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OPTIMIZATION OF GEOMETRIC PARAMETERS FOR IMPELLER DESIGN IN AN AXIAL FLOW PUMP

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Abstract

This work is mainly concentrated on increasing the efficiency (η) and reducing the Net Positive Suction Head (NPSH) required by optimizing the design through the geometrical parameters involved. Blade thickness, Chord cascade solidity, chord angle and hub angle are the geometric variables evaluated. In order to establish the relation between the geometrical parameters and the objective functions (η and NPSH), a statistical approach in the form of ANOVA and RSM is used and the DOE is performed using Taguchi method. The data for the geometrical parameters were selected based on the technical values commonly used in the present impeller design. The values of objective functions for the analysis were taken from the calculations done using simulation results using appropriate equations. The effect of geometrical parameters on the objective functions is analysed and the optimization of parameters is carried out using RSM in Minitab software. .

Introduction

Important applications of axial flow pumps lie in the agricultural and the industrial fields. Also, effective transport is facilitated by them. Axial flow pumps have lower head, higher flow rates and not so complex structure compared to other pumps. Even with the advantages the axial pumps are prone to consume more energy than the other fluid machinery. Hence, there is a need to design and manufacture the hydraulic equipment which consumes less energy as the it is the need of the hour due to the raise in the energy prices.

Design efficiency and work performance improvement of the fluid machineries is been taken up by many researchers. The reduction of cost incurred due to physical experiments and prototyping can be reduced by simulation analysis and optimizations through building a well defined numerical model using FEM (finite element analysis) approach [1, 2]. In order to carry out the numerical analysis CFD (computational fluid dynamics) is used to epitomize the flow nature and the potential modifications which can be made improve the performance of the centrifugal pumps

[3,4] and radial pumps [5]. Using an optimal impeller, pump efficiency of a helicon-axial-multiphase pump is increased by adopting non-dominated sorting genetic algorithm – II (NSGA-II) and artificial neural network (ANN) [6]. Also, for the increase in pump efficiency, optimization of design of the guide vane behind the impeller is considered as the current solution [7]. Similarly, numerical simulation and DOE were used to improve the performance of a mixed flow pump by optimising the impeller and diffuser [8]. By reviewing the findings of these methods it is seen that the combination of CFD-based methods and optimization techniques proves to be very efficient in predicting and improving the work performance of the pumps.

By considering the literature it is seen that the improve in the performance of the pump by impeller geometry optimization has been effectively accomplished. With proper extension of blade inlet and by enlarging the blade inlet angle along with the optimal slots the new impeller design leads to significant improvement in the pump cavitation performance [9, 10]. An optimum value for vane rake angle for obtaining superior cavitation performance was proposed [11]. Based on the genetic algorithm and CFD simulation improved design for blade thickness and leading-edge ellipse ratio was also proposed [12]. In the abovementioned works the major concentration is only on the optimization of impellers for improving the cavitation performance. Although the researchers have concentrated on the optimization of impellers, less focus is on the impeller geometrical parametric optimization which can resolve the transactions between the efficiency of the pump (η) and net positive suction head (NPSH). Pump performance not only depends on the efficiency but also the required NPSH which becomes a very important factor to be considered as it effects and damages the pump is increased drastically which leads to the blockage or in the reduction of fluid flow [13]. Hence in the design, minimizing the NPSH required becomes the important criteria. As the axial flow pumps have significant applications it is very important to have a model (numerical or statistical) for optimizing the geometric parameters which helps in the increase of efficiency of the design. The efficiency and the NPSH required can be varied by varying the pump components in general and impeller geometry in particular. The manufacturing cost can be reduced by significantly improving the prototyping performance through generation of optimal solution. Hence, an effective model for optimizing the design parameters is basically required and this work focuses on the generation of such statistical model for prediction and optimization.

The original aim of this work is to build a statistical model using DOE (Taguchi), analysing the effect of parameters (ANOVA) and to predict the best geometric parameters (RSM – response surface methodology). Various impeller geometrical parameters like blade thickness, cascade solidity of the blade, chord angle and hub angle are considered for the study and the values are obtained through the numerical simulation (which is not discussed in this article). Best compromise solution for the pareto set is generated finally and the best geometrical parameters are obtained which leads to increase in the efficiency and decrease in the NPSH required.

