International Journal of Fluid Machinery and Systems
Vol. 3, No. 1, January-March 2010

Original Paper

Performance Improvement of High Speed Jet Fan

Young-Seok Choi[1], Joon-Hyung Kim[1], Kyoung-Yong Lee [1] and Sang-Ho Yang [2]

[1]Energy System Technology Center, Korea Institute of Industrial Technology
35-3, Hongcheon-ri, Ipjang-myeon, Seobuk-gu, Cheonan, 330-825, Korea
yschoi@kitech.re.kr, kjh82@ kitech.re.kr, chrisst@kitech.re.kr
[2]Samwon E&B Co., Ltd 1289-3, Jungwang-Dong, Shihung-City, Kyunggi-Do, Korea
shyang@sebco.co.kr

Abstract

In this paper, a numerical study has been carried out to investigate the influence of jet fan design variables on the performance of a jet fan. In order to achieve an optimum jet fan design and to explain the interactions between the different geometric configurations in the jet fan, three-dimensional computational fluid dynamics and the DOE method have been applied. Several geometric variables, i.e., hub-tip ratio, meridional shape, rotor stagger angle, number of rotor-stator blades and stator geometry, were employed to improve the performance of the jet fan. The objective functions are defined as the exit velocity and total efficiency at the operating condition. Based on the results of computational analyses, the performance of the jet fan was significantly improved. The performance degradations when the jet fan is operated in the reverse direction are also discussed.

Keywords: Optimum design, Jet fan, Rotor blade, Stator blade, Bell-mouth, CFD (Computational Fluid Dynamics), DOE (Design of Experiments).

1. Introduction

As road tunnels become longer and traffic in these tunnels increases, ventilation becomes even more important. The purposes of ventilation in tunnels are: 1) to discharge pollutants emitted by cars, such as carbon monoxide (CO) and exhaust gases, in order to maintain a comfortable and safe driving environment; 2) to reduce concentrations of pollutants to below acceptable levels in order to ensure the safety of humans in emergencies and during maintenance work; and 3) to discharge smoke in case of fire. Therefore, appropriate ventilation plans are mandatory when designing and constructing tunnels.

Tunnel ventilation methods can be divided into natural ventilation and mechanical ventilation. In general, tunnels of shorter than 500 m can be naturally ventilated by the "piston effect" of cars running inside the tunnels. However, more recently constructed tunnels tend to be longer than 500 m. It thus becomes necessary to use mechanical ventilation to maintain a safe environment.[1]

Mechanical ventilation methods are divided into longitudinal, semi-transverse and transverse methods. In Europe, Japan and Korea, longitudinal ventilation methods using low-cost, highly efficient jet fans are employed. In longitudinal ventilation, jet fans are installed in a tunnel at certain intervals and the fast-flowing air produces kinetic energy that facilitates ventilation. Longitudinal ventilation methods not only make it possible to reduce tunnel sectional area compared to semi-transverse and transverse methods, but also result in reduced construction and operational costs since individual air inlets and outlets are not required.[2]

Jet fan technology is a core technology in longitudinal ventilation methods. Studies to improve the performance of jet fan are currently being conducted in Europe and Japan. In this study, the design variables for jet fan rotors were established and the effects of changes to the variables on jet fan performance were analyzed using a design of experiments (DOE) approach and numerical analyses. The effects of the variables on jet fan performance were also numerically analyzed. Design variables include the numbers of rotor-stator blades, tip clearance, stator geometry and inlet shapes. Finally, newly designed jet fans were introduced and the performance improvement was checked by using CFD.

2. Jet fan geometry and numerical analysis method

2.1 Jet fan geometry

Jet fans are air blowers that are installed on the ceiling or walls of road tunnels and underground roadways to provide longitudinal ventilation as shown in Fig. 1. Jet fans consist of a casing that holds a silencer, a rotor, a motor as a power source and

Received December 9 2009; revised January 13 2010; accepted for publication January 15 2010: Review conducted by Prof. Youn-Jea Kim. (Paper number O09051)
Corresponding author: Young-Seok Choi, Principal Researcher, yschoi@kitech.re.kr

a stator that fixes the motor to the casing. The total assembly is hung from the ceiling of a tunnel. Hence, jet fans must be proven safe and durable, especially after being in operation for a long time.

Jet fans are similar to axial fans in shape, but they rotate more quickly in order to create high speed airflow. They are also limited in size and have silencers on two sides in order to reduce flow noise. Also jet fans are required to have reversible performance to discharge smoke at fire; Therefore, Jet fans are technology-intensive products.

2.2 Numerical analysis method

The rotor to be modeled had six blades and the stator nine blades. As shown in Fig. 2, numerical analysis of the blade area of one rotor and two stators were conducted using periodic conditions, taking analysis time into consideration.

Structured grids were created using ANSYS CFX-TurboGrid, a grid creation program for turbomachinery. The grid system is shown in Fig. 3; the number of the created cells is around 160,000.

Jet fan performance was predicted using ANSYS CFX ver.11, which is a three-dimensional viscous fluid analysis program. To examine the characteristics of the flow fields inside the rotor and the stator, three-dimensional Navier-Stokes equations were used to analyze the incompressible turbulent flow. The governing equations used in the numerical analysis were discretized by a finite volume method using a high-resolution scheme with at least second-order. The turbulent flow model was the shear stress transport k-ω model. As a boundary condition, the atmospheric pressure was given to the inlet area with total pressure and to the outlet area with static pressure as shown in Fig. 2. The rotation speed of the rotor was 1780rpm. The working fluid used was air.

