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# TWO-LEVEL DESIGN OPTIMIZATION OF HIGH SPECIFIC-SPEED CENTRIFUGAL PUMP

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## ABSTRACT

*A two-level Design of Experiment (DoE) method is used to determine the optimum value of fluid dynamic variables for the optimum performance of high specific speed centrifugal pump considering individual and interaction effects of design variables. Each variable is designated two levels and all the effective combinations are analyzed to find out accurate results. The optimization problem has been formulated with a non-linear objective function to minimize fluid dynamic losses and net positive suction required head of a pump depending on the weighting factors selected as the design compromise. The optimum solution is obtained by Hook-Jeeves direct search method. The optimized efficiency and design variables of centrifugal pump are presented in this paper as a function of specific speed. The computer program developed in the present work is best suited for specific speed between range of 60-80.*

***Keywords:*** *Centrifugal Pump, Design of Experiments, Design Variables, Specific Speed.*

## I. INTRODUCTION

Centrifugal pump has been designed as highly capable pumping machine owing a large number of geometric and fluid dynamic variables. Most of the design processes and performance analysis of centrifugal pump are essentially based on empirical or semi-empirical rules opted by many designers [12-17]. While designing a pump, due concentration is focused on important parameters like required head, maximum efficiency, the stable flow characteristics, the non-cavitation performance. The design process involves a number of compromises between the maximum efficiency and suppression of cavitation which otherwise reduces the life of the centrifugal pump. Involved design variables are to be optimized for efficient performance and enhanced life cycle of centrifugal pump, thus, makes design of centrifugal pump a multi-objective optimization problem that rarely has been considered so far in the literature.

The few designers investigated an optimization process to increase efficiency and head and decrease the required Net Positive Suction Head ($NPSH_R$) at two different flow rates [5-11]. Some presented an optimization process on centrifugal pumps and used the analytical equations for hydraulic efficiency, head and the input power [2-5]. They suggested four optimal solutions which can be selected depending upon the requirement. They tried to increase the hydraulic efficiency and head and decrease the input power. The available research work mainly focused on performance optimization of centrifugal pump based on only a few design variables which restricts the analysis to individual effects of variables. Apart from individual impact, the relation/interaction also plays an important role on practical performance of centrifugal pump. To the best of the knowledge, no research had been carried out to study both individual as well as interaction effects on the performance optimization of centrifugal pump.

Present work focuses on optimizing the design variables for two objectives: maximizing efficiency and minimizing $NPSH_R$. Final objective function is formulated by assigning weight factors to efficiency and $NPSH_R$. In addition to individual effect, relationship or interaction between variables also play an important role on the optimization of centrifugal pumps. Eighteen design variables including geometric and hydraulic are selected. These variables and respective interactions control the performance of centrifugal pump. Each variable is assigned two values called lower and higher level and design of experiments methodology is employed to predict the effects of individual variable and its interaction with other variables. An automated computer design code using *Hooke-jeeves direct search method* [1, 13] is developed which can be used to find optimum solution sets from these experiments for the desired efficiency and required net positive suction head levels. The final set of design variables can be determined from above investigate sets by deciding weight factors for a particular requirement.

## II. DESIGN OF EXPERIMENTS

Optimum design of the centrifugal pump means determining the best combination of design variables based on the optimization criteria. Developing the optimal design by planning and executing experiments requires hundred of runs and several weeks and months of time. Several design methodologies like robust design method [9], analysis of variance (ANOVA), neural network, programming techniques and Computational Fluid Dynamics (CFD) tools are available for analyzing and optimizing the performance of a centrifugal pump. The primary goal in selecting one of these methodologies is usually to extract the maximum amount of unbiased information regarding the effect of different variables on the performance. In the presence of two or more variables, knowledge of variables-interaction effects is of prime importance to the designer. Design of experiments methodology, which is used in present work, not only facilitate the designer to find out the effect of each individual variable but also of interaction/relation between variables which are not possible with one variable at a time approach. This methodology also plays an important role to determine critical variables which essentially affects the performance.

The effect of a variable is defined to be change in response produced by change in its levels i.e. testing values of the variable. Commonly one of these levels is taken to be the initial operating condition. These levels should be taken sufficiently far apart so that the chance is increased for capturing any non-linearity of the relationship between the control variables. The difference in response between the levels of one variable is different for different levels of other variables. When this occurs there is interaction between the variables.