Methodology

The efficiency and the NPSH required of an axial flow pump are optimized together through the numerical experiments and the statistical model which is mentioned earlier. The efficiency of an axial flow pump is given by:

$$\eta = \frac{(\Delta E_k + \Delta E_p)60}{2\pi n T} \quad (1)$$

Where, ΔE_k – Kinetic energy difference, ΔE_p – pressure energy difference in inlet and outlet in unit time, n – rotation speed and T – torque put by the fluid on the rotation axis.

NPSH is the total energy in the fluid without vaporization facilitating the overcoming of frictional losses from suction nozzle till the impeller eye and is given by:

$$NPSH\ required = \frac{P_{in} - P_{min}}{\gamma} + \frac{U_{in}^2}{2g} \qquad (2)$$

Where, P_{in} – Inlet pressure, P_{min} – whole blade minimum pressure, γ = specific weight of the fluid and U_{in} – inlet fluid velocity.

Four key geometrical parameters are considered for the study and they are Blade thickness (H), cascade solidity of the chord (σ_c), chord angle (β_c) and hub angle (β_h). Figure 1 shows the design variables of the impeller blades. The levels considered for the DOE and analysis are shown in table 1.Parameter ranges are considered with respect to the current impeller technical values and are obtained from real company (M/S NXL FLOW INSTRUMENTS, Bengaluru) and information available from literature [1-8]. The values for the efficiency (η) and NPSH required are obtained from calculation done using numerical simulations using equations 1 and 2.

Table 1: Levels of the parameters

Symbol	Parameters	Level-1	Level-2	Level-3
H	Thickness of the blade (mm)	6	8	10
σ_c	Cascade solidity of chord	0.74	0.79	0.84
β_c	Chord angle (degree)	20	22	24
β_h	Hub angle (degree)	35	44	54

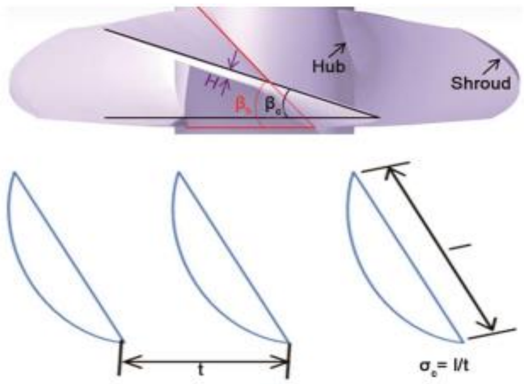

Fig 1: Impeller blades design variables

Formulation of optimization process is given through the below expressions:

Optimized value $X = [H, \sigma_c, \beta_c, \beta_h]$

Pump efficiency (maximize) = $\eta(H, \sigma_c, \beta_c, \beta_h)$

Net positive suction head required (minimize) = $NPSH\ (H, \sigma_c, \beta_c, \beta_h)$

Range from: $6 \leq H \leq 10$ (mm), $0.74 \leq \sigma_c \leq 0.84$, $20 \leq \beta_c \leq 24$ (deg), $35 \leq \beta_h \leq 54$ (deg).

Optimization route

The framework for DOE and multi objective optimization is created and worked as such. Initially, the design parameters are defined and using Taguchi the DOE model for the chosen parameters is done. From the inputs of DOE the numerical model simulation of the axial pump is carried out to calculate the objective functions for different experimentations. After obtaining the data of the objective functions the response surface methodology model is built and the relationship between the inputs (design factors) and the outputs (efficiency and NPSH required) is established. At the end, the optimization procedure is carried out using the regression equations in the RSM.

The flow chart showing the steps in the RSM process is given in figure 2.

