공학석사학위논문

거니플랩이 원심팬의 공력성능에 미치는 영향

Effect of Gurney Flap on the Performance of a Radial Fan

2014 년 8 월

서울대학교 대학원

기계항공공학부

김 민 지

거니플랩이 원심팬의 공력성능에 미치는 영향

Effect of Gurney flap on the Performance of a Radial Fan

지도교수 송 성 진

이 논문을 공학석사 학위논문으로 제출함

2014 년 8 월

서울대학교 대학원

기계항공공학부

김 민 지

김민지의 공학석사 학위논문을 인준함

2014 년 8 월

위 원 장	강 신 형
부위원장	송 성 진
위 원	김 호 영

Abstract

Effect of Gurney Flap on the Performance of a Radial Fan

Minji Kim

Department of Mechanical and Aerospace Engineering

The Graduate School

Seoul National University

In this research, Gurney flap is applied to rotating radial fan and the mechanisms it improves the fan performance will be explained by numerical study. The CFD results were validated with experimental results and it shows good agreement. With the Gurney flap, the fan produces more diffusion with larger change of relative velocity than the reference case. It results in higher static pressure rise and this can be explained with stagnation effect by Gurney flap and the flow deflection due to the flap angle and the force driven by the pressure gradient between the pressure side and the suction side. Total pressure loss increased with Gurney flap.

However, this was not significant compared to the increment of static pressure rise with Gurney flap.

……………………………………

keywords : Gurney flap, Radial fan, Performance

Student Number : 2012-23156

Nomenclature

c	Chord length of original blade
h	Gurney flap height
P_s	Static pressure
P_t	Total pressure
ΔP_s	Static pressure difference between fan inlet and outlet
Q	Volume flow rate
R	Fan radius
T	Torque
ω	Rotational speed
ρ	Air density
η	Efficiency
U	Rotational velocity $(= R \cdot \omega)$ [m/s]
W	Relative velocity [m/s]
V	Absolute velocity [m/s]
C_p	Pressure coefficient $\left(= \frac{P_s - P_{s,inlet}}{\frac{1}{2}\rho(\omega R)^2}\right)$
C_{pt}	Total pressure coefficient $\left(= \frac{P_t - P_{t,inlet}}{\frac{1}{2}\rho(\omega R)^2}\right)$
Y	Loss coefficient $\left(= \frac{P_{t,inlet} - P_{t,outlet}}{\frac{1}{2}\rho(\omega R)^2}\right)$

Contents

Figures

Tables

1. Introduction

Fans are devices for moving air by rotating impeller using centrifugal or propeller actions. They are widely used in industry and domestic field for heating, ventilating, humidity control, cooling and refrigeration and air purification[1]. Pressure rise and flow rate through a fan tend to increase as the size of fan increases when the rotating speed is constant. However, there is a limitation due to product design and demands for downsizing. Gurney flap can be suggested to improve fan performance without increase of the product size.

Gurney flap, a small device attached to the trailing edge on the pressure surface of wing, was first used by Dan Gurney to increase downforce generated by rear wing of racing car. Gurney flap increases lift. Drag also increases with gurney flap but within proper height, it increases aerodynamic performance of wings by increasing lift-to-drag ratio. Since it is a simple and inexpensive way to get high lift, Gurney flap applied in car, helicopters and aircrafts' design. When this high-lift device, Gurney flap, is applied to rotating fan blade, it can be expected to improve the fan performance.

Li et al.[2, 3] and Wang et al.[4] investigated the effects of height, mounting angle and location of Gurney flap on airfoil. It is found that Gurney flap is effective in high lift coefficient region and increases the effective camber of the airfoil. The highest performance was achieved when the Gurney flap was applied at trailing edge, and optimal height exists. Giguère[5] found that, to improve lift-to-drag ratio, Gurney flap should submerged within the boundary layer at the trailing edge.

However, Studies of Gurney Flap on turbomachinery have conducted relatively recently and the explanation of the effect of Gurney flap on rotating machines is not sufficient. Janus[6] conducted numerical analysis with fan blades in two dimensional linear cascade model. Flow separation on suction surface decreased and pressure rise also increased with Gurney flap. Byerley et al.[7] and Chen et al.[8] applied Gurney flaps on turbine cascade. Byerley et al. found that Gurney flap delayed or eliminated laminar separation on suction surface by experiment. With Gurney flap, profile loss and exit velocity increased and flow turned toward the suction surface compared to clean blade. Chen et al. numerically found that Gurney flap weakened the adverse pressure gradient on the suction side and thins the separation bubble thickness. Transition onset was delayed with the Gurney flap. Myose et al.[9] conducted flow visualization study with Gurney flap in compressor cascade at low Re and showed that Gurney flap delayed the stall at large incoming flow angles. Greenblatt[10] and Dundi et al.[11] applied Gurney flap on rotating fans and study the effect of Gurney flap on rotating machines experimentally. Greenblatt[10] applied Gurney flap to rotating axial fan and studied about the effect of height and thickness of Gurney flap. All cases with Gurney flap produced higher non-dimensionalized pressure rise than baseline case in all flow rate range. Because addition of Gurney flap gave extra weight to fan blade, thin Gurney flap increased static efficiency most. Efficiency was lower at low Re but maximum efficiency increased with Gurney flaps. Greenblatt get 18% increase of static efficiency with 10% thin flap. Dundi et al.[11] investigated the effect of Gurney flap on radial fan with different Re. Efficiency increased with Gurney flap, dominantly at low Re and maximum flow rate slightly increased. In Jang[12]'s study, Gurney flap was applied to rotating radial fan and the effect of geometric parameters of Gurney flap was investigated systematically. Jang changed height and mounting angle of Gurney flap and found optimal shape of Gurney flap. Static pressure rise was increased with Gurney flap in all flow rate region and the maximum efficiency was also increased when h/c=5% and Θ=45°.

This research investigated the effect of Gurney flap on radial fan by numerical study based on Jang[12]'s work to explain the mechanisms how the Gurney flap increases pressure rise and efficiency of radial fan with detailed flow fields.