Experimentation involves first determining the more important feasible variables. Next the desirable levels of the selected variables are identified. Finally, it may be of interest to find the relationship between the variable levels, the corresponding responses, and the physical economic constraints that are imposed. Although different kind of designs can be used at each of these stages, multi-variable experiments are usually employed. One such multi-variable experiment used in exploratory stage is the $m^n$ factorial experiments which involves ‘n’ variables, each at ‘m’ levels. So the total number of experiments is $m^n$. These experiments may be realistically or virtually using software tool. In case number of experiments exceeds to a greater extent, the available techniques may be used to cut short the number of experiments but the same is avoided to get accurate results.. In present work, eighteen variables are identified, each at two levels, thus, results in $2^{18}$ i.e. 32768 experiments. All the experiments have been conducted through design code developed in C++ language using *Hooke-jeeves direct search method.*

**Table 1: Identified Design Variables**

| S. No. | Variables | Levels | | Description of Variables |
|---|---|---|---|---|
| | | Lower | Higher | |
| 1. | $D_{sh}/D_h$ | 0.8 | 0.95 | B= Runner width in m<br>D= Diameter in m<br>$D_e$= Runner eye diameter in m<br>$D_{h=}$=Hub diameter in m<br>$D_{sh}$= Shaft diameter in m<br>$f_i$ = $i^{th}$ weighting factor<br>t = Blade thickness in m<br>U= Peripheral velocity in m/s<br>$V_m$ = Absolute velocity in m/s<br>$V_r$= Relative velocity in m/s<br>$V_{rui}$=Whirl component of relative velocity in m/s<br>$V_u$= Whirl component of Velocity in m/s<br>Z = Number of blades<br>α=Angle at which water enter/leave the runner<br>β = Blade angle<br>$\sigma_f$= Blade cavitation coefficient<br>Φ= Flow coefficient<br>Ψ= Head coefficient |
| 2. | $D_e/D_1$ | 0.8 | 1 | |
| 3. | $D_1/D_2$ | 0.4 | 0.9 | |
| 4. | $D_3/D_2$ | 1.15 | 1.3 | |
| 5. | $B_3/B_2$ | 1.5 | 2 | |
| 6. | $t/D_2$ | 0.006 | 0.016 | |
| 7. | $B_2/D_2$ | 0.04 | 0.1 | |
| 8. | Z | 5 | 12 | |
| 9. | $\beta_1$ | 20 | 40 | |
| 10. | $\beta_2$ | 20 | 40 | |
| 11. | $\alpha_2$ | 25 | 45 | |
| 12. | $\sigma_f$ | 0.3 | 0.45 | |
| 13. | Φ | 0.1 | 0.2 | |
| 14. | Ψ | 0.5 | 0.7 | |
| 15. | $V_m / V_{m1}$ | 0.8 | 1 | |
| 16. | $V_{m0}/V_{m2}$ | 1.2 | 1.5 | |
| 17. | $V_u / U_2$ | 0.2 | 0.6 | |
| 18. | $V_{rui}/ V_r$ | 1.4 | 1.6 | |
| **SUBSCRIPTS:** 0=Eye of pump, 1=Inlet of pump, 2=Outlet of impeller and 3=Inlet of volute | | | | |

## III. IDENTIFICATION AND SPECIFICATION OF DESIGN VARIABLES

Optimizing the design of centrifugal pump involve kinematic and dynamic analysis for various combination of design variables and selecting best of them for a designed optimization criteria. These design variables are categorized in to three categories: (a) uniquely identifiable (b) identifiable in linear/non-linear combination and (c) unidentifiable [11]. Identifying the variables for the analysis plays an important part in optimizing the design of centrifugal pump. Many variables have significant effect on the performance of the centrifugal pump. While taking into account the number of variables, variables which can be dealt feasibly are selected. The work in this paper is limited to the few variables that have much influence on the performance. Identification of these variables may require information regarding physical structure i.e. geometric variables and fluid motion constraints i.e. hydraulic variables of the centrifugal pump. A few of geometric and hydraulic variables are: Vane angle, Number of vanes, Runner discharge width, Hub/Tip ratio, Inclination of the mean stream line with axial direction, Blade Cavitation factor, Flow coefficient, Head coefficient, Blade velocity and Relative velocity. The variables identified for present work are illustrated in Table 1. Next step is to identify the desirable levels i.e. lower and higher, for these identified variables. Levels chosen for the experiment should be realistic and should be able to predict any non-linearity of the relationship between variables. Based on the experiment conducted by various researchers, each variable has been assigned two values called levels for the analysis. Levels for above said variables are given below in the Table-1 [3].

