International Journal of Fluid Machinery and Systems
Vol. 4, No.1, January-March 2011

DOI: 10.5293/IJFMS.2011.4.1.014
ISSN (Online): 1882-9554

Original Paper

Design Optimization of Mixed-flow Pump in a Fixed Meridional Shape

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Abstract

In this paper, design optimization for mixed-flow pump impellers and diffusers has been studied using a commercial computational fluid dynamics (CFD) code and DOE (design of experiments). We also discussed how to improve the performance of the mixed-flow pump by designing the impeller and diffuser. Geometric design variables were defined by the vane plane development, which indicates the blade-angle distributions and length of the impeller and diffusers. The vane plane development was controlled using the blade-angle in a fixed meridional shape. First, the design optimization of the defined impeller geometric variables was achieved, and then the flow characteristics were analyzed in the point of incidence angle at the diffuser leading edge for the optimized impeller. Next, design optimizations of the defined diffuser shape variables were performed. The importance of the geometric design variables was analyzed using 2^k factorial designs, and the design optimization of the geometric variables was determined using the response surface method (RSM). The objective functions were defined as the total head and the total efficiency at the design flow rate. Based on the comparison of CFD results between the optimized pump and base design models, the reason for the performance improvement was discussed.

Keywords: Mixed-flow Pump, Impeller, Diffuser, Optimal Design, CFD (computational fluid dynamics), DOE (design of experiments)

1. Introduction

The mixed-flow pump, which is used in industrial fields, consumes thousands of kilowatts of electricity. That is why saving energy by improving the efficiency of the pump is so important in this era of high gas prices. The importance of the hydraulic design for the mixed-flow pump is still growing because the main concern is the efficiency and suction performance, especially in high value-added industries such as nuclear power generation and seawater desalination.

Total head rise and efficiency are the most important pump characteristics. In designing a pump, it is crucial to improve the efficiency and satisfy exact total head at the design flow rate. Thus, we used computational fluid dynamics (CFD) and design of experiments (DOE) to design an optimal mixed-flow pump impeller and diffuser in order to save time and expense.

In this study, the optimal design of the impeller and diffuser was used to improve the performance of the mixed-flow pump. The controlled design variables in the vane plane development [1] of the impeller were defined with fixed meridional geometry. The optimization of the impeller was conducted using the traditional design method and DOE.

Diffuser optimization was achieved by analyzing the optimally designed shape of the impeller and by considering the exit flow characteristics of that impeller. The design variables controlling diffuser vane plane development were defined when the meridional view was fixed, as for the impeller. The traditional design method and 2^k factorial designs were used to analyze the influence of the design variables of the diffuser's vane plane development on the performance of the mixed-flow pump. The main design variables selected were used to perform the optimization of the diffuser using the response surface method (RSM).

Received April 16 2010; revised September 6 2010; accepted for publication December 9 2010: Review conducted by Prof. Tadashi Tanuma. (Paper number O10010J)
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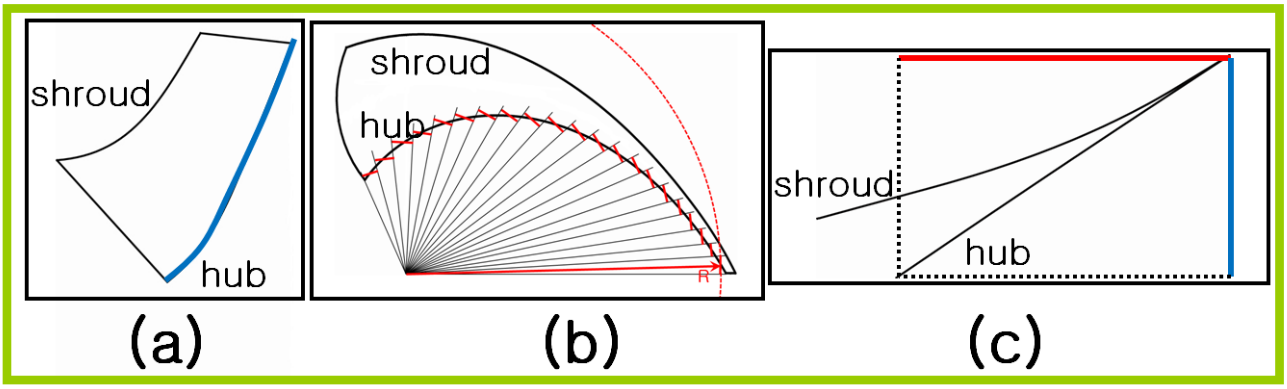


Fig. 1 Traditional impeller design method: (a) meridional view; (b) front view; (c) vane plane development

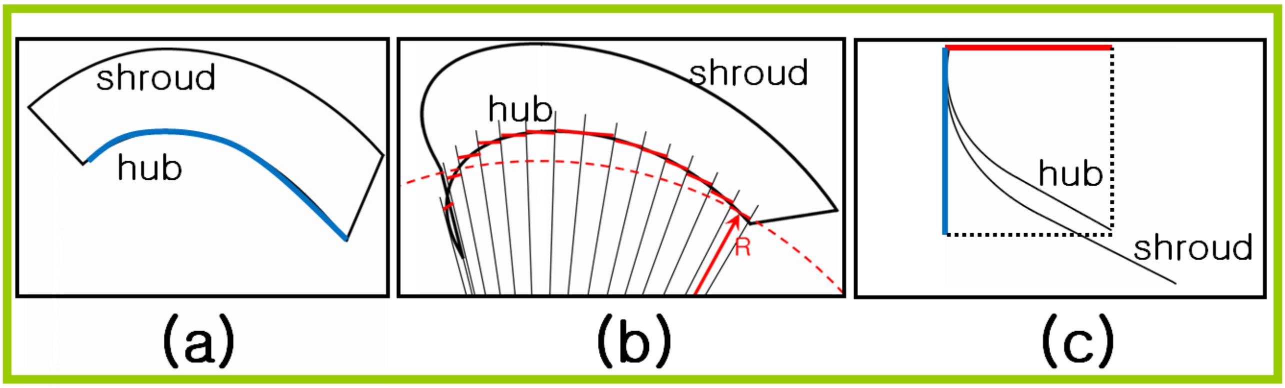


Fig. 2 Traditional diffuser design method: (a) meridional view; (b) front view; (c) vane plane development

