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The Effect of Fan Blade Shape on Airflow and Electrical Power Consumption: A Virtual Simulation Study

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Abstract. This paper investigates how the shape of the fan blades affects airflow and electrical power consumption utilizing NASA's FoilSim JS online simulation tool. Three common blade types were tested: flat (0% chamber, 1% thickness), curved (4% camber, 12% thickness), and streamlined symmetric airfoil (0% camber, 12% thickness – NACA 0012). All blades were tested under identical airflow conditions of speed, altitude, chord, span, and angle of attack. The drag coefficient directly applied from the software shows the curved blades have CDrag of 0.113, while both flat and streamlined blades show a CDrag of 0.048. With the same voltage and motor efficiency, greater air resistance requires more current. The curved blade uses 135% more electrical power than the flat or streamlined. Surprisingly, the flat plate works about the same as the streamlined airfoil. This is because the lowest thickness allowed from the simulation is 1%, meaning that assuming the flat plate is perfectly flat cannot be achieved. The software's simplified calculations may also affect the result. However, the main result is clear: if the blades are more curved but not well streamlined, drag increases and needs more power. The paper ends with an advice for designing energy-efficient fans, such as for cooling, and transformer ventilation.

Keywords: fan blade shape, coefficient(CDrag), power consumption, angle of attack

1. Introduction

From a small cooling fan in a laptop to large industrial fans in wind tunnels, electric fans are widely used in modern technology. These devices change electrical energy into moving air. According to the U.S. Department of Energy [1], electrical motor systems such as fans, pumps and compressors use nearly 40% of the world's electricity, meaning that by calculating based on ratio, even a small increase in fan efficiency can save a large amount of energy that is used across millions of devices.

The efficiency of a fan depends largely on the shape of its blades. A considerable functioning blade designs for moving a large amount of fluid while using less force from the motor and less electrical energy from battery. In contrast, a poorly shaped blade creates turbulence and high air resistance by using a large amount of energy. Drag coefficient (CDrag) is used to measure how much a shape resists airflow. The lower The lower the CDrag, the less force the motor needs, and less electrical current it uses. (the voltage stays the same) [2].

Understanding this relationship connects two important areas – fluid mechanics and electrical circuits. Fluid mechanics is the study of how air flows and electrical circuits are the study of current,

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voltage and power. In this project, a simulation tool developed by NASA – FoilSim JS is used to carry out virtual wind tunnel experiments. Information below shows the represents of the Three design choice:

1. Flat plate – the simplest shape, with the least thickness
2. Curved blade – similar to many household fan blades with concave surface.
3. Streamlined symmetric airfoil – shaped like an aircraft wing (NACA 0012), known for low drag [3].

In the experiment, there are total data of five different angles of attack (0°, 5°, 10°, 15°, 20°) being analyzed to observe how each blade shape performs under the range of operating conditions. The angle of attack is the tilt between the blade and the airflow. In a fan, it works on the installation angle relative to the airflow it creates. Therefore, by measuring CDrag across these angles, the most energy-efficient condition could be selected (around 5˚) and also see how performance changes at higher angles, such as during startup or under overload conditions.

2. Theoretical background

2.1. Drag force and drag coefficient

When a solid object moves through a fluid (or when fluid flows past a stationary object), the fluid creates a drag force that opposes the motion. The size of this force can be calculated using the drag equation:

$$F_D = \frac{1}{2}\rho v^2 C_D A \tag{1}$$

Where:

F_D: drag force (N)

P: fluid density (for air at sea level, ≈ 1.225 kg/ m^3)

V: velocity between object and fluid (m/s)

A: reference area (frontal projected area, m²)

C_D: drag coefficient (depends only on shape and surface roughness, dimensionless) [4].

By adjusting the shape of an object, the CDrag value can be varied. For example, a flat facing the airflow has a Cd of about 1.2, while a streamlined airfoil can have a Cd as low as about 0.04. This means the difference is roughly a factor of 30, showing the importance of drag reduction to a considerable design.