2. Numerical Analysis

2.1 Simulation Method

CFD study was conducted to explain the larger pressure rise and higher efficiency with Gurney flap. The same radial fan with Jang[12]'s experiment was used for CFD calculation. The specification of the target fan is listed on Table 1. One Gurney flap case was compared with reference fan without Gurney flap to figure out the effect of Gurney flap. Gurney flap with h/c=5%, θ=45°, which showed best

Table 1 Fan specification

Diameter	340 mm
Height	87.8 mm
Chord length(c)	130 mm
Number of blades	7
Thickness of blade	3 mm

efficiency in Jang[12]'s experiment, was applied maintaining constant diameter. Simplified circular fan housing replaced the original one to make the outlet uniform and eliminate the effect of relative location between blades and casing.

The commercial code, Ansys-CFX 13.0, was used. Steady-state calculation was conducted with k-ε turbulence model. The convergence criteria was set to 10^{-5}. Calculation domain was separated into three parts, inlet, fan, and outlet domains. Inlet and outlet domains were set as stationary and fan domain was set as rotational domain with 700 rpm. Mass flow rate measured in the experiment was used as inlet boundary condition. Opening condition with 1 atm was used for outlet boundary condition. Solid surfaces were set as no slip walls. Mixing plane method was used at the interfaces between rotating and stationary domains. The domain and boundary conditions are shown in Fig. 1.

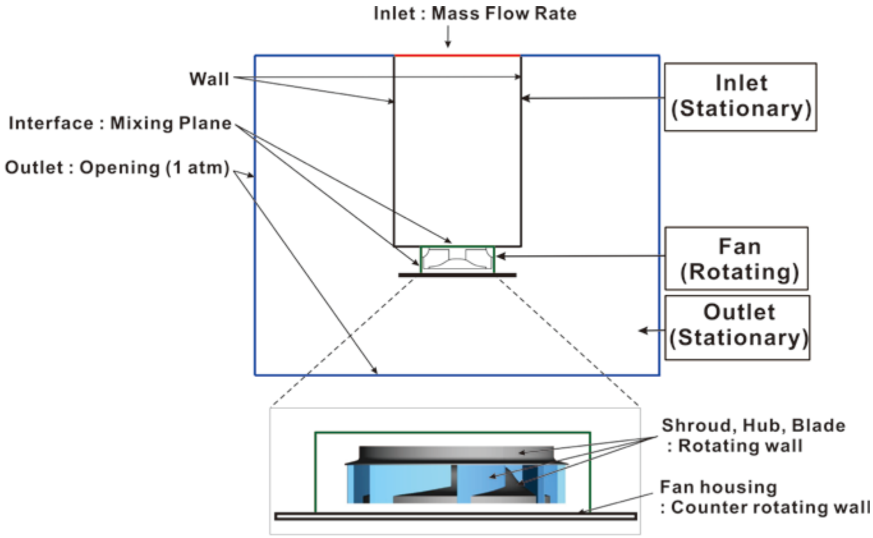

Fig. 1 Boundary conditions

Tetrahedral and prism mesh were generated using ICEM-CFD as shown in Fig. 2 and Fig. 3. Grids with y+ ~ 2 were generated at all surfaced in fan domain and y+<30 overall. Figure 4 shows the result of grid independence check. Grid independence check was conducted using the values of torque acting on blades with four different meshes. Proportion of grids in each domain was maintained in each case. 14.5 million elements were used. About 60 percent of total grids were placed in the fan domain to see the flow field inside the radial fan.

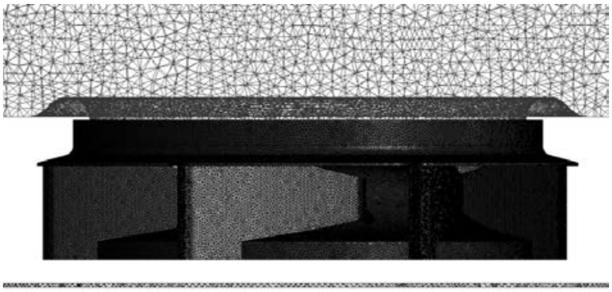

Fig. 2 Grid generation

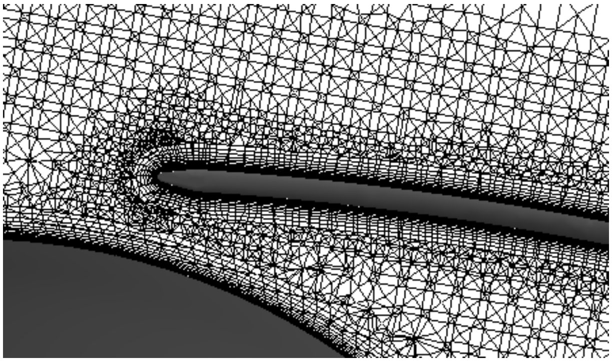

Fig. 3 Prism meshing near wall

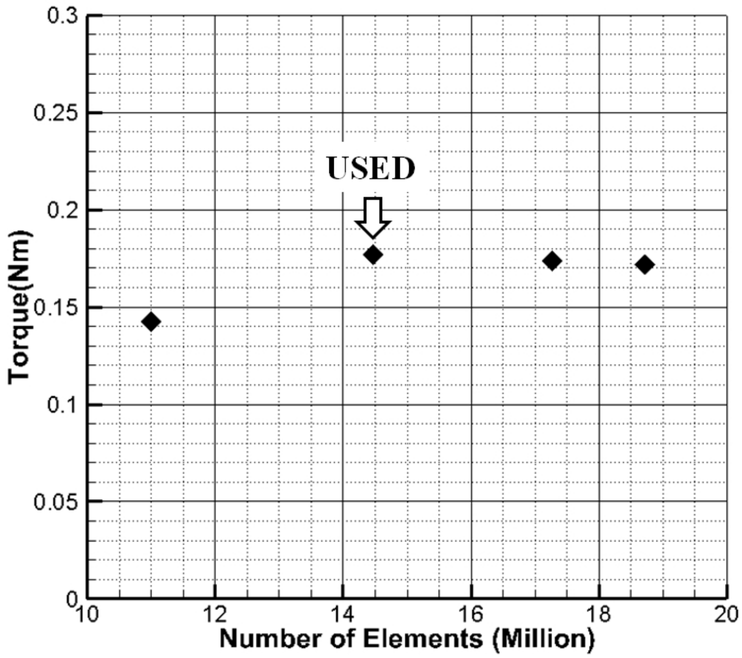

Fig. 4 Grid independence

2.2 CFD Validation

CFD results were validated with experimental data from Jang's experiment. Figure 5 shows ϕ-ψ curves normalized by the experimental values at design point. In results of reference case, CFD results were under-predicted but the trend matched well with the experiment. And the difference between the reference and Gurney flap cases at design point was similar in both CFD and experiment.

