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# PERFORMANCE OPTIMIZATION OF A MULTISTAGE CENTRIFUGAL PUMP FOR HEAVY END RECOVERY USING DESIRABILITY FUNCTION APPROACH

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**ABSTRACT:** *Optimal geometrical (operational)/performanceparameters of a radial split axial pull-out barrel casing multistage centrifugal pump of BB5 class used for heavy end recovery in a natural gas to liquid plant was determined in this study. Impeller discharge diameter,pump suction pipe diameter, impeller blade length, blade discharge angle, impeller discharge widthand radial tip clearance constitutethe factors whose influences on the pumps major flow parameters(efficiency, flow rate, head and speed) were evaluated. The experimental plan applied is completely randomized single replicate Box-Wilson central composite circumscribed block design comprisingthirty-two factorial points, ten centre pointsand twelve axial points while desirability function approach was used in the multi-response optimization of response function of the pump parameters developed. Results revealed 417mm, 366mm, 70mm, 39°, 36 mm and 64mm as the optimal pump suction piping diameter, impeller discharge diameter, impeller blade length, blade discharge angle, impeller radial tip clearance and impeller blade discharge widthrespectively. Performance analysis showed that the pump operates with an efficiency, flow rate, head and speed of 78.30%, $191.55m^3/h$, 967.50m and 2505rpm respectivelyat these optimal factors setting and itsenergy consumption reduced by 1.2%.*

**KEYWORDS:** Centrifugal pump, heavy end recovery, natural gas-to-liquid plant, optimal operational parameter, efficiency, energy consumption,

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## INTRODUCTION

A pump is a machine used to transport liquids or liquid-solid mixture through a piping system as it is capable of imparting kinetic energy to the fluid system [1],[2],[3],[4] and [5]. Pumps are preferred to mobile tankers for transporting fluids because they are cheaper to operate, maintain and time saving. Large volume of fluid can be transported to a distance of up to thousands of kilometers in a few seconds with the aid of pumps through pipelines, thereby reducing material handling risks, environmental pollution and theft. The two main types of pump are rotor-dynamic and positive displacement pumps, and the centrifugal pump tends to encompass all rotor-dynamic pumps. Rotor-dynamic pumps, imparts mechanical energy continuously to fluid by means of a rotating element (rotor) called impeller while in the positive displacement pumps mechanical energy is impartedperiodically to the fluid by means of a plunger (piston) or diaphragm (for the reciprocating pumps) or rotor (for rotary pumps) or screw (for screw pumps) [6]. The dynamic pumps have wider application in petroleum, petrochemical and natural gas industries when high flow rate is required while positive displacement pumps are used when high pressure is required. Also, radial flow low specific speed centrifugal pumps offer considerable high pressures at minimal energy consumption, and therefore their applications outweigh those of positive displacement pumps in recent times, particularly in natural gas-to-liquid plants where they are used for condensate transfer.

Natural Gas – To – Liquid (GTL) plant is a petrochemical plant which converts natural gas to liquid fuels. Naturalgas is compressed from a gas plant (GP) and subjected to auto-thermal reformation in the presence of oxygen and super heated steam to yield carbon monoxideand methanol. The carbon monoxide is sent to Fischer Tropsch reactors where it undergoes hydrogenation to yield hydrocarbon gaseous effluent and other products. Thereafter, the gaseous effluent (tail gas) from the reactorsis condensed to liquid hydrocarbon, heavy end recovered (HER) at the unit chiller (Fig. 1). Separation of impurities in the condensate takes place in the condensate separator before it is pumped into the unit absorber stripper from which the liquid hydrocarbon is pumped through heat exchangers to the hydrocracker where complex hydrocarbon molecules are broken down into simpler molecules to form diesel, LPG and other hydrocarbon liquids.

