Investigation of Airflow from a Regular Ceiling fan using CFD Simulation

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Abstract - *Ceiling fans are the most commonly used electrical appliance in homes situated in tropical regions. Although it has a simpler construction, the dynamics of airflow behind it is quite complex as it depends upon various factors such as the structural design of fan, size of the room, environmental conditions, etc. In this study, airflow from a regular ceiling fan is investigated using computational fluid dynamics. Using* 2^k *factorial design, the results from CFD simulation are analyzed so as to reduce the number of computational cases and investigate for the dominant parameter affecting the airflow with the help of a Pareto chart. The data is then used for obtaining a regression equation for the same. From the study, it was found out that the angle of attack and length of the blades were dominant parameters in the airflow characteristics. Thus, modifications in performance of the fan can be easily done on its structure without actually changing its drive unit which is beneficial in high volumetric efficiencies with less power consumption.*

Key Words: Ceiling fan, airflow, computational fluid dynamics, dominant parameter, angle of attack, blade length, speed.

1. INTRODUCTION

Ceiling fans are the most widely used electrical appliance in homes situated in tropical regions. Compared to air conditioners, a fan is less power consuming along with the ease of maintenance and thus is an economically viable choice to common-man for its comfort. A typical ceiling fan has the purpose of recirculating the air, enclosed in the room, by accelerating it with the help of blades inclined at specific angles. Thus, a ceiling fan recirculates the air in a room by means of external power via the blades.

Generally, the power to the fan is provided by motors, placed in its hub. A hub is the main, central rotating part to which the fan blades are connected. A typical ceiling fan consist of a capacitor-start type of motor due to its high initial torque. The speed of the motor in the fan can be controlled with the help of voltage regulators. The blades of fan are of specific length and are inclined at specific angles to the hub, which is known as the angle of attack. The entire assembly of the fan is hung to the ceiling of the room by means of a rod. Thus, the airflow from a fan depends on the blade length, angle of attack, speed, size of the room, etc.

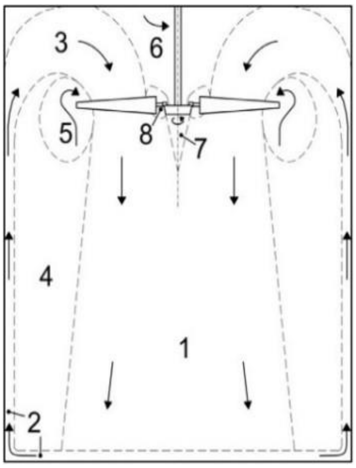


Figure 1: Different flow regions identified by A Jain [1]

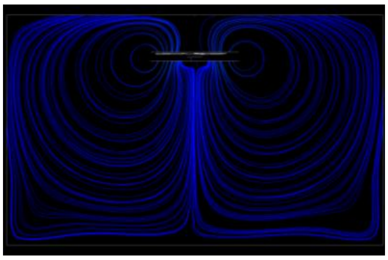


Figure 2: Velocity streamlines of the airflow from CFD

A. Jain et al. [1], in their work, demonstrated the flow field around a ceiling fan with the help of an experimental setup. The flow characteristics of the fan inside a closed room was experimentally visualized and different flow regimes were studied, as from figure 1. It was observed that there were 8 major flow regions under a ceiling fan. The region below the fan (region 1), was considered to be the one with high-velocity and swirling nature. It was found out that essentially this was the region where a person would feel the maximum comfort. The air from region 1 moves along the edges of the room which is region 2, characterized by its laminar property and low speed. Region 2 is bounded based on the size of the room and space occupied by people. The air then gradually reaches region 3, which is above the blades of the fan, where it thickens and develops a radial component in addition to its vertical component. It then enters the blades of the fan again. Region 4, as can be seen in figure 1, is sandwiched between the region 1 and 2 respectively. The region is characterized with very small velocity as it is the region recognized to be less effective. Region 5 is the region where vortex formation from the tip of the blade is maximum, as seen in figure 2. Regions 6, above the fan, and region 7, below the hub of fan are characterized by very low velocity profiles and are considered to be dead or recirculation zones. The recirculation region between the blade and the hub is region 8. Like tip vortices, this region too is attached to the blade and rotates with it. Air below the blade turns around through this gap to reach the flow above the blade. Figure 2 gives a better idea on the airflow characteristics with the help of velocity streamlines.

