effects of different inner gear teeth length on the cavitation. When the SEC values were examined, it was observed that high parameters (600 - 700 liters) could be achieved with low SEC values (100-110 Wh / m3) by selecting the appropriate parameters. It is observed that low flow rates generally have higher energy consumption. This suggests that it is due to the fact that the pump inlet and outlet pressure is reduced at low shaft speeds.

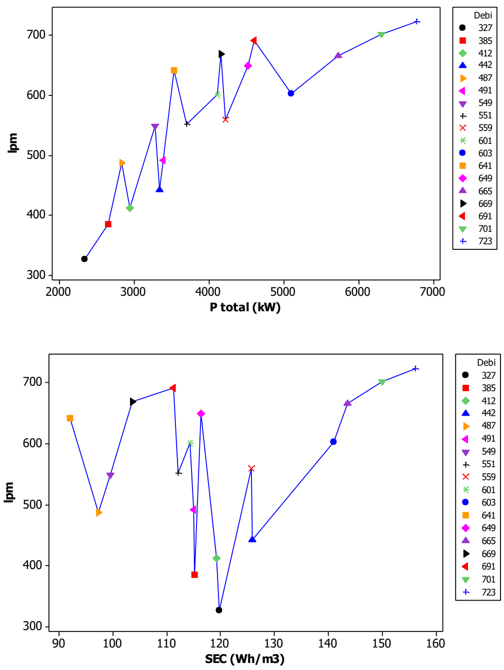


**Figure 5.** Change of PTotal (left) and SEC (right) according to flow rate.

### 5.2. Taguchi Method and Variance Analysis Results

The results obtained were analyzed using the Minitap program.While these analyses are evaluated, S/N ratio charts are obtained by selecting 'flow rate is higher, Ptotal (kW) value is the smallest, and SEC value is the smallest' (Figure 6). When these results are evaluated, the flow rate is normally directly proportional to both parameters. The increase in shaft rotation speed and inner gear tooth length causes an increase in flow rate. Although it was observed that Ptotal (kW) was inversely proportional to experimental parameters, it was determined that the increase in inner gear tooth length would not show the same inverse proportion. When SEC Value S/N ratios were examined, it was determined that the pumps operate with minimum energy consumption in the number of 600 and 700 RPM spindle speeds. According to these results, the optimum results of SEC, the most important factor for energy consumption, can be achieved by selecting 85 mm inner gear tooth length and 700 RPM spindle speed.