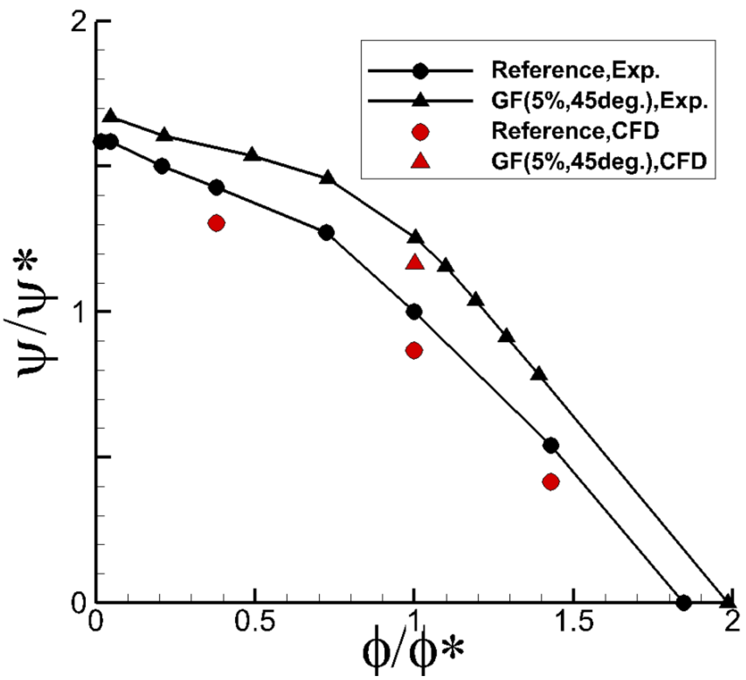

Fig. 5 CFD validation

3. Results

3.1 Flow field in the passage

Change of pressure through a fan can be explained using Euler turbine equation. Using the absolute, relative, and rotating velocities at the inlet and exit of blade, the equation can be expressed as following.

$$\Delta P_t = \rho\left(\frac{U_2{}^2 - U_1{}^2}{2} - \frac{W_2{}^2 - W_1{}^2}{2} + \frac{V_2{}^2 - V_1{}^2}{2}\right)$$

The pressure rise from the first term, which is from radius change, is centrifugal effect and the second term is diffusion in relative frame. The third term is change in absolute kinetic energy. Among these, first two terms determine static pressure change. Centrifugal effect did not change in reference and Gurney flap cases because the fan size is constant. So, the second term, which is related to diffusion, can change the static pressure rise. Static pressure rise and relative velocity distribution in the passage were checked to see how flow changed passing through the blade passage and the results are in Fig. 6 and

Fig. 7. In Fig. 6, planes were drawn at 60%, 70%, 80%, 90% and 100% of the fan diameter from the center. Static pressure rise was similar up to plane 3. From plane 3 to 5, more static pressure rise was obtained with Gurney flap especially on the pressure side. In Fig. 7, relative velocity distribution was also similar up to plane 3. From plane 3 to 5, flow is accelerated on PS in reference case. However, flow decelerates in Gurney flap case from plane 3 to 4, which is the upstream of Gurney flap. The large static pressure rise on the pressure side can be explained by stagnation effect due to the flap. Comparing plane 3 to 5, overall relative velocity was also smaller with GF resulting in higher static pressure rise in the rear part of the passage.