S. Ho et al. [2] in their study for thermal comfort using ceiling fans suggested several numerical formulations and mathematical models for optimum thermal comfort. The study considered the combined effect of the location (height) of the inlet and the air speed from the fan (vertical to the room or axial to the fan). Thus, average velocity was one of the primary variable in the study which had a great effect on the optimal thermal comfort. The study predicted that the inlet temperatures and high speed from the fans were one of the major parameters in thermal comfort.

The study of Babich F. et al. [3] compared various turbulence models for the CFD simulation of ceiling fans with experimental data. The study suggested that k-ω SST model developed accurate solutions when compared with the experimental data. The simulated values for both the swirling and axial movements of air showed greater accuracy with this turbulence model.

The present work develops an understanding in the airflow from a regular ceiling fan with the help of computational fluid dynamics [4]. The parameters which are considered in the study are mainly the fan's structural parameters such as speed, blade length and angle of attack. Other parameters such as the size of the room, temperatures of the surrounding, density of air, cross-ventilations in the room, etc. are also some of the parameters that might affect the airflow but are not considered due to ease of computation. The dominant parameter in airflow characteristics is found out using 2^k factorial design from the results of the simulation. The present study also employed spectral analysis technique to find out one of the cases of the design. With the help of this study, modifications in fan can be done by the designer without changing the driving unit (motor) of the fan. Thus, it is advantageous for a designer in terms of cost and complexity in design. It also provides a tool to the designer in designing and verifying the data.

2. METHODOLOGY

2.1. Design of the ceiling fan

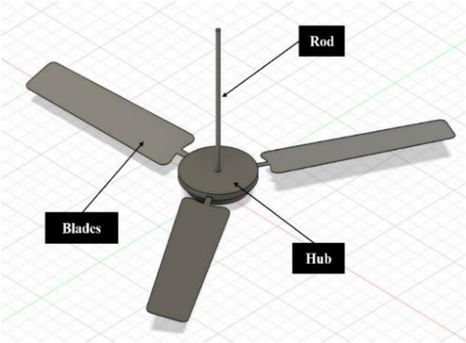


Figure 3: Assembly of fan

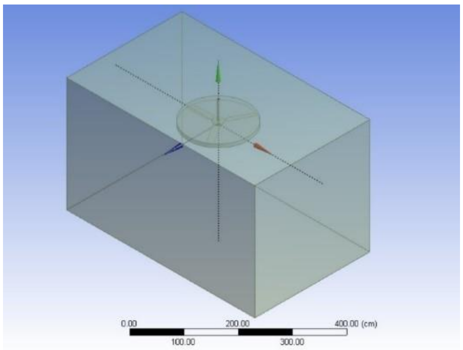


Figure 4: Position of fan in the control volume

The assembly of fan consists of the hub, blades and rod as shown in the figure 3. Based on the parametric study for number of blades of Adeeb et al. [5][10], it was observed that three blade configuration was desirable for good energy efficiency and volumetric efficiency for the performance of fan. Thus, a three blade configuration of fan is considered for the study. A set of 4 different blades with different angle of attacks and dimensions are considered for different cases in the study. The angle of attack is varied between 6° to 12° based on the optimum performance results of J. Rao [6]. The hub and the rod of the fan is considered to be the same for all iteration. The dimensions of the fan can be noted from table-1.

Part	Dimension
Hub diameter	24 cm
Rod diameter	9 cm
Rod length	49 cm
Blade length	38 cm, 56 cm
Angle of attack	6°, 12°

Table 1: Dimensions of each component

From figure 4, the position of the fan in the control volume can be clearly observed. The assembly of fan is hung in the centre of the control volume for uniform flow characteristics [7] [12]. The size of the room is considered to be 4.5x3x3 m.