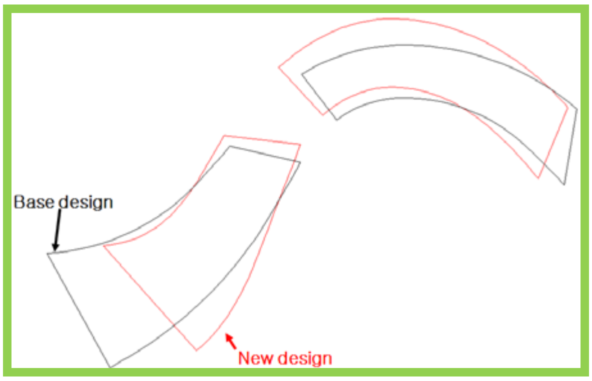


Fig. 3 Comparison of meridional views

2. Mixed-flow pump design method

2.1 Traditional design method

The shape of the impeller and diffuser can be presented in the meridional and front views, as shown in Figs. 1 and 2 [1, 2]. In Fig. 1, a) is a meridional view showing the blade shape and represents information on the direction of axis and radius; b) is a front view representing the radius and rotational direction; and c) is the vane plane development of the impeller and diffuser. The vane plane development shows the blade angle distribution. Axis x of the vane plane development indicates the total length of the arc at each radius from the front view. Axis y indicates the total length of the blade in the meridional view. Based on these explanations, the blade angle distributions can be easily seen in the vane plane development. The blade angle distribution is usually achieved by connecting the inlet blade angle and the outlet blade angle smoothly. The inlet and outlet angles of the blade are mainly derived from the pump design theory.

The meridional view shows the shape and size of the blade. The impeller meridional shape was designed using our own datebase (D/B). The outlet shape of the impeller and the area distribution of the diffuser are important when designing the meridional shape of the diffuser. The meridional shape of the diffuser was achieved by controlling these two factors.

Figure 3 shows the newly designed impeller and diffuser shape. Even though the radius of the newly designed shape is bigger than the original by 6.7%, it has a size advantage because the length of the meridional view was shortened by 22% in the axis direction.

The simplified vane plane development, which describes the angle and length of the blade, greatly influences the performance of the mixed-flow pump by determining the shape of the impeller and diffuser. As a result, it is essential to analyze the performance characteristics of the pump according to the changes in various design factors that make up vane plane development, and to find optimal design conditions while considering the contributions of each factor.