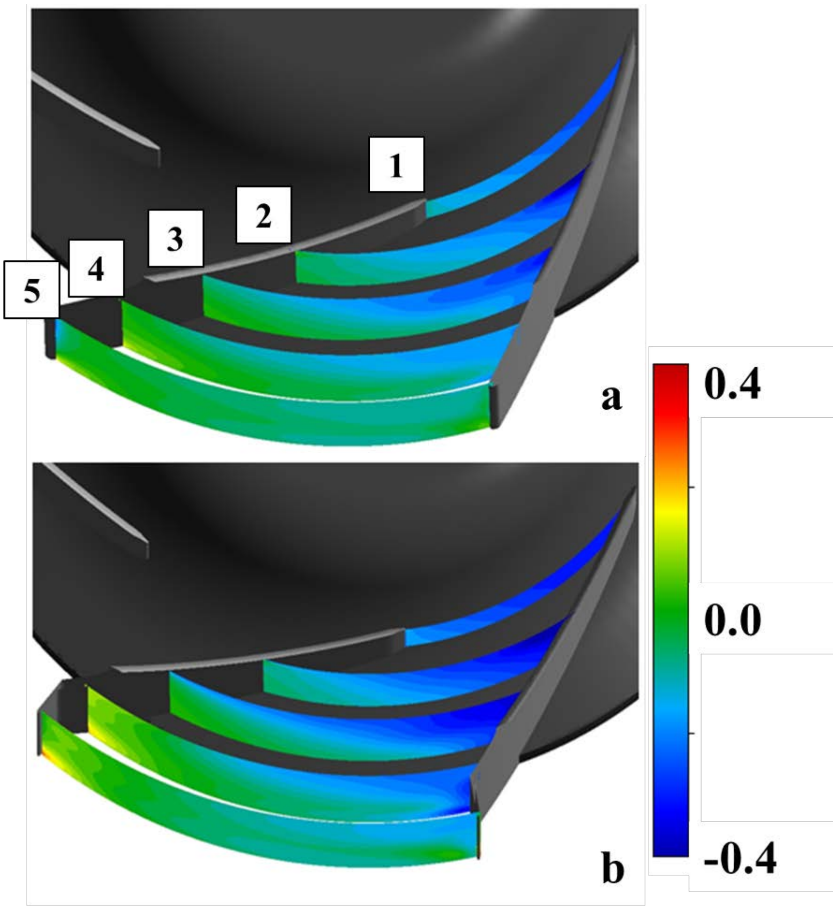

Fig. 6 Cp distribution in the blade passage

a) Reference, b) Gurney flap case

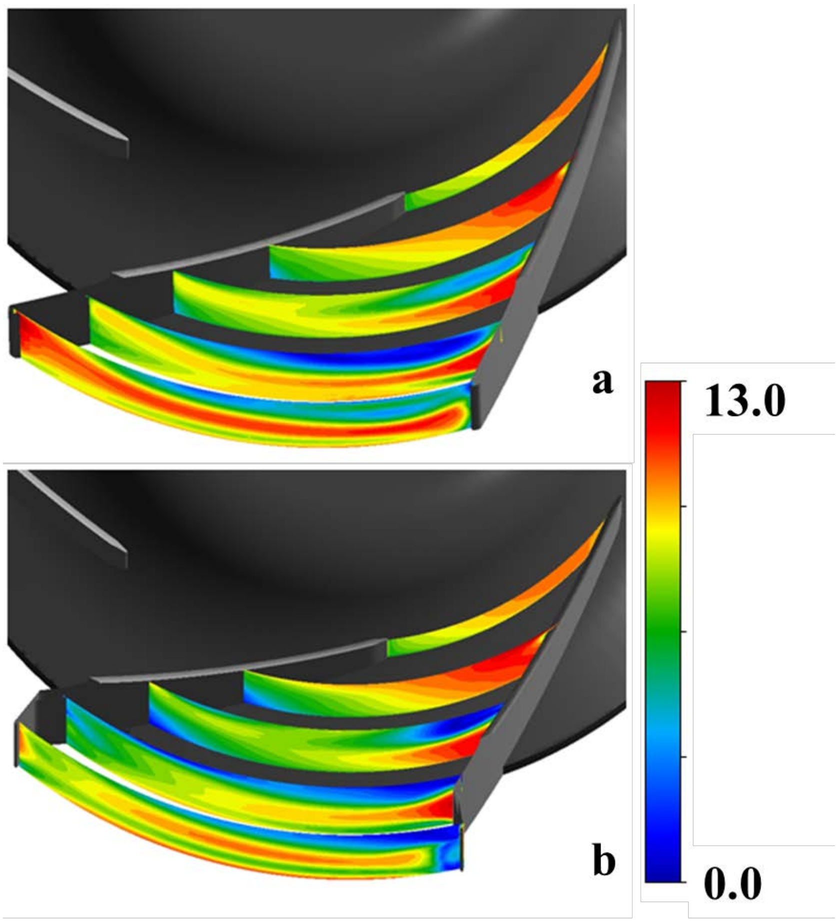

Fig. 7 Relative velocity distribution in the blade passage

a) Reference, b) Gurney flap case

3.2 Flow Deflection

Figure 8 and 9 show streamlines around the blade trailing edge in reference and Gurney flap cases at the locations of 40, 50, and 60% of span. The flow angle was changed with Gurney flap at the exit of fan compared to reference case. The loading of blade increased with Gurney flap as shown in Fig. 10. In reference case at the blade trailing edge, the pressure difference between pressure side and suction side went to zero gradually, therefore flow was not able to follow the blade angle near trailing edge and deviated in the opposite direction of rotation. However, with the Gurney flap, the pressure difference between pressure side and suction side was larger than reference case even at the trailing edge, so the larger force acted from pressure side to suction side near trailing edge and deviation decreased with Gurney flap. This change was shown most clearly at 60% of span(Fig. 8c and 9c), which was close to shroud. In Fig. 8c, flow lost momentum near shroud on suction surface and deflected a lot at the exit of fan. However the amount of deflection at the same location decreased with Gurney flap in Fig. 9c. It can be concluded that the change of flow angle with Gurney flap was caused by flap angle and the larger pressure gradient across the passage. Considering that the radial component of velocity at the exit of fan was similar in both cases, the change of the flow angle affected tangential component of the relative velocity, resulting in smaller relative velocity at the exit of the fan with Gurney flap. CFD results in Fig. 11 and 12 show these changes in relative velocity. Overall tangential component of relative velocity decreased with Gurney flap while the radial velocity didn't change much.

