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Original Paper

Design Optimization of Centrifugal Pump Impellers in a Fixed Meridional Geometry using DOE

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Abstract

This paper reports on an investigation (using RSM with commercial CFD software) of the performance characteristics of the impeller in a centrifugal pump. Geometric parameters of vane plane development were defined with the meridional shape and frontal view of the impeller. The parameters are focused on the blade-angle distributions through the impeller in a fixed meridional geometry. For screening, a 2^k factorial design has been used to identify the important design parameters. The objective functions are defined as the total head rise and the total efficiency at the design flow-rate. From the 2^k factorial design results, it is found that the incidence angles and the exit blade angle are the most important parameters influencing the performance of the pump.

Keywords: Centrifugal pump, Impeller, Optimization, RSM(Response surface method)

1. Introduction

The centrifugal pump is a centrifugal fluid-machine that can transform mechanical energy into fluid-pressure and kinetic energy, through an impeller that is rotated by external power. In order to determine the best shape for yields the best performance in a centrifugal pump, about it is necessary to have meridional-view and front-view data on the basic shape and blade-angles of the impeller. The classical method for obtaining such data is based on the basic pump-theory, in which the sought parameters are derived from specifications of performance. Inlet blade-angle and exit blade-angle are usually determined by the fluid angle of the inlet and outlet, according to meridional parameters. The sweep angle, which is related to the blade-length, is a dependent variable and not an important design parameter of impeller, if a smooth blade-angle distribution is employed. From the combination of meridional-view and front-view data, the shape of impeller can be described by a vane plane, and the length and the angle of the blade at the impeller inlet and exit can readily be derived from the vane plane.

Because the vane plane determines the shape of impeller and affects on the performance of pump, it is essential to understand how the performance of the pump is affected by several design parameters and also to compute the best values for each parameter.

In our study, we defined the parameters of the vane plane were allowed to vary, but the shape of meridional geometry of impeller was fixed, thus allowing for a systematic analysis of the effect of the parameters on performance. The analysis was based on 2^k factorial designs, with numerical analysis done through commercial CFD codes instead of actual experiment, and consisted of examining changes in performance for each impeller shape. The parameters for best performance were computed by using the response surface method.

2. Impeller geometry and numerical analysis method

2.1 Impeller geometry

The shape of the impeller may be represented by a meridional view and a frontal view. Fig. 1(a) is a meridional view and represents the direction of axis and radius of the impeller. Fig. 1(b) is a frontal view showing the angle of impeller and represents the radius and rotational direction; and Fig. 1(c) is a vane plane development that is made by combination of the meridional view and front view of impeller. The angles of inlet and exit as well as the length of impeller are readily included in Fig. 1(c).

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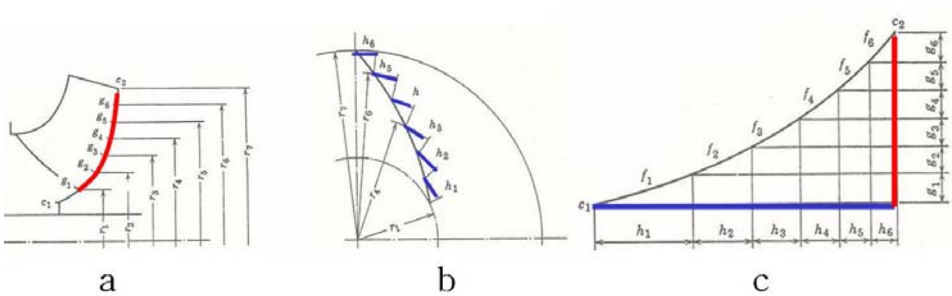

Fig. 1 Traditional impeller design method a) meridional view, b) front view, c) vane plane development[1,2]