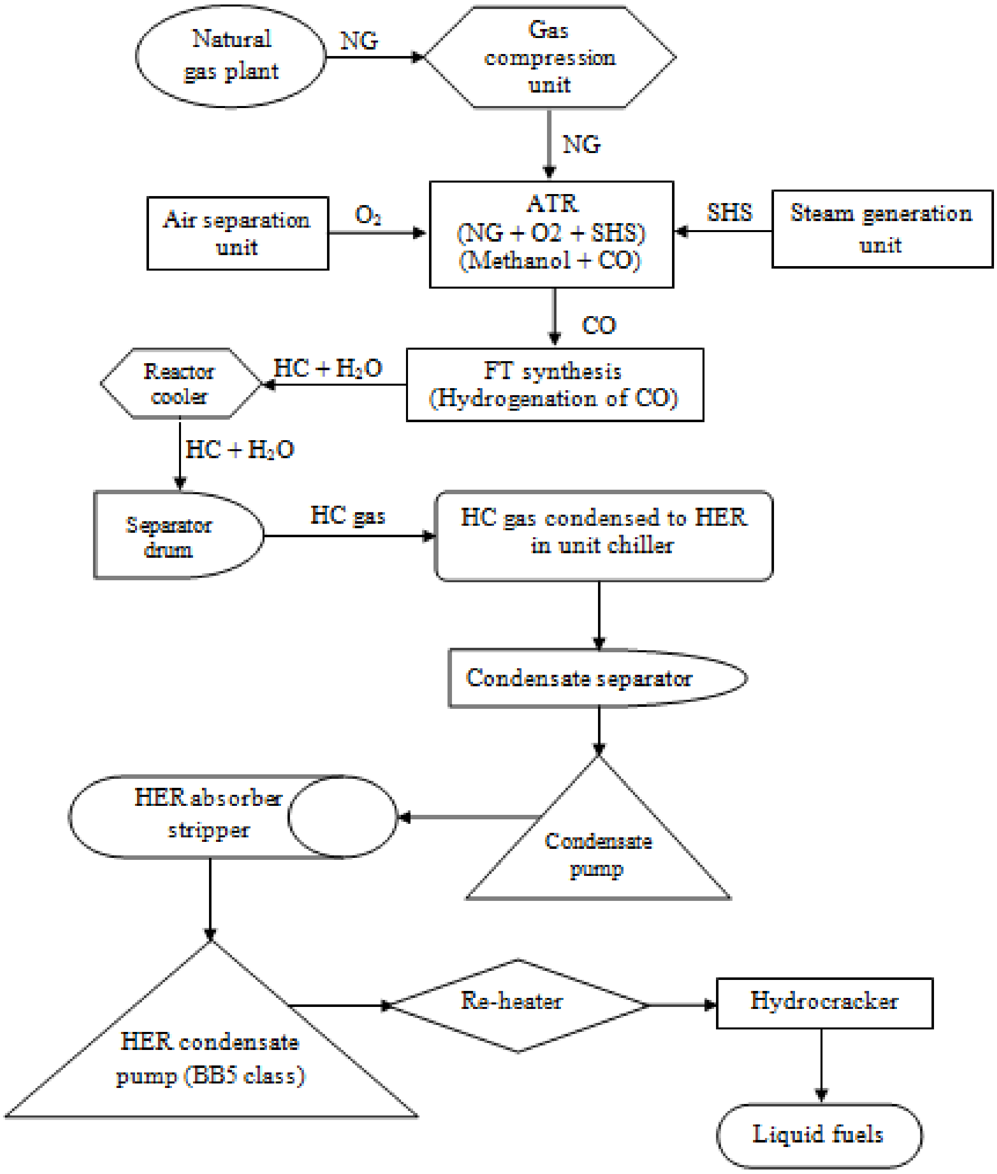


Fig. 1: Heavy End Recovery formation/flow process

Although, transportation of condensates among various units of the plant is achieved using different centrifugal pumps, radial split axial pull-out barrel casing multistage centrifugal pumps of BB5 class is mainly used for its outstanding high head capability, though its application is characterized by high cost and energy dissipation. This is because of the inherent mechanical and hydraulic losses associated with the available designs [7],[1],[8],[9],[10] and [11]and also the quest to match the pumps with varied processes and pipeline systems. Pump damage and outright loss of units due to operational errors, mismatch of drives and the pump units, procurement cost due to pump replacement resulting from system adjustment (modification or upgrade) and low productivity due to poor performance characteristics of the pumps are common in this sector. Thus, HI and Euro pump [13] indicated that pumping systems account for about 20% of world energy usage. When pump systems operates with low efficiency, they drain corporate profits with high energy and maintenance costs, shorten mean time between repairs and increase carbon (IV) oxide emission [12].

Every centrifugal pump user is interested in operating the pump with optimal power, speed, efficiency, flow rate and head. Determination of optimal settings of the operational parameters required for desired levels of these performance indicators of the pump isa serious concern in using centrifugal pumps for heavy ends recovery in natural gas to liquid plant. This is because performance parameters of the pump are related in a way that improving one deteriorates another. Although, optimal levels of some of these parameters have been predicted by different authors, practical implementation of their predictions was not satisfactory because the predictions were either based on single response/factors optimization approach or that all the major variables and responsesidentified in [14], [15], [16] and [17]were not considered where multi-factors/responses procedures were applied. Kim and Kim [18] improved the efficiency of a mixed flow pump by 7.05% using three-levels full factorial design in which two variables defining the straight vane length ratio and the diffusion area ratio are selected as design variables and the efficiency was evaluated as the objective function. Chakraborty and Pandey [19] formulated mathematical models of centrifugal pumps efficiency and head with respect to number of impeller blades. Singh and Nataraj [20] applied response surface method to develop empirical models of low specific speed centrifugal pump which were visualized using computational fluid dynamics with the total head and efficiency as the objective functions and impeller eye diameter, vane exit angle and blade exit width as the variables.Wang *et al*[21] established a functional relationship between the efficiency and impeller outlet slope, impeller blade stagger angle and blade outlet width of a multistage pump through quadratic regression orthogonal test. Thus, pump suction pipe diameter and the configuration of the impeller profiles (number of impeller blades, blade length, impeller discharge diameter, and bladedischarge angle and blade discharge width) constitutes the major factors that affects the main flow (performance) parameters of centrifugal pump. These parameters are considered because they have been duly correlated in [22], [8], [9], [23], [10], [24] and others with other factors such that their optimal settings will cushion the effects of slip, solidity, surface roughness, cavitation, viscosity, temperature, recirculation and other geometrical parameters on the pump efficiency, flow rate, head and speed.It is therefore desired to operate this pump at the maximum possible efficiency and minimum possible energy consumption anywhere it is being used.

Since natural-gas-to liquid hydrocarbon technology increases the prospect of monetizing a resource previously considered as stranded gas/waste over decades and potential for safe play on increasing stricter legislation on flaring and toxic emissions, there is need to establish a multi-factors/responses basedoptimal operational parameters frameworkof radial split multistage centrifugal pumps (BB5 class) used for heavy end recovery in order to minimize cost of pumping in this sector. In multi objective empirical optimization of this nature, response surface design with desirability function optimization approachis usually applied in the estimation of response functions with the objective of improving all the responses of interest simultaneously irrespective of their nature whether linear or nonlinear using small number of experimental runs to save time and cost [25].Desirability function optimization technique is mostly preferred to others such as path of steepest ascent and mathematical programming techniques because it can be used when the response models are all linear, quadratic (or nonlinear) or mixture of linear and quadratic and all responses are given equal considerations. Method of steepest ascent applies when the response models are all linear while mathematical programming method applies when one response is of primary or most important interest and constraints are defined on all other responses [25]. Thus, this work applied response surface design with desirability function approach to determine optimal geometrical parameters of radial split axial pull-out barrel casing multistage centrifugal pumps of BB5 class used for transporting HER in a natural gas-to-liquid (GTL) plant.

## MATERIALS AND METHODS

The radial split axial pull-out barrel casing multistage centrifugal pump of BB5 class (Fig. 2) evaluated has an integral class 900 flanged nozzles of 8'' (200mm) and 4'' (100mm) diameters at the suction and discharge ends respectively, and seven impellers of uniform geometrical dimensions; with discharge diameter of 400mm, blade length of 150mm, discharge blade angle of 50°, discharge blade width of 30mm, and radial tip clearance of 2 mm.

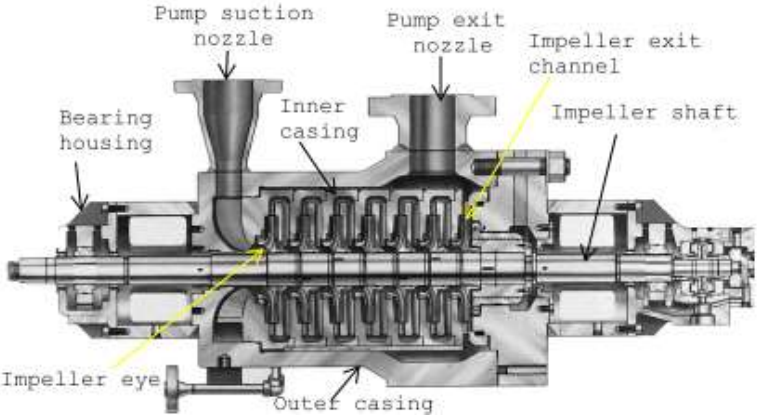


Fig. 2: Radial split axial pull-out barrel casing multistage centrifugal pump [26]

The pump has rated discharge capacity of $158.7m^3/h$, rated differential head of $1000.389m$, rated power of $326.2kW$, and efficiency of 66.3% at rated capacity, maximum head of $1140m$ at rated impeller and maximum power of $380kW$ at rated impeller; the preferred operating region is $130m^3/h$ - $215m^3/h$ while the allowable operating region is $60m^3/h$ - $215m^3/h$ (Sulzer, 2007). It is driven with a $500HP$, $4000V$, $3573RPM$, $60Hz$, 3-phase induction motor.

