Flow Pattern Evaluation for Aluminum CPU Cooling Fan Blades

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Abstract-

The increasing thermal output of modern CPUs demands more efficient cooling solutions to maintain optimal performance and prolong system lifespan. Traditional CPU cooling fans commonly use plastic (polypropylene) blades, which are limited in heat absorption and mechanical durability. This study investigates the performance of aluminum fan blades as an alternative, leveraging their superior thermal conductivity and strength. Using SolidWorks for 3D modeling and meshing, followed by Computational Fluid Dynamics (CFD) simulations, various blade designs and angles are evaluated to optimize airflow and thermal dissipation. The analysis focuses on key performance indicators such as airflow velocity, heat dissipation rate, and overall cooling efficiency. Results indicate that aluminum blades significantly improve heat suction and thermal transfer from the CPU surface, although their higher density introduces a trade-off with fan speed due to increased inertia. Adjustments in blade angle further enhance cooling performance by directing airflow more effectively. This research offers practical insights into the design of advanced CPU cooling systems, highlighting the potential of aluminum blades to improve thermal management in high-performance computing environments.

Keywords – CPU fan, cooling efficiency, CFD simulation, Thermal performance, Airflow optimization etc.

1. Introduction

In recent years, the exponential growth in computing power and data processing demands has led to significant advancements in Central Processing Unit (CPU) technology. Modern CPUs now operate at higher clock speeds and incorporate more transistors than ever before, resulting in an increased rate of heat generation. If not effectively managed, this heat buildup can lead to thermal throttling, reduced performance, component degradation, and in severe cases, system failure. Consequently, thermal management has emerged as a critical aspect of CPU design and system integration. Among various cooling methods, forced air cooling using CPU fans remains the most widely adopted due to its cost-effectiveness and ease of integration [1].

Traditional CPU cooling systems utilize plastic (typically polypropylene) fan blades due to their lightweight, ease of manufacturing, and low cost. However, plastic materials exhibit low thermal conductivity and limited heat absorption capacity. As a result, their efficiency in actively removing heat from the vicinity of the processor is suboptimal. Moreover, plastic blades are prone to wear and deformation under prolonged exposure to high temperatures, raising concerns about their long-term durability and effectiveness. These limitations necessitate the exploration of alternative materials that can offer enhanced thermal performance and structural integrity [2][3].

Aluminum, known for its excellent thermal conductivity and mechanical strength, presents a promising alternative for CPU fan blades. With a thermal conductivity of approximately 235 W/m·K—significantly higher than that of plastic—aluminum can effectively absorb and dissipate heat from surrounding components. Additionally, aluminum is resistant to thermal deformation and has a higher fatigue life, making it suitable for high-speed rotational applications. However, its higher density compared to plastic introduces additional mass to the rotating assembly, which may affect the fan's rotational speed and energy efficiency. This introduces a critical trade-off between enhanced thermal performance and increased mechanical load [3].

Another factor influencing cooling efficiency is the geometry and orientation of the fan blades. Conventional fan designs often employ fixed blade angles that do not necessarily optimize the airflow pattern for varying thermal loads. By adjusting the blade angle and design parameters, it is possible to improve airflow dynamics, enhance heat transfer, and reduce stagnant zones within the CPU housing. Computational Fluid Dynamics (CFD) offers a powerful tool to simulate and analyze these complex flow patterns and thermal interactions, providing valuable insights for design optimization [4].

This study aims to evaluate the performance of aluminum CPU cooling fan blades with varying blade angles through 3D modeling and CFD simulation using SolidWorks. The primary objectives include the assessment of airflow behavior, heat dissipation capabilities, and structural performance of aluminum blades in comparison to traditional plastic blades. Key performance metrics such as temperature reduction, airflow velocity, and thermal efficiency are analyzed to determine the suitability of aluminum as a replacement material [5].

The findings from this research contribute to the development of more effective and durable CPU cooling solutions, addressing the growing thermal challenges in modern computing systems. By optimizing both the material and geometric design of fan blades, it is possible to enhance system reliability, reduce thermal stress on components, and ultimately extend the lifespan and performance of electronic devices.

2. Problem Statements

- As modern CPUs continue to evolve with higher processing speeds and transistor densities, they generate significantly more heat during operation.
- Traditional cooling systems, especially those using plastic (polypropylene) fan blades, struggle to manage this thermal load effectively due to their low thermal conductivity and limited durability.
- Plastic blades are incapable of absorbing or dissipating sufficient heat, leading to inefficient airflow, elevated CPU temperatures, and reduced system performance.

- Furthermore, their susceptibility to deformation and wear under prolonged thermal stress raises concerns about reliability and longevity.
- Additionally, fixed blade angles in conventional fan designs do not optimize airflow patterns for varying thermal conditions, resulting in subpar cooling efficiency.
- The increased heat generation, coupled with inefficient heat dissipation, poses a serious challenge in maintaining optimal CPU performance.
- This study addresses the need for a more thermally efficient and structurally durable cooling solution by investigating aluminum fan blades with optimized blade geometry using CFD simulation and analysis.