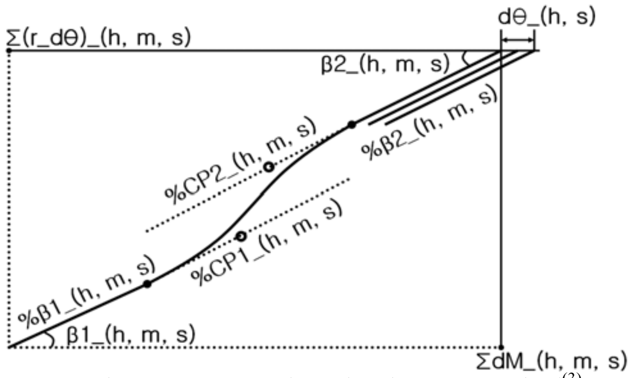

Fig. 2 New vane plane development method[3]

Fig. 3 3D geometry and grid system of the impeller[3]

In order to determine the variation in the performance of the impeller as the parameters of the vane plane change we chose the design variables given in Fig. 2. Σ(r_dΘ)_(h, m, s), which is associated with the sweep angle of impeller, is the total of all the lengths of circular arcs in the radius of the frontal view of the impeller and correspond to the total length on the x-axis of Fig. 1(c). ΣdM_(h, m, s) is the sum of all the blade-lengths and correspond to the length of the y-axis in Fig. 1(c). β1_(h, m, s) is the inlet angle of the impeller blade, β2_(h, m, s) is the exit angle of impeller blade, dΘ_(h, s) is the difference between hub and shroud circumferential angles at the impeller exit.

In traditional impeller design, the length of the blade and the sweep angle in the vane plane can be different, according to the inlet and exit angles of the impeller.

Generally, blade-length and sweep-angles are determined by the given inlet and exit angles because they are defined by a curved line smoothly connecting the inlet and exit angles. In such design, if the sweep angle of the blade is fixed for given inlet and exit angles, it is not possible to smoothly connect the inlet and exit blade angles of the impeller. In order to get a smooth connection for given sweep-angle and inlet and exit blade-angles, we proposed a modification of the traditional design method. We get a new design method for a fixed Σ(r_dΘ) (Fig. 2) by using a Bezier curve to maintain a smooth curve in the vane plane. The Bezier curve, shown as the line in the middle of Fig. 2, is a curved line that smoothly connects the start and end points by using control points; the shape of the curved line can be changed with the position of each control point. If the control points were determined as shown in Fig. 2, then it is possible to get a smooth curved line of blade for given inlet and exit angles.

The fixed meridional shape in the present study is a centrifugal pump with six blades, and the specific speed (rpm, m^3/min, m) is 280. The rotational speed of the pump is 593rpm, the operating flow rate is 8145CMH, and the total head is 70m.

2.2 Numerical analysis method

The 3D-geometry of the impeller was generated using ANSYS CFX-BladeGen, and the structured grid system was calculated using the ANSYS CFX-TurboGrid, which is a grid generation program of general fluid machinery. Though there are 6 impellers, we carried out numerical analysis on only one blade passage using periodic condition because the shape of the blades is identical. The 3D shape and mesh of the impeller is presented in Fig. 3. The number of generated mesh is about 80,000.

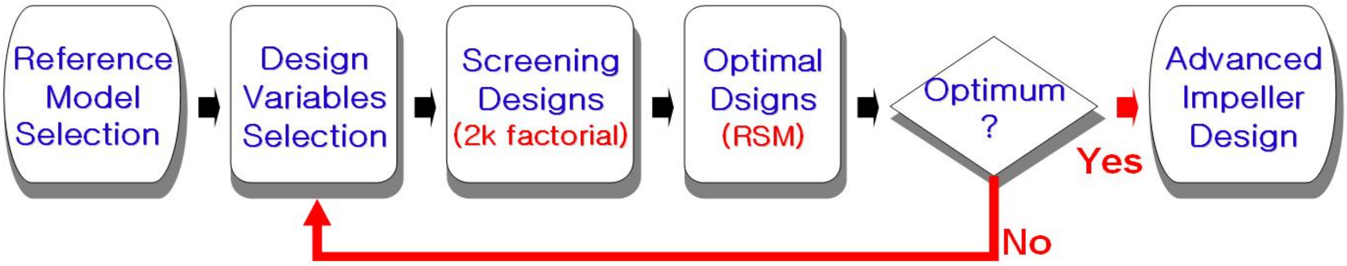

Fig. 4 Optimization process flowchart(4)