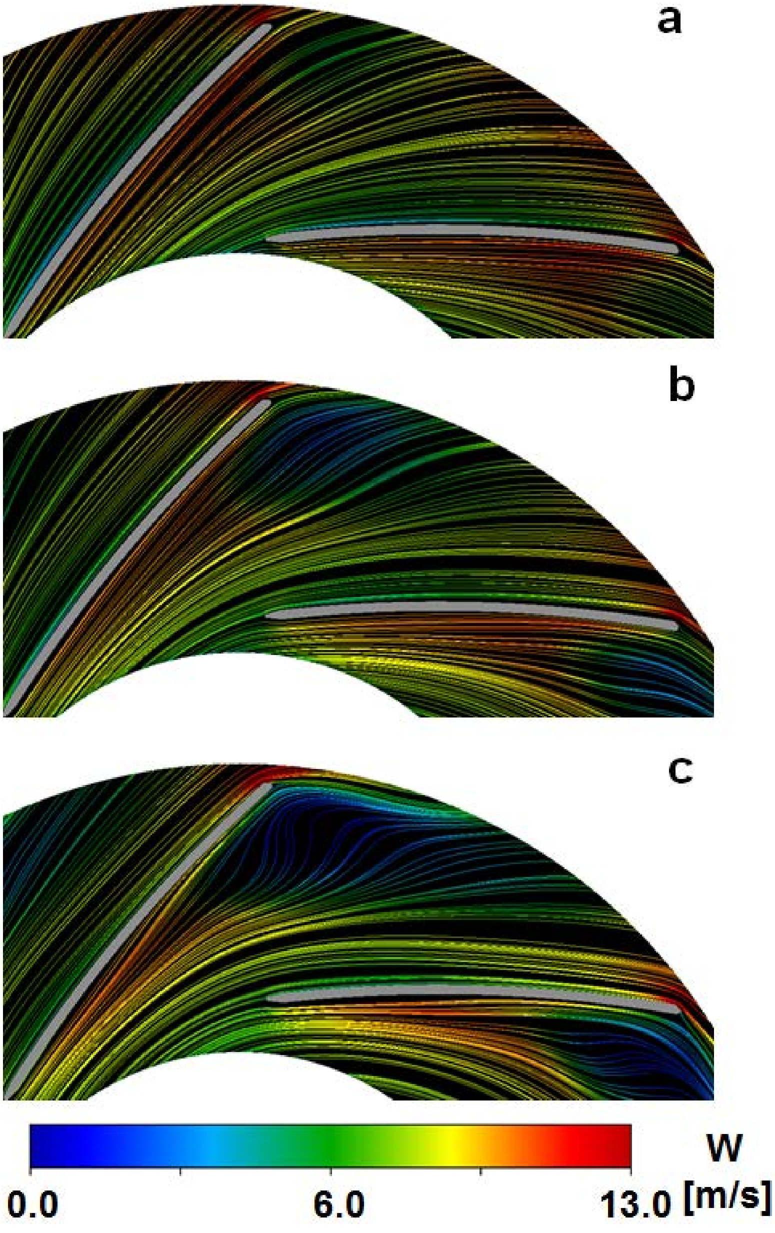

Fig. 8 2D streamlines in reference fan

a) 40% span, b) 50% span, c) 60% span

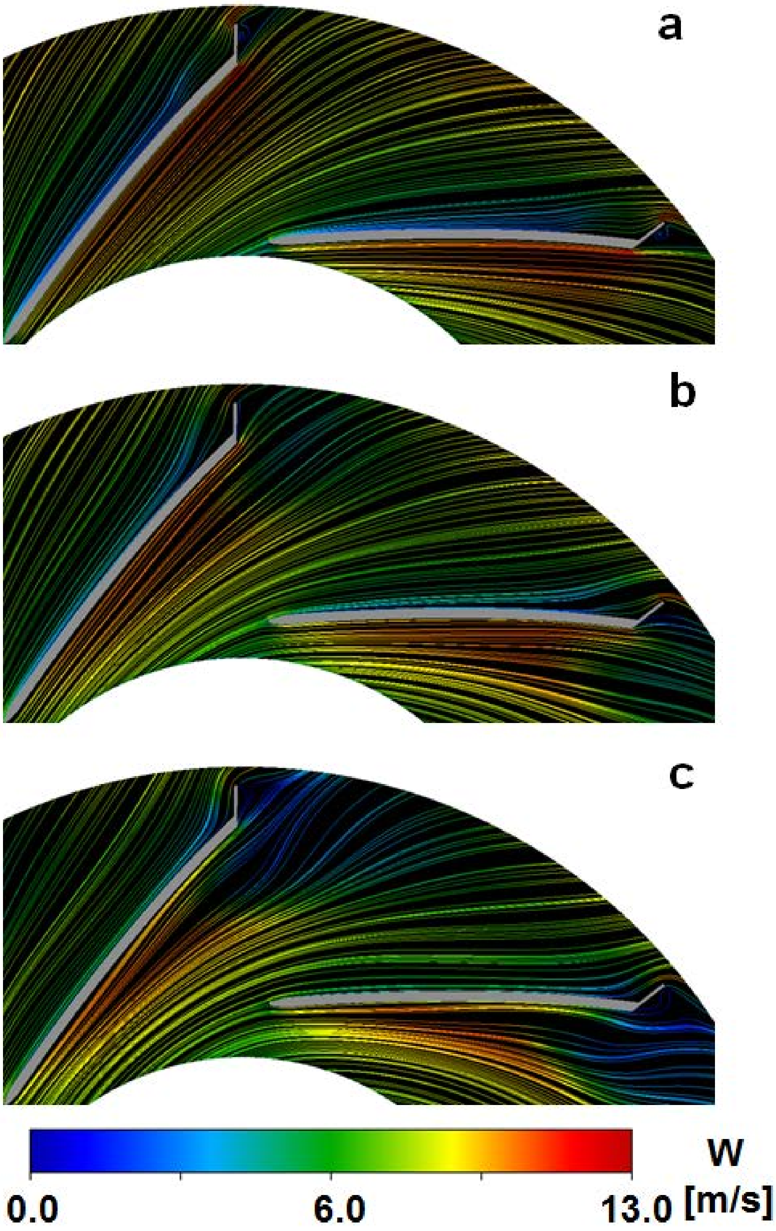

Fig. 9 2D streamlines in Gurney flap fan

a) 40% span, b) 50% span, c) 60% span

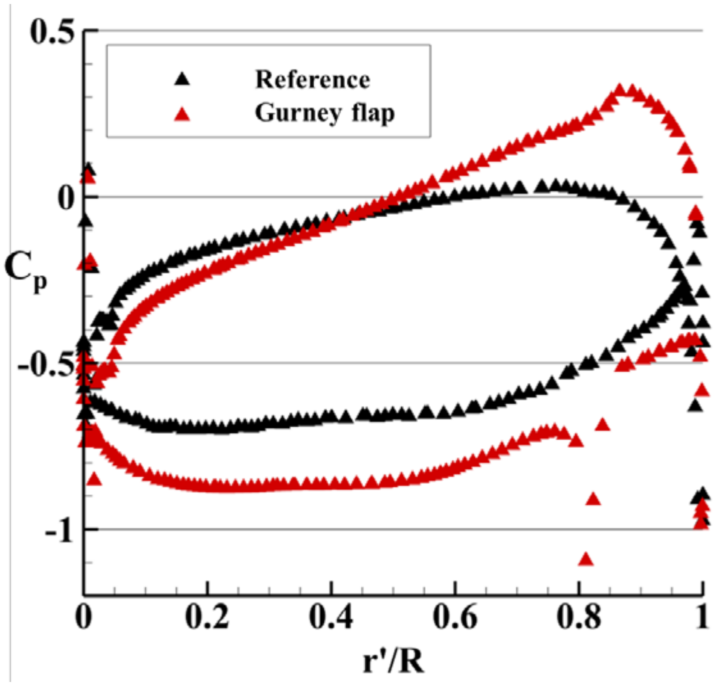

Fig. 10 Blade loading at 50% span

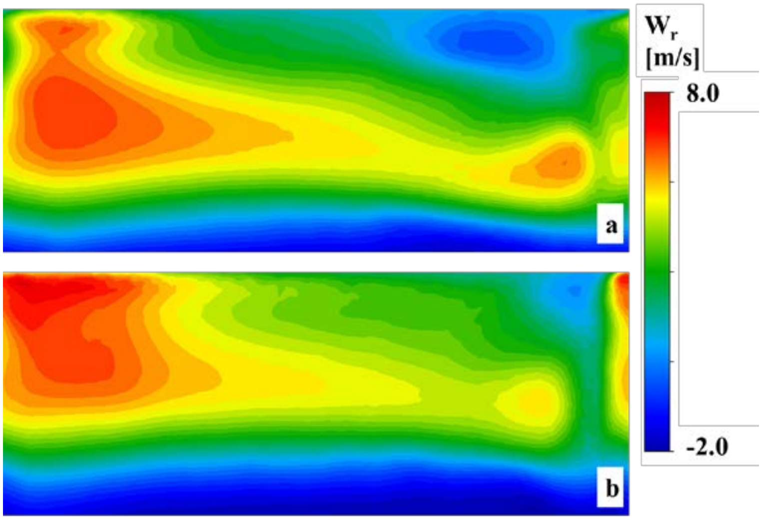

Fig. 11 Radial component of relative velocity at the exit of fan

a)Reference, b)Gurney flap case

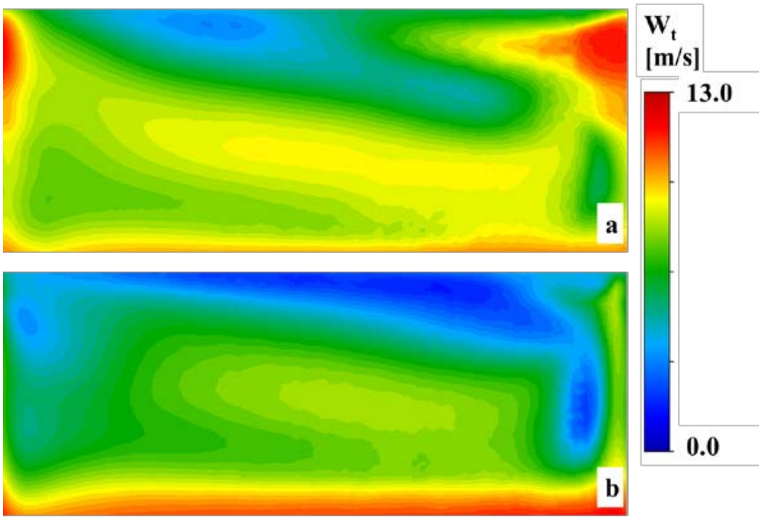

Fig. 12 Tangential component of relative velocity at the exit of fan

a)Reference, b)Gurney flap case

The values of three terms in Euler turbine equation were calculated using the mass averaged velocity to see the contribution of each component quantitatively. Table 2 shows the difference between the results from Gurney flap and reference cases with non-dimensionalized values. Centrifual effect was the same in both cases, the difference in first term was zero. As expected, more static pressure rise was obtained by more diffusion with Gurney flap. Compared to the difference of static pressure coefficient from experiment, the sum of first and second terms is similar but larger because diffusion process contains loss. More kinetic energy change was also obtained with Gurney flap so that more pressure rise would be converted in the diffuser.

Table 2 Pressure rise from different velocity components

<table>
<tr><td rowspan="2"></td><td colspan="2">(Gurney flap) – (Reference)</td></tr>
<tr><td>CFD</td><td>Experiment[1]</td></tr>
<tr><td>$\left[1-\left(\frac{U_1}{U_2}\right)^2\right]$</td><td>0</td><td rowspan="2">0.121</td></tr>
<tr><td>$-\left[\left(\frac{W_2}{U_2}\right)^2-\left(\frac{W_1}{U_2}\right)^2\right]$</td><td>0.161</td></tr>
<tr><td>$\left[\left(\frac{V_2}{U_2}\right)^2-\left(\frac{V_1}{U_2}\right)^2\right]$</td><td>0.193</td><td>-</td></tr>
</table>

3.3 Loss