2.2 Discretization of domain

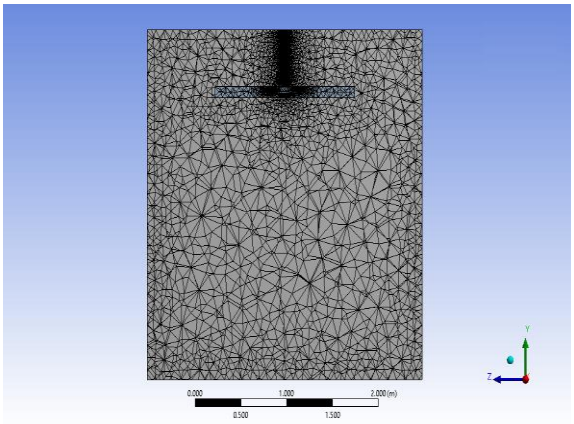


Figure 5: Cross-section of the discretized domain

The domain is discretized with ICEM-CFD in ANSYS. The domain, as in figure 5, has unstructured mesh with an average element size of 9.463e-02 m. As it can be observed that the mesh is refined such that it is fine around the fan's blade so as to observe recirculation and vortices. Also, the boundary or the walls of the control volume have fine mesh too for observing the recirculation effects. The mesh is similar for all the cases considered in the study.

2.3 Boundary conditions for the simulation

The air in the room is considered to be at STP for all the cases in the study. For the sake of simplicity, it is assumed that there is no external influence from the surrounding i.e. assuming the windows and doors of the room to be closed. For different cases of study, boundary conditions of the fan is different although the room parameters remain the same. Since 2^k factorial design is used, each case has to have a maximum and minimum value. Since there are 4 set of blades, each blade has a blade length of 38 and 56 cm respectively. Similarly the angle of attack is varied with a minimum of 6° and maximum of 12° [6]. The speed of the fan is an essential parameter since regular economical fans do not exceed with a speed of 300 rpm. Thus, the maximum speed for the simulation is 300 rpm at full voltage. For determining the minimum speed that a fan can have at full voltage, the speed of a fan-in-use is considered since it's the minimum speed that the fan achieves over time. To find that speed, spectral analysis is used.

2.3.1 Determination for minimum speed at full voltage using spectral analysis

From the assembly of fan, it can be noted that a regular ceiling fan has no proper arrangement for measuring its speed without disassembling it. Thus, a different method is incorporated to check the speed of the fan without actually disassembling it. Since fans are durable and are used for a long time, the rated speed and the actual speed may definitely show variation due to the problems with the bearings, bad capacitor usage, motor windings issue, etc. Over time, the bearings in a typical fan becomes gummed up from dirt and oil, or may even dry out and may need proper lubrication, which is one of the main reasons in the reduction of speed. A spectral analysis of the noise generated by the fan is used to check the speed of the fan. A regular spectral analyzer application for phones is used for it. For the verification of the data showed by the application, a test noise of 1500 Hz was generated and tested on the application as from figure 6. The data showed by the application was found to be correct as shown in the figure 7.