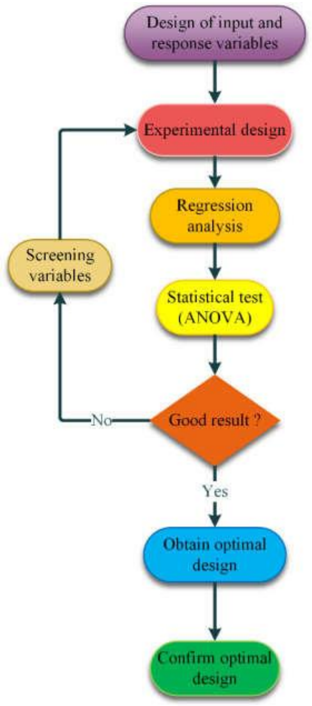

Fig 2: Response surface methodology flow chart

Results

The parameters considered are used in the Minitab software to create design of experiments (Taguchi) by the virtue of which the L9 orthogonal array is formed. For the 9 different input parametric combination through numerical computation the efficiency and the NPSH required are found. Then the values are incorporated in the array table and the design is analysed for the input-output relationship. Table 2 shows the L9 orthogonal array formed along with the values of the objective functions.

The design is analysed and the signal to noise ratio graph with the condition – larger is better is plotted using the response table. Table 3 shows the response table for signal to noise ratio of efficiency effected by the different parameters considered. As seen from the table as well as graph (fig 3 – main effects plot), it is clear that the major affecting factor is the thickness of the blade followed by the chord angle and then the cascade solidity of the chord and finally the hub angle.

Table 2: L9 orthogonal array

H	σc	βc	βh	η	NPSH
6	0.74	20	35	76.2	9.4
6	0.79	22	44	76.9	9.2
6	0.84	24	54	79.3	8.5
8	0.74	22	54	80.4	8.7
8	0.79	24	35	83.7	7.2
8	0.84	20	44	82.1	7.5
10	0.74	24	44	81.4	8.7
10	0.79	20	54	81.6	8.8
10	0.84	22	35	80.7	8.9

Table 3: Response Table for Signal to Noise Ratios

Larger is better

Level	H	σc	βc	βh
1	37.78	37.99	38.05	38.08
2	38.28	38.14	37.99	38.07
3	38.19	38.14	38.22	38.11
Delta	0.50	0.15	0.23	0.04
Rank	1	3	2	4

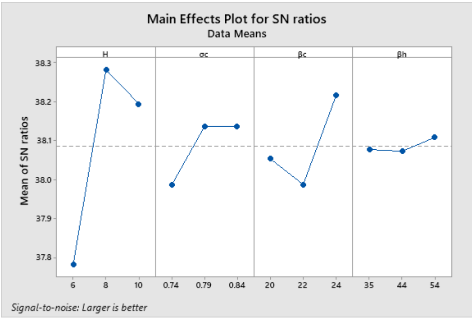

Fig 3: Main effects plot for efficiency

Similarly, the Taguchi design is analysed for the behaviour of NPSH required when the parametric values change within the given range. Response table is obtained with a condition of smaller is better as the NPSH values should get reduced in the pump overall. As seen from the previous analysis, the major influencing parameter is thickness of the blade followed by the chord angle and then the cascade solidity of the chord and finally the hub angle.

Table 4: Response Table for Signal to Noise Ratios

Smaller is better

Level	H	σc	βc	βh
1	-19.11	-19.01	-18.62	-18.53
2	-17.81	-18.44	-19.02	-18.52
3	-18.89	-18.36	-18.18	-18.76
Delta	1.30	0.66	0.84	0.23
Rank	1	3	2	4

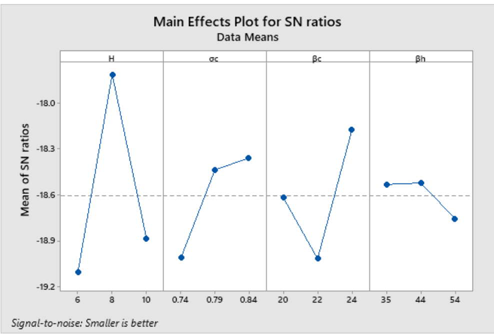

Fig 4: Main effects plot for NPSH

Analysis of Variance is also performed on the taken data set to look out for the contribution percentage of each parameter on the individual output. Regression equation for both the outputs is generated and table 5 and 6 gives the contribution of parameters on the behaviour of output.