Gurney flap increased the amount of pressure rise generated by diffusion as explained. The centrifugal effect, which refers to the first term in the equation above, is free from loss. However, losses are included in the deceleration process and the pressure rise generated from the flow deceleration is less than that from ideal process[13]. Therefore, it might be considered that the loss in the case with

[1] * From Jang[12]'s experimental data

Gurney flap would increase because the amount of pressure rise through diffusion process was larger in Gurney flap case. Loss coefficient calculated at the exit of the fan with Gurney flap was slightly lower than the reference case but the difference between two cases were not significant. Figure 13 shows the total pressure coefficient calculated based on total pressure in rotating frame at inlet, outlet and the five radial locations shown in Fig. 6 (Plane 1 to 5). The difference of total pressure between the adjacent planes is plotted in Fig. 14. Total pressure in the rotating frame changed in streamwise direction. Near the leading edge, from plane 1 to 2, the change of C_{pt} was almost the same in reference and Gurney flap cases. In the mid-chord region, C_{pt} decreased more with Gurney flap because the diffusion process generated loss. Near trailing edge region, at plane 4, C_{pt} decreased much in reference case. In Fig. 15, streamlines near trailing edge showed that separation occurred near shroud on the suction side in reference case. However it was supressed with Gurney flap. C_{pt} decreased more with Gurney flap at the downstream of the flap and this can be explained by the larger wake due to the flap. In other words, compared to reference case, Gurney flap increased loss by larger diffusion and larger wake behind the flap, but it eliminated or suppressed separation near trailing edge and near shroud region and resulted in similar total pressure change with reference case. Loss coefficient calculated at the exit of fan was slightly larger with Gurney flap, however, compared to increase of loss with Gurney flap, increase of static pressure rise was larger. Therefore, efficiency can be improved with Gurney flap.