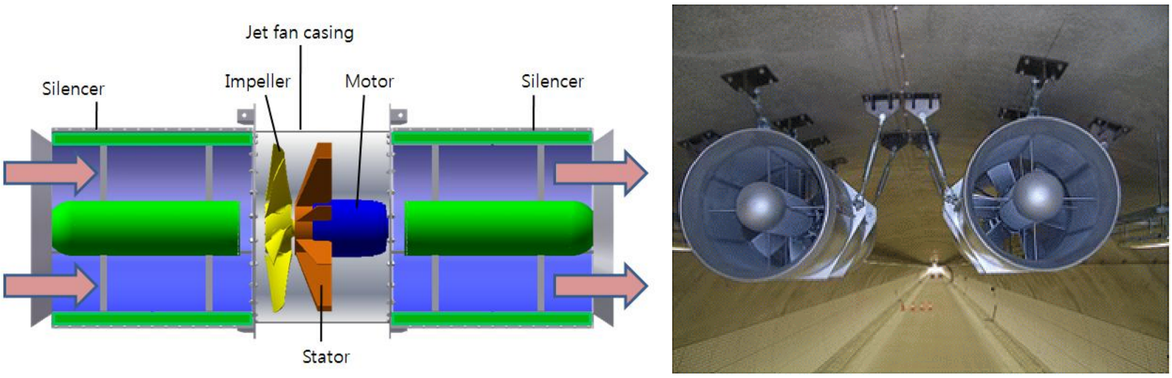


Fig. 1 Jet fan geometry

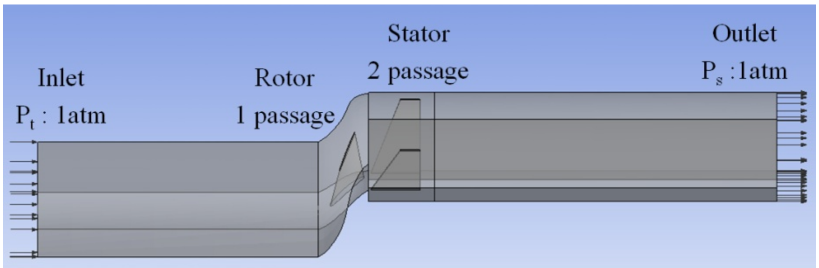


Fig. 2 Flow field and boundary conditions of the jet fan

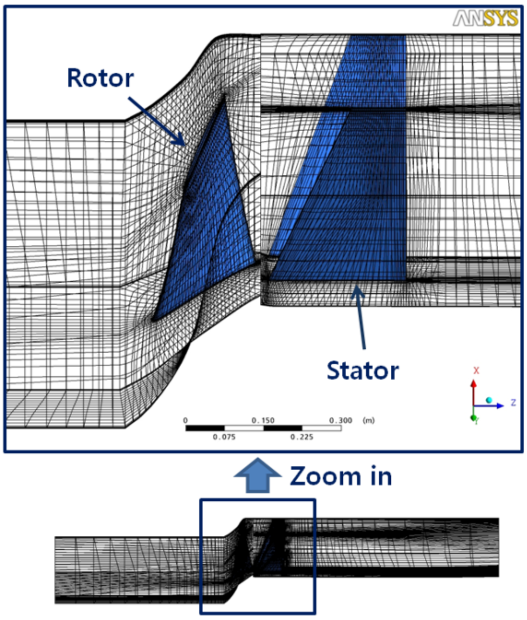


Fig. 3 Grid for jet fan numerical analysis

3. Rotor design

3.1 Rotor design variables

The design variables necessary to design the jet fan rotor are shown in Fig. 4. Variables to control rotor size were established as R_h and R_s. Here, R_h represents the radius of the hub of the jet fan rotor and R_s represents the radius of the shroud. The ratio between the two variables is defined as the hub-tip ratio. The variables necessary to control the thickness and profile shape of the blade were defined as $Th_{max,h}$, $Th_{max,s}$, CL_h and CL_s. Here, $Th_{max,h}$ represents the maximum blade thickness at the hub and $Th_{max,s}$ represents the maximum blade thickness at the shroud. The blade thicknesses are associated with structural stability and the blade has a symmetrical shape with the point of the maximum thickness located in the middle of the blade. CL_h represents the chord-length of the blade profile at the hub and CL_s represents the chord length of the blade profile at the shroud. Finally, to control the blade angle of the rotor, the angles of incidence $i\beta$ related to the inlet blade angles at the hub and at the shroud were defined as $i\beta_h$ and $i\beta_s$ respectively. The angles of incidence were defined as the angles made by the relative flow angles at the hub and at the shroud and the blade angles on the basis of the mean axial direction speed of 32m/s. Since a straight blade shape without any camber was adopted for the rotor for the reversible performance of the jet fan, the rotor shape would be determined when the inlet blade angle and the chord-length have been defined.

3.2 2^k factorial designs

The DOE is a method to select important causes at low costs among numerous causes that bring about abnormal changes based on modern statistical analysis methods and quantitatively measure the effects.[3,4] Using this method, one can separately measure the effects of two or more kinds of factors at the same time. In this study, 2^k factorial designs were used to analyze the effects of jet fan rotor design variables. Results were analyzed using Minitab14. In this study, fractional factorial experiments were conducted where the number of experiments could be reduced by confounding high-order interactions with low significances, taking into consideration the number of interesting factors, the number of experiments that could be carried out, costs and time. The resolution of the fractional factorial designs was the level IV where the main effects did not confound with secondary interactions but secondary interactions confounded with each other.[5,6]

For the factorial experiments, the jet fan rotor design variables R_h, CL_h, CL_s, $Th_{max,h}$, $Th_{max,s}$, $i\beta_h$, $i\beta_s$, which were expected to affect the performance of the jet fan, were selected (Table 1). The ranges of changes of the variables were set to be ±10% of the reference values for R_h, CL_h, CL_s, $Th_{max,h}$, $Th_{max,s}$ and $\pm 3^{\circ}$ for $i\beta_h$ and $i\beta_s$, as shown in the table. Other variables were fixed to be the same as those of the base model.

Finally, 16 sets of factorial experiments were created with seven factors as shown in Table 2. The results of numerical analyses of the 16 sets of factorial experiments are shown in Table 3. To analyze the performance of the jet fan based on the jet fan rotor design variables in the factorial experiments, response variables must be defined. The response variables were defined based on the fan outlet velocity of the jet fan(V_{out}) and the efficiency.