Pareto charts are drawn to show the effects of the geometric parameters visually and figure 5a shows the Pareto chart for efficiency by which it is seen that the factor – thickness of the blade have major effect on the efficiency followed by C, B and D. Residual plots are drawn to understand the goodness-of-fit in ANOVA. By examining the residual plots (figure 5b) it is seen that the ordinary least squares assumptions are being met. This means that the ordinary least squares regression has produced unbiased estimates with minimum variance. From the normal probability plot it is seen that the residuals are normally distributed and there is no abnormality seen. From the residuals versus fit, the distribution of data is seen very near to the line 0 which shows that the residuals have a constant variance. With the versus order fit plot it is seen that the residuals are uncorrelated with each other. Histogram of residuals is used to observe that the data are skewed or the outliers does not exist in the data.

Similar observations are made through the graphs plotted (figure 7b) for residuals for NPSH required and the observations are as similar to that of the efficiency. The regression equation is derived from the software which gives the relation between the output and the inputs through algebraic representation.

Regression Equation

$$\eta = 53.1 + 0.942\,H + 13.7\,\sigma c + 0.375\,\beta c + 0.0126\,\beta h$$

Table 5: Analysis of Variance for Efficiency

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	4	27.5445	58.33%	27.5445	6.8861	1.40	0.376
H	1	21.2817	45.07%	21.2817	21.2817	4.33	0.106
σc	1	2.8017	5.93%	2.8017	2.8017	0.57	0.492
βc	1	3.3750	7.15%	3.3750	3.3750	0.69	0.454
βh	1	0.0862	0.18%	0.0862	0.0862	0.02	0.901
Error	4	19.6777	41.67%	19.6777	4.9194		
Total	8	47.2222	100.00%				

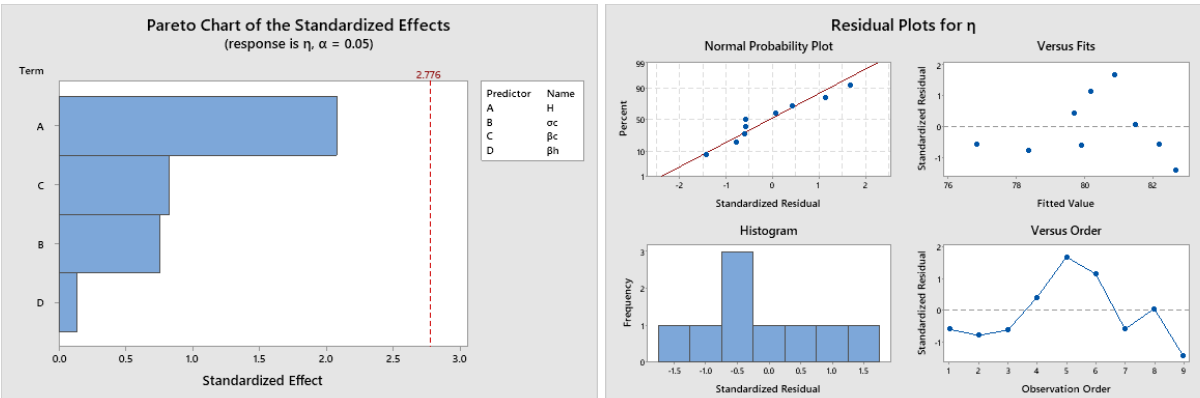

Fig 5 a and b: Pareto chart and residual plot for Efficiency

Surface plots for four of the combinations of X and Y (inputs) v/s the efficiency (figure 6) is plotted to understand the behaviour of the output with respect to the inputs.