The effects of six major geometric parameters of this pump used for heavy ends recovery on its four major performance parameters were investigated at Escravos Gas to Liquid plant in Warri, Delta State of Nigeria. The test medium, HER has normal density, viscosity and pumping temperature of $500kg/m^3$, $1.08cP$ and $241.3°C$ respectively. The performance parameters evaluated include efficiency, flow rate, total head and impeller speed. The efficiency is the ratio of the total hydraulic energy delivered to the total mechanical energy used. The flow rate is the volume of the liquid delivered per unit time. The head is the maximum distance to which the liquid can be delivered against all flow resistances. Impeller speed is the rotational speed at which the impeller can be driven to deliver the required flow rate and head.The geometric parameters (Fig. 3) weredischarge diameter ($D_2$), pump suction pipe diameter ($d_1$), blades length ($l_b$), blade discharge angle ($\beta_2$), impeller radial tip clearance ($t$) and discharge width ($B_2$) (fig. 3) while efficiency ($\eta$), flow rate ($Q$), head ($H$) and speed ($N$) constitutes the flow/performance parameters of the pump studied.

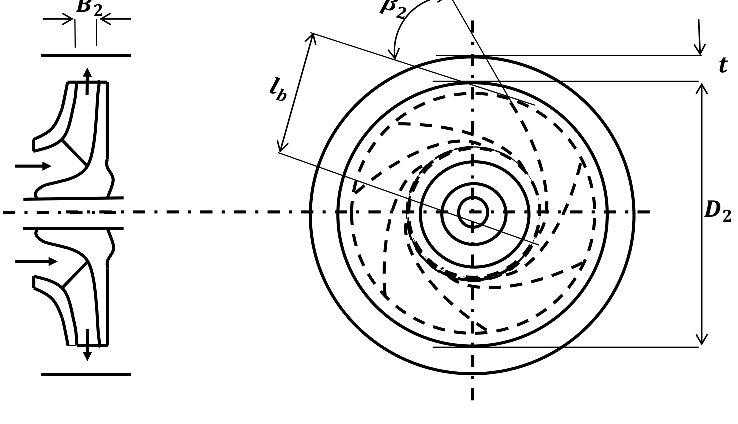

Fig. 3: Impeller profile of the radial split axial pull-out barrel casing multistage centrifugal pump of BB5 class

The determination of the optimal settings of the performance and operational parameters of the pump involves model selection, experimental design, data collection, model fitting, model validation and optimization [25].The empirical relationships between the performance and operational parameters of the pump were evaluated using a response surface design generated with MINITAB. This is a completely randomized single replicatecentral composite circumscribed (CCC) blocked design comprisingthirty-two factorial points $(-1, 1)$, ten centre points $(0)$ and twelve axial or star points $(-\alpha, \alpha)$ amounting to fifty-four experimental runs based on six factors with half fraction. The centre and axial points were used to estimate curvature in the design, and for rotatability [27], [28] and [25], the value of the axial points was computed from eq. (1):

$$\alpha = \sqrt[4]{nf} \tag{1}$$

where $nf$ is the number of the factorial points in the design. The high and low levels of the factors were determined from physical measurement and the limits are as shown in Table 1. This was achieved by running the pump at varying impeller profiles and suction pipe diameter in a set upas shown in fig. 3. The performance of the pump at each factor combination was tested by first opening the suction valve fully and flooding the pump with HER, then open the discharge and instrumentation valves and finally switch on the electric motor. The speed of the pump taken from the installed tachometer, suction and discharge pressures taken from the installed pressure gauges and flow rates taken from the installed flow meter were recorded for the two factor combinations and each experimental run.Thereafter average of the speed, suction and discharge pressures and flow rates were calculated and recorded.

Table 1: Limits of the pump operational parameters

| S/N | Factor Description | Factor Symbols | | Factor Values | |
|---|---|---|---|---|---|
| | | Coded | Actual | High (+1) | Low (-1) |
| 1 | Impeller discharge diameter $(mm)$ | $x_1$ | $D_2$ | 400 | 380 |
| 2 | Pump suction pipe diameter $(mm)$ | $x_2$ | $d_1$ | 350 | 200 |
| 3 | Length of impeller blades $(mm)$ | $x_3$ | $l_b$ | 150 | 100 |
| 4 | Blade discharge angle (°) | $x_4$ | $\beta_2$ | 50 | 30 |
| 5 | Impeller radial tip clearance $(t)$ | $x_5$ | $t$ | 22 | 2 |
| 6 | Blade discharge width $(mm)$ | $x_6$ | $B_2$ | 50 | 30 |

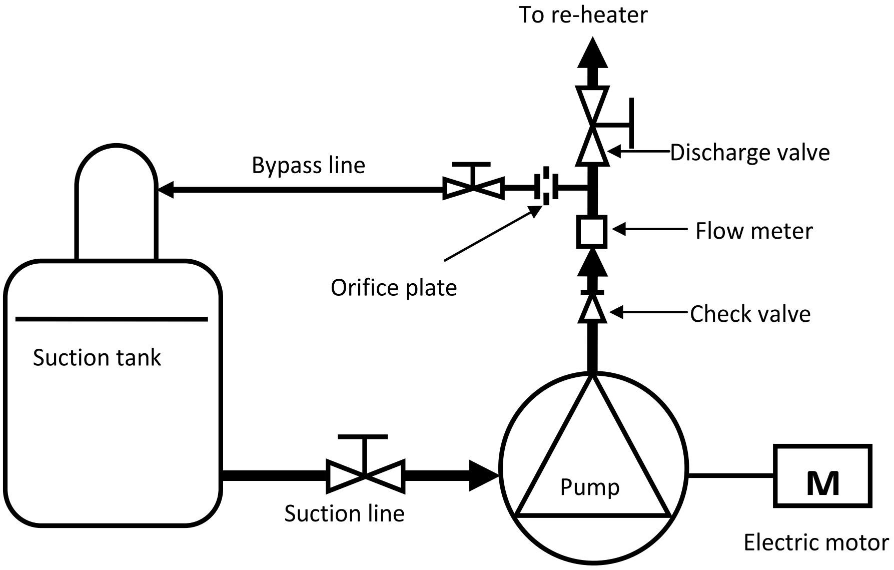


Fig. 3: Schematic view of a centrifugal pump test set up

Then the differential pressure developed by the pump was calculated from eq. (2);

$$p = p_2 - p_1 \quad (2)$$

where $p_2$ and $p_1$ are average discharge and suction pressures respectively.