2.2. Relationship to electrical power

Consider a small DC motor driving a fan. The motor produces a torque (τ) to overcome the aerodynamic drag on the blades. The mechanical power required is [5, 6]:

$P_{mech} = \tau \cdot \omega$

where ω is the angular velocity (rad/s). The torque is proportional to the drag force (Fd) multiplied by a characteristic radius. Therefore, $P_{mech} \propto$ Fd.

The electrical power drawn from the power supply is:

$P_{elec} = U \cdot I$

U represents the voltage (constant for a fixed power supply) and (I) is the current. The motor's efficiency (η) links mechanical and electrical power:

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$P_{mech} = \eta \cdot P_{elec}$

Assuming the motor efficiency and angular velocity remain the same when comparing different blade shapes (a reasonable approximation for a small fan at the same speed), we obtain:

$I \propto P_{elec} \propto P_{mech} \propto Fd \propto Cd$

Thus, the electrical current is directly proportional to the drag coefficient. This simple relationship is the foundation of our comparison: the blade with the lowest Cd will draw the least current and therefore consume the least electrical power.

2.3. Angle of attack and its importance

The angle of attack (α) is the angle between the blade's chord line and the direction of the incoming airflow. For a fan that is rotating at a constant speed, the direction of the relative wind changes depending on the blade's pitch. At small angles of attack (about 0°-5°), drag is low and lift is moderate. As (α) increases, both lift and drag increase.

However, above an angle range (usually around 12°-15° for many airfoils), the airflow begins to separate from the surface of the blade. This causes a sharp increase in drag and a drop in lift, a condition known as stall.

The relationship between CDrag and (α) helps fan designers choose the most efficient blade angle for stable and low-power operation.

3. Methods

3.1. Simulation tool

FoilSim JS, a browser-based interactive educational tool developed by NASA, was applied to the experiments. It solves simplified aerodynamic equations (based on potential flow with empirical corrections) for a given airfoil shape. The software outputs lift force, drag force, lift coefficient (CLift), drag coefficient (CDrag), Reynolds number, and lift-to-drag ratio. It is an ideal software that has lower requirements for professionalism, making it accessible for learning basic aerodynamics. It has also been compared with classical aerodynamic data and shows reasonable agreement for standard airfoil shapes [7].

3.2. Experimental setup

All simulations were performed with the following fixed, shown in Table 1.

Table 1. Consistent data values applied for three different types of blades parameters (units: metric)

Parameter	Value
Altitude	0 m (sea level)
Airspeed	36 km/h = 10 m/s
Chord length	1.0 m
Span	5.0 m
Reference area	Reference area (A) Chord × Span = 5.0 m²

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3.3. Tested blade shapes

The three blade cross-sections was defined using the Shape panel in FoilSim JS, illustrates in Table 2.

Table 2. Blade type camber (%) thickness (% chord) description

Blade Type	Camber (%)	Thickness (% chord)	Description
Flat	0	1	Partially flat paddle
Curved	4	12	Moderate camber, typical of household fans
Streamlined (NACA 0012)	0	12	Symmetric airfoil, very low drag design.

The thickness value of 1% is the smallest allowed in the software, and it is used to approximate an almost perfectly thin flat plate. However, it still has thickness and results in experimental error. The NACA 0012 airfoil (0% camber, 12% thickness) is a standard symmetric airfoil that is widely used as a reference in aerodynamics and is well documented in textbooks and engineering studies [3].

3.4. Procedure

The procedure is as follows:

1. Navigate to the FoilSim JS website.
2. Click "Reset" to ensure default settings.
3. Set Units to "metric"
4. In the Flight panel, set Altitude = 0 m and Speed = 36 km/h.
5. In the Size panel, set Chord = 1.0 m and Span = 5.0 m.
6. For each blade shape:

Click the Shape panel.
Enter the Camber and Thickness values.
Set Angle-deg = 5.
Press Enter after each input.
Read the CDrag value from the Output area (under Data or Gages).
Record the value in a data table.

