Optimization of Process Parameters to Maximize the Efficiency of a Vacuum Pump Using Taguchi Method and ANOVA

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Abstract- **In this analysis, Taguchi method; a Design of Experiment (DOE) technique wasused to optimize the process parameters and improve the efficiency of a Liquid Ring Vacuum Pump (LRVP). The tools and techniques such as, orthogonal array, signal-to-noise ratio (S/N), and the analysis of variance(ANOVA)were employed in Taguchi method to study the process parameters of the liquid ring vacuum pump. Three factors namely sealing water temperature; Speed of the pump and Sealing fluid pressure were considered as the process parameters. Accordingly, a suitable orthogonal array L_9 (3^3) was selected and experiments were conducted. After conducting the experiments the efficiency and (S/N) ratios were calculated. With the help of graphs, optimum parameter values were obtained; ANOVA was performed to calculate the percentage contribution of each factor and confirmation experiments were carried out to validate the results of Taguchi analysis.**

Index Terms:**ANOVA, Design of Experiment: Taguchi method, S/N ratio, Orthogonal array and Liquid ring vacuum pump.**

I. INTRODUCTION

A Liquid Ring Vacuum Pump (LRVP) is a device that removes gas molecules from a sealed volume in order to create a partial vacuum. The vacuum pumps are used throughout the forming section of the paper machine in a paper production plant to remove the excess water from the paper pulp. In the paper production plant that this study was conducted, the total power consumption was 1600 KWh/MT of paper produced, in it 620 KWh/MT of paper produced was utilized by the paper machine and more than 50% of that was due to the operation of the vacuum pumps.

The basic working of LRVP [8] is that, it has a bladed impeller attached eccentric to the axis of the circular casing. At the start of the operation, liquid rotates with the rotor and it touches with the casing due to centrifugal force. The internal surface of the water ring will be at varying distances from the axis of the rotor because of the eccentricity. Where the liquid ring is nearest to rotor, it fills the entire space between two rotor blades. As the rotor moves the liquid ring moves away from the rotor. Thus air is drawn into the chamber which is formed by the two adjacent blades and capped off by the liquid ring. Moving liquid ring acts as piston in suction stroke and it continues till the position where maximum distance between rotor and liquid ring is achieved. All the chambers between the initial position and the above mentioned point act as inlet branch. And opposite action takes place in the remaining chambers, which are acting as outlet branch.

The parameters which affect the efficiency of a vacuum pump, such as sealing water temperature, sealing fluid pressure, speed of the pump, concerned with the operation of it were taken for optimization using the Taguchi method in this study. The experimental setup to optimize process parameters were determined by Taguchi's experimental design method. Orthogonal arrays of Taguchi, the signal-to-noise (S/N) ratio, the analysis of variance (ANOVA), were employed to find the optimal levels and to analyze the effect of process parameters on the efficiency of LRVP. Confirmation test with the optimal levels of process parameters were carried out in order to illustrate the effectiveness of Taguchi's optimization method.

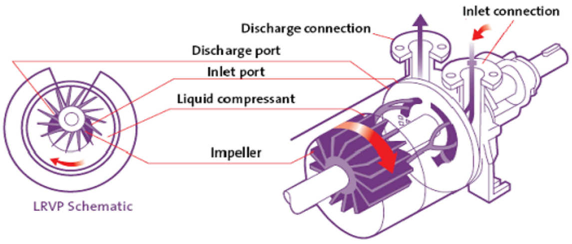

Fig.1. Liquid ring vacuum pump (LRVP)

II. EXPERIMENTAL PROCEDURE

The LRVP that was utilised for the experimental purpose was model CL 9002 of the vacuum pump manufacturer NASH Engineering Company, USA. The working conditions of the vacuum pump are displayed in the Table I. The efficiency of the vacuum pump was calculated using (1),

$$\text{Efficiency of Vacuum Pump} = [(C*\Delta p) / P] \qquad (1)$$

Where 'C' is the Capacity (m^3/sec.), Δp is the Pressure Difference between the inlet and the outlet of Vacuum Pump (N/m^2) and 'P' is the power in Watts. The various readings necessary for the analysis can be obtained from the Digital control system, which is used to monitor and operate the devices.