The head $(m)$ generated by the pump was calculated from eq. (3) [29]:

$$H = \frac{10200p}{\rho} \quad (3)$$

where $p$ is the generated (differential) pressure $(barg)$, $\rho$ is the liquid density $(kg/m^3)$. Average of the flow rate was also calculated. Then the pump efficiency (%) was calculated from eq. (4):

$$\eta = \frac{\rho g Q H}{P_s} \quad (4)$$

where $g$ is gravitational acceleration $(m/s^2)$ whose value is taken as $9.81 m/s^2$, $Q$ is average flow rate $(m^3/h)$ of the pump and $P_s$ is the rated (input) power to pump impeller and average pump speed, $N$ $(rpm)$ was computed. Since driver and pump shafts were connected with rigid coupling slip speed is negligible and therefore driver's shaft speed is equivalent to pump shaft speed.

The transformation equations relating the coded and actual values of the factors factors are shown as follows:

$$x_1 = \frac{D_2 - 390}{10}$$
(5)

$$x_2 = \frac{d_1 - 275}{75}$$
(6)

$$x_3 = \frac{l_b - 125}{25}$$
(7)

$$x_4 = \frac{\beta_2 - 40}{10}$$
(8)

$$x_5 = \frac{t - 12}{10}$$
(9)

$$x_6 = \frac{B_2 - 40}{10}$$
(10)

The completely randomized single blocked CCC design layout used in this investigation is shown in Table 2. Theexperimental results shown in this table were analyzed using MINITAB to estimate quadratic (response surface) models of the form:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} {x_{ii}}^2 + \sum_{i<j}^{\frac{k(k-1)}{2}} \beta_{ij} x_i x_j + \epsilon$$

(11) where $y$ represents each of the responses in their natural forms and units ($\eta$ (%),$Q$ $(m^3/h)$, $H$ $(m)$ and $N$ $(rpm)$), $x$ represents each of the factors in their coded forms, $\beta$ represents the coefficient of each term of the models, $k$ represents number of factors in the models, $\epsilon$ represents error in each estimate, $i = 1, 2, \dots, k$ and $j > i$. Then analyses of variance, lack-of-fit test and residual analyses were conducted using MINITAB to check the adequacy of the estimated models to approximate the measured data well at 95% confidence interval. If $F_{cal} > F_{tab}$and $p - val >$ 0.05, the models are adequate approximation of the measured data; if $F_{calLOF} > F_{tabLOF}$ and $p - valLOF >$ 0.05, the model have no significant lack-of-fit. More so the more the residuals approximate or form 'S' shape along a straight line and the smaller the presence of outliers in the normal probability plots the more the adequacy of the fitted models. Also if the residuals are normally distributed along the mean lines of the residuals versus fitted value and residual versus observation order with little or no cluster, the models are adequate, and little or lack of skewness and outliers in the histogram showed that the model are adequate. When the adequacy of the models was established, regressional analyses were also conducted to check the significance of each term of the models. If $|T|_{cal} > T_{tab}$ and $p - val >$ 0.05 for each term of the models, the term is said to have significant effect on the response. Finally coefficients of determination ($R^2$and $adj - R^2$) and error standard deviation ($S$) were determined to check the goodness of fit of the models. The more $R^2$ and $adj - R^2$ approximate to 100% and the smaller the value of $S$ the better the models approximate the measured data well. Thereafter, the adequaciesof the fitted function in predicting the pumps' responses were confirmedexperimentally before determination of optimal levels of the pump's parameters from the developed models using desirability function. The optimization results were also confirmed experimentally.

