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AN INVESTIGATION ON HVLS FAN PERFORMANCE WITH DIFFERENT BLADE CONFIGURATIONS

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날개 형상에 따른 HVLS의 성능에 관한 연구

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High-volume low-speed (HVLS) fans are one category of ceiling fan installed in large enclosings such as warehouses, large barns and health clubs in order to generate comfortable air circulation. As a rotary blade, aerodynamic performance of a HVLS fan is predominantly related to its airfoil(s), and the pitch and twist angles. This paper first, investigates the effects of airfoil on the performances of three different HVLS fans with NACA 5414, 6413 and 7415 airfoils. The fans have six untwisted blades with the diameter of 6 m and rotate at 60 RPM. The blades pitch angels are 12°, 12° and 13°, respectively. The results are presented in the form of the aerodynamic forces and moments, volumetric flow rate and streamlines. Regarding the volumetric flow of air, the results show that the model with NACA 7415 has the best performance. Hence, two other HVLS fans with the same airfoil but, with four and five blades are studied in order to investigate the effects of number of blades. From the point of view of air circulation still the six-bladed fan is the best one; however, the five-bladed fan is more efficient in power consumption.

Key Words : High-volume low-speed fan, Pitch angle, Volumetric air flow, k-ε turbulence model

1. Introduction

High-volume low-speed fans (HVLS) are rather new solutions for generating a silent, comfortable gentle air circulation in large enclosing such as warehouses, large barns and health clubs. Unlike residential ceiling fans that are typically 0.9 m to 1.3 m in diameter, the diameter of HVLS fans are between 2.5 ~ 7.5 m. Also, in spite of normal ceiling fans, HVLS fans rotate very slowly in the range of 45 ~ 80 RPM. Technically speaking, HVLS fans must satisfy the two requirements as[1]:

(a) The volumetric air flow through the blade disc during a single revolution must be no less than 14 cubic meters;
(b) The blade tip speed of a HVLS fan must not be greater than 27 m/s.

The main benefits of HVLS fans are their capability to be used in both summer and winter together with the heating, ventilation and air conditioning; their low noise and gentle air flow and also the average energy savings of 49 percent plus consequent reductions in the generation of CO_2 and carbon[2-3].

Since parametric investigation of a HVLS fan is highly expensive and to some extent impossible, the CFD has employed as a reliable functional gadget. Hence, many

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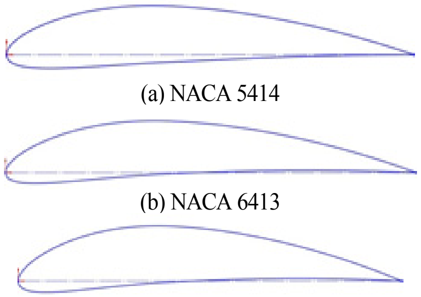


(a) NACA 5414

(b) NACA 6413

(c) NACA 7415

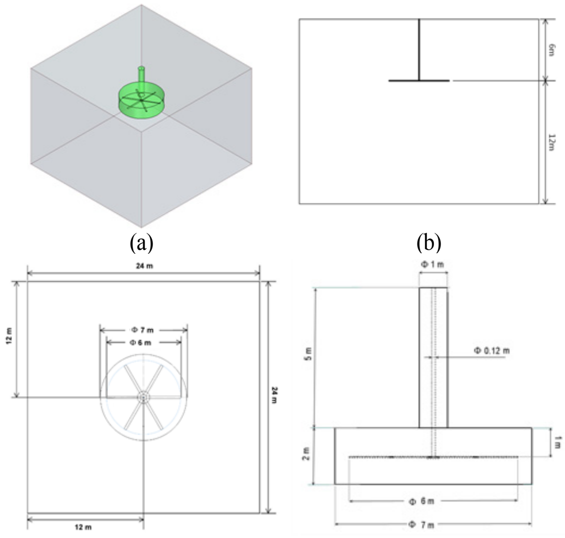
Fig. 1 Geometry of the airfoils

studies have been conducted on the inquiry of HVLS fans' performance inside enclosing. Momoi et al.[4] examine the utilization a ceiling fan for airflow control in a large air-conditioned room. The research presents the measured airflow pattern around a ceiling fan and compares it with the CFD simulation results and concludes that the CFD result are in good agreement with the measurement result concerning the average of air velocity. In another study, Forrest and Owen[5] have investigated a product MegaFan company and also NACA 0012 in order to model the airflow and heat transfer in a heated warehouse building to investigate the levels of de-stratification offered by HVLS fans. Despite the majority of the research works which are based on CFD, some filed measurements are also available[6-7].