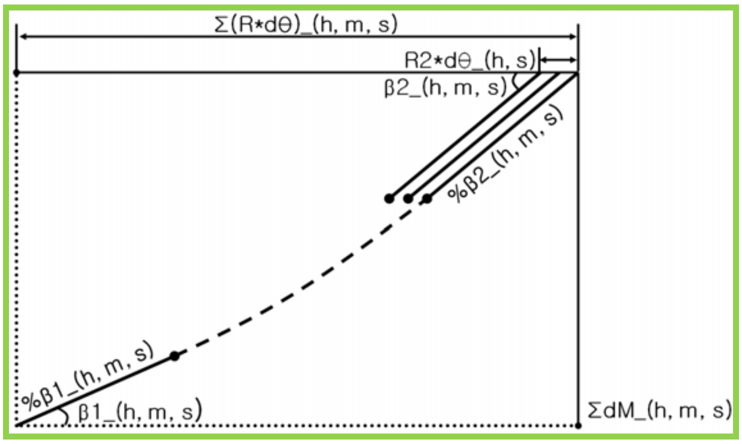


Fig. 4 Impeller design variables in vane plane development

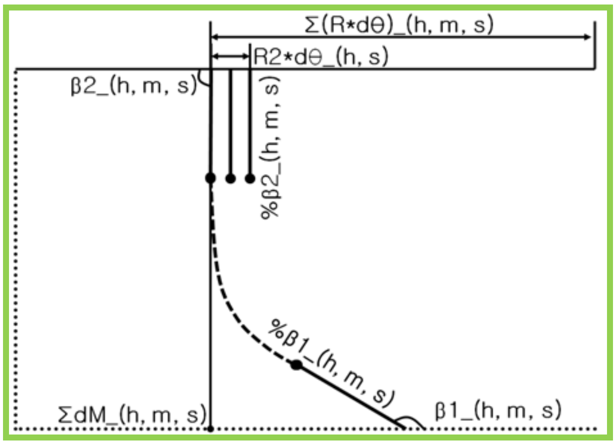


Fig. 5 Diffuser design variables in vane plane development

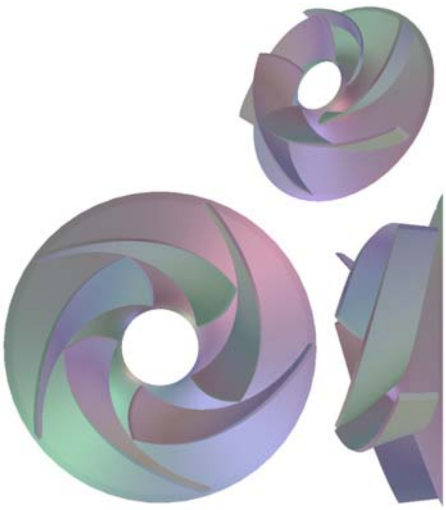


Fig. 6 Three-dimensional geometry of impeller

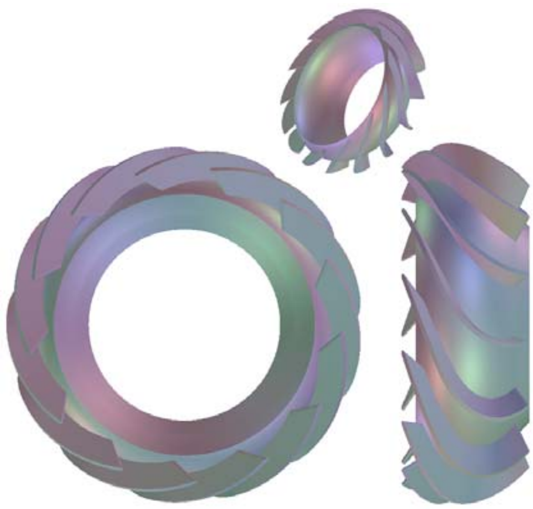


Fig. 7 Three-dimensional geometry of diffuser

2.2 Design variables in the vane plane development

In this study, vane plane development was used to design the blade shapes of the impeller and diffuser. In an attempt to control this vane plane development effectively, a detailed definition of the design variables of the vane plane development is provided as shown in Figs. 4 and 5 [3, 4], in order to clarify the optimization process of the impeller and diffuser design using the traditional design method. The meridional view was designed and unchanged after analyzing various existing data bases.

In the diagram, 'h' means hub, 'm' means mid-span, and 's' means shroud. Σ(R*dθ)_(h, m, s) indicates the total length of the arc at each radius from the front view. ΣdM_(h, m, s) represents the total values of blade length in the meridional view. %β1_(h, m, s), and %β2_(h, m, s) show the portion of blade having the same blade angle at the leading edge and trailing edge respectively, and they are presented as a percentage of length out of the whole length of the y-axis. β1_(h, m, s) means the inlet angle of the blade from the impeller and diffuser, while β2_(h, m, s) means the outlet angle of the blade from the impeller and diffuser. R2*dθ_(h, s) shows the inclination level toward the circumference from the hub and shroud at the outlet of the impeller and diffuser. The inlet and outlet sections were connected by a smooth curved line whose angle changed linearly. Three-dimensional geometry of the impeller and diffuser in Figs. 6 and 7 are shown using the vane plane development variables with given meridional view.

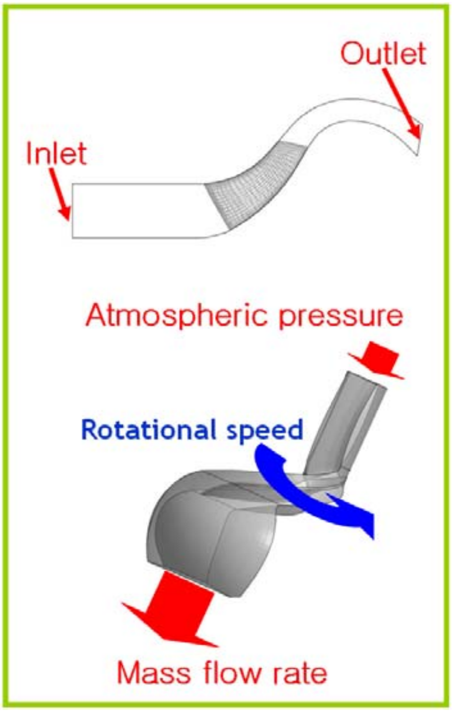


Fig. 8 Boundary conditions for the impeller calculation

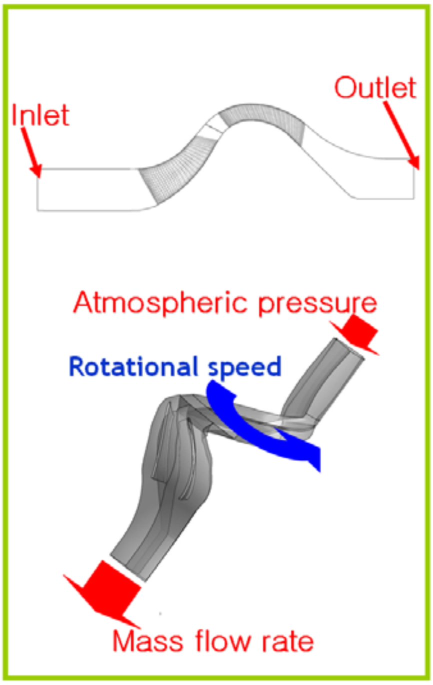


Fig. 9 Boundary conditions for the impeller and diffuser calculation

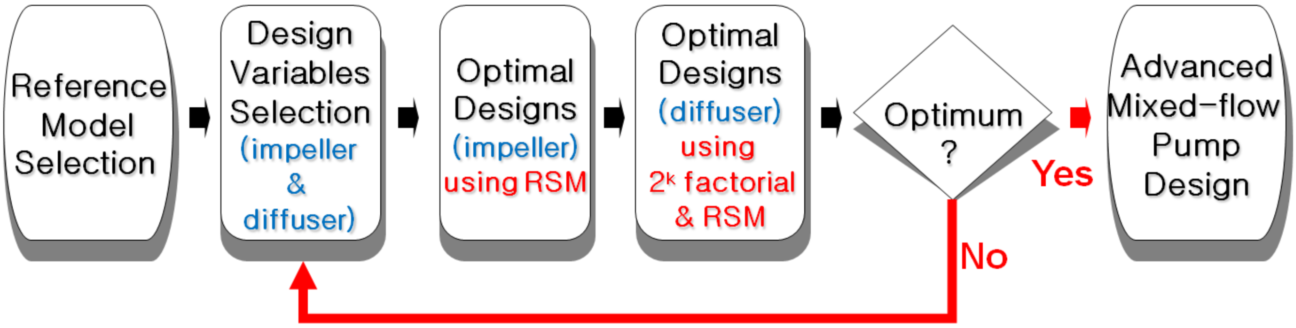


Fig. 10 Optimization process flowchart

3. Numerical analysis method

The three-dimensional shape of the impeller and diffuser was generated using the ANSYS CFX-BladeGen program The structured grid system was generated using ANSYS CFX-TurboGrid, which is a fluid machinery grid generation program.