Table 2: Design table for the response surface study of the pump

| **Design order** | | **Coded factors** | | | | | | **Responses** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| StdOrder | RunOrder | $x_1$ | $x_2$ | $x_3$ | $x_4$ | $x_5$ | $x_6$ | η (%) | Q $(m^3/h)$ | H (m) | N (rpm |
| 1 | 1 | -1 | -1 | -1 | -1 | -1 | -1 | 47.00 | 101.17 | 1112.20 | 3570 |
| 21 | 2 | -1 | -1 | 1 | -1 | 1 | -1 | 56.85 | 133.31 | 1020.98 | 3285 |
| 11 | 3 | -1 | 1 | -1 | 1 | -1 | -1 | 54.39 | 127.64 | 1020.18 | 3030 |
| 26 | 4 | 1 | -1 | -1 | 1 | 1 | 1 | 64.25 | 156.61 | 982.18 | 2470 |
| 39 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 61.89 | 147.64 | 1003.59 | 2745 |
| 34 | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 60.76 | 143.80 | 1011.56 | 2750 |
| 40 | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 61.79 | 146.76 | 1008.02 | 2740 |
| 29 | 8 | -1 | -1 | 1 | 1 | 1 | 1 | 63.02 | 153.08 | 985.64 | 2480 |
| 22 | 9 | 1 | -1 | 1 | -1 | 1 | 1 | 63.43 | 154.55 | 982.58 | 1945 |
| 19 | 10 | -1 | 1 | -1 | -1 | 1 | -1 | 55.73 | 130.58 | 1021.79 | 3030 |
| 12 | 11 | 1 | 1 | -1 | 1 | -1 | 1 | 63.84 | 155.63 | 982.10 | 2470 |
| 10 | 12 | 1 | -1 | -1 | 1 | -1 | -1 | 58.50 | 137.58 | 1018.00 | 3020 |
| 23 | 13 | -1 | 1 | 1 | -1 | 1 | 1 | 63.02 | 152.88 | 986.93 | 2475 |
| 2 | 14 | 1 | -1 | -1 | -1 | -1 | 1 | 51.93 | 123.17 | 1009.39 | 3285 |
| 38 | 15 | 0 | 0 | 0 | 0 | 0 | 0 | 61.79 | 146.49 | 1009.87 | 3010 |
| 35 | 16 | 0 | 0 | 0 | 0 | 0 | 0 | 61.79 | 146.49 | 1009.87 | 2750 |
| 7 | 17 | -1 | 1 | 1 | -1 | -1 | -1 | 57.12 | 134.71 | 1015.19 | 3030 |
| 13 | 18 | -1 | -1 | 1 | 1 | -1 | -1 | 59.32 | 139.54 | 1017.76 | 3020 |
| 17 | 19 | -1 | -1 | -1 | -1 | 1 | 1 | 50.27 | 116.64 | 1031.85 | 3570 |
| 37 | 20 | 0 | 0 | 0 | 0 | 0 | 0 | 61.79 | 147.43 | 1003.43 | 2750 |
| 16 | 21 | 1 | 1 | 1 | 1 | -1 | -1 | 63.30 | 151.49 | 1000.39 | 2485 |
| 25 | 22 | -1 | -1 | -1 | 1 | 1 | -1 | 50.94 | 118.67 | 1027.66 | 3560 |
| 20 | 23 | 1 | 1 | -1 | -1 | 1 | 1 | 68.82 | 166.69 | 988.46 | 1600 |
| 36 | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 61.79 | 146.21 | 1011.80 | 2750 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 9 | 25 | -1 | -1 | -1 | 1 | -1 | 1 | 49.93 | 117.29 | 1019.21 | 3020 |
| 27 | 26 | -1 | 1 | -1 | 1 | 1 | 1 | 68.71 | 165.74 | 992.48 | 2485 |
| 6 | 27 | 1 | -1 | 1 | -1 | -1 | -1 | 60.14 | 141.19 | 1019.77 | 3020 |
| 31 | 28 | -1 | 1 | 1 | 1 | 1 | -1 | 50.91 | 123.45 | 987.33 | 2480 |
| 8 | 29 | 1 | 1 | 1 | -1 | -1 | 1 | 62.61 | 150.73 | 994.50 | 2490 |
| 15 | 30 | -1 | 1 | 1 | 1 | -1 | 1 | 62.61 | 150.73 | 994.50 | 2490 |
| 3 | 31 | -1 | 1 | -1 | -1 | -1 | 1 | 63.02 | 153.48 | 983.07 | 2470 |
| 4 | 32 | 1 | 1 | -1 | -1 | -1 | -1 | 60.96 | 144.51 | 1009.95 | 3015 |
| 32 | 33 | 1 | 1 | 1 | 1 | 1 | 1 | 70.00 | 172.56 | 971.23 | 1400 |
| 18 | 34 | 1 | -1 | -1 | -1 | 1 | -1 | 57.16 | 134.08 | 1020.66 | 3025 |
| 24 | 35 | 1 | 1 | 1 | -1 | 1 | -1 | 65.48 | 160.29 | 978.08 | 1400 |
| 14 | 36 | 1 | -1 | 1 | 1 | -1 | 1 | 62.61 | 150.83 | 993.77 | 1940 |
| 33 | 37 | 0 | 0 | 0 | 0 | 0 | 0 | 60.55 | 142.34 | 1018.41 | 3010 |
| 30 | 38 | 1 | -1 | 1 | 1 | 1 | -1 | 62.82 | 152.24 | 987.90 | 2490 |
| 5 | 39 | -1 | -1 | 1 | -1 | -1 | 1 | 55.37 | 129.86 | 1020.82 | 3290 |
| 28 | 40 | 1 | 1 | -1 | 1 | 1 | -1 | 65.07 | 159.21 | 978.48 | 1940 |
| 45 | 41 | 0 | 0 | -2.3784 | 0 | 0 | 0 | 51.58 | 121.11 | 1019.61 | 3555 |
| 51 | 42 | 0 | 0 | 0 | 0 | 0 | -2.3784 | 51.79 | 120.36 | 1030.24 | 3560 |
| 52 | 43 | 0 | 0 | 0 | 0 | 0 | 2.3784 | 62.19 | 148.78 | 1000.78 | 2740 |
| 47 | 44 | 0 | 0 | 0 | -2.3784 | 0 | 0 | 61.09 | 144.20 | 1014.30 | 3015 |
| 48 | 45 | 0 | 0 | 0 | 2.3784 | 0 | 0 | 62.40 | 149.32 | 1000.45 | 2740 |
| 49 | 46 | 0 | 0 | 0 | 0 | -2.3784 | 0 | 61.78 | 146.19 | 1011.80 | 3010 |
| 42 | 47 | 2.3784 | 0 | 0 | 0 | 0 | 0 | 62.61 | 150.84 | 993.77 | 2485 |
| 46 | 48 | 0 | 0 | 2.3784 | 0 | 0 | 0 | 62.4 | 150.03 | 995.70 | 2490 |
| 43 | 49 | 0 | -2.3784 | 0 | 0 | 0 | 0 | 48.58 | 109.66 | 1060.67 | 3570 |
| 53 | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 61.79 | 146.21 | 1011.80 | 3010 |
| 50 | 51 | 0 | 0 | 0 | 0 | 2.3784 | 0 | 62.19 | 148.77 | 1000.78 | 2740 |
| 54 | 52 | 0 | 0 | 0 | 0 | 0 | 0 | 61.99 | 148.10 | 1002.14 | 2750 |
| 41 | 53 | -2.3784 | 0 | 0 | 0 | 0 | 0 | 61.79 | 147.43 | 1003.43 | 3290 |
| 44 | 54 | 0 | 2.3784 | 0 | 0 | 0 | 0 | 61.94 | 148.00 | 1001.98 | 2490 |

## RESULTS AND DISCUSSION

The developed coded responses functions of the radial multistage centrifugal pump of BB5 class investigated are as follows;

$\eta$ (%)= 61.45 + 2.19$x_1$ + 2.63$x_2$ + 1.70$x_3$ + 0.79$x_4$ + 1.03$x_5$ + 1.90$x_6$- 1.04$x_2{}^2$- 0.73$x_3{}^2$ - 0.73$x_6{}^2$ - 0.93$x_1x_6$ - 1.85$x_2x_3$ + 1.30$x_2x_6$ + 1.11$x_5x_6$
(12)

$Q\ (m^3/h)$ = 145.58 + 6.25$x_1$ + 7.66$x_2$ + 4.88$x_3$ + 2.69$x_4$ + 3.40$x_5$ + 5.74 - 2.73$x_3{}^2$ - 2.51$x_1x_6$ –4.88$x_2x_3$ - 2.48$x_3x_4$ + 2.89$x_3x_6$
(13)

$H\ (m)$ = = 1010.55 - 7.92$x_1$ - 11.20$x_2$ - 6.86$x_3$ - 6.20$x_4$ - 6.76$x_5$ - 8.95$x_6$+ 3.08$x_2{}^2$ + 4.49$x_2x_3$ + 4.21$x_2x_4$ (14)

$N\ (rpm)$ = 2908.31 - 258.69$x_1$ - 260.16$x_2$ - 193.31$x_3$ - 100.99$x_4$ - 153.58$x_5$ - 172.47$x_6$ - 153.12$x_1x_5$- 104.06$x_3x_5$ (15)