Table 1 Numerical analysis set of 2^k factorial

2^k No	Θ_h	Θ_s	iβ1_h	iβ1_m	iβ1_s	β2	%β1_h	%β1_s
1	-10	-10	0	0	0	-5	10	10
2	10	-10	0	0	0	5	30	30
3	-10	10	0	0	6	-5	30	30
4	10	10	0	0	6	5	10	10
5	-10	-10	6	0	6	-5	30	10
6	10	-10	6	0	6	5	10	30
7	-10	10	6	0	0	-5	10	30
8	10	10	6	0	0	5	30	10
9	-10	-10	0	6	6	-5	10	30
10	10	-10	0	6	6	5	30	10
11	-10	10	0	6	0	-5	30	10
12	10	10	0	6	0	5	10	30
13	-10	-10	6	6	0	-5	30	30
14	10	-10	6	6	0	5	10	10
15	-10	10	6	6	6	-5	10	10
16	10	10	6	6	6	5	30	30
center	0	0	3	3	3	0	20	20

The ANSYS CFX-10, which is an analyzing program for three-dimensional viscous fluid, was used for the numerical analysis. A three-dimensional Reynolds average Navier-Stokes equation was used in order to analyze incompressible turbulent flow inside of the impeller. The governing equation was discretized using a finite volume method, and a high resolution scheme which has more than second degree of accuracy was used to solve the convection-diffusion equations. A shear stress transport k-ω model, which is suitable for the prediction of flow separation, was used.

Atmospheric pressure was fixed at the impeller inlet and mass flow rate was given at the outlet. The rotational speed of the impeller is 593rpm. Water was used as a working fluid.

3. Optimum design using DOE

3.1 DOE (Design of Experiments)

In this study, 2^k factorial designs and response surface method of design of experiments were used as numerical optimization techniques.[5,6] Minitab14, a commercial program, was used for the analysis of DOE. The optimization flowchart is shown in Fig.4.

3.2 2^k factorial designs

In this study, we carried out 2^k factorial designs using fractional factorial designs to reduce the number of experiments by confounding the interaction of higher order terms. Using 2^k factorial designs, we could reduce the number of elements concerned, the number of experiments we can perform, the cost and the time. We used fractional factorial designs with four factors and the resolution used is Level IV. Therefore the number of DOE set was 16. Some of the effects were confounded and the confounded effects could not be estimated separately. Among the various design parameters in vane plane development, the chosen parameters that could affect performance were Θ_h, Θ_s and %β1_h, %β1_s, which are associated with the length and the sweep angle of the blade. The parameters iβ1_h, iβ1_m, iβ1_s and β2 which are related with inlet/exit angle of blade were also selected.

Θ_h is the sweep angle of the hub on the impeller blade and Θ_s is the shroud. iβ1_h, iβ1_m and iβ1_s are the incidence angles at the leading edge of the blade on the hub, mid span and shroud respectively. The incidence angles are parameters showing the difference between flow angle and the blade angle. β2 is the blade angle at the impeller's trailing edge. %β1_h, %β1_s shows the portion of blade with the same blade angle at the leading edge in hub and shroud respectively, and is presented as the percentage of length out of the x-axis.

The range of each design parameter was set as ±10° for Θ_h and Θ_s, ±3° for iβ1_h and iβ1_s, and ±5° for beta2 from the standard value of design. For %β1_h %β1_s, the possible variation range is ±10% from the standard value. Table 1 shows the experimental conditions in which the 2^k factorial designs were adopted.