7. Repeat for all three shapes.

Each measurement was taken once after confirming that the program had converged, meaning the CDrag value had become stable. Because the simulation is deterministic and produces the same result under identical conditions, repeated measurements were not required.

4. Results

4.1. Drag coefficient vs. angle of attack

Table 3 shows the measured CDrag values for the three blade shapes at angles from 0˚ to 20˚

Table 3. CDrag values for flat, curved, and streamlined blades at various angles of attack

Angle (˚)	Flat plate (Thick=1, Cam=0)	Curved (Thick=12, Cam=4)	Streamlined (Thick=12, Cam=0)
0	0.011	0.035	0.019
5	0.048	0.113	0.048
10	0.146	0.233	0.130
15	0.260	0.332	0.251
20	0.302	0.298	0.291

Note: All CDrag values are dimensionless.

4.2. Observations

For all three CDrag increase with angle of attack, which is the expected trend.

The curved blade has the highest CDrag at from 0° to 15°.

At 20˚, the flat plate and streamlined airfoil share similar values (0.302 and 0.291 vs. 0.298), while the curved blade still remains among the highest.

The flat plate and streamlined airfoil have similar values of CDrag at 0˚ (0.011 vs. 0.019) and exactly the same at 5˚ (0.048). The streamlined blade shows a slightly higher efficiency, has slightly lower CDrag than the flat plate (e.g., 0.130 vs. 0.146 at 10°; 0.251 vs. 0.260 at 15°), although the differences are small in this simulation.

At 20°, both the flat plate and streamlined blade show a continued increase (0.302, 0.291), while the curved blade's CDrag drops slightly from 0.332 at 15° to 0.298 at 20°, which is likely to be the stall behaviour or flow reattachment effects in the model.

4.3. Power consumption at typical operating angle (5˚)

For a typical fan, the design angle of attack is around 5˚. Using the relationship $I \propto Cd$ from Section 2.2, it can estimate the relative electrical current and compare percentage increase in power use against the flat plate.

At 5°, the flat plate and streamlined airfoil both have the same drag coefficient (0.048), while the curved blade is higher at 0.113. Since current is proportional to Cd, this means the curved blade will draw more current under the same conditions.

Compared to the flat plate (taken as the reference), the curved blade increases current by:

$(0.113 - 0.048) / 0.048 \times 100\% \approx 135\%$

This clearly shows that even at a normal operating angle, blade shape has a strong effect on energy use when speed and voltage are kept constant. See comparisons in Table 4.

Table 4. Relative electrical current and power increase at 5° angle of attack

Blade type	CDrag (5˚)	Relative current (flat = 100%)	Increase over flat
Flat plate	0.048	100%	/
Curved	0.113	235.4%	+135.4%
Streamlined	0.048	100.0	0%

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The curved blade needs about 135.4% more electrical current than the flat plate (or streamlined blades) to maintain the same rotational speed. In practical terms, if a fan with flat blades draws 1.0 ampere , a fan with curved blades would draw about 2.354 amperes.

4.4. Additional aerodynamic metrics (lift and L/D)

Although the main focus of this study is drag, the software also provides additional outputs, including lift force and the lift-to-drag ratio (L/D). Table 5 presents these values for the three blade shapes at an angle of attack of 5˚

Table 5. Lift, drag, and L/D ratio at 5° angle of attack

Blade type	Lift (N)	Drag (N)	L/D ratio
Flat plate	162	15	10.8
Curved	311	35	8.9
Streamlined	178	15	11.9

The streamlined airfoil has the highest L/D ratio (11.9), meaning that it produces the most lift for each unit of drag. The curved blade produces the highest total lift (311 N), but it also has much higher drag (35 N), which reduces its efficiency and gives a lower L/D value (8.9). The flat plate falls between the two.

For fan applications, high lift is useful because it helps move more air, but low drag is just as important since it reduces the power needed to run the fan. Overall, the streamlined airfoil provides the best balance between these two factors.