These coded functions were converted into the following actual response functions of the pump from the transformation eq. 5 to10:

$$\eta\ (\%) = 5.91 * 10^{-1}D_2 + 1.91 * 10^{-1}d_1 + 6.26 * 10^{-1}l_b + 7.90 * 10^{-2}\beta_2 + 3.41 * 10^{-1}t + 3.79B_2 - 1.85 * 10^{-4}{d_1}^2 - 1.17 * 10^{-3}{l_b}^2 - 7.30 * 10^{-3}{B_2}^2 - 9.30 * 10^{-3}D_2B_2 - 9.87 * 10^{-4}d_1l_\mathrm{b} + 1.73 * 10^{-3}d_1B_2 + 1.11 * 10^{-2}tB_2 - 357.70$$
(16)

$$Q\ (m^3/h) = 1.63D_2 + 6.73 * 10^{-1}d_1 + 9.11 * 10^{-1}l_b + 1.18\beta_2 + 3.40 * 10^{-1}t + 9.30B_2 - 4.85 * 10^{-4}{d_1}^2$$

$-2.51 * 10^{-2} D_2 B_2 - 2.60 * 10^{-3} d_1 l_b - 3.31 * 10^{-3} d_1 \beta_2 - 3.85 * 10^{-3} d_1 B_2 \quad - \quad 700.17$ (17)

$H\ (m) = \quad 1648.99 \ -7.92 * 10^{-1} D_2 - 9.74 * 10^{-1} d_1 - 9.33 * 10^{-1} l_b - 2.16\beta_2 - 6.76 * 10^{-1} t - 8.95 * 10^{-1} B_2$
$+5.48 * 10^{-4} {d_1}^2 + 2.31 * 10^{-3} d_1 l_b + 5.61 * 10^{-3} d_1 \beta_2$ (18)

$N\ (rpm) = \quad 8571.95 \quad -7.50 D_2 - 1.81 d_1 - 7.73 l_b - 10.10 \beta_2 + 619.97 t - 17.25 B_2 - 1.53 D_2 t - 0.14 d_1 t$ (19)

The standardized residual plots which include the normal probability plot, histogram, residual versus fitted value and residual versus observation order shown in Fig. 6 to 9 indicate that the developed models statistically fitted the pump responses adequately while Fig. 10 to 13 (model confirmatory test results) showed that the percentage errors between the actual and predicted responses lie within plus and minus five (i.e. $\pm$ 5%). This result showed that the fitted functions are good fitsforthe pump responses and can be used for further analysis/optimization of the system.