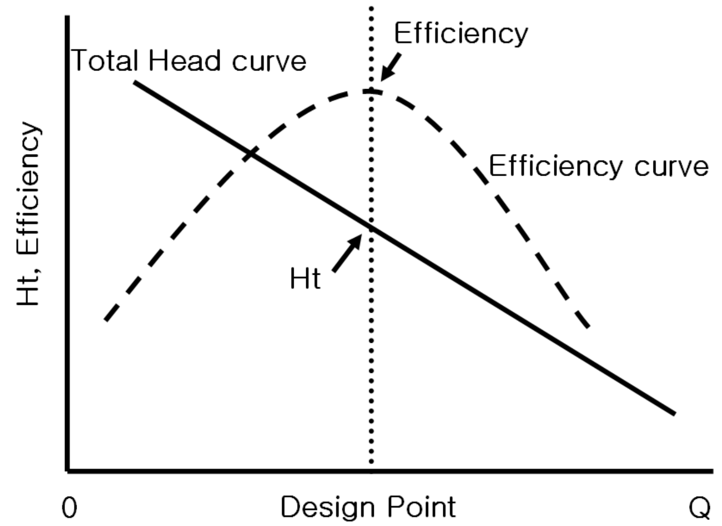

Fig. 5 Total head curve and efficiency curve

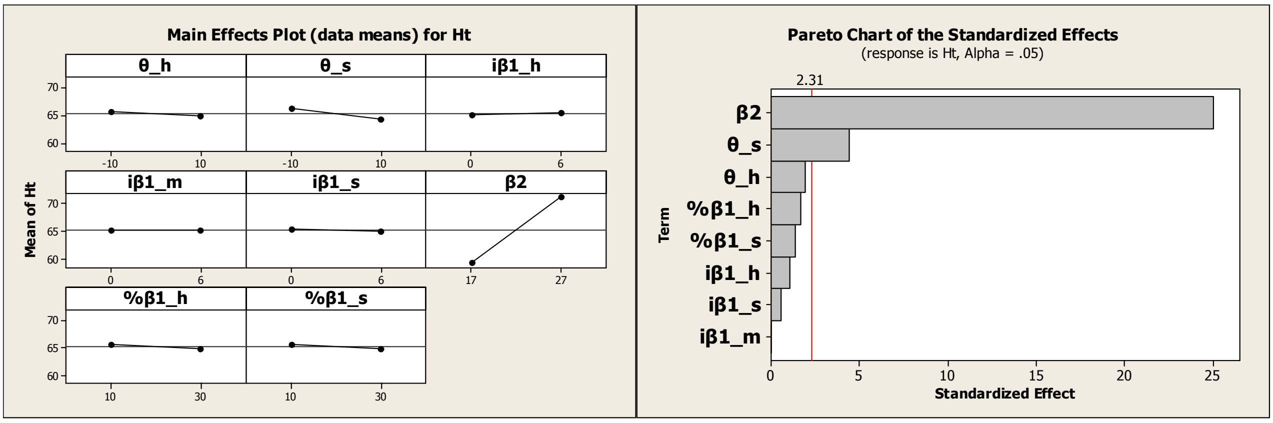

Fig. 6 Main effects plot and Pareto chart for Ht

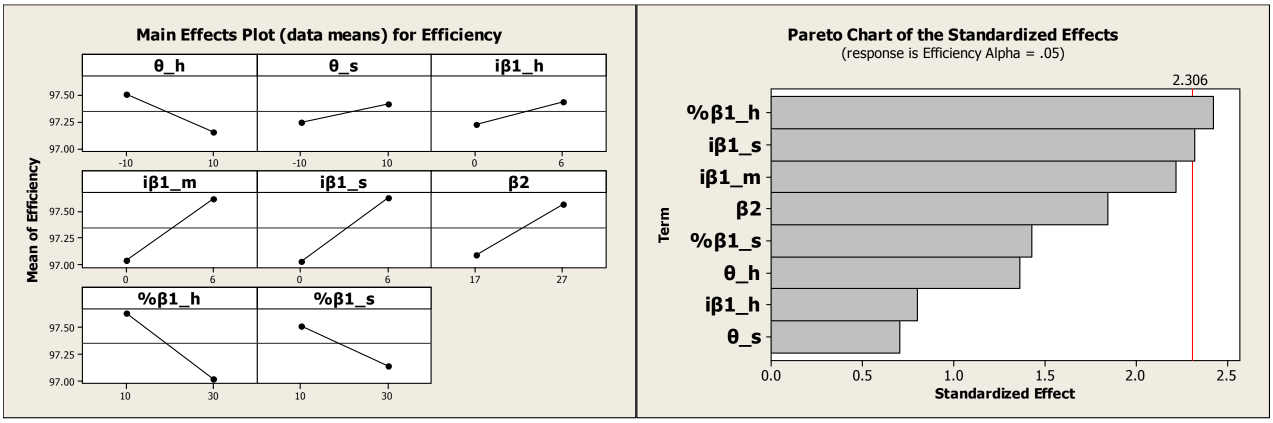

Fig. 7 Main effects plot and Pareto chart for efficiency

In 2^k factorial designs, a response variable should be defined to analyze the performance of the impeller according to the design parameters. The actual response variable has been defined in the head curve and the efficiency curve of the pump shown in Fig. 5. The design flow-rate is considered to be ideal if the flow-rate at the maximum efficiency corresponds with the designated required flow-rate. We defined the Total Head curve and Efficiency curve as Ht, Efficiency at the required design point in order to observe the effect of the design parameters of vane plane development.

The effects of parameters of the vane plane development on the performance of the impeller are presented in Fig. 6 and 7 using main effects plot and Pareto Chart. Fig. 6 and 7 show the influence of factors on Ht and Efficiency. The β2, Θ_s, and Θ_h are factors in order of