## IV. OPTIMIZATION CRITERIA AND MULTI-OBJECTIVE FUNCTION

The analysis in present work is carried out under the following three assumptions:

(i) the flow enters without any pre-swirl,

(ii) the flow in the vane-less space is of free-vortex type, and

(iii) the volute casing is constructed of gradually increasing circular cross-sections with a constant average velocity.

The design optimization problem for centrifugal pump is defined through design specifications, design constraints, design variables, and objective function. Design specifications, design constraints and design variables are already defined in Table 1.

Both the efficiency and $NPSH_R$ in centrifugal pumps are important objective functions to be optimized simultaneously. In the present work multi-objective function is defined to maximize efficiency and minimize $NPSH_r$ for given flow conditions in case of a centrifugal pump.

Efficiency is defined as the ratio of rate at which useful work is done by the pump (Δp.Q) and power required (W).

$$\eta = \frac{\Delta p \, . \, Q}{W} \tag{1}$$

$NPSH_r$ is expressed under the no-prewhirl condition as given in equation 2.

$$NPSH_R = (1 + \sigma_f)\frac{V_{m2}^2}{2g} + \sigma_f \frac{V_2^2}{2g} \tag{2}$$

where the blade cavitation coefficient $\sigma_f$ is the variable needed to define the inlet performance of pump.

The centrifugal pumps are designed either for maximizing efficiency i.e. $\eta \geq 0.90$ or minimizing $NPSH_R$ i.e. $NPSH_R \leq 4$ meter.

However, in the present work, both efficiency and $NPSH_r$ are optimized simultaneously. So, a compromise is made and combined optimization criterion is defined as given in equation 3.

$$\eta_p \geq 0.80 \text{ and } NPSH_R \leq 4.5 \text{ meter} \tag{3}$$

The objective function for centrifugal pump is elaborated in terms of efficiency ($\eta_p$) and Net Positive Suction Head required ($NPSH_R$). A compromise is made to optimize the loss of efficiency and $NPSH_R$ as illustrated in equation 4.