The effects of the jet fan rotor design variables on the performance of the jet fan were analyzed using Pareto charts, as shown in Figs. 5 and 6. Figure 5 is the result of analyzing the effects of the factors on V_{out} and Figure 6 is the result of analyzing the effects of the factors on efficiency. Based on the results in Fig. 5, it was determined that $i\beta_s$, CL_h and R_h affected the response variable V_{out} in the order of precedence. However, as shown in Fig. 6, it was determined that the effects of the single variables affecting efficiency were slight and the effects of compounding interactions between two variables were significant. When these results are integrated, it can be seen that if the shape of the rotor is symmetrical (without any camber) for reversibility, the blade angle and chord length can be changed to increase V_{out}, however, efficiency would only improve slightly.

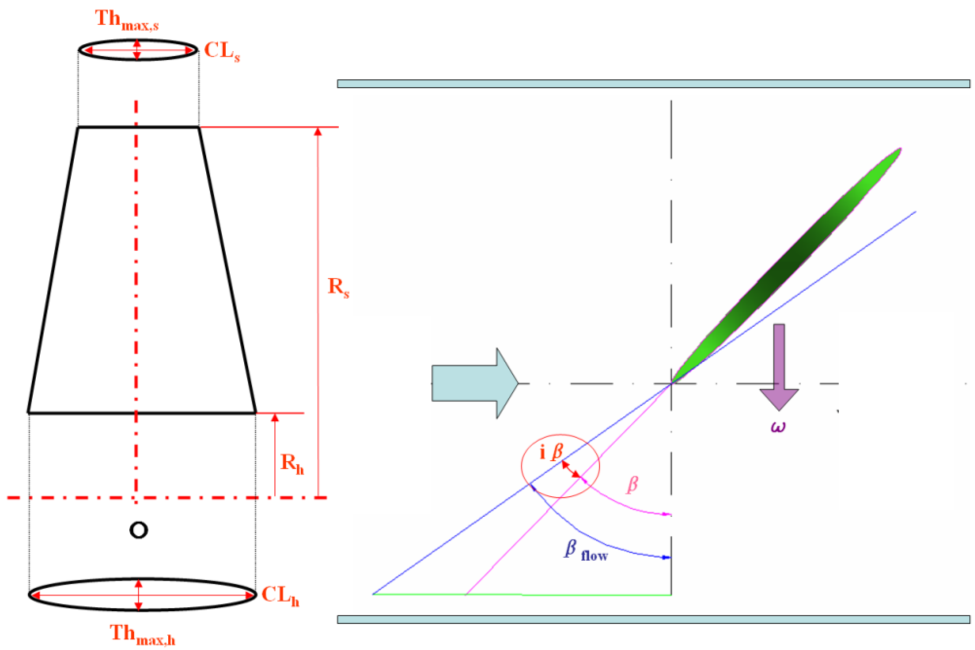


Fig. 4 Design variables of the jet fan rotor

Table 1 Design variables of the jet fan rotor

variable	center	range
R_h	201.5mm	±10%
$Th_{max,h}$	14.2mm	±10%
$Th_{max,s}$	6.9mm	±10%
$i\beta_h$	3°	±3°
$i\beta_s$	3°	±3°
CL_h	258mm	±10%
CL_s	258mm	±10%

Table 2 Numerical analysis set of 2k factorial design

Set	R_h	$i\beta_h$	$i\beta_s$	CL_h	CL_s	$Th_{max,h}$	$Th_{max,s}$
1	181.35	0	0	232.2	232.2	19.0	7.6
2	221.65	0	0	232.2	283.8	19.0	9.2
3	181.35	6	0	232.2	283.8	23.2	7.6
4	221.65	6	0	232.2	232.2	23.2	9.2
5	181.35	0	6	232.2	283.8	23.2	9.2
6	221.65	0	6	232.2	232.2	23.2	7.6
7	181.35	6	6	232.2	232.2	19.0	9.2
8	221.65	6	6	232.2	283.8	19.0	7.6
9	181.35	0	0	283.8	232.2	23.2	9.2
10	221.65	0	0	283.8	283.8	23.2	7.6
11	181.35	6	0	283.8	283.8	19.0	9.2
12	221.65	6	0	283.8	232.2	19.0	7.6
13	181.35	0	6	283.8	283.8	19.0	7.6
14	221.65	0	6	283.8	232.2	19.0	9.2
15	181.35	6	6	283.8	232.2	23.2	7.6
16	221.65	6	6	283.8	283.8	23.2	9.2
17 (center)	201.50	3	3	258.0	258.0	21.1	8.4

Table 3 Numerical analysis result of 2^k factorial design

Set	Q [CMS]	dP_t [pa]	Torque [J]	Efficiency [%]	V_{out} [m/s]
1	32.3	514.8	122.4	73.0	28.77
2	31.3	524.4	124.0	71.0	29.16
3	32.6	518.0	126.6	71.5	28.97
4	33.2	597.7	146.2	72.8	30.95
5	37.5	707.5	194.0	73.4	33.35
6	36.2	709.4	191.2	72.1	33.75
7	37.6	698.1	198.5	70.9	33.42
8	38.4	793.2	221.5	73.7	35.78
9	34.2	576.2	144.6	73.0	30.40
10	34.0	620.2	157.3	71.9	31.69
11	34.7	588.3	150.3	72.8	30.83
12	35.8	698.7	184.2	72.9	33.38
13	39.3	772.1	220.5	73.9	34.99
14	38.3	797.9	226.1	72.5	35.69
15	39.9	792.1	238.8	71.0	35.49
16	40.3	873.9	256.1	73.8	37.56
17 (center)	36.6	685.1	182.3	73.7	33.24