The impeller has five blades and the diffuser has 13 blades. By using periodic condition, flow passages with one impeller blade and two diffuser vanes were combined for the numerical analysis of the entire pump.

To analyze the linked interface of the impeller and diffuser, stage-average interface conditions were applied. Figures 8 and 9 show the boundary conditions for the impeller only and entire pump calculation. We set the atmospheric pressure on the inlet section of the impeller, and gave the mass flow rate on the exit section as a boundary condition. The rotational speed of the impeller was 580rpm. When the numerical analysis was performed for the impeller only, the inlet part of the impeller was simplified as a straight pipe and the outlet part was expressed as the same meridional shape without the diffuser vane. After mesh test, 90,000 grids were used for the impeller and 180,000 were used for the diffuser.

The ANSYS CFX-11, which is a commercial CFD code, was used for the numerical analysis. A three-dimensional Reynolds average Navier-Stokes equation was used to analyze incompressible turbulence flow inside the pump. The governing equation was discretized using a finite volume method. A high-resolution scheme, which has more than a second degree of accuracy, was used to solve the convection-diffusion equations. For the turbulent model, the shear stress transport k-ω model, which is appropriate for the prediction of flow separation, was used to analyze turbulent flow through the impeller and diffuser. We used water as a working fluid. Disk friction losses, mechanical losses, leakage losses, and the tip clearance effect are not included in this calculation.

4. Design of Experiments

Design of experiments is based on a modern analysis of statistics. It helps us select the main cause of abnormal fluctuations from many possible causes. In this study, 2^k factorial designs and the RSM of design of experiment were used as numerical optimization methods to optimize the design [5, 6, 7]. Minitab14, a commercial program, was used for the analysis of DOE. The optimization flowchart is shown in Fig. 10. In DOE, a response variable should be defined in order to analyze the performance of the impeller according to the design parameters.

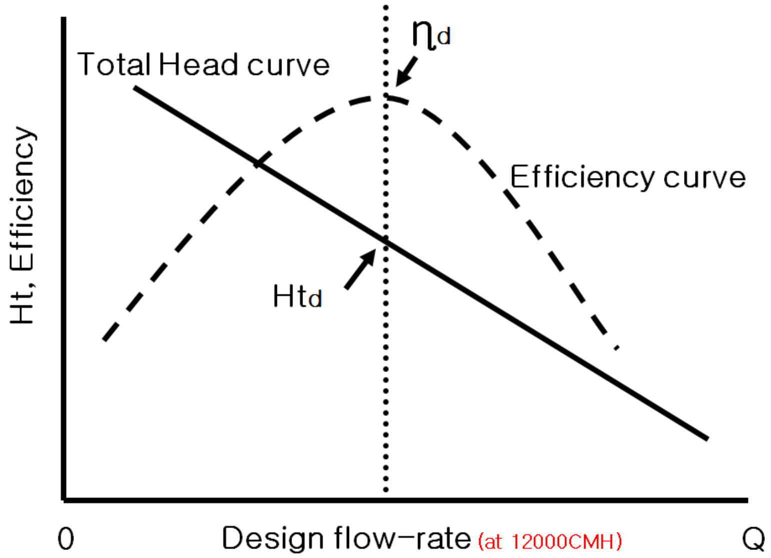


Fig. 11 Total head curve and efficiency curve

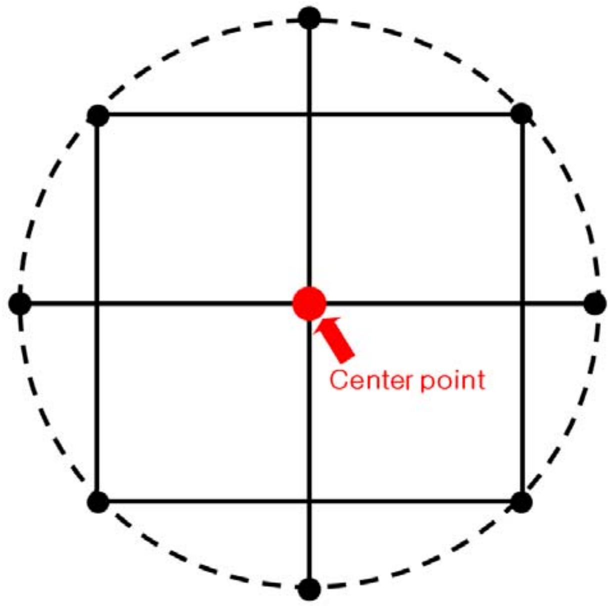


Fig. 12 Central composite design with two factors

The actual response variables are defined in the total head curve and the efficiency curve of the pump, as shown in Fig. 11. The design flow-rate is considered to be ideal if the flow rate at maximum efficiency corresponds with the required flow rate. We defined the total head as Ht_d and efficiency as η_d at the required design flow-rate in order to observe the effect of the vane plane development design variables.

4.1 2^k factorial designs

Usually, 2^k factorial designs are represented as n^k. This is the DOE in which the number of factors is k and the number of levels is n. The experiments are performed at every possible level of combination of all factors. The number of performed experiments should be at least n^k, without repetition.

The advantage of the factorial experiment is that we can assume the main effect (the sole effect of the factor) and interaction effect (the effect between factors) of all factors. It is a convenient screening method that can be used to find the core factor when there are many factors involved at the beginning of the experiment. Response surface analysis is used to find the changes around the optimum numerical value.