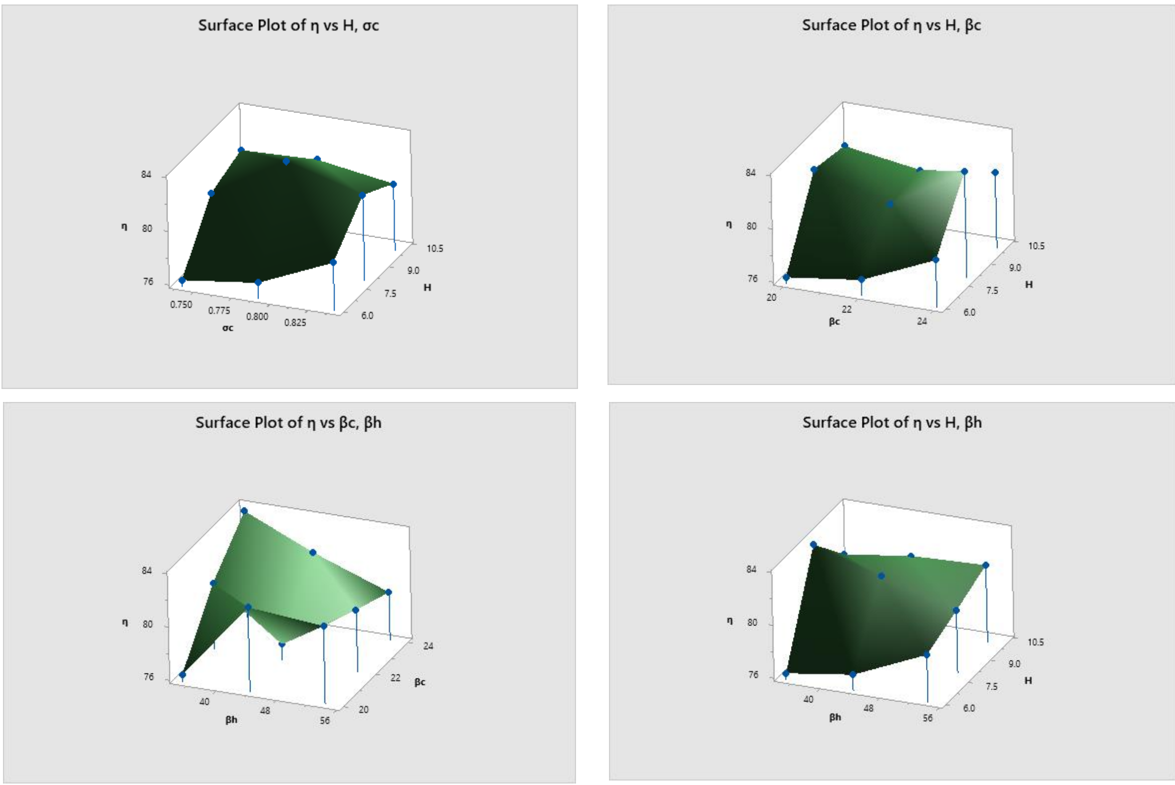

Fig 6: Surface plots for Efficiency

Regression Equation

NPSH = 16.00 - 0.058 H - 6.33 σc - 0.108 βc + 0.0090 βh

Table 6: Analysis of Variance for NPSH

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	4	1.00870	23.45%	1.00870	0.25217	0.31	0.861
H	1	0.08167	1.90%	0.08167	0.08167	0.10	0.769
σc	1	0.60167	13.99%	0.60167	0.60167	0.73	0.441
βc	1	0.28167	6.55%	0.28167	0.28167	0.34	0.590
βh	1	0.04370	1.02%	0.04370	0.04370	0.05	0.829
Error	4	3.29352	76.55%	3.29352	0.82338		
Total	8	4.30222	100.00%				