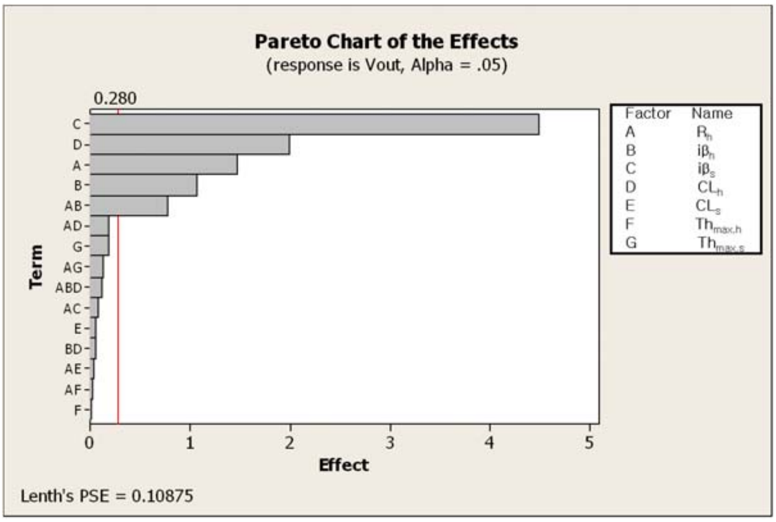


Fig. 5 Pareto plot for V_{out}

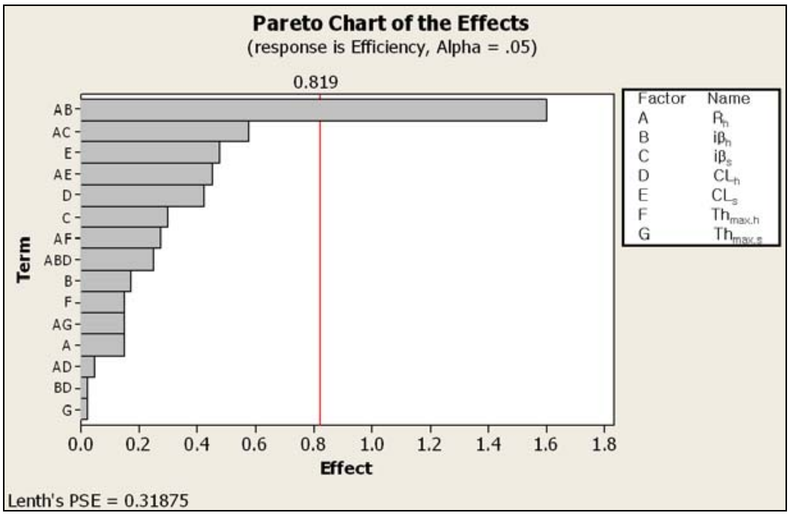


Fig. 6 Pareto plot for efficiency

4. Effect of various design variables

Based on the result mentioned in Section 3, it was determined that the design of jet fan rotors played only a limited role in designing high efficiency jet fans. Therefore, to improve the performance of jet fan, the effects of other design variables should be analyzed.

Accordingly, other variables that were believed to affect jet fan were selected. Those variables were the number of the jet fan rotors, tip clearance, the number and shape of jet fan stators and the shape of the jet fan inlets. To analyze the effects of these variables on jet fan performance, one-factor numerical analyses were performed and the results analyzed. When analyzing the results, the results of the numerical analyses of the existing jet fan model were used as reference data for comparison.

4.1 Effect of the number of rotor blades

To examine the effect of the number of jet fan rotor blades on the jet fan performance, numerical analyses of the number of jet fan rotor blades were carried out. Based on the six rotor blades of the existing jet fan model, numerical analyses were carried out on five blades and seven blades; the results are shown in Fig. 7. It was determined that as the number of jet fan rotor blades increased, V_{out} increased and efficiency decreased. Although the effective outlet velocity could be increased by increasing the number of rotor blades, losses caused by the large number of blades also increased. Thus, the efficiency decreased somewhat. Therefore, although the number of blades may be increased to obtain high outlet velocities, the number should be determined considering the torque limits of each blade and production costs due to structural problems.

4.2 Effect of tip clearance

To examine the effect of tip clearance on jet fan performance, numerical analysis of tip clearance changes were carried out and the results analyzed. Based on the 5 mm tip clearance of the existing jet fan model, numerical analyses were carried out on 3 mm and 7 mm tip clearances; the results are shown in Fig. 8. From the figure, it can be seen that as the tip clearance increased, both V_{out} and efficiency decreased. This is believed to be because of the increased losses caused by tip leakage flow following the increased tip clearances. It is important to select appropriate tip clearances by analyzing production tolerances and considering thermal expansions in case of fires and the dynamic characteristics of the blades.