In this study, considering the number of factors concerned, the number of possible experiments expenses and time, we used fractional factorial designs in which the number of experiments is reduced by deleting less meaningful interactions.

4.2 Response surface method

We used the RSM to examine the relationship between one or more response factors and quantitative experimental factors or factor groups. The purpose of the RSM is to find the optimal conditions of a factor that could optimize the response factor. By applying a central composite to the main factor, which greatly influences the response variable, we generated an experimental set and applied the RSM to it. The central composite designs with two factors are shown in Fig. 12.

Table 1 Design target (real), design specifications of CFD and CFD results of the base design model

	Design target(real)	Design specifications of CFD		Base design model (CFD result)	
		Impeller exit	Pump exit	Impeller exit	Pump exit
Q (CMH)	12,000	12,000	12,000	12,000	12,000
Total head (m)	60	more than 70 m	more than 65 m	57.84	55.96
Efficiency (%)	to be maximized	to be maximized	to be maximized	97.62	93.86

Table 2 Numerical analysis set of the RSM for the impeller design

RSM No	β2_h	β2_s	Ht_d	η_d
1	32	32	69.39	97.81
2	38	32	72.39	97.25
3	32	38	72.76	97.69
4	38	38	75.37	97.75
5	30.76	35	70.50	97.68
6	39.24	35	74.49	97.73
7	35	30.76	70.29	97.75
8	35	39.24	74.68	97.70
center	35	35	72.62	97.79

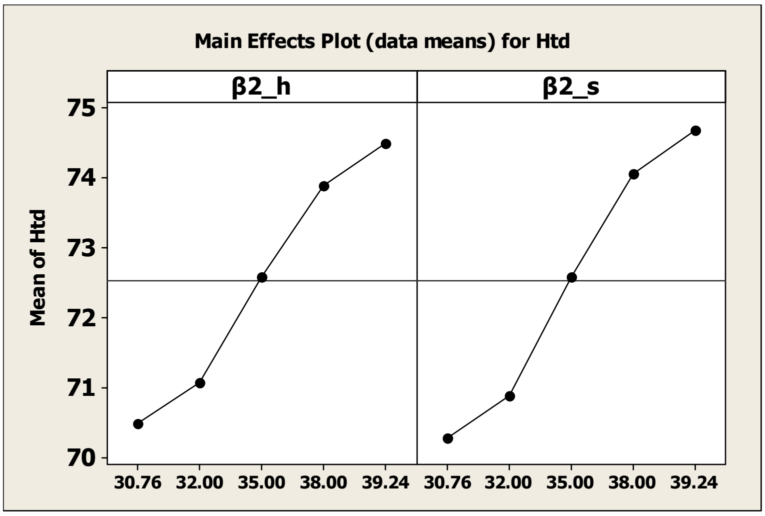


Fig. 13 Main effects plot for total head

5. Optimal mixed-flow pump design

Table 1 shows the real design target and the modified design specifications for the CFD cases and the CFD results for the base design model. The specific speed (rpm, m^3/min, m) of the pump is 380, the flow rate is 12,000 CMH, the total head is 60m, and the efficiency should be maximized at the design flow-rate. According to the numerical analysis of the base model, however, the numerical analyses for the impeller and pump do not satisfy 60 m. As a result, a new pump design that satisfies the specifications is needed.

Because of the simplified flow domain, without including tip clearance and roughness, the results of the numerical analysis are expected to be higher than the design target. Thus, we modified the design specifications for the CFD results. Design specifications for the numerical analysis are shown in Table 1. The total head was defined to be higher than 70m from the impeller and 65 m from the pump. The efficiency should be maximized at the design flow rate.

5.1 Optimal impeller design

For an optimal impeller design, we selected β2_h, β2_s in Fig. 3 as the two main design variables that most influence the efficiency and total head at the design flow-rate. The numerical analysis sets were generated by these two design variables using the central composite method. Table 2 shows the numerical analysis sets to which the RSM was applied. The other design variables were fixed.

The design variables %β1_(h, s) and %β2_(h, s) in Fig. 4 were fixed at 20%. The inlet blade angle β1_h and β1_s are related to the newly defined design variables iβ1_h and iβ1_s that represent the difference between the fluid and blade angles at the inlet of the impeller. The design variables iβ1_h and iβ1_s were fixed at 6° and 2°, respectively, based on the results of previous work [4, 5].

The effect of the impeller design variables on the total head is presented using a main effects plot, shown in Fig. 13. By analyzing the design variables that influence the total head and efficiency, we can see that the bigger the design variables of β2_h and β2_s are, the more the total head increases.