Table I. Working conditions of the vacuum pump

Press. Diff. (N/m^2)	Capacity (m^3/s)	Inst. Power Cons. (W)
23547.52	3.85	233000

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Taguchi methods [1]-[6] which combine the experimental design theory and the quality loss function concept have been used in developing robust designs of products and processes. For the purpose of observing the degree of influence of the LRVP process parameters on the efficiency of vacuum pump three factors, each at three levels, were taken into account, as shown in Table II.

Table II. Factors and their levels

Factors	Code	Levels		
		1	2	3
Sealing water temperature (^{0}C)	**T**	25	30	35
Speed of the pump (RPM)	**N**	300	250	200
Sealing fluid pressure (Kg f/cm^2)	**P**	1.5	2.0	2.5

Henceforth the parameters sealing water temperature, speed of the pump and sealing fluid pressure will be referred to as T, N and P respectively.

To select an appropriate orthogonal array for conducting the experiments, the degrees of freedom are to be computed. Degrees of Freedom: Sum of (Number of levels – 1) for each factor including error and one for the mean value.

Total Degrees of Freedom = 9

The most suitable orthogonal array for this experimentation is L_9 array, since the total degrees of freedom must be either less than or equal to the total number of times the experiment is being carried out. In accordance with the L_9 orthogonal array, experiments were conducted with their factors and their levels as mentioned in Table II. Each of the above 9 experiments were conducted 5 times (45 experiments in total) to account for the variations that may occur due to the noise factors.

III. RESULTS AND DISCUSSIONS

A. Analysis of the S/N Ratio

Taguchi method stresses the importance of studying the response variation using the signal - to - noise (S/N) ratio[1]-[6], resulting in minimization of quality characteristic variation due to uncontrollable parameter. The Quality characteristic that we want to improve is the Efficiency of the vacuum pump. The objective is to increase the efficiency through Taguchi method. Hence the Objective Function is Larger-the-Better.

S/N Ratio for this function $\eta=-10 \log_{10}[\sum_{j=1}^{n}(1/y_j)^2 /n]$ (2)

Where 'y' is the quality characteristic: efficiency and 'n' is the sample size.

The experimental layout with the selected values of the factors, their mean efficiency for the 5 trials and the signal noise ratio are shown in Table III.

Table III. Experimental layout, mean efficiency and S/N ratio

Exp. No.	Control Factors			Mean Eff. of 5 trials	S/N Ratio (η)
	T (^{0}C)	N (RPM)	P (Kgf/cm^2)		
1	25	300	1.5	0.35510	-8.994180963
2	25	250	2.0	0.35114	-9.092064596
3	25	200	2.5	0.34726	-9.191772691
4	30	300	2.5	0.34608	-9.226555846
5	30	250	1.5	0.34430	-9.268645801
6	30	200	2.0	0.34008	-9.372477429
7	35	300	2.0	0.35216	-9.073490211
8	35	250	2.5	0.34712	-9.194627301
9	35	200	1.5	0.35154	-9.085402888

Then the mean S/N ratios at each level for various factors have to be calculated. The factor levels corresponding to the highest average S/N ratio will optimize the condition of maximum efficiency. In order to evaluate the influence of each factor on the efficiency of LRVP, the S/N ratio for each factor should be computed. The S/N ratio for single factor can be calculated by averaging the values of S/N ratios at different levels as given below.

$$S_{T1}= (\eta_1+\eta_2+\eta_3) \quad S_{T2}= (\eta_4+\eta_5+\eta_6) \quad S_{T3}= (\eta_7+\eta_8+\eta_9)$$

$$S_{N1}= (\eta_1+\eta_4+\eta_7) \quad S_{N2}= (\eta_2+\eta_5+\eta_8) \quad S_{N3}= (\eta_3+\eta_6+\eta_9) \quad (3)$$

$$S_{P1}= (\eta_1+\eta_5+\eta_9) \quad S_{P2}= (\eta_2+\eta_6+\eta_7) \quad S_{P3}= (\eta_3+\eta_4+\eta_8)$$

S/N ratios for different factors at different levels were calculated using (3) and tabulated in Table IV.