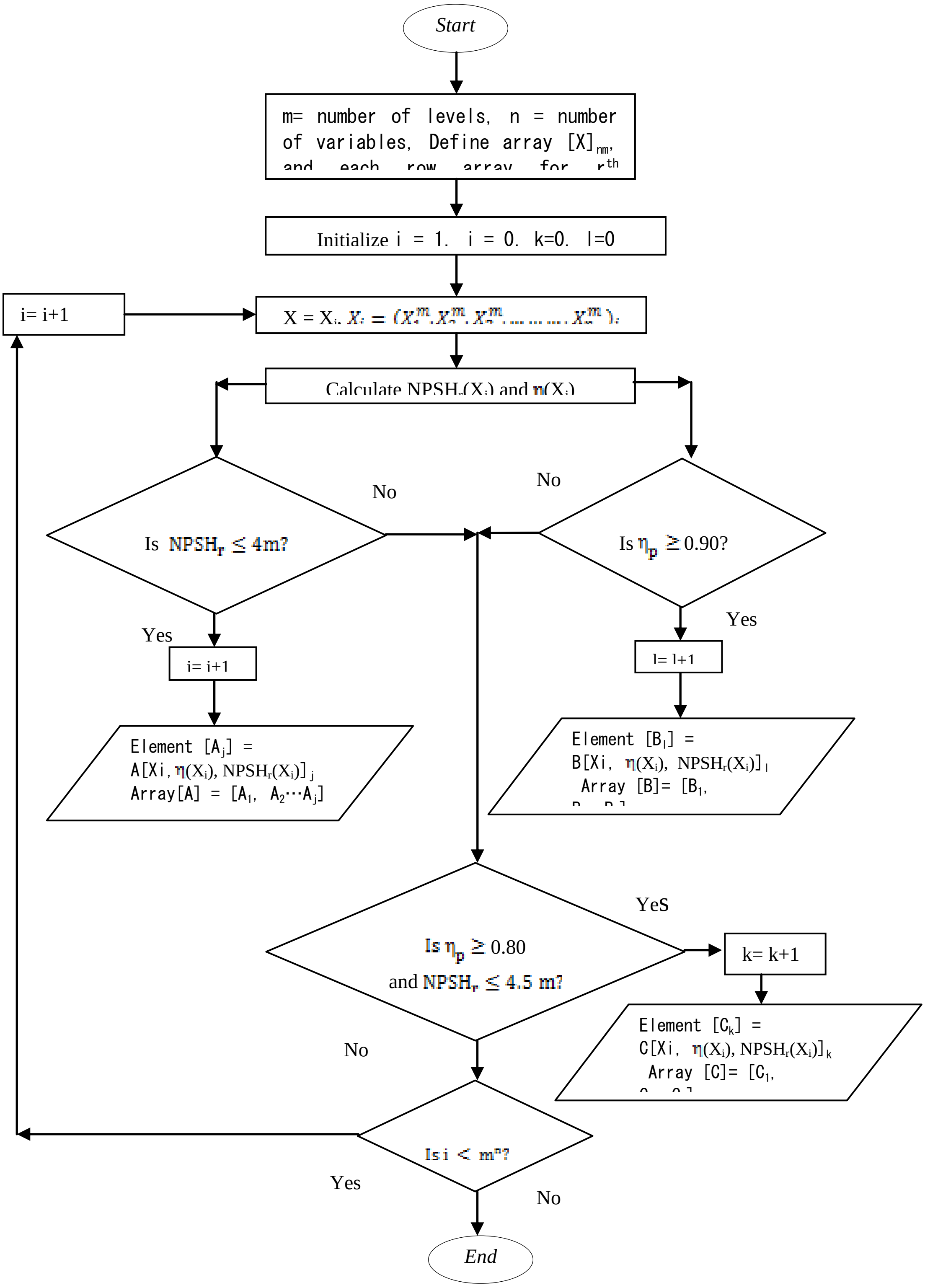

**Fig 1:- Flow Chart of Hook-Jeevas Direct Search Method**

$$Z = f_1(1-\eta_p) + f_2\left(\frac{NPSH_R}{H}\right) \tag{4}$$

where coefficients $f_1$, $f_2$ are the weighting factor for the loss of efficiency and ratio of Net Positive Suction Head required ($NPSH_R$) and available manometer head (H) respectively.

The outlet performance and optimal design can be obtained by defining the weighting factor $f_1$ & $f_2$ as given in equation 5.

$$0 \le f_i \le 1 \text{ and } \sum_{i=0}^{j} f_i = 1 \tag{5}$$

## V. EXPERIMENTS

A simple and efficient computer code using C++ language is developed for the design optimization of centrifugal pump. The flow chart for the algorithm is shown in Fig. 1. A systematic search is initiated for the solution within the considered domain of variables. Optimization requires a set of sorting values of design variables and geometric and hydraulic constraints. A two dimensional array i.e. $[X]_{nm}$ is created for specifying the value of 'n' number of variables at 'm' number of levels. All the combinations ($m^n$) are tested to satisfy the designed objective function. A number of sets are selected satisfying different objective functions i.e.

- array [A] for $NPSH_r \le 4m$,
- array [B] for $\eta \ge 0.90$
- array [C] for $NPSH_r \le 4.5m$ and $\eta \ge 0.80$.

Sorting point search procedure is then carried out to analyze all these feasible combinations and selecting the best one to locate the final set of design variables and geometric and hydraulic constraints to satisfy designed objective function.

## VI. RESULTS & DISCUSSION

Based on two level design optimization, experiments were conducted for 32768 sets of design variables and best combinations are find out for three criterions. For the turbo machines having similar design geometry, same specific speed, similar flow mechanisms and same efficiency, the optimum design code developed in this work is used to find optimum value of design variables as a function of specific speed.

**First criteria i.e. $\eta \ge 0.90$**

Fig.2 describes the performance of pump i.e. efficiency vs specific speed. The operating region is defined based on the first criteria i.e. $\eta \ge 0.90$.