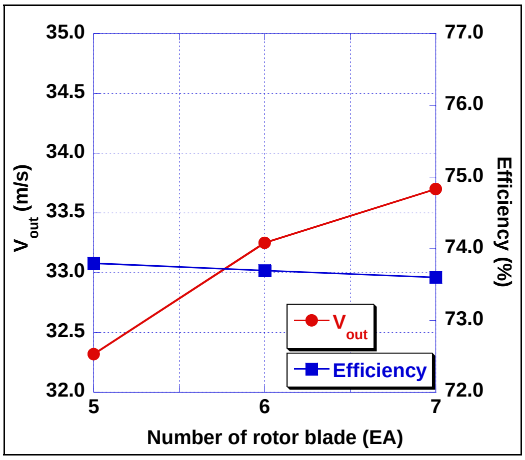


Fig. 7 Effect of the number of rotor blades

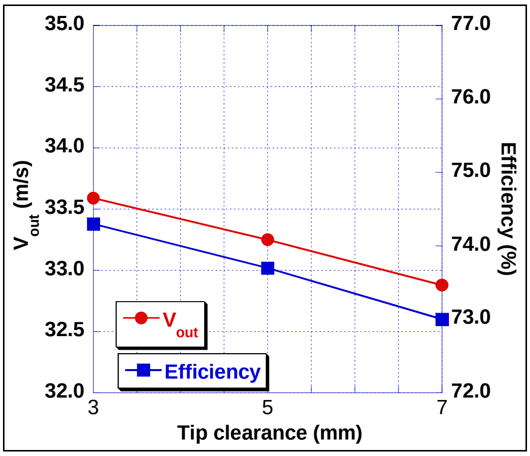


Fig. 8 Effect of tip clearance

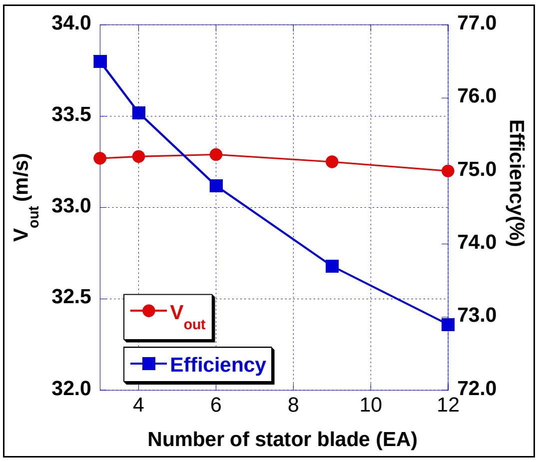


Fig. 9 Effect of the number of stator blades

4.3 Effect of the number of stator blades

In the case of the existing model, stators are located close to the downward side of the rotor and are straight in the axial direction, as shown in Fig. 2. The roles of the stator are to recover the rotational velocity component into pressure behind the rotor and to fix the motor to the casing. To examine the effect of the number of jet fan stator blades on jet fan performance, one-factor calculations were carried out on the number of the jet fan stator blades. Based on the nine stator blades of the existing jet fan model, numerical analyses were carried out on three, four, six and twelve blades; results are shown in Fig. 9. It was determined that as the number of jet fan stator blades increased, efficiency decreased. As for V_{out}, the effect of the number of stator blades was not significant compared to efficiency.

4.4 Effect of stator geometry

As mentioned in Section 4.2, it was determined that as the number of stator blades increased, losses also increased. The shape of existing stators was straight in the axial direction as shown in Fig. 10. Therefore, if the jet fan rotor outlet flow has circumferential velocity components as shown in Fig. 10, flow separations will occur because of the difference between the flow angles and the blade angles. This will cause decreased jet fan efficiency. If the number of blades is greater, this phenomenon will occur across all the blades and thus efficiency will decrease further. The reason why stators should be straight is to allow for the reversibility of jet fans. That is, to obtain the same outlet velocity when the rotor rotates in the opposite direction, the flow at the rotor inlet should have an axial direction velocity component.

Based on analyses of the existing model, it can be seen that around 10% of the total pressure at the rotor outlet is lost while passing the stator. Therefore, changing the shape of the stator a little would improve the performance of the jet fan during forward rotations. But performance deterioration for the reverse rotations should be checked.

To examine the effect of the shape of the stator on jet fan performance, numerical analyses were conducted. To carry out the analyses, the stator shape was made to be as shown in Fig. 11. The stator blade shape was not straight, but had the blade angle (β_{stator}). To determine the reference value of the stator blade angle, the mean rotor outlet flow angle α was calculated using the C_m(meridional velocity component) and C_u(circumference velocity component) of the existing jet fan model. The calculated α value was 16.24°. Numerical analyses were performed on the shapes of the stator with angles increased or decreased by 3° based on the β_{stator} value (16.24°), the same as the calculated α value. Results are shown in Fig. 12. Both V_{out} and efficiency were shown to be highest at the reference stator angle (16.24°). In particular, it can be seen that efficiency increased by around 5% compared to the straight blade. Relationships between the stator angles and the efficiency can be inferred from the velocity vectors shown in Fig. 13. When the stator blade angle is small, flow separation will occur on the suction surface of the stator inlet. As the angle increases, the flow separation will decrease and as the angle becomes larger than the angle at the maximum efficiency point, flow separation will occur on the pressure surface.