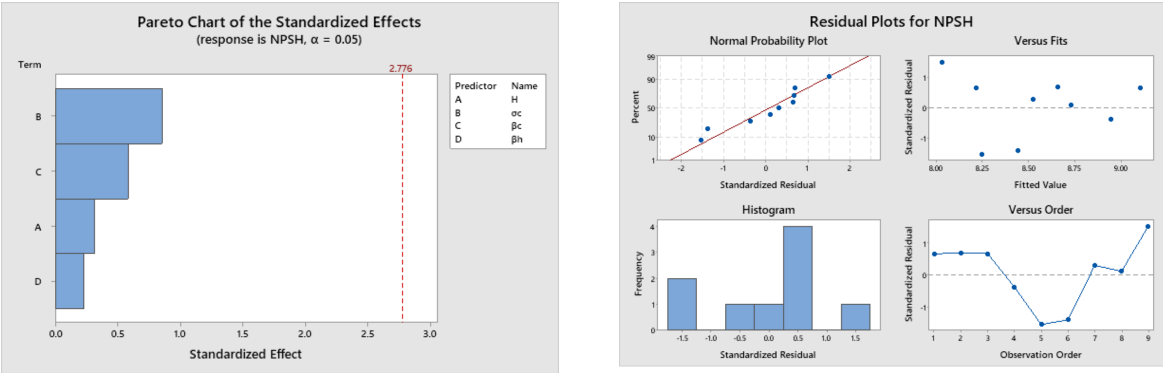

Fig 7 a and b: Pareto chart and residual plot for Efficiency

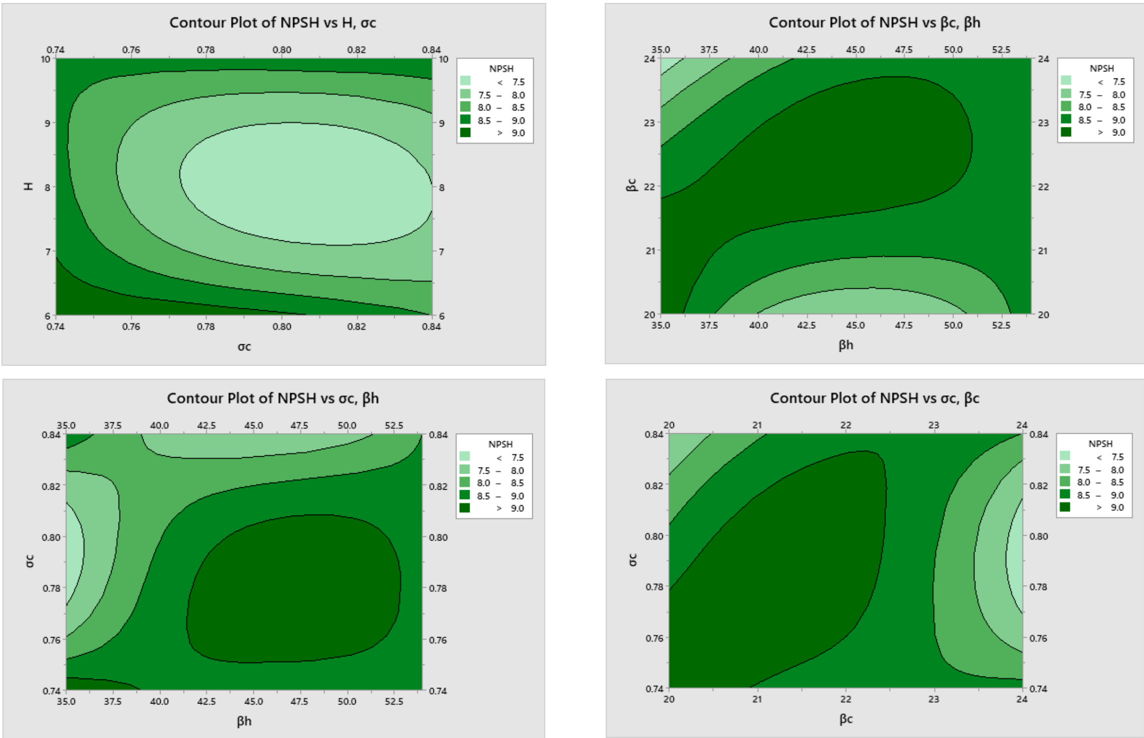

Fig 8: Contour plots for NPSH required

The contour plots are drawn (figure 8) to understand the relationship between the fitted response (NPSH required) and the two continuous variables. A two dimensional view in which points have same response value are connected to produce contour lines and the results are interpreted on the basis of colour gradient. The light green colour indicates the best combination values of inputs in the plot giving optimized output values.