influence on the response value Ht, and the effect of β2 outperforms other factors. That is, in the same external diameter, we can get a required total head effectively by controlling β2. Following β2, it is obvious that Θ_s and Θ_h are the influential parameters affecting the head in design flow rate. The %β1_h, iβ1_s, and iβ1_m are the factors in order that influence on the response of Efficiency. Because iβ1_s and iβ1_m is parameters associated with the inlet blade angle of the impeller, Efficiency is greatly affected by the inlet incidence angle. The incidence angles at the shroud and mid span are more influential than at the hub, and the Efficiency tends to increase as the incidence angle increased.

Table 2 Numerical analysis set of RSM

RSM No	iβ1_h	iβ1_s	β2	Ht	Efficiency
1	13	4	21	61.59	97.79
2	19	4	21	61.88	97.90
3	13	10	21	61.88	97.55
4	19	10	21	62.01	97.36
5	13	4	27	71.21	98.03
6	19	4	27	71.40	98.07
7	13	10	27	71.40	97.87
8	19	10	27	71.39	97.54
9	10.95	7	24	67.05	97.92
10	21.05	7	24	67.31	97.81
11	16	1.95	24	66.98	98.10
12	16	12.05	24	67.14	97.23
13	16	7	18.95	57.14	97.67
14	16	7	29.05	73.75	98.05
15	16	7	24	67.21	98.02