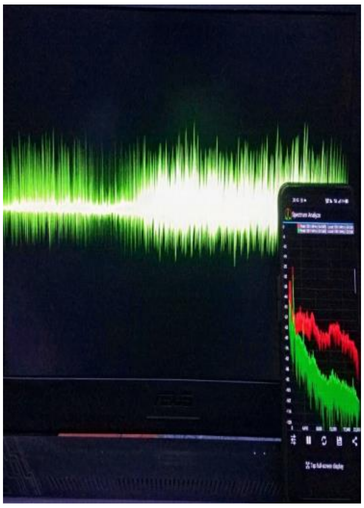


Figure 6: Test frequency for verification

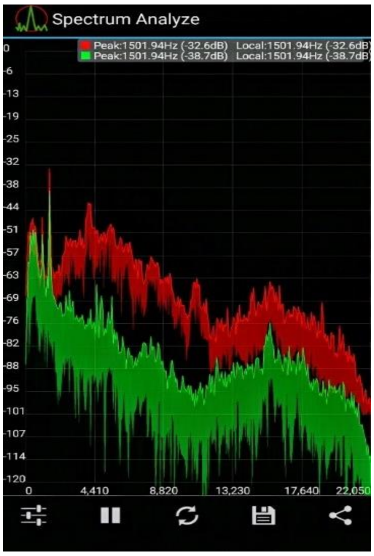
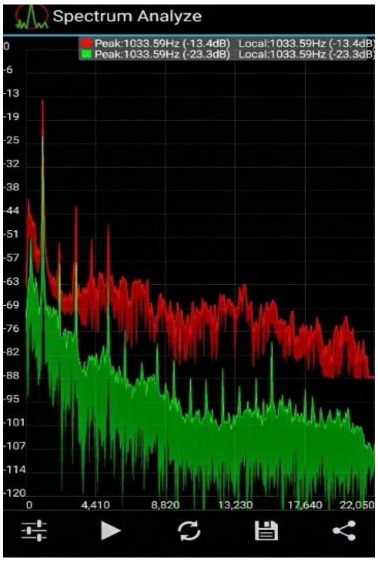


Figure 7: Screen capture of test frequency



Spectrum Analyze

Peak:1033.59Hz (-13.4dB) Local:1033.59Hz (-13.4dB)
Peak:1033.59Hz (-23.3dB) Local:1033.59Hz (-23.3dB)

Figure 8: Screen capture of frequency of noise

Thus, based on the data recorded by the analyzer in figure 8, the peak frequency of noise generated by fan can be seen as 1033.59 Hz. But this is the frequency of the noise generated by the fan for all the 3 blades. Thus, the frequency of each blade is 344.53 Hz. Also, the relation between the frequency and angular speed is given by $\omega = 2\pi f$, wherein ω is the angular speed and f is the frequency. Thus, the speed of the fan is approximately 227 rpm. Thus, we take the minimum speed for our case to be 227 rpm.

Thus, the boundary conditions for various cases of the simulation is tabulated below.

Case	**Angle of attack (degrees)**	**Chord length (cm)**	**Speed (rpm)**
Case 1	6	38	227
Case 2	6	38	300
Case 3	6	56	227
Case 4	6	56	300
Case 5	12	38	227
Case 6	12	38	300
Case 7	12	56	227
Case 8	12	56	300

Table 2: Details of each case

3. RESULTS & DISCUSSIONS

The simulation used k-ω turbulence model for solving the cases for the problem in ANSYS FLUENT [3]. The simulation was ran for all the cases as discussed in the table 2. The results are based on the average velocity from all of the cases. The reason for considering average velocity as a primary result is because the thermal comfort for humans is based on how well the convective heat transfer between the environment and the body takes place. Thus, velocity of air is a primary variable in optimum thermal comfort for people sitting below an ordinary ceiling fan [2] [8]. The results for all the cases are discussed below which consist of the velocity surface plots and the velocity contours.