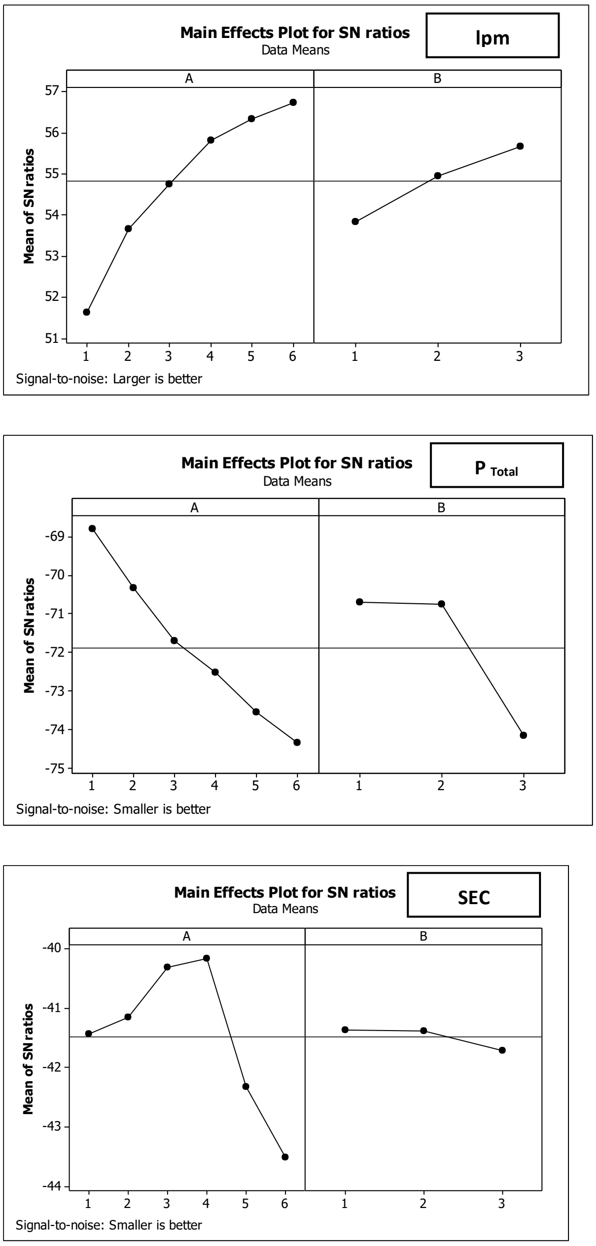


**Figure 6.** S/N ratios of flow rate, power and energy consumption variations.

The impact intensities of the motor shaft speed and the flow rate of the inner gear tooth , Ptotal and SEC results were calculated using Anova variance analysis (Table 7). In these computations, the sum of the squares (Seq SS) ratio is taken as reference. Flow rate change was calculated with the minimum error rate (0.8%) and 83% rate change was determined as the most effective parameter. In the calculation of Ptotal (kW) results, the error rate was at acceptable levels and it was determined that the number of spindle speeds by 50% and the inner gear tooth by 45% were effective.

Since the rate of % SEC result error rate is high, the reliability of the results is low; in other words, as P = 0.05. is bigger, the difference between the groups was not deemed to be statistically significant.

**Table 7.** Anova Variance Analysis results.

| | Source | Seq SS | F | % Effect |
|---|---|---|---|---|
| lpm | A | 196434 | 199,66 | 83,47 |
| | B | 36920 | 93,82 | 15,69 |
| | Error | 1968 | | 0,84 |
| | Total | 235322 | | |
| $P_{total}$ (kW) | A | 13281374 | 24,29 | 50,33 |
| | B | 12014465 | 54,94 | 45,53 |
| | Error | 1093449 | | 4,14 |
| | Total | 26389288 | | |
| SEC | A | 365,60 | 0,88 | 6,66 |
| | B | 4288,50 | 25,78 | 78,17 |
| | Error | 831,81 | | 15,16 |
| | Total | 5485,91 | | |

### 5.3. Response Surface Method (RSM) Results

The RSM model of the experimental design determined using the Minitap program was created. Surface / counter plot was occurred for SEC and lpm results (Figure 7-8). This method gives a wider result area than the Taguchi method. In other words, it provides a predictive prediction within the parameter levels other than the specified parameters. Unlike S / N ratios, these results show that the optimum RPM value for the SEC results is close to 600 and the gears length is less than 85 mm. The changes in the lpm results followed the values in the S / N graphs at approximately the same rate.