Table IV. Sum and average S/N ratios for different factors at different levels

Level	Sealing water temperature (T, ^{0}C)		Speed of the pump (N, RPM)		Sealing fluid pressure (P, Kg f/cm^2)	
	Sum (S_{Tj})	Avg. S/N ratio	Sum (S_{Nj})	Avg. S/N ratio	Sum (S_{Pj})	Avg. S/N ratio
1	-27.278018	-9.092673	-27.294227	-9.0980757	-27.348230	-9.1160766
2	-27.867679	-9.289226	-27.555340	-9.1851126	-27.538032	-9.1793441
3	-27.353520	-9.117840	-27.649653	-9.2165510	-27.612956	-9.2043186

The optimum factor levels can be easily identified from graphs between S/N ratios of each factor on the Y- axis and Levels on the X- axis. The graphs of which are shown on the next page.

B. Analysis of Variance (ANOVA) results.

ANOVA [1]-[7] was used to determine the significance and percentage contribution of each parameter influencing efficiency of the liquid ring Vacuum pump.

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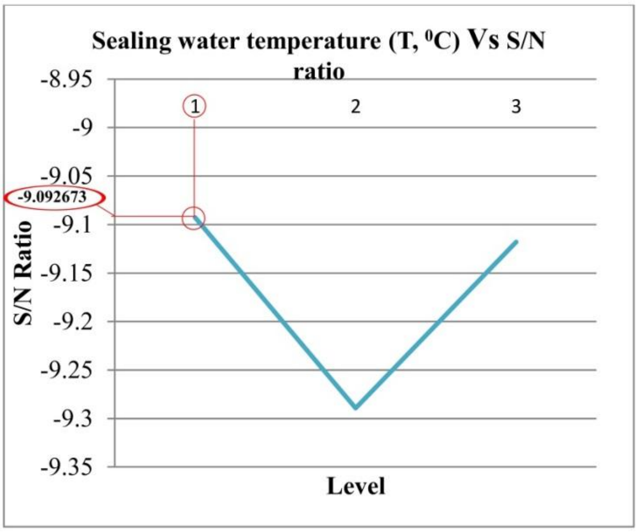