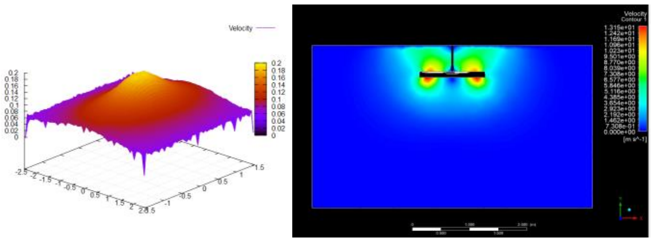


Figure 9: Simulation results of Case 1

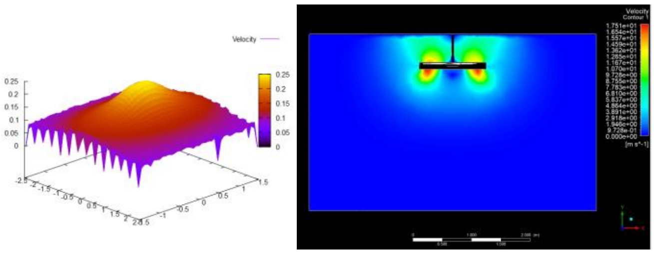


Figure 10: Simulation results of Case 2

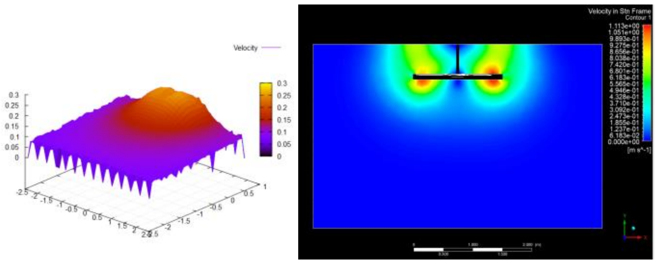


Figure 11: Simulation results of Case 3

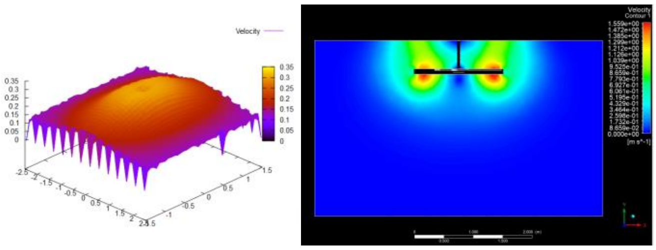


Figure 12: Simulation results of Case 4

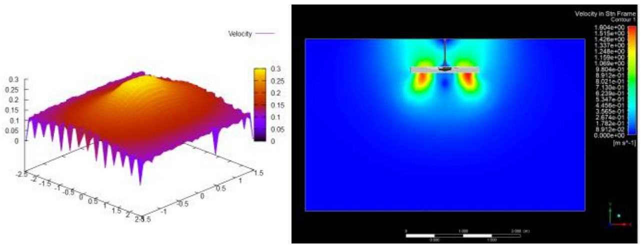


Figure 13: Simulation results of Case 5

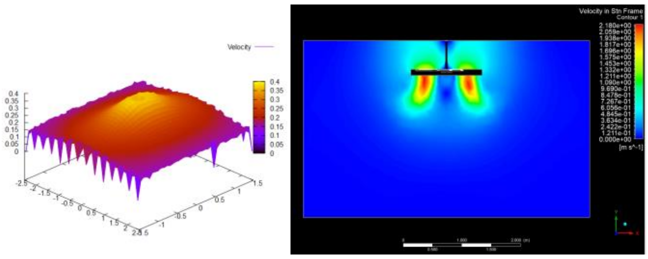


Figure 14: Simulation results of Case 6

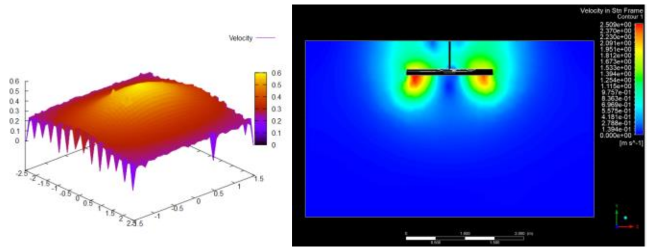


Figure 15: Simulation results of Case 7

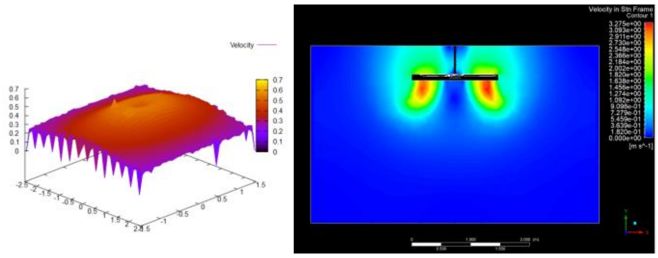


Figure 16: Simulation results of Case 8

It can be observed that the surface plot for average velocity for all the cases show similar trends. The area or distance of the air dissipated remains the same. The peak velocity for all the cases is in the centre of domain and ranges from 0.2 ms^{-1} to 0.7 ms^{-1}. One peculiarity of the surface plot for all the cases is that the velocity at boundaries is close to 0.1 m/s since the region recirculates the airflow back to the top of the domain. The velocity contours from the all the cases show that the region below the blades have the highest recirculation velocities. The air in the region below the fan have high swirl nature and thus tend to form a half-cone or frustum-like profile as it reaches the ground. Thus, it is the region for maximum thermal comfort. From figure 17, overall comparison for all the cases can be observed. It can be observed that average velocity of case 7 and 8 are maximum while that of case 1 and case 2 is the least.