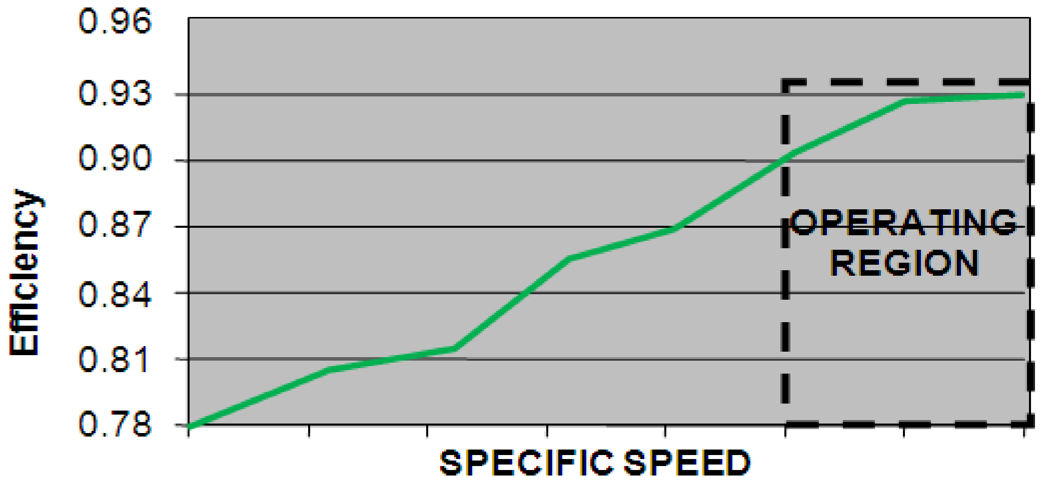

**Fig.2. Specific Speed-Efficiency**

The set of design variables for above performance is given in Table 2.

**Second criteria i.e. $NPSH_r \leq 4m$**

Fig.3 demonstrates the variation of specific speed with $NPSH_R$. In Fig.3, it is observed that when specific speed increases then the value of $NPSH_R$ decreases. The operating region is defined based on the second criteria i.e. $NPSH_r \leq 4m$.

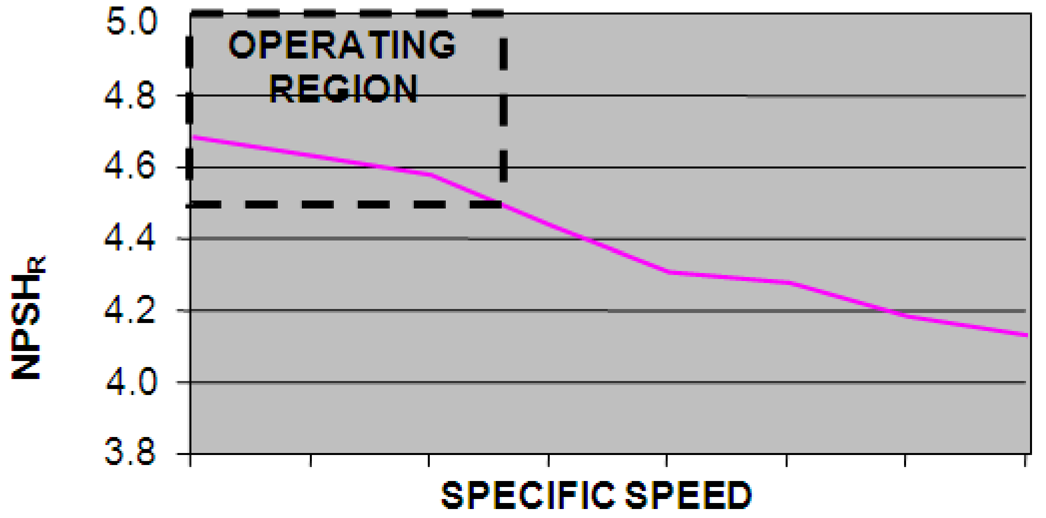

**Fig. 3. Specific Speed-$NPSH_R$**

The set of design variables for above performance is given in Table 2.

**Third condition $NPSH_r \leq 4.5m$ and $\eta \geq 0.80$**

The objective function is formulated as a weighted linear sum of the loss of efficiency and $NPSH_R$. The weighting factors $f_1$ & $f_2$ remains in the range between 0 & 1. Since both the efficiency and $NPSH_R$ are usually of prime interest, thus the region is identified satisfying the third condition $NPSH_r \leq 4.5m$ and $\eta \geq 0.80$, see Fig. 4. For the desired objective function, the peak performance occurs in the high specific speed region. The calculated optimum design variables are compared with their usual design ranges recommended by the pump hand book [17] and found well within this recommended range. Advantage of computer permits the wide range of design variables to be investigated in a very short time. Accuracy of the result depends on the accuracy of the information fed into the computer and choice of suitable variables.