The research presented here is one part of a comprehensive industrial HVLS fan project proposed by Korea Railroad Research Industry (KRRI), which is carried out at CFD-ERC at Sogang University. The final goal for this literature is to investigate the best case among three models with the NACA 5414, 6413 and 7415 airfoils with the pitch angles of 12^o, 12^o and 13^o, respectively. Also it studies the effects of different number of blades. All of the CFD simulations have been carried out using steady-state assumption with multiple reference frame (MRF) technique using Realizable k-ε turbulence model in STAR-CCM+ Version 8.04.

2. Turbulence model

For an acceptable CFD simulation, a proper turbulence model plays an important role. A good choice of turbulence model can result in an agreeable simulation, while an inappropriate one misleads to waste of time, energy and wrong results. If the blades were highly twisted with different local pitch angles, the SST-k-ω



(a) (b)

(c) (d)

Fig. 2 Domain shape and the location of the fan

would be required[8]. However, because of the simplicity of the present blades with untwisted configurations and as it is recommended in many references[5-6,9], a k-ε[10] (or a k-ε-based) turbulence model can be considered as an appropriate model for the present HVLS fan simulations.

The Realizable k-ε model[11] which is adopted in the present paper is a relatively recent development and differs from the standard model in two important ways: (a) The model contains a new formulation for the turbulent viscosity; (b) A new transport equation for the dissipation rate, ε, has been derived from an exact equation for the transport of the mean-square vorticity fluctuation. For the wall treatment in the Realizable k-ε model there is an options which is called "all-wall treatment". This option is a hybrid treatment that is suitable for both coarse and fine meshes[12]. In present research this option is used for the simulations.

3. Geometrical of the model

The NACA 5414, 6413 and 7415 airfoils used in the present study are shown in Fig. 1(a)-(c). The HVLS fans' diameters are Φ = 6 m, with a constant chord length of 20 cm. In addition, the size of the enclosing is assumed to be 24 m x 24 m with the height of 18 m. In order to use the MRF technique, an inner axi-symetric domain with ╩ section is created. The details of the domain dimensions are shown in Fig. 2.

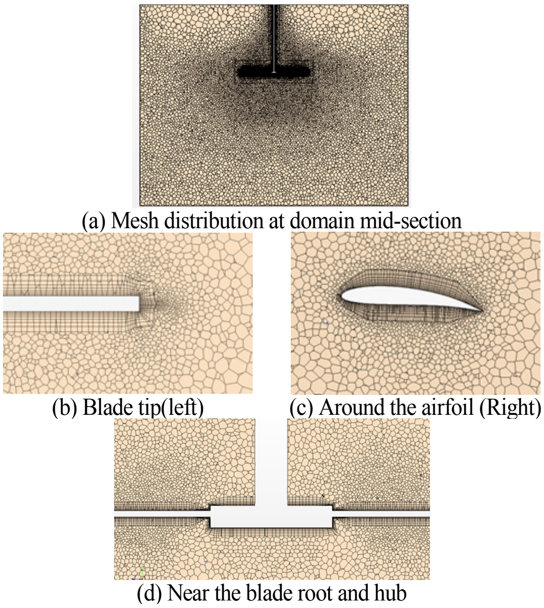


Fig. 3 Mesh system generated by the setting listed in Table 1, 2

4. Mesh resolution and CFD settings

The two-sub-domain configuration (Fig. 2(a)) also can help us to put more cells inside the inner domain. Table 1, 2 present the details of mesh resolution for the inner and outer domains, respectively. The mesh is polyhedral mesh with 8 prism layers at the blade surface. Fig. 3 shows the mesh arrangement at different locations. By applying the mesh setting of Table 1, 2, total number of cells in the inner and outer domains are 4.1 and 1.1 million, respectively.

Table 1 Details of mesh information for inner domain

Model	No. of prism layer/Factor /Total thickness(mm)	Min size (mm)	Max size (mm)	Surface growth rate
Blade	8/1.3/ 30	5	10	1.3
Hub	8/1.3/30	8	15	1.3
Tip	8/1.3/30	0.5	1.5	1.3
Shaft	-	20	100	1.3
Top surface (at ceiling)	-	40	120	1.3

Table 2 Details of mesh information for outer domain

Model	No. of prism layer/Factor /Total thickness(mm)	Min size (mm)	Max size (mm)	Surface growth rate
Floor	-	60	250	1.3
Side walls	-	60	250	1.3
Ceiling	-	100	500	1.3
Interface around rotor	-	30	100	1.3
Interface around shaft	-	20	80	1.3