Fig.3. Sealing water temperature (T, ^{0}C)S/N ratio Vs. Levels, with result

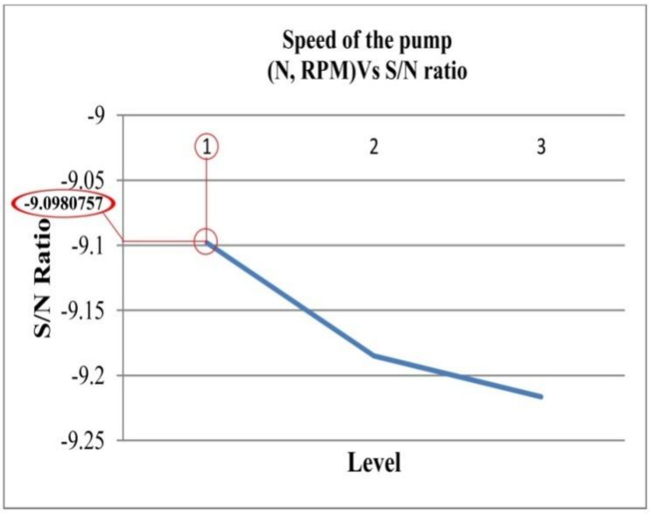

Fig.4. Speed of the pump (N, RPM)S/N ratio Vs. Levels, with results

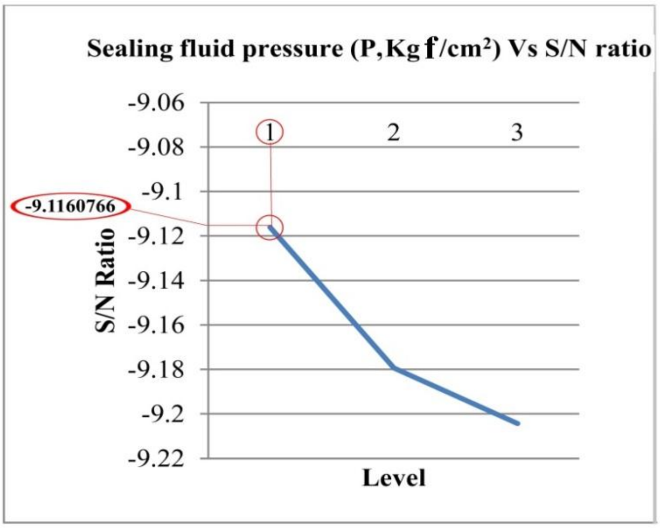

Fig.5. Sealing fluid pressure (P, Kg/cm^2)S/N ratio Vs. Levels, with results

In this study, the analysis of variance was at a level of significance of 5% and level of confidence as 95%. Statistically, there is a tool called an F test, named after R.A. Fisher, to see which design parameters have a significant effect on the quality characteristic. In the analysis, the F-ratio is a ratio of the mean square of factor to the mean square of error, and is traditionally used to determine the significance of a factor. The basic property of ANOVA is that the total sums of the squares (total variation) are equal to the sum of the SS (sums of the squares of the deviations) of all the condition parameters and the error components, which is adding the variations of each factors.

Total sum of squares was calculated from the S/N Ratio table III, using (4).

$$SS_T = \sum_i^m \eta_i^2 - \frac{1}{m}\left[\sum_{i=1}^m \eta_i\right]^2 \quad (4)$$

Where m = total no. of exp., i = 1…m

Sum of squares due to each factor (e.g., sealing water temperature SS_{FT}) was calculated from S/N ratio for the individual control factors.

$$SS_{FT} = \sum_{j=1}^t \frac{(s_{\eta j})^2}{t} - \frac{1}{m}\left[\sum_{i=1}^m \eta_i\right]^2 \quad (5)$$

Where, j = level, t = repetition, m = total no. of exp.

Similarly sum of squares of other factors were also calculated using (5),Sum of squares due to the errors were calculated using (6).

$$SS_E = SS_T - SS_{Fx} \quad (6)$$

The mean squares of the factor and error were calculated using (7) and (8).

$$MS_{FX} = SS_F/v_F \quad (7)$$

$$MS_E = SS_E/v_E \quad (8)$$

F test for different factor calculated using the (9).

$$F_T = MS_F/MS_E \quad (9)$$

The percentage contribution of each factors were found out by (10), (11), (12), and (13).

$$\%T = SS_{FT} / SS_T \quad (10)$$

$$\%N = SS_{FN} / SS_T \quad (11)$$

$$\%P = SS_{FP} / SS_T \quad (12)$$

$$\%E = SS_{FE} / SS_T \quad (13)$$

The ANOVA table with results is given in the next page.

For 95% confidence, the F value at 2 degrees of freedom for both nominator and denominator is 19 [7], which is less than all of the F values that we have got. That is, 108.5324 for sealing water temperature (T), 37.6875 for Speed of the pump (N) and 19.5603 for Sealing fluid pressure (P), hence they are significant.The P-value reports the smallest pre-set significance level (suitable and unsuitable) at which the factor becomes insignificant, from the calculations Table V.The P values of, sealing water temperature (T), Speed of the pump (N) and Sealing fluid pressure (P) are 0.009129717, 0.025848135 and 0.048637215.