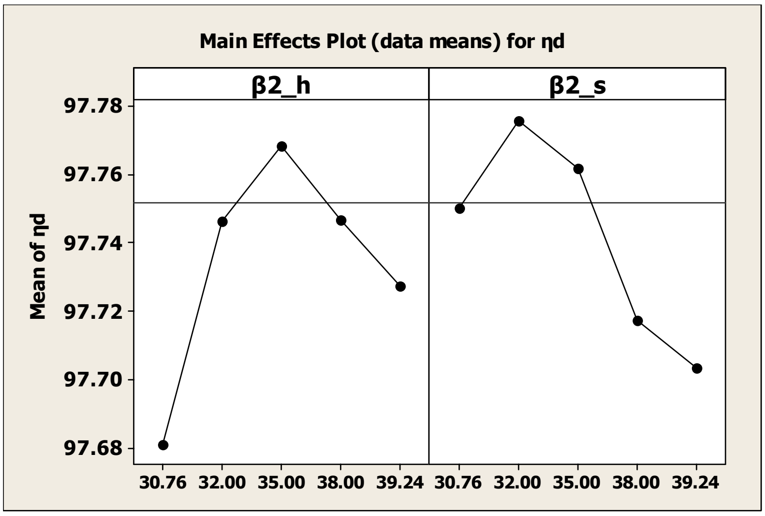


Fig. 14 Main effects plot for η_d

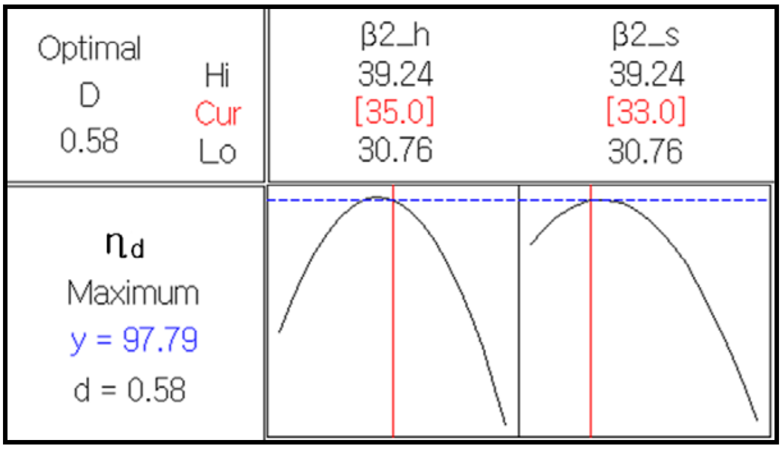


Fig. 15 Plot for response optimization

Table 3 Comparison of total head and efficiency (impeller only)

	Total head	Efficiency
Base design model	57.84	97.62
Optimization model	71.56	97.84

(a) (b)

Fig. 16 Comparison of three-dimensional geometry; (a) Base design model of impeller; (b) Optimization model of impeller

The effect of the impeller design variables on efficiency is also presented using a main effects plot, shown in Fig. 14. We can confirm that the efficiency is high when β2_h is 35° and β2_s is 32°. In Table 2, most of the RSM sets satisfy 70 m of total head. Thus, the RSM response variables were defined to improve efficiency at the design flow rate.

In order to decide the optimal impeller shape, a response optimization method was used, as shown in Fig. 15. As a result of the response optimization and using a regression model, the efficiency was predicted to be 97.79% when β2_h is 35° and β2_s is 33°. This result was optimal since it satisfies the target value of the design. The chosen optimization design was numerically analyzed and the efficiency was predicted to be 97.84%. The calculated total head was 71.56 m, exceeding the 70 m target value of the design. Efficiency improved by 0.22% compared to the base design model, as shown in Table 3. Figure 16 shows the impeller three-dimensional geometry of the base design model and the optimization model.

Table 4 Numerical analysis set of 2^k factorial designs for the diffuser design

2^k No	iβ1_h	iβ1_s	β2_h	β2_s	Ht_d	η_d
1	3	3	77	77	68.62	92.70
2	9	3	77	83	69.41	93.74
3	3	9	77	83	69.14	93.39
4	9	9	77	77	69.49	93.88
5	3	3	83	83	68.56	92.62
6	9	3	83	77	69.58	93.99
7	3	9	83	77	69.08	93.30
8	9	9	83	83	69.22	93.51
center	6	6	80	80	69.60	94.02

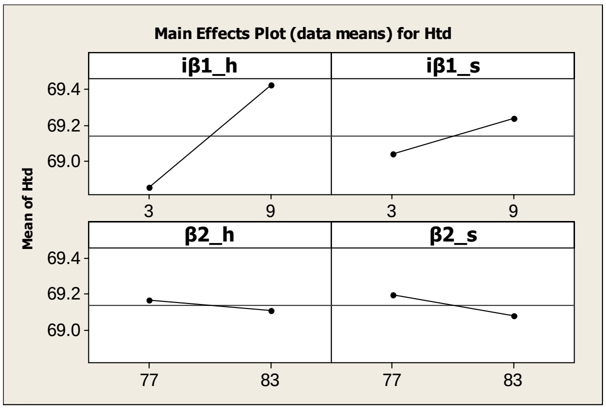


Fig. 17 Main effects plot for total head

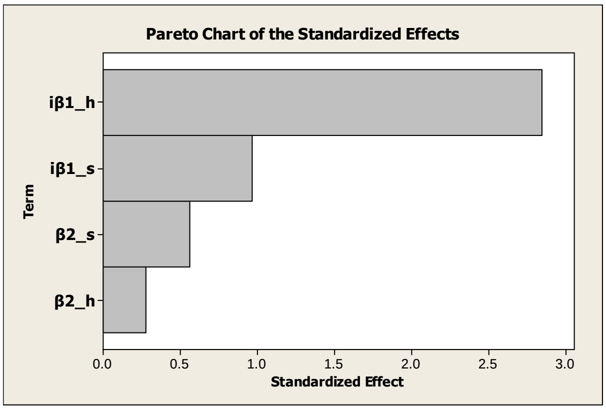


Fig. 18 Pareto chart for total head

5.2 Effect of diffuser design variables

To analyze the influence of the diffuser vane plane development design variables on the performance of the mixed-flow pump, the impeller shape was fixed as an optimization design, and the 2^k factorial designs were applied after defining only the diffuser vane plane development design variables. Although the level of resolution of fractional factorial designs is Ⅳ, which means the main effect is not confounded with the second interaction; there were complications in the second interactions. This caused us to generate nine experimental conditions for the numerical analysis, including a center point using four design variables. Table 4 shows the numerical analysis sets of 2^k factorial designs.

Of the various vane plane development design variables, the selected design variables for the 2^k factorial designs are iβ1_h and iβ1_s, which are related to the inlet angle of the diffuser, and β2_h and β2_s, which are the exit angles of the diffuser. Using the empirical aspect and analyzing the diffuser vane plane development of previous design databases, %β1_(h, s) was fixed to 30% and %β2_(h, s) was fixed to 5%. The variation range of the design variables iβ1_h, iβ1_s, β2_h, and β2_s were thought to be ±3° from each base design value.