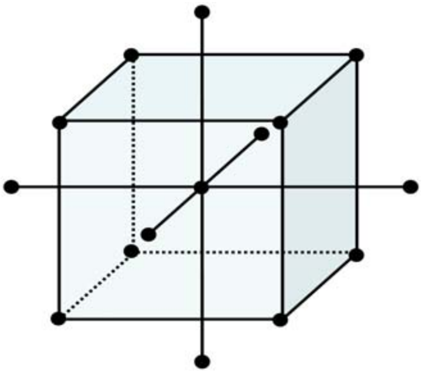

Fig. 8 Central composite design with three factors

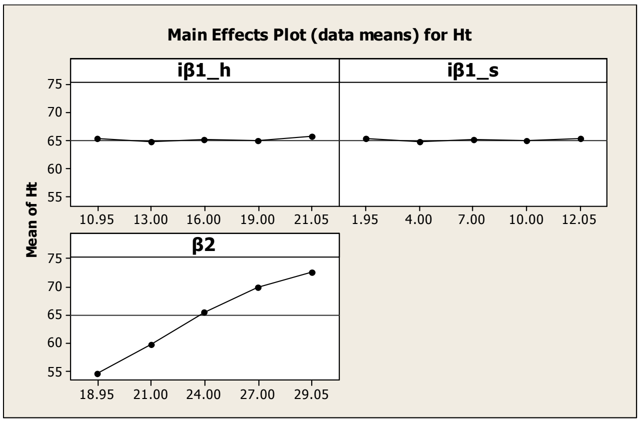

Fig. 9 Main effects plot for Ht

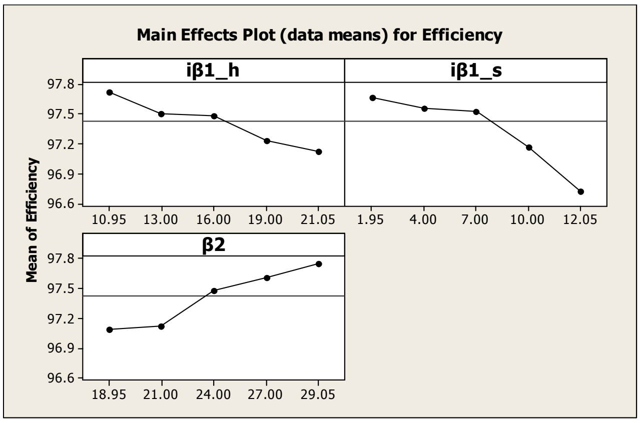

Fig. 10 Main effects plot for efficiency

3.3 RSM (Response surface method)

The RSM explores the relationships between several explanatory variables and one or more response variables. The main idea of RSM is to use a set of designed experiments to obtain an optimal response. In a previous study, we screened the ibeta1_h, ibeta1_s and beta2 as main factors that affect the efficiency and head of the impeller using 2^k factorial designs. Central composite designs (CCD) with three factors were used for the RSM resulting in 20 experimental conditions of numerical analysis. The Central composite designs with three factors were shown in Fig. 8. For the RSM procedure, the value of the factors, excepting the 3 main factors, were fixed from the results of the 2^k factorial designs. The fixed value of %β1_h and %β1_s are 20%, and the value of iβ1_m was fixed as mean value of iβ1_h and iβ1_s. Θ_h and Θ_s could be excluded using the conditions connecting the inlet/exit blade angle smoothly.

Table 2 shows specific experimental conditions applied to the response surface method. We omitted the 16-20 repeated experimental conditions because we supposed no errors in the CFD. Actually, we can find the errors in the real experiments (Those values could be found through real experimentation, not in the purview of this study). The effects of impeller design parameters on the head and efficiency are shown in Fig. 9 and 10. As the β2 increases, the head and efficiency also increase. But as the iβ1_s increases, the efficiency decreases, showing an opposite tendency to the parameter β2.