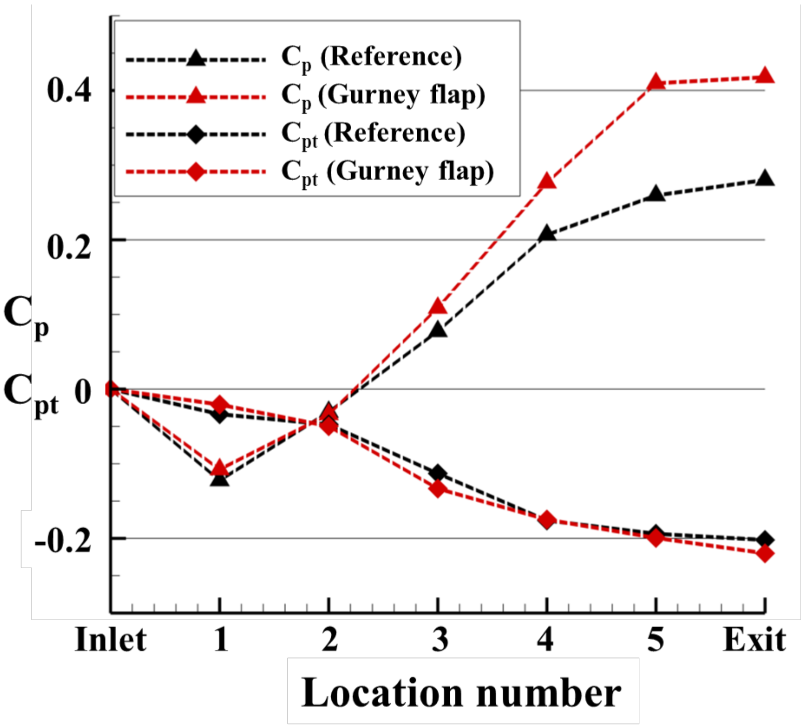

Fig. 13 Pressure coefficient change along the stream

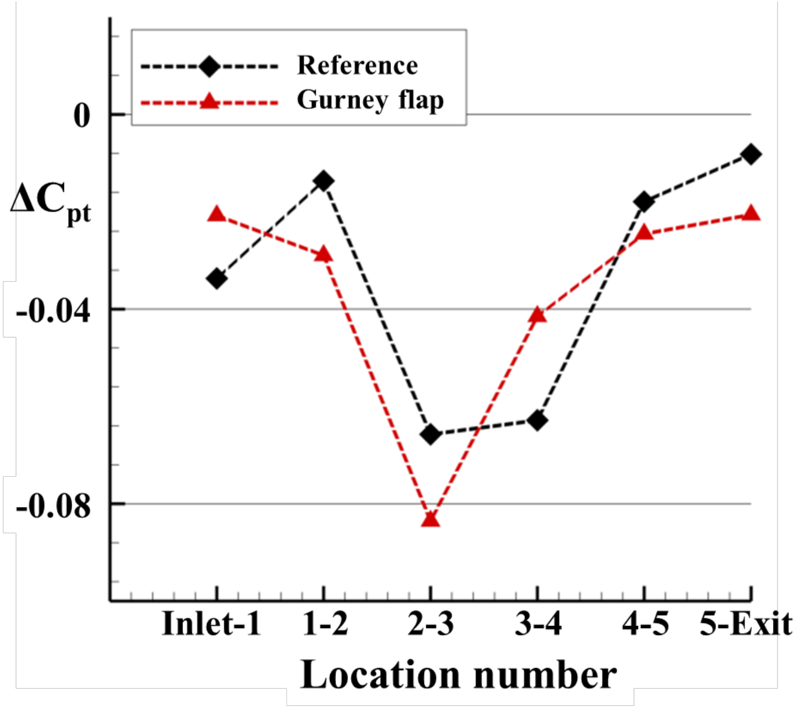

Fig. 14 Difference of total pressure coefficient

between the adjacent planes

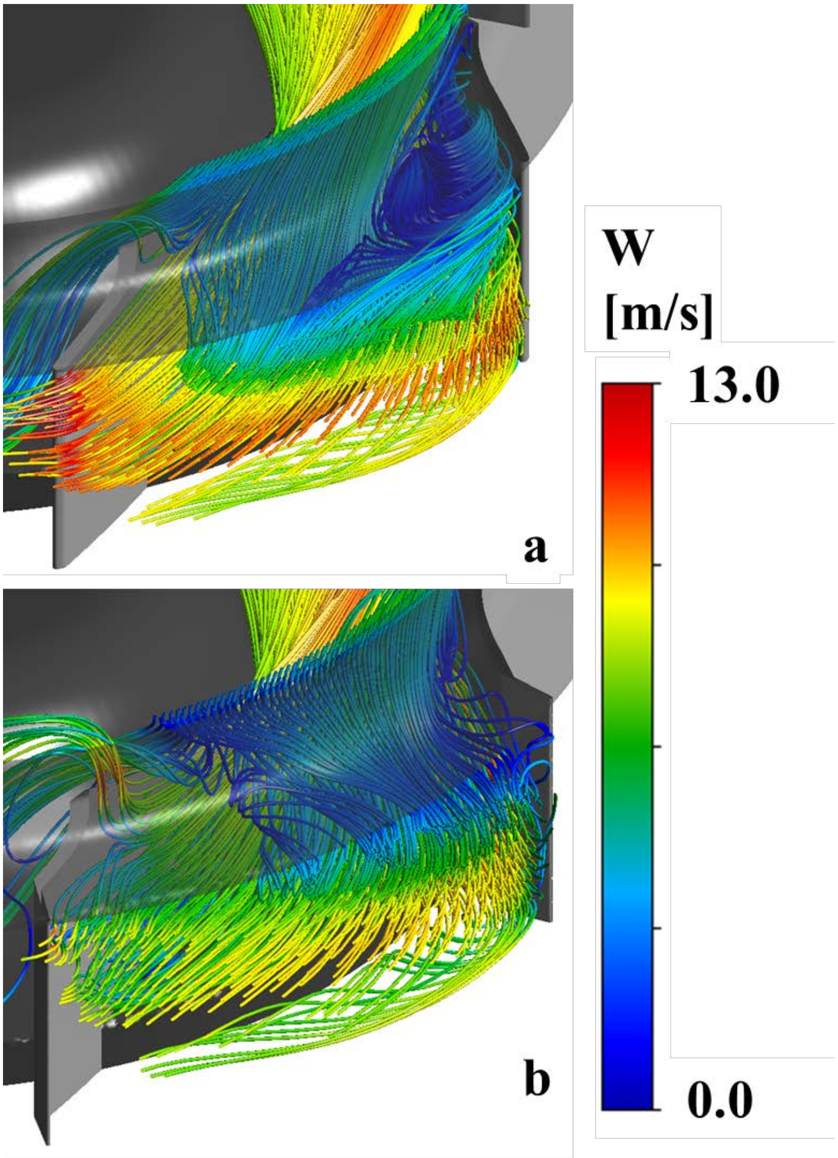

Fig. 15 Streamlines near trailing edge

a)Reference, b)Gurney flap case

4. Conclusions

1. This research investigated the Gurney flap on radial fan blade and explained the mechanisms how Gurney flap increased static pressure rise and efficiency of the radial fan by numerical study.

2. Blade loading increased with Gurney flap and flow angle decreased with Gurney flap due to the flap angle and the force driven by the pressure gradient across the passage.

3. With Gurney flap, diffusion increased resulting in more static pressure rise through the radial fan due to the stagnation effect of the Gurney flap and change of flow angle

4. Overall loss was not much different between reference and Gurney flap cases. Even though Gurney flap increased loss with larger diffusion and larger wake, it reduced separation near trailing edge region which occurred in reference case.

5. Gurney flap enlarged the static pressure rise through the fan with a given input and was able to increase static efficiency.

References

1. Jorgensen, R., *Fan Engineering: An Engineer's Handbook*. 1970: Buffalo Forge Company.

2. Li, Y.C., J.J. Wang, and P.F. Zhang, *Influences of mounting angles and locations on the effects of Gurney flaps*. Journal of Aircraft, 2003. **40**(3): p. 494-498.

3. Li, Y.C., J.J. Wang, and P.F. Zhang, *Effects of Gurney flaps on a NACA0012 airfoil*. Flow Turbulence and Combustion, 2002. **68**(1): p. 27-39.

4. Wang, J.J., Y.C. Li, and K.S. Choi, *Gurney flap-lift enhancement, mechanisms and applications*. Progress in Aerospace Sciences, 2008. **44**(1): p. 22-47.