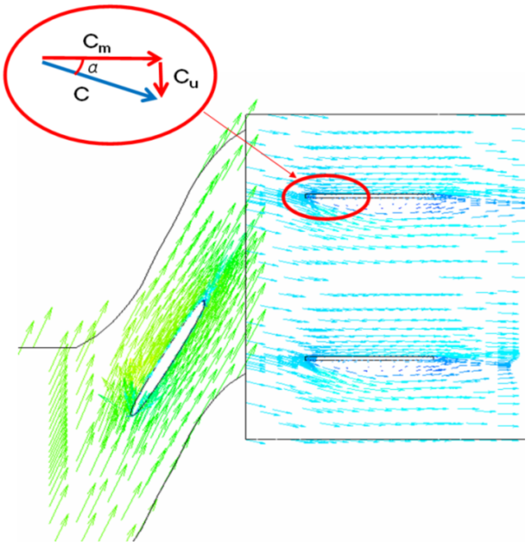


Fig. 10 Velocity vector

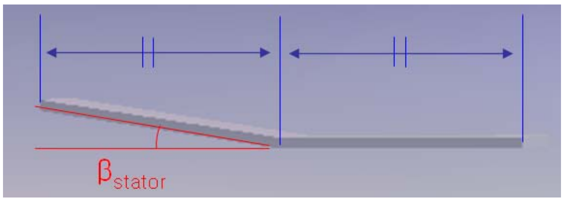


Fig. 11 Design of the stator blade

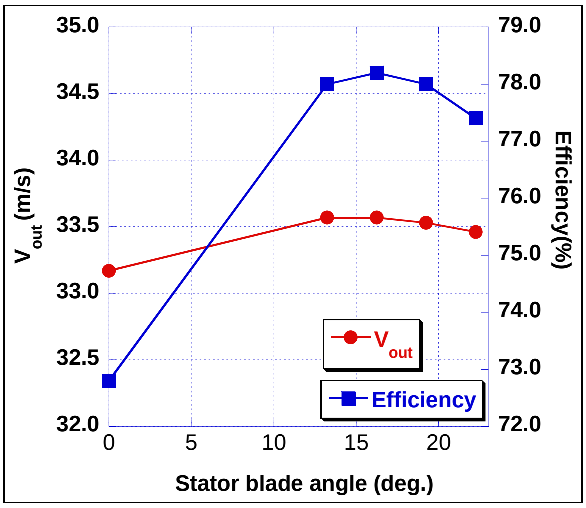


Fig. 12 Effect of stator blade angle

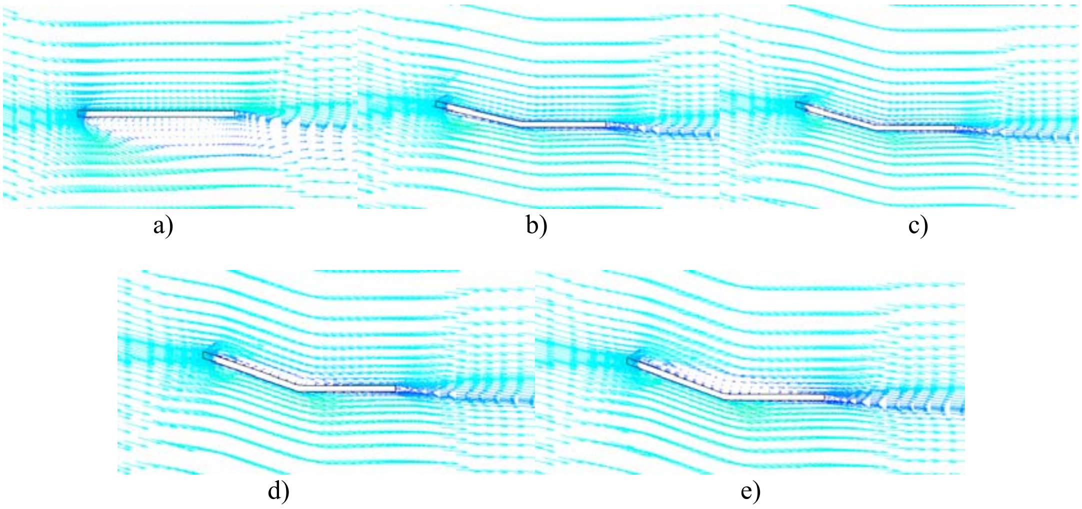


Fig. 13 Velocity vectors through the stator blade (at mid-span)
a) 0 °; b) 13.24 °; c) 16.24°; d) 19.24° ; e) 22.24°

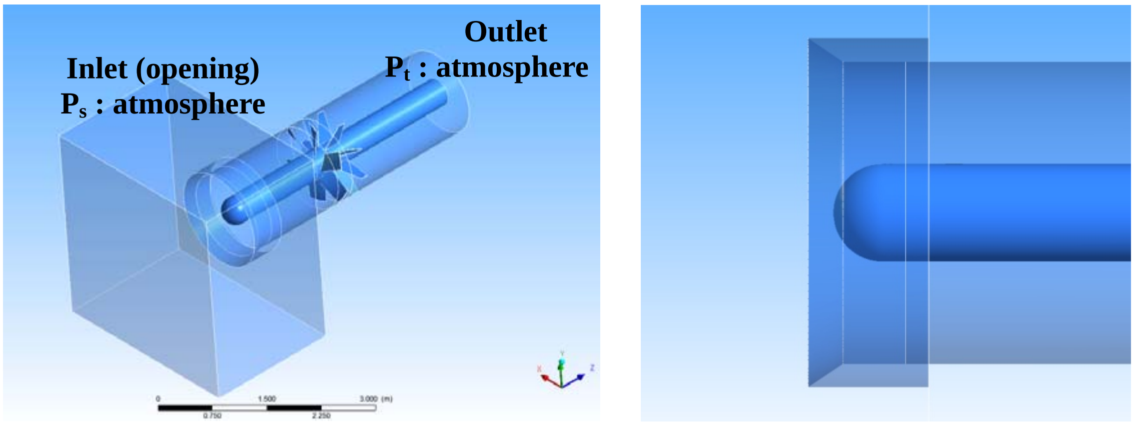


Fig. 14 Geometry of model 1

Table 4 Numerical analysis result of base model and model 1

	Q [CMS]	dP_t [pa]	Torque [J]	Efficiency [%]	V_{out} [m/s]
Base model	35.61	644.01	167.91	73.52	32.35
Model 1	35.56	644.70	191.75	64.14	32.33

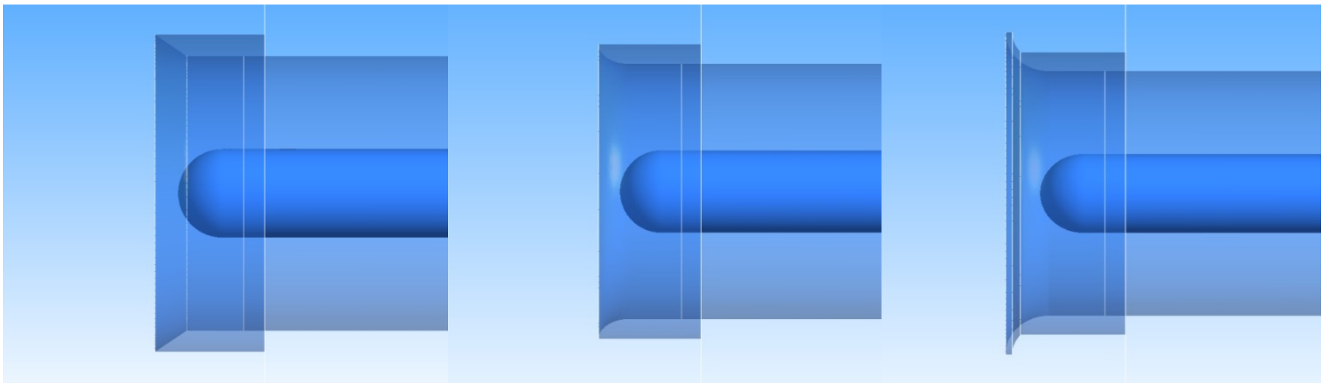
4.5 Effect of inlet shape

To predict jet fan performance more accurately, numerical analyses were performed on the jet fan model (model 1) considering actual inlet shape, as shown in Fig. 14. The boundary condition for the numerical analysis is shown in the figure. Table 4 shows the results of the numerical analyses compared to the results from the existing jet fan model (base model) that were arrived at without considering the effect of the inlet. The results of the numerical analyses of model 1 showed much lower jet fan efficiency compared to the results of the numerical analyses of the base model, arrived at without considering the effect of the inlet shape. (Efficiency decreased by around 9.4 %)

