High-Volume Low Speed (HVLS) Fan Blade Design for a Large Naturally Ventilated Space

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Abstract

High Volume Low Speed (HVLS) fan is gaining popularity for the use in large and naturally ventilated spaces in Singapore's buildings, such as sports hall and hawker centre (Singapore's low-cost food court), etc., to ensure good Indoor Air Quality (IAQ) and to improve thermal comfort. The aim of this paper is to study the design of different HVLS fan blades to improve its performance and its impact on airflows and velocities in a naturally ventilated food court. The approach of the study is through CFD simulations using OpenFOAM of different HVLS fan blades design and apply it to a hawker centre building in Singapore. There are four types of blade designs, especially on the blade's tip design, studied in this research work.

Introduction

In hot and humid climate of Singapore, the use of air conditioning system is very extensive to cool down building spaces. However, it is not energy efficient, especially in transient spaces such as atrium, hawker center (Singapore's low-cost food court), and aboveground open-air Mass Rapid Transit (MRT) station. One of the solutions is to install HVLS fan, which operates by rotating at a lower resolution per minute as compared to "traditional" ceiling fan. Yet, an HVLS fan is able to produce more draft and reduces electricity consumption (Tetlow, K., 2018). The diameter of HVLS fans span between 3 and 7 meters (Moshfeghi, 2014). The fan size is determined by the land size, which the fan would be installed. A bigger area requires a larger fan. While the use of HVLS fans are getting more popular, the use of Computational Fluid Dynamics (CFD) simulation to evaluate the performance of an HVLS fan is still very challenging for most of consultants. Engineers and HVLS

fan suppliers would base on generic catalogue to design and calculate the assumed air velocity and flow pattern. As a result, design errors emerge.

In this research work, four blade designs were studied their performances for further improvement for the newly designed HVLS fan blade. The new blade design would have an improved air velocity and larger in coverage area. In addition, the influence of fan speeds, i.e. rotation per minute (RPM), of the new blade were also studied. With the improvement in air velocity and circulation, its RPM can be further lowered and hence, reducing energy consumption.

Methodology

The overall CFD simulation scenarios in this study are shown in the following diagram (Figure 1). There are two stages of simulations. The first stage is to select the best performance blade of four blade designs (*Figure 2*). The four blade designs are circular arc, double wedge, twisted blade and modified branded HVLS fan with extended flap at 0°.

After conducting the first stage of simulations, it was found that Blade Design 4 has the best performance by evaluating the average air speed produced by the fan (the results are discussed in the next section). A comparison study was also done between the original blade design of branded HVLS fan and modified blade design selected in the second stage of simulation.

The simulations then moved on the second stage, where different flap angles were tested, ranging from 0° to 70° with intervals of 10° increment (*Figure 3*). The selected fan blade design from the second stage simulations was then applied into a hawker centre space as shown in Figure 4 to Figure 6

Figure 1: Simulation scenarios and fan development stage.

Figure 2: Four blade designs in first stage of CFD simulation.

CFD Methodology

The whole process of simulation used a two-step sequential procedure, where firstly, a regional model based on multiple reference frame (MRF) approach for a single HVLS fan was developed. This model was used to obtain the velocity and turbulence profiles of fan-induced flows. These profiles were then applied as the boundary conditions in a hawker centre space to emulate the impacts of multiple HVLS fans

Figure 3: Different flap angles studied in the second stage of CFD simulation.

Figure 4: Hawker centre used in simulation study.

Figure 5: Positions of fans in the Hawker Centre.

Figure 6: Placement of the fan from floor level (section).

Figure 7: Mesh systems of fan blade simulations.

The domain sizes for fan blade design simulations (Figure 7) and hawker center application (Figure 8) are X-16m, Y-16m, Z-47m and X-70m, Y-52m, Z-10.32m, respectively. The total number of cells are 5,105,979 and 5,492,357 for fan blade design simulations and hawker

center application respectively. Figure 9 shows the mesh systems for multiple reference frame (MRF) zone.

Figure 8: Mesh systems of hawker center simulations.

Figure 9: Mesh systems of MRF zone.

The simulations used OpenFOAM, an open source CFD toolbox (OpenCFD, 2018). Table 1 shows the different steps that needs to be done before the actual simulation can be performed and the meshing level used.

Table 1: Steps to conduct CFD simulation using OpenFOAM.

Steps taken	Processes in each step
1) Meshing of HVLS fan and MRF Zone (fanMesh)	<p>Background mesh, i.e. Level 0</p> <ul style="list-style-type: none"> $dx = 16/25 = 0.4$; $dy = 16/25 = 0.4$; $dz = 5/15 = 0.33$; <p>Meshing level for local mesh around the fan: 4</p> <ul style="list-style-type: none"> $dx = 0.4/2^4 = 0.025$; $dy = 0.025$; $dz = 0.020625$; <p>Mesh within the bounding box min (-2 -2 -0.5) -> max (2 2 0.5) were refined to level 4</p> <p>Meshing level for fan: 7</p> <p>Meshing level for MRF Zone: 6</p> <p>Meshing shape: Hexahedron</p>
2) Simulate the fan rotation to obtain the wind profile (fanRotate)	<p>Rotation speed of the fan was input into the system.</p> <p>Different speed would be used for different scenarios.</p> <p>The baseline of the rotation speed is 90 revolutions per minute.</p>
3) The MRF zone are separated into 2 different zones, i.e. pressure side	<p>The fan is separated into two sides – pressure side and suction side.</p> <p>Pressure side refers to the wind produced (downdraft) during</p>