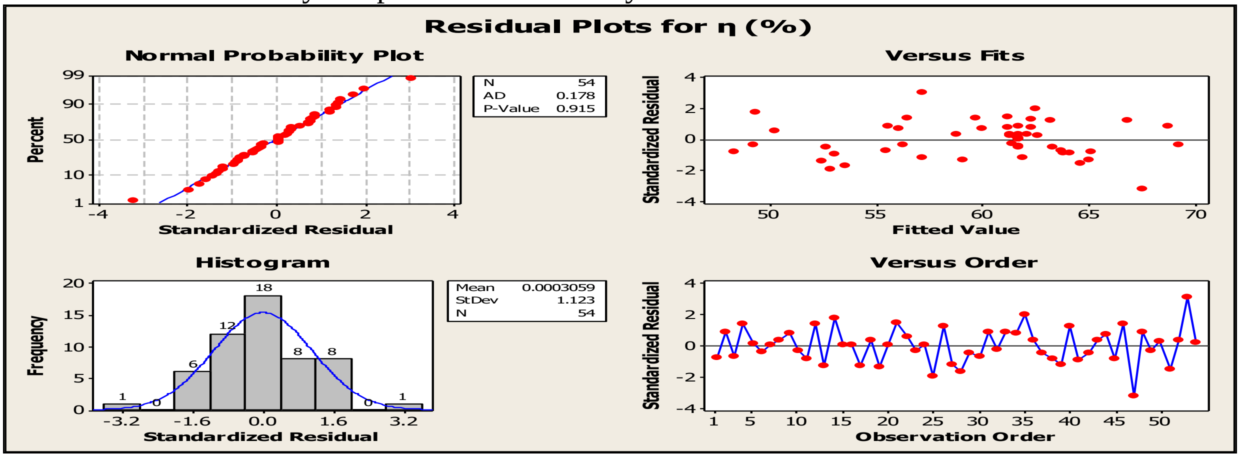


Fig. 6: Residual plots for the pump efficiency model

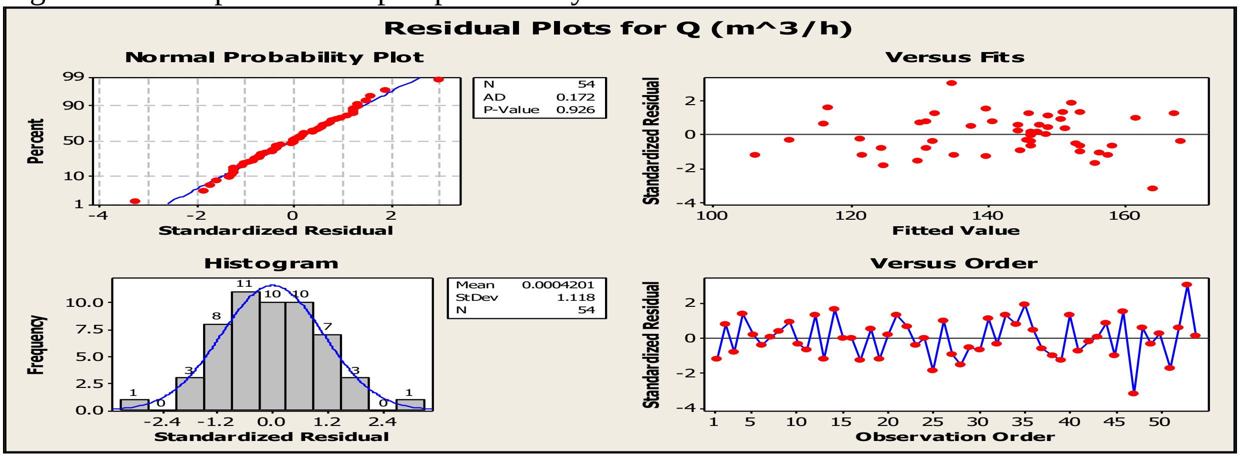


Fig. 7: Residual plots for the pump flow rate model

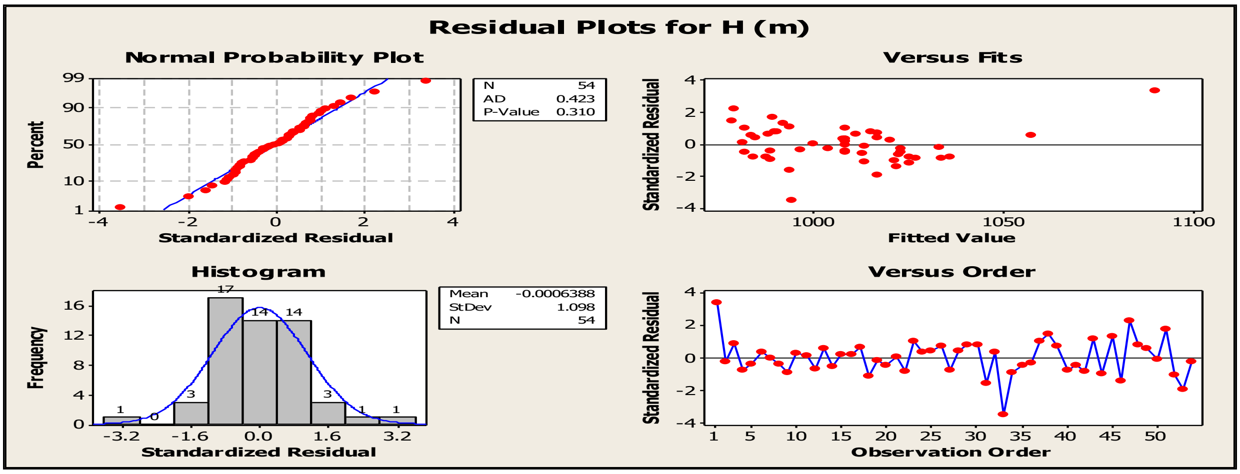


Fig. 8: Residual plots for the pump head model

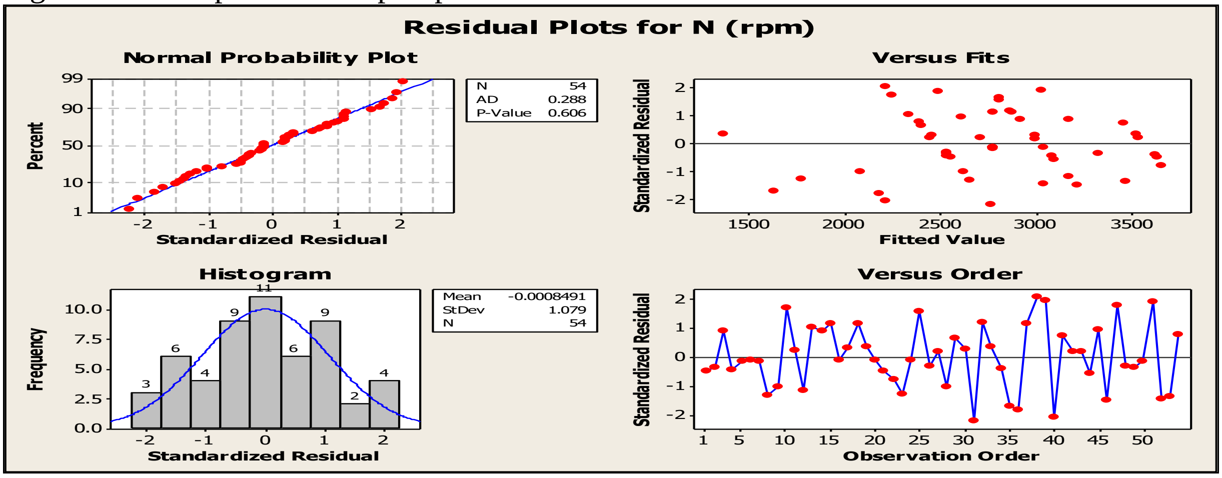


Fig. 9: Residual plots for the pump speed Model

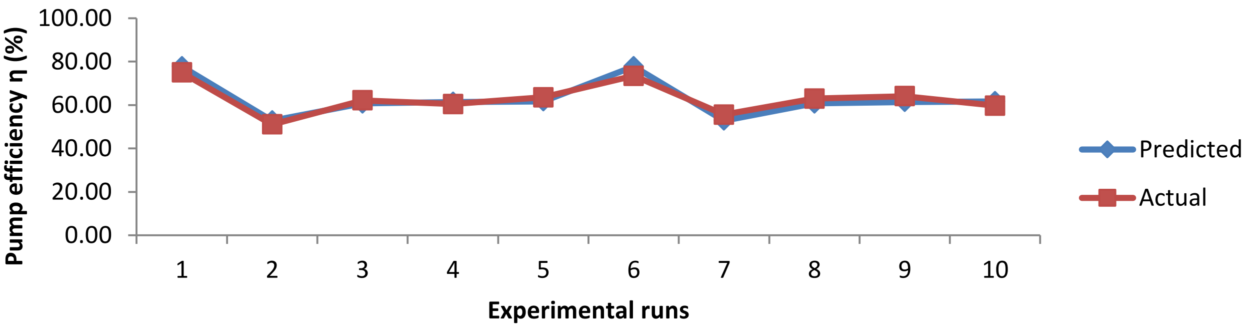


Fig.. 10: Confirmatory test for pump efficiency

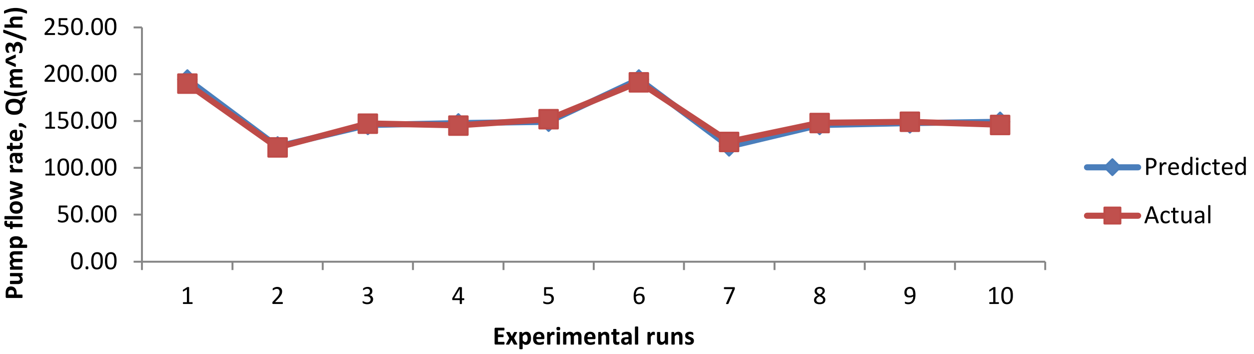


Fig.. 11: Confirmatory test for pump flow rate

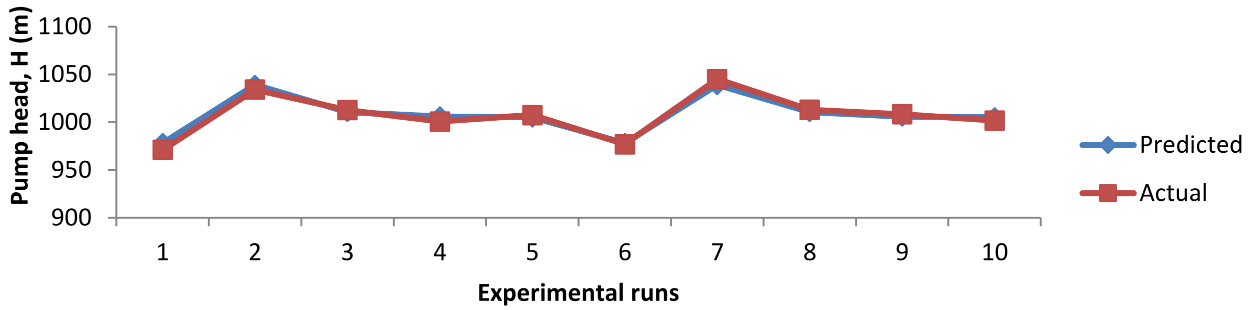


Fig.. 12: Confirmatory test for pump head

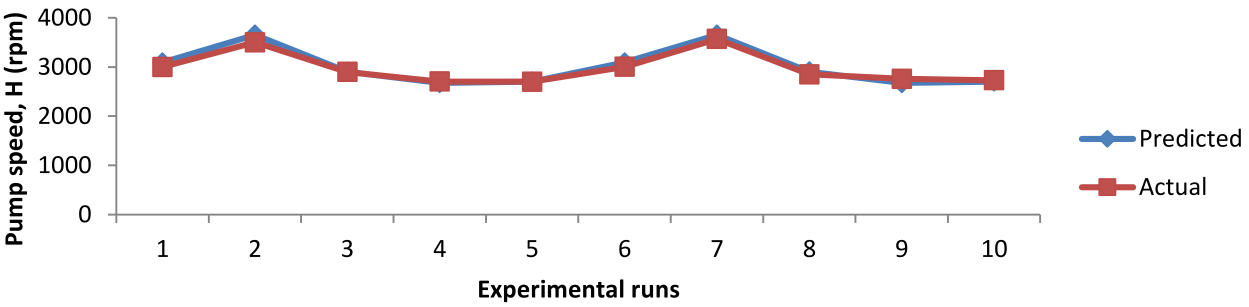


Fig.. 13: Confirmatory test for pump speed

The optimization plot (Fig.14) indicated that optimal setting of overall pump efficiency, pump flow rate, pump head and pump speed are respectively 78.37%, 191.61$m^3/h$, 967.63$m$ and 2500$rpm$ with coded input variables at -2.3784, 1.8979, -2.1862, -0.1201, 2.3784 and 2.3784 respectively. Now substituting these coded optimal values in the transformation equations the approximate optimal values of impeller discharge diameter ($D_2$), pump suction piping diameter ($d_1$), length of impeller blade ($l_b$), blade discharge angle ($\beta_2$), impeller radial tip clearance ($t$) and impeller blade discharge width ($B_2$) are respectively 366$mm$, 417$mm$ 70$mm$, 39°, 36 $mm$ and 64$mm$. The pump performed with efficiency, flow rate, head and speed of 78.30%, 191.55$m^3/h$, 967.50$m$ and 2505$rpm$ with these optimal factor