The efficiency deterioration is due to the flow separation caused by the shape of the bell mouth. Two different models were proposed as shown in Fig. 15. Model 2 is a model with an ellipse shape. Model 3 is also ellipse shape as model 2, but it is enlarged by 50 mm in the axial and radial direction.

Table 5 summarizes the results of the individual models. In the case of model 2, the degrees of improvement in efficiency and outlet velocity compared to model 1 were very small, but in the case of model 3, efficiency increased by around 9% and V_{out} increased by around 1.3 m/s.

To determine the cause of these improvements in performance, the velocity vectors at the inlet areas of the individual models were analyzed. Results are shown in Fig. 16. The phenomena that occurred at the inlet area of model 1 were slightly reduced in model 2, which was redesigned. Flow separation hardly occurred at all in the inlet area of model 3. It was determined that, along with improved flow in the inlet area, the inflow axial velocity into the jet fan rotor was more uniform in model 3 than in model 1. This may also results in improved rotor efficiency.

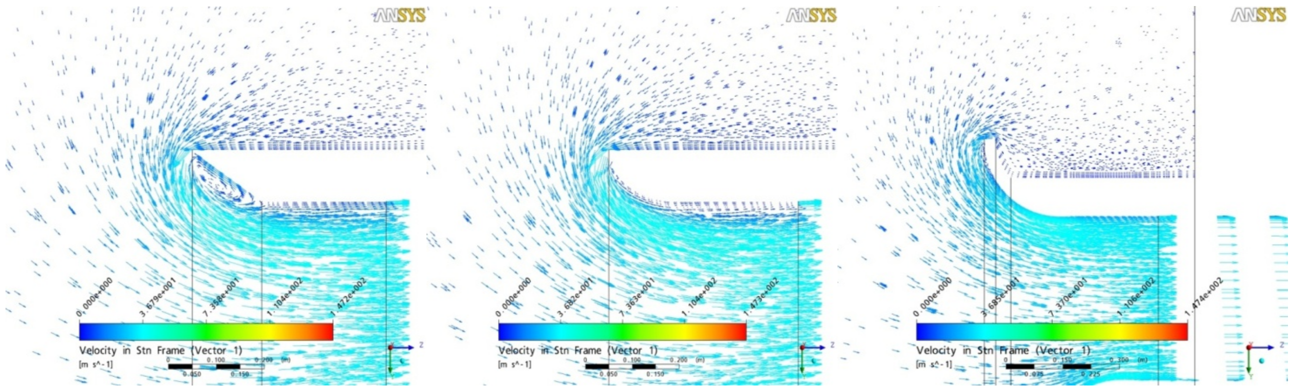


a) b) c)

Fig. 15 Geometry of inlet shape: a) model 1; b) model 2; c) model 3

Table 5 Numerical analysis results for the base model, model 1, model 2 and model 3

	Q [CMS]	dP_t [pa]	Torque [J]	Efficiency [%]	V_{out} [m/s]
Base model	35.62	646.42	167.92	73.48	32.35
Model 1	35.56	644.70	191.75	63.65	32.33
Model 2	35.56	643.55	191.74	64.01	32.31
Model 3	36.34	685.46	184.73	72.35	33.03



a) b) c)

Fig. 16 Velocity vectors near inlet bell mouse:
a) model 1; b) model 2; c) model 3

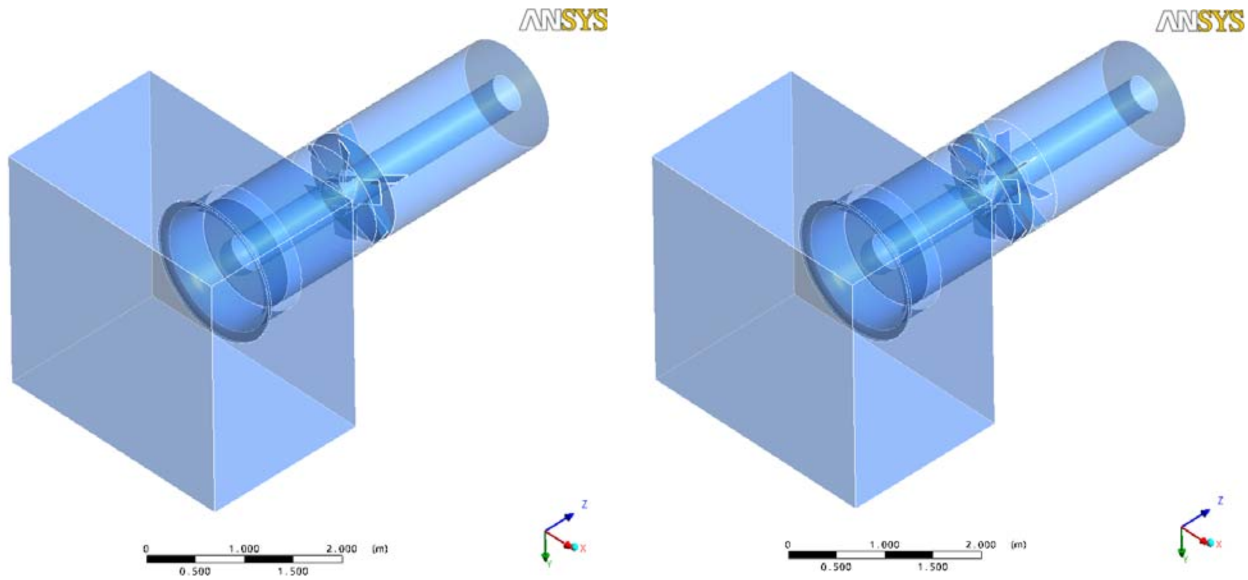
5. Improved jet fan design

In this study, the effects of jet fan design variables on jet fan performance were reviewed. To make designs that would improve jet fan performance, the shape of the inlet area, the number of the stator blades and the shape of the stator were determined to be variables that greatly affected jet fan performance. Finally, we selected optimum design variables based on the results mentioned above and created two models (Fig. 17).