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Table V. Data representation for ANOVA Results

Source	Sum of squares	Degree of freedom	Mean square	F	P Value	Significant (yes/no)	% Contribution
T	0.069864	2	0.034932	108.5324	0.009129717	Yes	65.08
N	0.024260	2	0.012130	37.6875	0.025848135	Yes	22.59
P	0.012591	2	0.006296	19.5603	0.048637215	Yes	11.73
E	0.000644	2					0.60
Total	0.107359	8	0.006296				100

Percentage (%) is defined as the significance rate of the process parameters on the Efficiency. The percentage numbers depict that the sealing water temperature, Speed of the pump and Sealing fluid pressure have significant effects on the Efficiency of the vacuum pump. It can be observed from Table V, that the sealing water temperature (T), Speed of the pump (N) and Sealing fluid pressure (P) affect the Efficiency by 65.08%, 22.59% and 11.73% respectively and the contribution of error is only 0.60%.

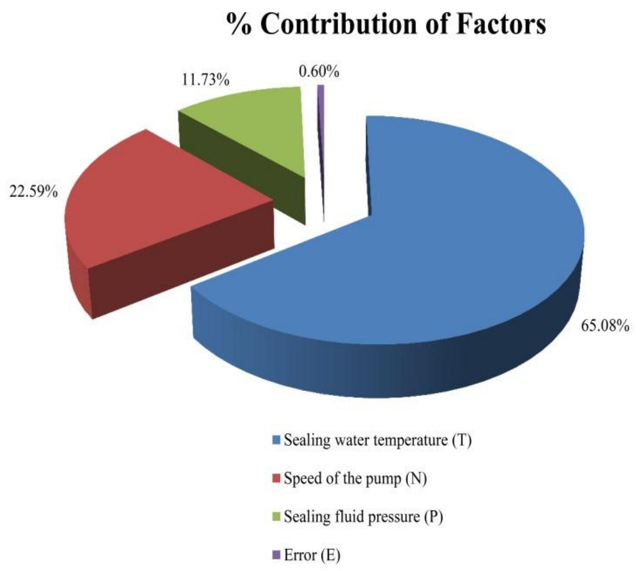

Fig.6. Percentage contribution of each factor

C. Confirmation Test

The experimental confirmation test [1]-[6] is the final step in verifying the results drawn based on Taguchi's design approach. The optimal conditions are set for the significant factors and a selected number of experimentsare run under specified working conditions. The average of the results from the confirmation experiments is compared with the predicted average based on the parameters and levels tested. The confirmation experiment is a crucial step and is highly recommended by Taguchi to verify the experimental results. In this study, 5 confirmation experiments were conducted by utilizing the levels of the optimal process parameters. The results of the confirmations experiments with the optimal conditions of 25 (^{0}C) sealing water temperature, speed of the pump at 300 (RPM), sealing fluid pressure at 1.5 (Kg f/cm^2) are given below. It can be seen that the results are consistent.

Table VI.Results of the confirmations experiments with the optimal conditions

Exp. No.	1	2	3	4	5	**mean**
Efficiency	0.3568	0.3489	0.3565	0.3643	0.3462	**0.35454**

IV. CONCLUSIONS

This study has discussed an application of the Taguchi method for investigating the effects of process parameters on the efficiency of vacuum pump. From the analysis of the results using the conceptual signal-to-noise (S/N) ratio approach, analysis of variance (ANOVA), and Taguchi's optimization method, the following can be concluded from the present study;

- Statistically designed experiments based on Taguchi methods were performed using L_9 orthogonal array to analyse Efficiency as response variable. Conceptual S/N ratio and ANOVA approaches for data analysis drew similar conclusions.
- Statistical results (at 95% confidence level) show that the sealing water temperature (T), Speed of the pump (N), and Sealing fluid pressure (P) affect the Efficiency by 65.08%, 22.59% and 11.73% respectively and the contribution of error is only 0.60%
- In this study, the analysis of the confirmation experiment for efficiency has shown that Taguchi parameter design can successfully verify the optimum process parameters (T1, N1,P1), which are sealing water temperature of 25 (^{0}C), speed of the pump 300 (RPM), sealing fluid pressure 1.5 (Kg f/cm^2).

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