Optimization results

Table 7: Parameters

Response	Goal	Lower	Target	Upper	Weight	Importance
NPSH	Minimum		7.2	9.4	1	1
η	Maximum	76.2	83.7		1	1

Table 8: Solution

Solution	**H**	**σc**	**βc**	**βh**	**NPSH Fit**	**η Fit**	**Composite Desirability**
1	8.10101	0.813737	24	35.0449	7.09479	83.9499	1

Table 9: Multiple Response Prediction

Variable	**Setting**
H	8.10101
σc	0.813737
βc	24
βh	35.0449

Response optimizer is used to identify the combination of input variable settings that optimize both the responses (efficiency and NPSH required). An optimum solution is calculated and an optimization plot (figure 9) is drawn. The results obtained are tabulated in table 9. Table 8 gives the solution of the problem in terms of best possible inputs to obtain best possible out puts. According to the results from the table the optimal parameters to obtain optimal outputs are H-8.10101, σc-0.813737, βc-24 and βh-35.0449. The optimal output values obtained are η-83.9499 and NPSH-7.09479.

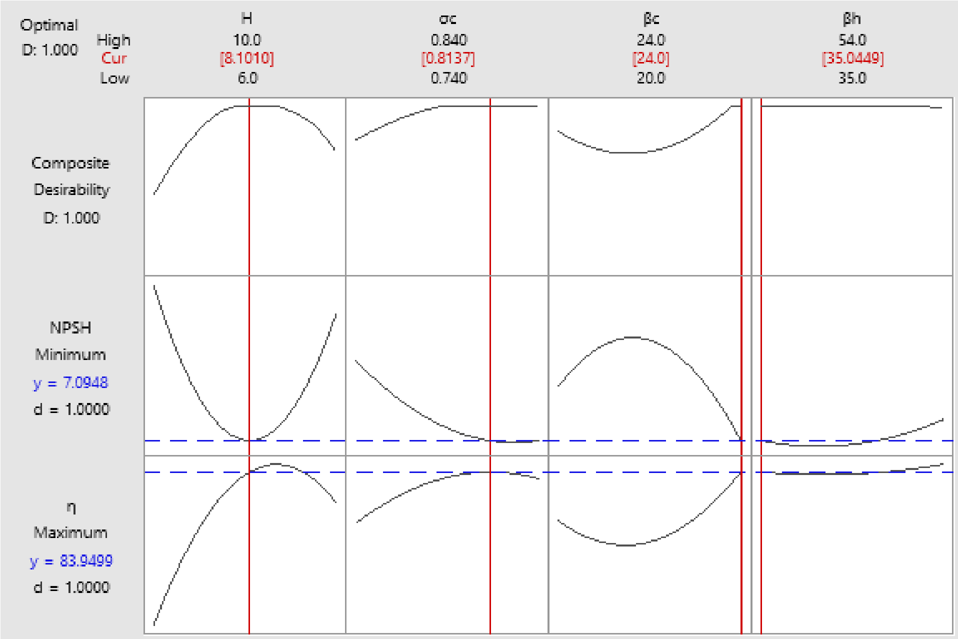

Fig 9: Optimization curves

Conclusion

This work has described the design process for an axial flow pump impeller parameter which are optimized to yield optimal outputs by increasing the efficiency and decreasing the NPSH. The major goal of this work was to develop a statistical design to understand the relation between the inputs and the outputs and also to optimize the parameters to obtain the optimal outputs. The work involves the Taguchi design of experiments and the analysis by ANOVA and finally the optimization done using response surface methodology. By the experimentation and results obtained two main conclusions can be drawn:

(i) The model developed using ANOVA and RSM is efficient enough to analyse the relationship between the parameters and the objective function and also is accurate in terms of predicting and optimising the parameters along with the optimal objective functions.

(ii) The optimized values are most satisfying as an approximate 9.4% reduction is seen in NPSH required with the optimum input values. Also the increase in efficiency is seen up to 7.8% which is far more superior than the initial values.

In a similar manner the optimization of guide vane geometry with a holistic approach is also necessary as it also serves as an important factor in the variation of efficiency and NPSH required.

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