5. Discussion

5.1. Interpretation of the flat plate vs. streamlined airfoil

The simulation shows that at 0° and 5°, the flat plate has almost the same CDrag as the streamlined NACA 0012 airfoil. This is surprising, since in real aerodynamics a flat plate at a positive angle usually has much higher drag due to strong flow separation.

A likely reason is that FoilSim JS uses a simplified potential-flow model with empirical corrections. For extremely thin shapes (1% thickness), the program may treat the flat plate as an ideal surface with mostly attached flow, which ignores much of the pressure drag that would appear in real conditions. In real wind tunnel experiments, a flat plate at 5° would typically have a CDrag closer to 1.0–1.2 [8], not 0.048.

Even with this limitation, the comparison between the curved blade and the streamlined airfoil is still meaningful because both have the same thickness (12%) and are treated consistently by the model. The curved blade shows a CDrag of 0.113 at 5°, which is more than twice that of the streamlined airfoil (0.048). This clearly indicates that adding camber increases drag at low to moderate angles. Physically, this happens because camber changes the pressure distribution, creating a larger low-pressure region on the upper surface, which increases drag even though it can also increase lift [9].

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5.2. Why the curved blade is so inefficient

Household fans often use curved blades because they look smooth and move air well at low speeds. However, the results show that between 5° and 15°, the curved blade has much higher drag than the symmetric airfoil. This is because the curved blade (4% camber) creates a larger pressure difference between its two sides. This increases lift, but it also increases pressure drag and induced drag. The symmetric airfoil (0% camber) generates lift mainly through angle of attack and keeps airflow more attached, so it has lower drag [10].

For fan design, this means symmetric or low-camber blades are more efficient when low power use is important. Curved blades can still be useful when high pressure is needed, but they require more energy.

5.3. Angle of attack trends and stall behaviour

Curved blades are prone to dynamic stall at higher angle of attack [11].

From Table 3., CDrag increases for all shapes as angle increases. For the curved blade, it rises from 0.035 at 0° to 0.332 at 15˚, then drops slightly to 0.298 at 20°.

This drop may indicate a stall. At high angles, airflow separates from the surface, which changes the pressure distribution. In real fans, this leads to noise, vibration, and poor performance, so high angles should be avoided.

The flat plate and streamlined airfoil do not show clear stall in this range, likely due to limits in the simulation model. In real conditions, they would also stall earlier than shown.

5.4. Practical implications for electrical engineering

Based on the experiment, three main implications are found: a curved-blade fan uses much more power than a streamlined design at the same speed; Lower power use improves battery life in devices like laptops and EVs; Lower current also reduces heating in the motor, improving efficiency and lifespan.

5.5. Limitations and future work

FoilSim JS is simplified and not full CFD software: The model is 2D, while real blades have 3D losses; airflow rate was not measured directly; only one airspeed was tested. The method of testing different airspeeds can be applied in the future. For further improvements, plot full lift–drag curves; compared with CFD tools then uild a physical model and test real current and airflow can be applied.

6. Conclusion

By using FoilSim JS, the three blade shapes: flat plate, curved blade, and NACA 0012 airfoil behave across angles of attack from 0° to 20°. The main findings are:

1) CDrag increases as the angle of attack for all shapes.

2) The curved blade has the highest drag at most angles, reaching 0.113 at 5°, around twice as much as the other two.

3) At 5°of attack angle, the curved blade uses about 135% more current than the flat or streamlined blade under the same conditions.

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4) The streamlined airfoil gives the best lift-to-drag ratio (11.9 at 5°), representing the idealist overall efficiency.

5) The flat-plate's drag is relatively low in the simulation due to the modelling limitation rather than real behaviour.

Overall, the results suggest that for energy-efficient fan design, symmetric or low-camber airfoils are better than highly curved blades. This design choice can significantly reduce power consumption in cooling systems used in electronics, vehicles, and large-scale infrastructure.

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