5. Giguere, P., et al., *Gurney flap scaling for optimum lift-to-drag ratio*. AIAA journal, 1997. **35**(12): p. 1888-1890.

6. Janus, J., *Analysis of industrial fan designs with Gurney flaps*. AIAA paper,

2000. **983**.

7. Byerley, A.R., et al., *Using Gurney flaps to control laminar separation on linear cascade blades.* Journal of Turbomachinery-Transactions of the Asme, 2003. **125**(1): p. 114-120.

8. Chen, P.-P., W.-Y. Qiao, and H.-L. Luo. *Investigation of Low Solidity LP Turbine Cascade With Flow Control: Part 2—Passive Flow Control Using Gurney-Flap*. in *ASME Turbo Expo 2010: Power for Land, Sea, and Air*. 2010. American Society of Mechanical Engineers.

9. Myose, R.Y., et al., *Flow Visualization Study on the Effect of a Gurney Flap in a Low Reynolds Number Compressor Cascade.* AIAA Paper, 2006. **7809**.

10. Greenblatt, D., *Application of Large Gurney Flaps on Low Reynolds Number Fan Blades.* Journal of Fluids Engineering-Transactions of the Asme, 2011. **133**(2).

11. Dundi, T.M.K., N. Sitaram, and M. Suresh, *Application of Gurney Flaps on*

a Centrifugal Fan Impeller. International Journal of Fluid Machinery and Systems, 2012. **5**(2): p. 65-71.

12. Jang, S.M., *Impact of Gurney Flap on Radial Fan Performance*. 2012, Seoul National University Graduate School: Seoul.

13. Cumpsty, N.A., *Compressor aerodynamics*. 2004, Malabar, Fla.: Krieger Pub.

요약(국문초록)

거니플랩이 원심팬의 공력성능에 미치는 영향

본 연구는 거니플랩이 회전하는 원심팬의 공력성능에 미치는 영향을 확인하고 그 메커니즘을 설명하였다. 에어컨용 후곡형 원심팬에 대하여 수치해석을 수행하였으며 수치해석 결과는 실험을 통해 검증되었다. 거니플랩은 유동각을 변화시키고 팬 입출구의 상대속도 변화를 크게 하여 팬 내부 유동의 확산을 증가시키며, 이를 통해 팬의 정압 상승량을 증가시킨다. 거니플랩을 적용하였을 때 전압 손실은 기본팬에 비해 커지나 정압 상승 증가에 비해 손실 증가량은 크지 않다. 거니플랩은 전압 효율과 팬 성능 향상에 기여할 수 있다.

···

주요어 : 거니플랩, 원심팬, 정압상승, 손실, 효율

학 번 : 2012-23156