The influence of the diffuser vane plane development on the total head is presented in Figs. 17 and 18, which show the main influence of the four design variables using a main effects plot and a Pareto chart. Figure 17 show that the design variables iβ1_h and iβ1_s have a greater influence on the total head than β2_h and β2_s.

For efficiency, the variation tendency of the total head and the efficiency is identical because there is no change in the torque due to the fixed optimal impeller shape. Accordingly, the variation tendency of the total head and the efficiency is identical because they are affected only by the difference of the total pressure through the mixed flow pump, which was caused by the change of the design variables from the diffuser vane plane development with the same impeller shape.

If we analyze the results of 2^k factorial designs in the main effects plot above, we can confirm that the inlet blade angle design is more important than the outlet blade angle design in enhancing the performance of the mixed-flow pump diffuser.

Table 5 Numerical analysis set of RSM for the diffuser design

RSM No	iβ1_h	iβ1_s	Ht_d	η_d
1	4	4	69.00	93.22
2	8	4	69.65	94.08
3	4	8	69.06	93.29
4	8	8	69.51	93.90
5	3.17	6	68.86	93.01
6	8.83	6	69.56	93.98
7	6	3.17	69.50	93.89
8	6	8.83	69.39	93.73
center	6	6	69.60	94.02

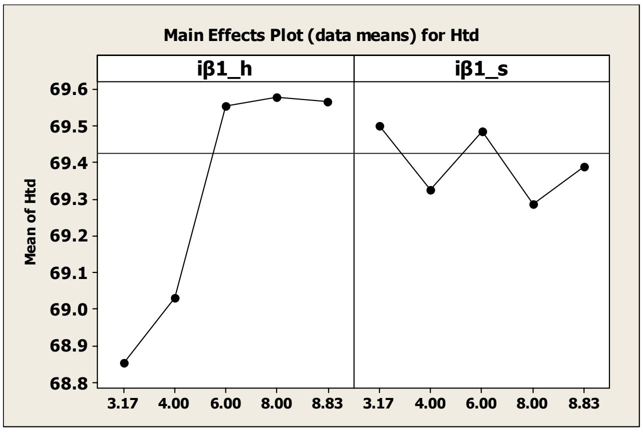


Fig. 19 Main effects plot for total head

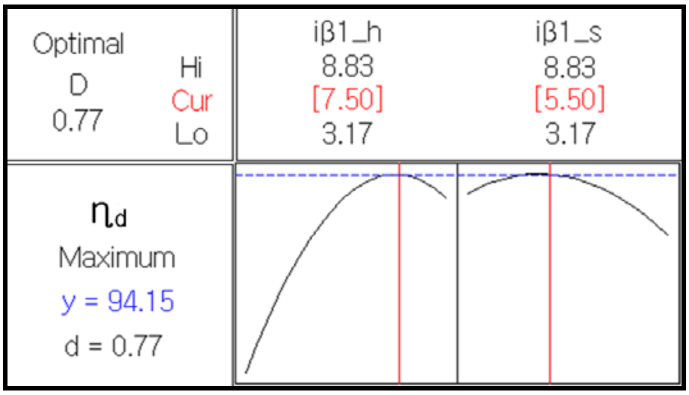


Fig. 20 Plot for response optimization

Table 6 Comparison of total head and efficiency (impeller+diffuser)

	Total head	Efficiency
Base design model	55.96	93.86
Optimization model	68.56	94.12

5.3 Optimal diffuser design

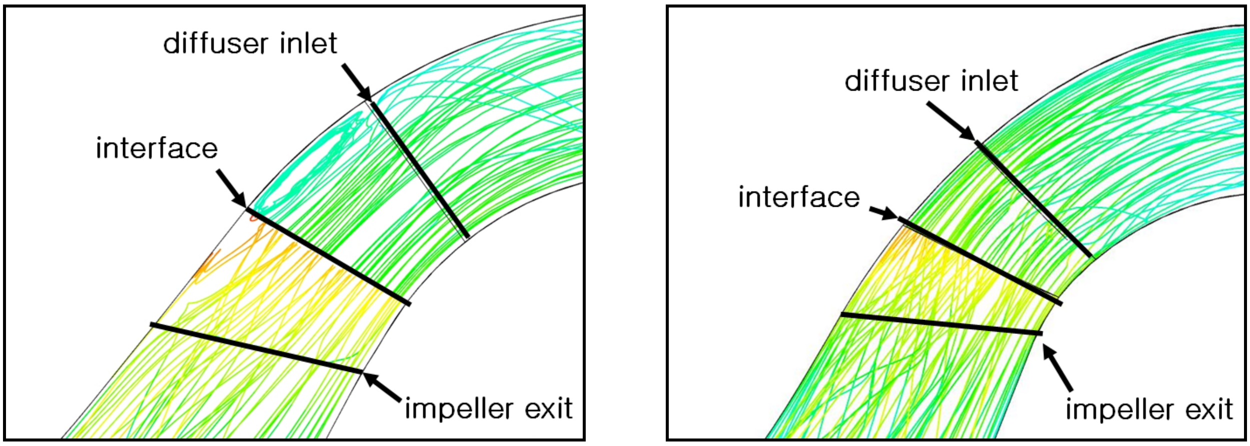
Upon analyzing 2^k factorial designs, the variables iβ1_h and iβ1_s, which greatly influence the performance of the mixed-flow pump in a fixed meridional shape, were selected as the design variables for further optimization using the RSM. The numerical RSM analysis sets were generated by these two design variables using the central composite method. The design variables, except the two main design ones, were fixed based on the results of the 2^k factorial designs. Table 5 shows the numerical analysis sets in which the RSM was applied.