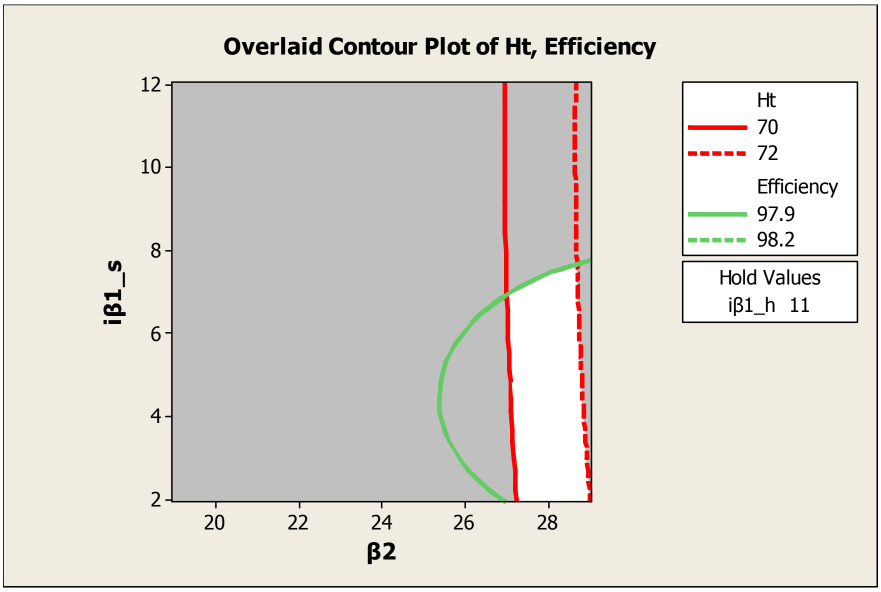

Fig. 11 Overlaid contour plot

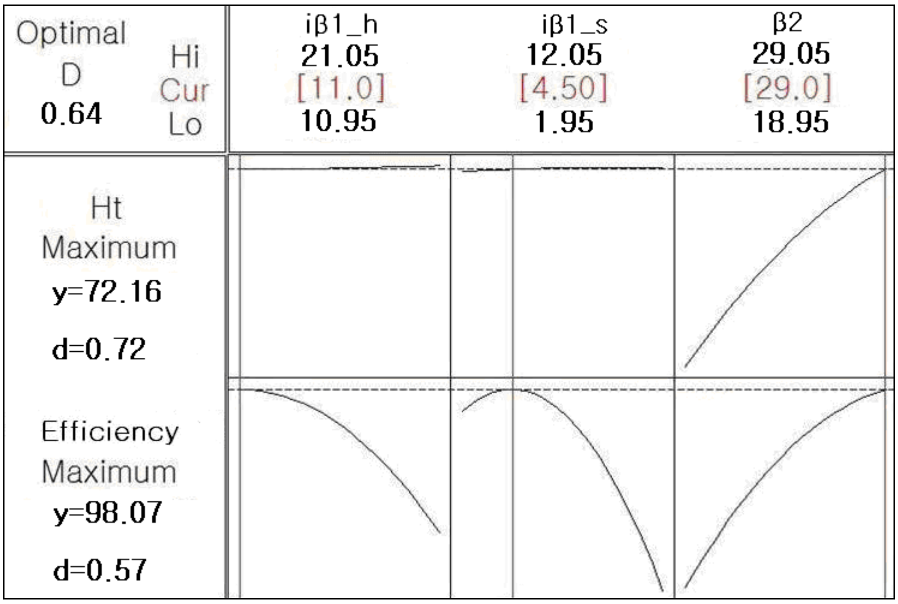

Fig. 12 Plot for response optimization

Table 3 Comparison of optimization results with design base

	iβ1_h	iβ1_s	β2	Ht	Efficiency
Optimization model(CFD)	11	4.5	29	72.32	97.98
RSM estimated value	11	4.5	29	72.16	98.07
Base design model(CFD)	3.0	3.0	22	65.47	97.72

In a fixed iβ1_h value as 11°, the overlaid contour plot was shown in Fig. 11. From Fig. 11, we can examine several response variables simultaneously. We can see from the overlaid contour plot that there are values of iβ1_s in the range of 2°-7.5°, and β2 in the range of 27-29°, satisfying the condition of head range 70-72m, and the efficiency range 97.9-98.2%.

In this study, we set the target of design as finding design parameters with a maximum efficiency point within a head range greater than 70m. To get an optimized design parameter satisfying both design targets, we used a response optimization method through MINITAB14. The results are shown in Fig. 12. As a result of response optimization, we could predict optimized design values as iβ1_h 11°, iβ1_s 4.5° and β2 29°. With these values, the head would be 72.16m and the efficiency 98.07%. We chose this result as an optimization design set. We performed numerical analysis with the optimized design parameters, and the CFD results and the predicted results from the response surface method were compared in Table 3. Compared with the initial values of design parameters, iβ1_h increased 8°, iβ1_s 1.5° and β2 7°. As a result, the head increased 10.46%, and the efficiency 0.26%.

We compared the result of performance prediction in response surface method with that of numerical analysis in optimization design, and found that predicted performance using response surface method was very accurate within 0.37% error in the head and only 0.18% error in the efficiency.

4. Conclusion

We studied the influence of design parameters in vane plane development on the performance of impellers with fixed meridional geometry. We also determined optimized impeller shape using the parameters of vane plane development.

[1]We set design parameters enabling a smooth impeller shape with given inlet/exit angles in a fixed meridional geometry.

[2]We defined the parameters of vane plane development as Θ_h, Θ_s, iβ1_h, iβ1_m, iβ1_s, β2, %β1_h and %β1_s. From the results of 2^k factorial design, we found that the most influential parameters on the head and the efficiency are iβ1_h, iβ1_s and β2.

[3]From the results of CFD on the optimized impeller shape, obtained by RSM, the head increased 10.46%, and the efficiency improved 0.26% compared with the original design.

Nomenclature

θ	Sweep angle	*h*	hub
β	Blade angle	*m*	mid span
$i\beta$	Incidence angle	*s*	shroud

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