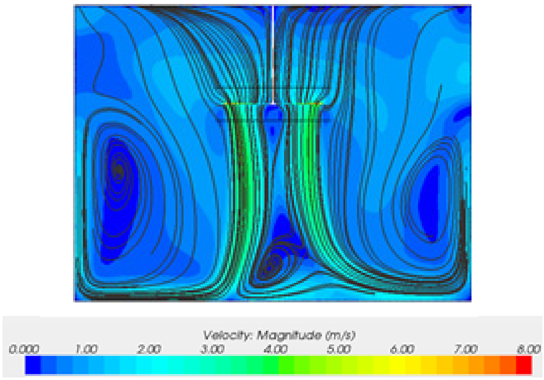


Fig. 4 Velocity magnitude and streamlines for the case with NACA 7415_AOA 13°

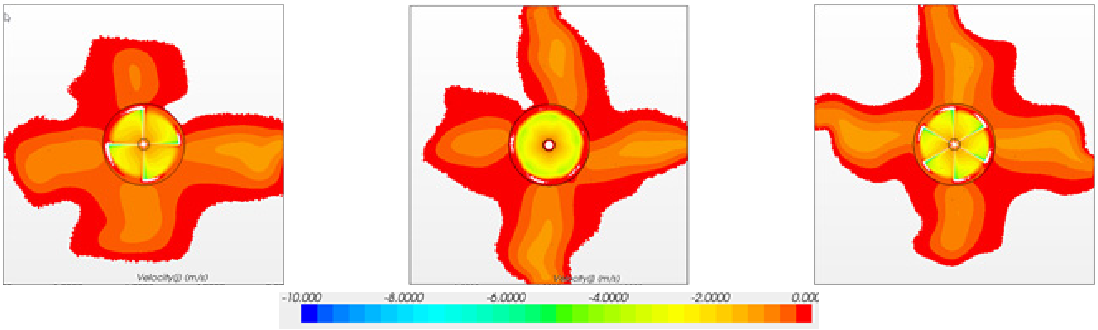
Since the Realizable k-ε model is adopted, the y+ value could be in the order of 100 and a coarse mesh also can result in an acceptable value. As mentioned earlier, the “all-wall treatment” option has been chosen, which ensures us about the accuracy of the results. Generally, because the system is rotary blades, numerical convergence is slow and it may need small value of under-relaxation factor or small timescale[8]. To assure the accuracy of the results, in addition to the residual values, the convergence of lift value over the blades has been also monitored as an additional convergence criterion.

5. Results and conclusions

Generally, there are several industrial parameters for the evaluation of, or comparison between, HVLS fans. From the point of view of the air circulation, the volumetric flow rate in a single blade revolution and the air speed value at some specific locations are usually considered as the industrially accepted factors for the HVLS fans performance. In addition, the aerodynamic loads are commonly studied as crucial factors for mechanical designing. In this section, these parameters are presented and compared for the different cases which are studied in the present research.

5.1 Comparison between cases with different airfoils

In this part, the results of the three models with NACA 5414, NACA 6413, NACA 7415 are listed in



(a) (b) (c)

Fig. 5 Downward velocity and the magnitude for the fan with four, five and six blades

Table 3. As the results of the volumetric flow rate (Q) show, the fan with the NACA 7415 generates the highest volumetric flow rate. However, from the aerodynamic point of view the blades of this HVLS fan undergo higher lift and torque values, and, hence, the HVLS fan with NACA 7415 needs more electrical power to be operated. In addition, the streamlines and the velocity contour of this case are presented in Fig. 4, which show that the area below the rotor and also the area close to the wall (~ 3 m) have high air recirculation.

Another criterion for the performance evaluation of HVLS fans is the effective area served by the fan in an empty enclosing (unobstructed space). As the protocols of HVLS fan suggest[12], the velocity of the generated air flow has to be measured at the heights of 100 mm, 1100 mm and 1700 mm above the floor surface. Table 4 presents the average of air velocity at the forementioned heights for all cases, in which the superiority of the case with NACA 7415 can be observed.

Industrially, it is important to design a product with an acceptable performance. Hence, a comparison between the nominal power required for NACA 7415_13° with three industrial fans is presented in Table 5, which shows the acceptable performance of the present model.

Table 3 Comparison between performances of the HVLS fans with different airfoils

Airfoil_Pitch angle	Lift(N)	Torque(N·m)	Q(m^3/s)
NACA 5414_12°	163.7	80.0	149.2
NACA 6413_12°	174.5	90.2	164.2
NACA 7415_13°	200.6	104.8	174.3

Table 4 Air velocities generated by different HVLS fans at different heights above the floor

Airfoil_Pitch angle	100 mm	1100 mm	1700 mm
NACA 5414_ 12°	1.49(m/s)	1.00(m/s)	0.78(m/s)
NACA 6413_ 12°	1.55(m/s)	1.06(m/s)	0.80(m/s)
NACA 7415_ 13°	1.75(m/s)	1.15(m/s)	0.86(m/s)

5.2 Effects of number of blades

As shown in the previous section, the HVLS fan based on NACA 7415 airfoil generates the highest volumetric flow rate and also the fastest air circulation. To investigate the effects of number of blades, here, three models of this HVLS with four, five and six blades are compared.