settings.This experimental results indicated over 99% successful prediction of the optimal performanceof the pump.This implies that reducing the impeller discharge diameter, impeller blade length and impeller blade discharge angle by 8.5%, 53.3% and 22% respectively and increasing the pump suction pipe diameter, impeller radial tip clearance and impeller discharge width by 19%, 64% and 28% respectively will increase the efficiency and flow rate of the pump by 18% and 21% respectively, and reduce its head and speed by 3.3% and 30% respectively. This also reduced the energy consumption by 1.2%. Furthermore, this analysis showed that all the factors investigated influenced the pump performance indicators significantly.

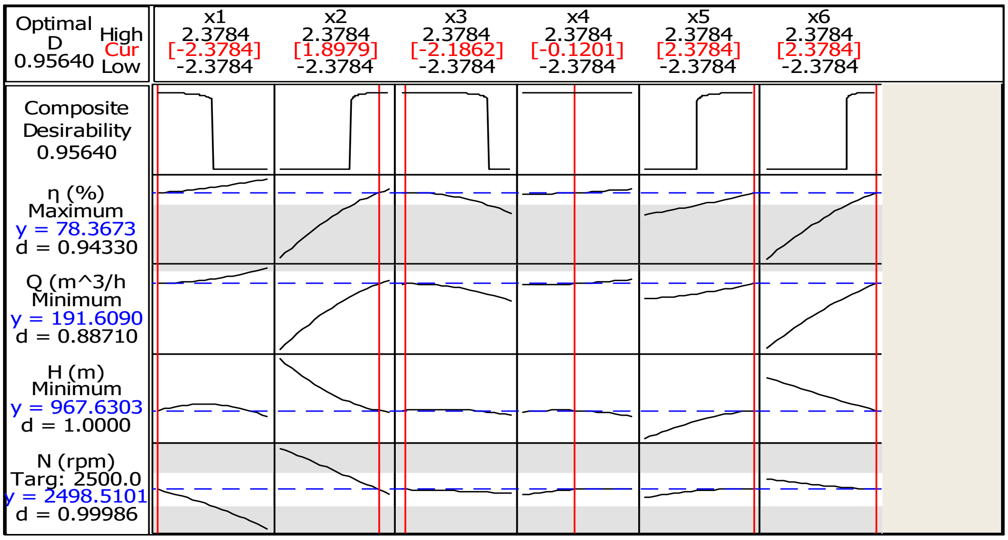

Fig.14: Optimization plot for the pump performance parameter models

## CONCLUSION

This study revealed 417$mm$, 366$mm$, 70$mm$, 39°, 36 $mm$ and 64$mm$ as the optimal pump suction piping diameter, impeller discharge diameter, impeller blade length, blade discharge angle, impeller radial tip clearance and impeller blade discharge width of a radial split axial pull-out barrel casing multistage centrifugal pump used for heavy end recovery respectively. Performance analysis showed that pump operates with an efficiency, flow rate, head and speed of 78.30%, 191.55$m^3/h$, 967.50$m$ and 2505$rpm$ respectively with these optimal factor settings.Operating this pump at this optimal factor setting also reduced its energy consumption by 1.2%.

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