The influence of the diffuser vane plane development design variables on the total head are shown in Fig. 19. By analyzing the design variables that affect the total head, we can see that the total head is predicted to be great when the design variable iβ1_h is around 8° and iβ1_s is around 5°. For efficiency, as we see from the 2^k factorial designs, since we fixed the optimal impeller design shape, the variation tendency of the total head and the efficiency is identical because there is no change in the torque.

In order to decide the optimal shape of the diffuser, we performed response optimization, as shown in Fig. 20. As a result, the efficiency was predicted to be 94.15% when iβ1_h is 7.5° and iβ1_s is 5.5°. This result was chosen to be an optimization design since it satisfies the target value of the design. The chosen optimization design was numerically analyzed and the efficiency was predicted to be 94.12%. Total head is 68.56 m here, satisfying the target value of the design of 65 m.

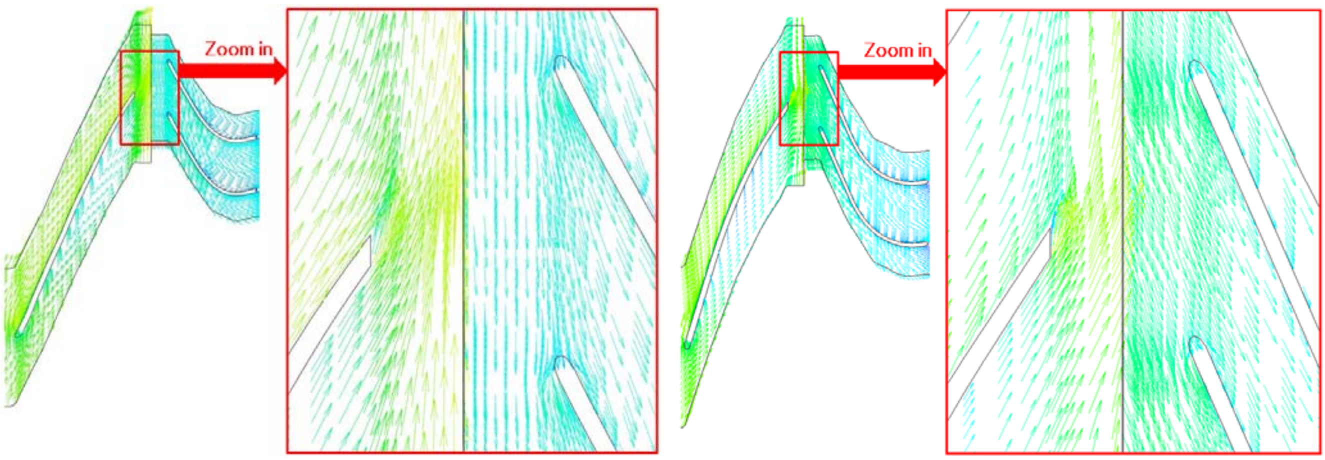
(a) (b)

Fig. 21 Comparison of three-dimensional geometry; (a) Base design diffuser; (b) Optimized diffuser



(a) (b)

Fig. 22 Comparison of steam lines near impeller exit and diffuser inlet; (a) Base design model; (b) Optimized model



(a) (b)

Fig. 23 Comparison of velocity vector near impeller exit and diffuser inlet (at 95% span); (a) Base design model; (b) Optimized model

Table 6 shows a comparison of the numerical analysis of the design flow-rates of the two models. For the optimally designed pump, the total head and efficiency improved by 24% and 0.26%, respectively, compared to the base design model. Figure 21 shows the diffuser's three-dimensional geometry for the base design model and the optimization model.

For a more accurate analysis, the steam lines near the impeller exit and the diffuser inlet region are presented in Fig. 22. While the backflow phenomenon could be seen on the shroud near the interface between the impeller and diffuser of the base design mixed-flow pump, the backflow phenomenon disappears from the optimized mixed-flow pump, which was designed by controlling the impeller and the diffuser design variables.

Back-flow occurs if the flow and blade angles do not correspond at the inlet part of the diffuser, causing efficiency to deteriorate. A blade-to-blade plot was used to see the fluid flow at the impeller exit and the diffuser inlet region. Figure 23 shows the velocity vectors in the B-B plane near the impeller exit and the diffuser inlet at a 95% span. In the base design model, the inlet and flow angles do not correspond. However, the fluid flow at the diffuser's leading edge in the optimal model is stable because the incidence angle was adjusted so that the inlet and flow angles correspond. The performance of the mixed flow pump was successfully improved by reducing the complex flow interaction between the impeller and diffuser.

6. Conclusion

The impeller and diffuser vane plane development design variables were defined when the meridional shape was fixed. The design optimization of the impeller and diffuser was performed using the traditional design method and DOE. The following conclusions have been drawn from this research.

[1] The impeller optimization design was developed by controlling the impeller vane plane development design variables using the RSM, satisfying the target value.

[2] Using 2^k factorial designs, the influence of the diffuser vane plane development design variables on the mixed-flow could be analyzed, and the greater influence of the design variables of the inlet section compared to those of the exit section could be confirmed. Also, it is possible to create a diffuser optimization design by controlling the design variables from the inlet part of the diffuser.

[3] By comparing the base design and optimized models with DOE, the total head and efficiency increased by 24% and 0.26%, respectively.

Nomenclature

$\beta 1$	Inlet blade angle [^{o}]	$\beta 2$	Outlet blade angle [^{o}]
$\%\beta 1$	Portion of same inlet blade angle [%]	$\%\beta 2$	Portion of same outlet blade angle [%]
$i\,\beta 1$	Incidence angle [^{o}]	h	Hub
m	Mid span	s	Shroud
R	Radius [mm]	M	Meridional view
θ	Sweep angle [^{o}]	Ht_d	Total head of design flow-rate [m]
Q	Flow rate [CMH]	η_d	Efficiency of design flow-rate [%]

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