and suction side. (fanZone)	rotation when air is pushed downwards. Suction side refers to the suction of surrounding air at the top surface of the fan. Figure below illustrates the pressure side and suction side.
4) Data obtained through fan rotation would be captured in the different zones. (fanData)	The location would be input in the x, y and z direction. In the study, 3 fans were used in the building, the location are as follow: Fan 1: 30, -24, 3 Fan 2: 36, -24, 3 Fan 3: 42, -24, 3
5) Meshing of building model and MRF Zone (centerMesh)	Meshing level for building: 3 Meshing level for MRF Zone: 3 Meshing shape: Hexahedron
6) Simulate the fan rotation in the building model to obtain the wind profile (windFlow)	Meshing and fan performance data was incorporated at this stage to produce the final result. This would enable us to view the performance of the fan in different building designs or fan installation height.

The assumptions used in the simulations are, as follows:

- Three-dimensional (3D) steady-state simulations for incompressible flow;
- Two-equation k- ϵ model with standard wall functions to deal with turbulence, as used in some studies (Bassiouny and Koran, 2011; Forest and Owen, 2010);
- Isothermal condition (air temperature is assumed to be 32°C);
- The local prevailing wind condition the surrounding buildings were not considered in this simulation

Results and Discussion

Figure 10 shows the first stage of simulation results. The average air speed was compared to identify the optimum blade design before moving on to the second phase of CFD simulations. Table 2 shows a summary of the air speed achieved in the first stage of simulation. The optimum blade design was blade design 4, i.e. extended flap with average speed of 1.658 m/s at floor level. Therefore, blade design 4 was selected to the second stage simulations where different blade angles were tested to

determine the optimum angle to produce the best average air speed at the occupancy level.

Figure 10: First stage simulation results.

Table 2: Average air speed of four blade designs.

Blade Design No	Average Air Speed (m/s)
Baseline (Branded HVLS Fan)	1.455
1 (Circular Arc)	1.569
2 (Double Wedge)	0.762
3 (Twisted Blade)	1.600
4 (Branded HVLS Fan with extended flap 0 deg)	1.658

Figure 11 shows the results obtained through simulations. Based on the second stage simulations, average air speed results on the floor level plan were obtained. They were then compared to identify the best performing blade angle as shown in Table 3: Average air speed of Blade Design 4 with different extended flap angle.

Angle of Extended Flap	Average Air Speed (m/s)
0	1.743
10	1.743
20	1.826
30	1.88
40	1.902
50	1.911
60	1.919
70	1.918

The ventilation performance of the newly design blade was compared with the baseline fan in Hawker Centre space as shown in Figure 12. The coverage area of a higher wind speed can be seen clearly, especially in the area below and nearby the fans. The overall average air speed at 1-meter height is 0.148m/s.

The optimum blade angle was 60°, with average speed of 1.919m/s at floor level, a significant increase as compared to the baseline fan (see Figure 10a), which average wind speed of 1.455m/s. This blade design was then selected for the application in the hawker centre space.

Figure 11: Second stage simulation results.

Table 3: Average air speed of Blade Design 4 with different extended flap angle.

Angle of Extended Flap	Average Air Speed (m/s)
0	1.743
10	1.743
20	1.826
30	1.88
40	1.902
50	1.911
60	1.919
70	1.918

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Figure 12: Performance of fan in Hawker Centre for baseline fan and Blade Design 4 Extended Flap at 60° (90RPM).

Figure 13: Performance of Blade Design 4 Extended Flap at 60° for 80, 70 and 60 RPMs.

Table 4: Average air speed of Blade Design 4 Extended Flap at 60° for various Rotation Per Minute (RPM).

Rotation Per Minute (RPM)	Average Air Speed (m/s)
90	1.919
80	1.700
70	1.488
60	1.271

Figure 14: Performance of fan in Hawker Centre for baseline fan and Blade Design 4 Extended Flap at 60° (70RPM).

With the performance improvement in air speed for the blade design 4, three different rotational speeds were studied to test the performance of the fan for potential energy consumption reduction. The parameters of the fan were kept the same, except for their rotational speed.

The results are shown in Figure 13 and Table 3: Average air speed of Blade Design 4 with different extended flap angle.

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. A similar average air speed of around 1.4m/s can be achieved by the newly designed blade only at 70 RPM as compared to 90 RPM for the baseline fan. The RPM reduction certainly reduces the energy consumption used to ventilate the space.

The simulation of the reduced RPM speed in the hawker center space (Figure 14) shows that it still can achieve a better air ventilation distribution as compared to the baseline fan at a lower RPM.

Conclusion

Through this study, it was found that blade designs and blade angles affect a fan's performance and area of coverage. At the initial stage, four blade designs were studied, before extended flap blade design (blade design 4) was chosen for further studies. The extended flap angle at 60° was found to have the best performance. From the different simulations, fans with different RPMs may be used to either increase air speed or decrease energy consumption. For instance, if building owners wish to achieve the similar velocity produced by traditional fan, he may adopt the newly designed blade yet rotating it at a slower rotational speed. Furthermore, when the newly designed blade rotates at the same speed as a traditional fan, the former is able to provide a much higher velocity.

Limitation of study

In the CFD simulation of hawkker centre space, the surrounding buildings were not modelled, and the external wind condition was not considered due the limited computing power.

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