First, the areas with downward flow are shown in Fig. 5(a)-(c). The figures clearly show that with an increase in number of the blades the downward area becomes wider. This results in a higher Q for the six-bladed model as presented in Table 6. However, it is notable that Table 6 also shows that from the point of view of energy, the five-bladed HVLS fan requires the minimum aerodynamic torque for generating one unit of volumetric flow rate,

Table 5 Comparison between the generated volumetric flow rate and the required power for different HVLS fans

HVLS fan	Diameter (m)	Speed (RPM)	Q (m^3/s)	Power (kW)
ProTav_5500	5.5	50-60	135.0	2.2
ProTav_6500	6.5	50-60	89.7	2.2
GFAN61	6.1	67	137.8	1.5
NACA 7415_13°	6.0	60	174.3	1.3

Table 6 Comparison between performances of the HVLS fans with NACA 7415_AOA 13° with different number of blades

Number of blades	Lift (N)	Torque (N·m)	Q (m^3/s)	Q/Torque
4	155	88	153.4	1.74
5	174.5	89	167.7	1.88
6	200.6	104.8	174.3	1.66

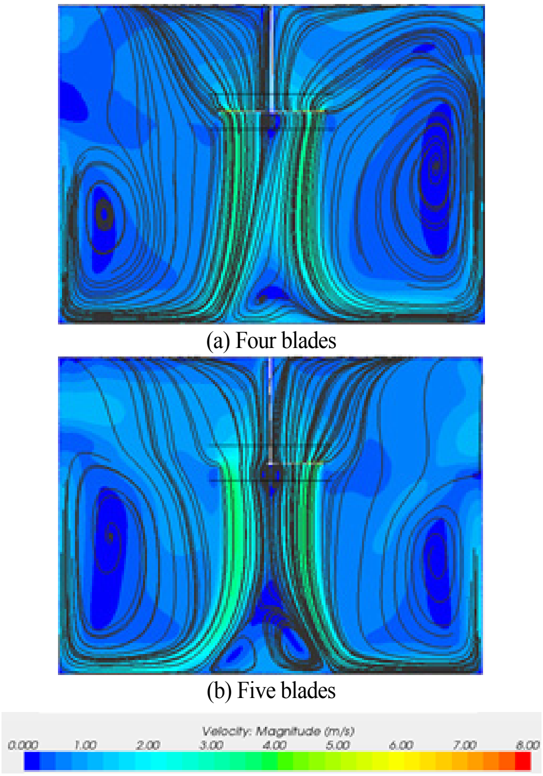


Fig. 6 Velocity magnitude and streamlines for the HVLS fans with different number of blades

which is a factor for optimum energy consumption.

In addition, it is noteworthy to mention another importance of the blade pitch angle and airfoil by comparing the result of five-bladed model of Table 6, 7 with the NACA 6413_12^o model in Table 3, 4. As the results demonstrate, the two HVLS fans, one with five and the other with six blades, behave very similar to each other. Consequently, this means that with an optimum design, one can considerably lighten the total weight of a HVLS fan. Furthermore, the streamlines and velocity magnitudes are presented in Fig. 6(a),(b). Similar to the Fig. 4, here also the recirculation areas exist below the fan disc and near the side walls.

Table 7 Air velocities generated by NACA 7415_AOA 13^o with different number of blades at different heights above the floor surface

Number of Blades	100 mm	1100 mm	1700 mm
4	1.49(m/s)	1.00(m/s)	0.74(m/s)
5	1.58(m/s)	1.07(m/s)	0.83(m/s)
6	1.75(m/s)	1.15(m/s)	0.86(m/s)

6. Concluding remarks

This paper investigates three different high-volume low-speed (HVLS) fans with NACA 5414, 6413 and 7415 airfoils. All of the fans have six blades with a diameter of Φ = 6 m and rotate at 60 RPM. The blades have untwisted rectangular shapes with a chord of 20 cm. The results show that although the HVLS fan based on the NACA 7415 generates the highest volumetric flow rate and fastest air circulation, it needs more torque. Furthermore, the compression between the four, five and six-bladed versions show that the six-bladed version again generates the highest volumetric flow rate and fastest air circulation.

However, from the point of view required torque per volumetric flow rate, the case with five blades is the most efficient. The strong influence of the airfoil and pitch angle is also noted by observing the similarity between the results of the NACA 7415_13^o(five-bladed) and NACA6413_12^o(six-bladed).

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