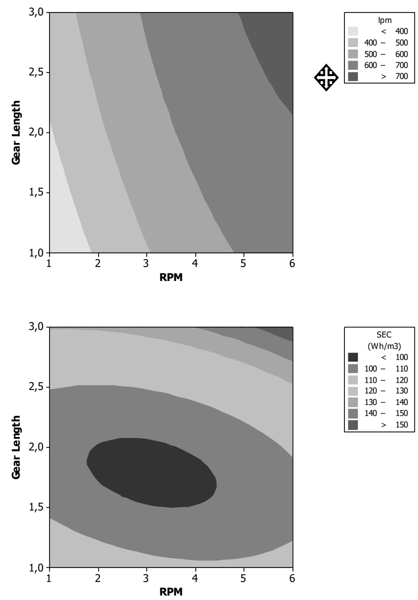


**Figure 7.** Results of contour plot.

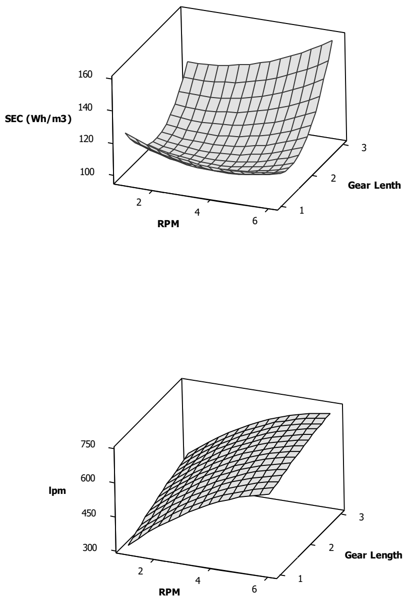


**Figure 8.** Results of surface plot.

Using the response optimizer, optimum values can be obtained for areas outside the parameter levels determined in the RSM method (Figure 10.). The accuracy of all RSM results is measured via the probability plot. The closer the points to the obtained curve, the higher the accuracy of the results (Figure 11.).

By using these RSM tools, it was observed that fuel transfer can be made with a SEC value of 98 Wh with 625 RPM and 81.7 mm gears length selection. When the probability plot results obtained for the SEC results were examined, it was determined that this result was obtained with high accuracy.

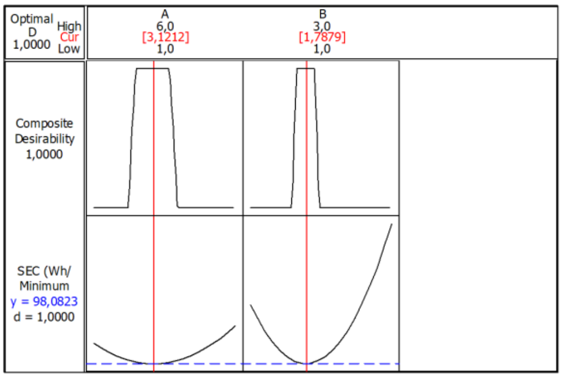


**Figure 10.** Results of response optimizer.

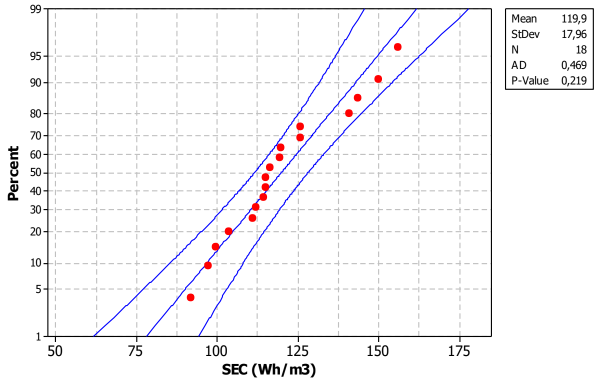


**Figure 11.** Results of probability plot.

## 6. CONCLUSION

That energy supply costs have increased in recent years has made energy saving compulsory. While R & D activities regarding pumps cost 1370 billion dollars, 303 trillion BTU energy savings can be made. If the fact that the need for energy consumption is much more in the industrial sector than that of the total of other areas and the widespread use of pumps takes place in the industry is taken into account, then the significance of the research is easily comprehensible.In this article, by specifying the optimum number of revolutions and gear lengths, it was intended to ensure the ideal energy expenditure for maximum fuel transfer.

Furthermore, the energy consumption is reduced during the transfer of fuel from 156,1 Wh/m3 to 92,0 Wh/m3. For a pump that runs 20 hours per week, 666 kWh energy saving is projected in ten years. When the severity of impacts of motor shaft revolution number and inner gear tooth length on the results of flow rate, Ptotal and SEC are calculated by using Anova Variance Analysis, it is seen that 83% rate change in flow rate is the most effective parameter. As for Ptotal (kW) results, it was calculated that shaft revolution number and star gear length influenced Ptotal (kW) results 50% and %45 respectively. Also, when the effect of changes in flow rates on Ptotal (kW) and SEC results was examined by using the scatter plotting chart, it was seen that higher energy consumption was observed in low flow rate values.

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