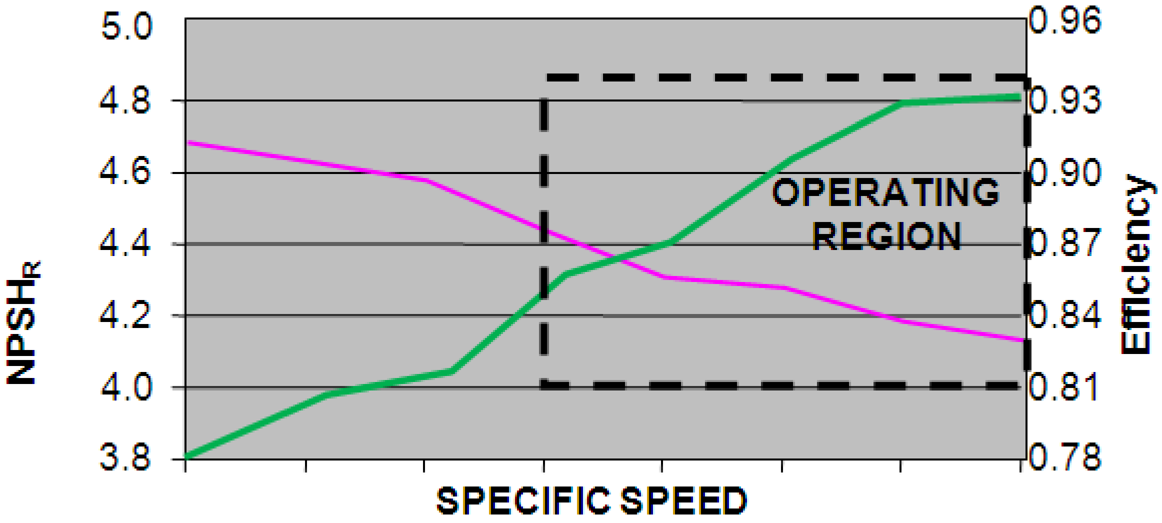

**Fig. 3. Specific Speed-Objective Function**

The set of design variables for above performance is given in Table 2.

**Table 2: Best Set of Design Variables for Three Criterions**

| S. No. | Variables | Value for first criterion $\eta \geq 0.90$ | Value for second criterion $NPSH_r \leq 4m$ | Value for third criterion $NPSH_r \leq 4.5m$ and $\eta \geq 0.80$ |
|---|---|---|---|---|
| 1. | $D_{sh}/D_h$ | 0.8 | 0.8 | 0.8 |
| 2. | $D_e/D_1$ | 1 | 0.8 | 0.8 |
| 3. | $D_1/D_2$ | 0.4 | 0.9 | 0.9 |
| 4. | $D_3/D_2$ | 1.15 | 1.15 | 1.15 |
| 5. | $B_3/B_2$ | 1.5 | 1.5 | 2 |
| 6. | $t/D_2$ | 0.016 | 0.016 | 0.006 |
| 7. | $B_2/D_2$ | 0.04 | 0.1 | 0.04 |
| 8. | Z | 5 | 12 | 12 |
| 9. | $\beta_1$ | 20 | 40 | 40 |
| 10. | $\beta_2$ | 20 | 40 | 40 |
| 11. | $\alpha_2$ | 45 | 25 | 25 |
| 12. | $\sigma_f$ | 0.3 | 0.3 | 0.45 |
| 13. | Φ | 0.1 | 0.2 | 0.1 |
| 14. | Ψ | 0.5 | 0.7 | 0.5 |

| | | | | |
|---|---|---|---|---|
| 15. | $V_m / V_{m1}$ | 0.8 | 0.8 | 0.8 |
| 16. | $V_{m0}/V_{m2}$ | 1.5 | 1.5 | 1.5 |
| 17. | $V_u / U_2$ | 0.2 | 0.6 | 0.6 |
| 18. | $V_{rui}/ V_r$ | 1.4 | 1.4 | 1.6 |

## VII. CONCLUSION

A design optimization program has been developed to obtain an optimum configuration of centrifugal pump under the simultaneous consideration of pump efficiency & $NPSH_R$ to avoid cavitation. The design variables & constraints selected in the present study have been described in Table-1 & variations in these optimized design variables are plotted as a function of specific speed. Designer can easily find the optimum values of design variables to meet their particular requirements of pump design. The optimized geometric and fluid dynamic design variables as a function of specific speed presented in this paper can be used as a practical design guide in the preliminary design phase of centrifugal pump. Based on two level design optimization, experiments were conducted for 32768 sets of design variables and finally, set of design variable values are find out for chosen three criterions for effective centrifugal pump utilization

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