Considering reversibility, model 4 was designed to have the inlet shape of model 3 with four stator blades. Without considering reversibility, model 5 was designed to have the inlet shape of model 3 and a stator blade angle of 16.24^{o}. The results of numerical analyses of the individual models are shown in Table 6, compared to model 1.

Both model 4 and model 5 performed excellently compared to the existing jet fan model. In the case of model 4, efficiency increased by around 10% and V_{out} increased by around 0.7m/s compared to the existing jet fan model with straight bell mouth. In the case of model 5, efficiency increased by around 12.5%, V_{out} increased by around 1.0m/s.

In the case of model 5 having some blade angles in the stator inlet, problems may occur if the performance in the forward direction is improved a lot but the performance in the reverse direction is reduced very much. To analyze the reversibility of model 5, the inlet/outlet conditions and rotation direction of model 5 were set conversely and numerical analyses were performed Results are shown in Table 7. During operation in the reverse direction, efficiency was reduced by 0.35% from 76.13% to 75.78%. The outlet velocity was reduced by around 3.33 m/s from 33.39 m/s to 30.06 m/s. It can be seen that, compared to the amount efficiency decreased by, effective outlet velocity decreased more. This is because the circumferential velocity component caused by the blade angle existed at the inlet of the rotor when operated in the reverse direction. It is believed that, if the stator blade angle can be simply converted according to the forward/reverse direction operations, truly reversible jet fans having high operational efficiency and outlet velocities can be developed.



model 4 model 5

Fig. 17 Geometry of models 4 and 5

Table 6 Numerical analysis results for model 1, model 4 and model 5

	Q [CMS]	dP_t[pa]	Torque [J]	Efficiency [%]	V_{out} [m/s]
Model 1	35.56	644.70	191.75	63.65	32.33
Model 4	36.34	695.04	183.50	73.68	33.04
Model 5	36.73	695.52	179.59	76.13	33.39

Table 7 Comparison of directional effect of model 5

	Q [CMS]	dP_t[pa]	Torque [J]	Efficiency [%]	V_{out} [m/s]
Model 5 forward	36.73	695.52	179.59	76.13	33.39
Model 5 reverse	33.12	707.72	165.71	75.78	30.06

6. Summary

1) Considering reversibility, rotor design variables were selected to review the characteristics of changes in jet fan performances caused by changes in the variables. The design variables that affected the outlet velocities were $i\beta_s$, CL_h and R_h in the order of precedence and the effect of confounding actions significantly affected efficiency.
2) The effects of the numbers of rotors/stator blades and tip clearance were numerically analyzed to provide design guidelines.
3) To satisfy reversibility, rotor designs must have symmetry and stator designs must be straight. Therefore, the circumferential velocity component behind the rotor created flow separation phenomenon at the stator, thereby decreasing jet fan performance. Changes in performance depending on stator blade angles were examined and decreased performance during reverse rotations at the blade angle for the best performance case was investigated.
4) Considering the effects of rotor and stator design variables, new jet fan designs were presented. Where the reversibility of the stator was not considered, efficiency increased by 12.5% and V_{out} increased by 1.0 m/s; V_{out} decreased by 3.33m/s and efficiency by 0.35% during reverse rotations. Where reversibility of the stator was considered, V_{out} and efficiency increased by 0.7m/s and 10% respectively.

Nomenclature

R_h	Radius of hub [mm]	β	Blade angle[^{o}]
R_s	Radius of shroud [mm]	β_{flow}	Flow angle[^{o}]
CL_h	Chord length of hub [mm]	$i\beta_h$	Incidence angle of hub[^{o}]
CL_s	Chord length of shroud [mm]	$i\beta_s$	Incidence angle of shroud[^{o}]
$Th_{max,h}$	Maximum thickness of hub [mm]	α	Absolute flow angle[^{o}]
$Th_{max,s}$	Maximum thickness of shroud [mm]	V_{out}	Fan outlet velocity [m/s]

References

[1] Ryu, J. H., Yoo, W. H. and Kim, J., 2003, "The Jet-fan Model Test for a Road Tunnel Ventilation," Journal of SAREK, Vol. 15, No. 8, pp. 630-640.
[2] Schlaug, R. N., Carlin, T. J., 1979, "Aerodynamics and Air Quality Management of Highway Tunnels," Administration, USA, pp. 2.49-2.56.
[3] Myers, R. H., Montgomery, D. C., 2002, "Response Surface Methodology: Process and Process and Product Optimization Using Designed Experiments, Second Edition," A Wiley-Interscience Publication, United States of America.
[4] Hicks, C. R., Turner Jr, K. V., 1999, "Fundamental Concepts in the Design of Experiments, Fifth Edition," Oxford University Press, New York.
[5] Kim, S., Choi, Y. S., Lee, K. Y. and Yoon, J. Y., 2009, "Design Optimization of Centrifugal Pump Impellers in a Fixed Meridional Geometry using DOE," International Journal of Fluid Machinery and Systems, Vol. 2, No. 2, pp. 172-178.
[6] Jung, U. H., Choi, Y. S., Kwon, O. M. and Lee, K. Y., 2007, "Optimum Design of Air Nozzle System for Automatic Car Wash Machine using CFD and DOE," Journal of Fluid Machinery, Vol. 10, No. 5, pp. 34-40.