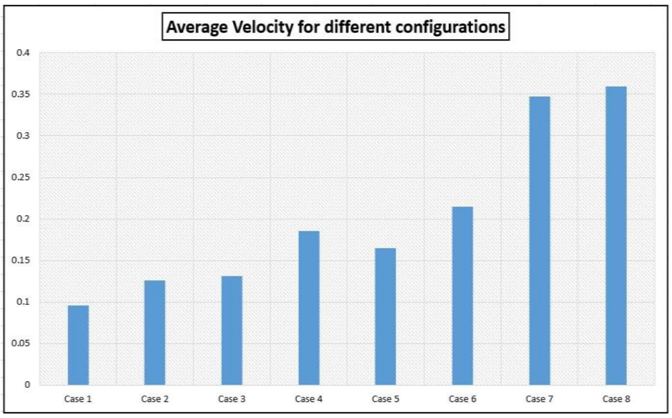


Figure 17: Overall comparison of all the cases

To get the relationship between each parameter considered in the simulation, 2^k factorial design is implemented. The parameters considered in the study are the angle of attack, blade length and speed of the fan. Thus, with the help of a Pareto chart, the dominant parameter and its relationship with other parameters is found out. From CFD simulation, the result (average velocity) of each case was found out. Thus, the data for Pareto chart formation is tabulated below. From table 3, it can be noted that angle of attack, speed & blade length are the parameters and average velocity is the effect to which the Pareto chart is formed.

Angle of Attack (°)	Speed (rpm)	Blade length (cm)	Average Velocity (m/s)
6	227	38	0.09596
12	227	38	0.164977
6	300	38	0.126266
12	300	38	0.214909
6	227	56	0.131501
12	227	56	0.347377
6	300	56	0.185615
12	300	56	0.35935

Table 3: Average velocity for all cases from CFD

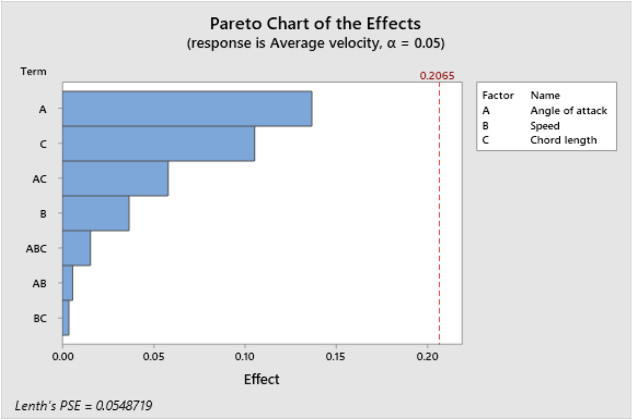


Figure 18: Pareto chart of the effects

From the Pareto chart, it is clear that the angle of attack along with the blade length was a dominant parameter in the airflow characteristics. Thus, a regression equation for the average velocity as a function of the fan parameters is:

$$v = 0.7905 - (0.1179*a) - (0.002328*b) - (0.02097*c) + (0.000343*a*b) + (0.003138*a*c) + (0.000065*b*c) - (0.000008*a*b*c)$$

Where, v = Average velocity, a = Angle of attack, b = Speed of the fan, c = Blade length.

4. CONCLUSION

From the Pareto chart it was observed that the airflow characteristics are greatly influenced by the angle of attack followed by the blade length. Thus, for increasing the performance of the fan without altering the driving unit, the structural parameters such as the angle of attack and the blade length can be improved by the designer. The regression equation from the study will help the designer in altering the performance based on structural parameters. Also, it can be noted that a person with less experience in working with drive units too can improve the performance of the fan by just optimizing the structure. Thus, it can be concluded from the study that not only does the speed contribute to the overall performance of the fan but the structural parameters such as angle of attack and blade length contribute greatly too. This not only helps in optimization but also helps in attaining higher efficiencies and higher energy savings.

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