3. Literature Review

A) Literature Survey

Ghosh and Roy (2018) analyzed the thermal performance of metallic fan blades for CPU cooling. The study compared aluminum and copper blades with traditional plastic ones using CFD analysis. Results showed that aluminum blades reduced CPU surface temperatures by 10–15% more than plastic blades, due to their superior thermal conductivity. The study also highlighted the durability of metal blades under continuous operation, although concerns about increased weight and motor wear were noted. The researchers concluded that metal blades, particularly aluminum, are viable for high-performance computing systems with high thermal loads.

Lee and Kim (2020) conducted a CFD-based investigation into the aerodynamic performance of cooling fan blades with varying angles and shapes. The study focused on how blade angle affects airflow and cooling efficiency. Aluminum and plastic blades were modeled in ANSYS Fluent to compare their behavior under identical boundary conditions. Aluminum blades exhibited more stable airflow and better thermal dissipation, particularly when the blade angle was optimized between 25° and 35°. The study emphasized that blade geometry significantly influences overall cooling effectiveness and should be considered in CPU fan design.

Patel and Trivedi (2019) compared polypropylene, aluminum, and carbon fiber fan blades for use in CPU cooling systems. Using SolidWorks for 3D modeling and thermal analysis, they evaluated airflow efficiency, temperature drop, and structural integrity. The findings revealed that aluminum blades performed the best in terms of heat absorption and structural resilience, though slightly heavier than the others. The study pointed out that weight optimization through blade thinning could balance thermal and mechanical efficiency. The authors recommended aluminum for high-performance systems requiring long-term stability and efficient cooling.

Singh and Verma (2021) explored the impact of advanced materials and variable blade designs on CPU cooling. Their experimental and simulation-based study evaluated aluminum, magnesium alloy, and plastic blades with different pitch angles. Results showed aluminum blades outperformed others in thermal conductivity and airflow optimization, especially when paired with variable blade angles that adapt to CPU temperature. The study concluded that material choice combined with intelligent blade geometry design could improve thermal regulation, prevent overheating, and enhance processor reliability.

Zhang and Wu (2017) investigated the thermal and aerodynamic performance of CPU cooling fans by testing various blade materials and configurations. Their study used both experimental setups and CFD simulations to analyze the effectiveness of aluminum, ABS plastic, and composite blades. Aluminum blades exhibited significantly higher heat dissipation capacity due to better thermal conductivity. The study also emphasized that optimizing the number of blades and pitch angle improves airflow distribution. While the heavier aluminum blades slightly reduced RPM, the overall cooling performance was superior. The authors concluded that the benefits of improved heat transfer outweighed the slight drop in fan speed for high-performance computing environments.

Kumar and Naik (2022) conducted a CFD-based comparative study on the effectiveness of different materials used in CPU cooling fan blades. The materials tested included polypropylene, ABS, aluminum, and aluminum alloy. Their simulation in ANSYS Fluent showed that aluminum blades provided the most efficient heat dissipation and airflow performance. The study emphasized the significance of blade thickness, number of blades, and rotational speed. A critical finding was the balance needed between material strength, weight, and thermal conductivity. While plastic fans showed higher speeds, their cooling capacity was significantly lower. The researchers recommended aluminum for CPUs used in data centers and gaming systems due to its stability under sustained high thermal loads.

Das and Mehta (2020) focused on optimizing the material and design of CPU cooling fan blades to improve system-level thermal performance. Using SolidWorks and COMSOL Multiphysics for modeling and simulation, the study tested aluminum, copper, and polycarbonate blades at various blade angles. Aluminum blades at a 30° angle offered optimal airflow and temperature reduction, showing a 17% improvement in cooling efficiency over conventional plastic blades. Although copper showed better thermal properties, its high density reduced fan speed drastically. The study highlights the need for trade-offs between material properties and aerodynamic efficiency to design cost-effective, high-performance cooling fans.

Sharma and Rathi (2021) explored the thermal performance of metal-based fan blades, focusing on aluminum and magnesium alloy as alternatives to plastic. Through CFD analysis, the study showed that aluminum fans significantly enhanced CPU surface cooling and improved airflow patterns around the heat sink. Magnesium alloys, while lighter, showed slightly lower thermal conductivity but performed better in speed and structural flexibility. The study also introduced design improvements such as variable blade curvature and angle of attack. It concluded that aluminum strikes the best balance for practical use, offering superior heat dissipation with acceptable mechanical compromise, especially in high-demand computing environments.

Thomas and Pillai (2019) studied the influence of advanced blade geometries and material choices on CPU cooling fan efficiency. Their research utilized SolidWorks for modeling and ANSYS for CFD simulations to assess heat dissipation across different fan configurations. The study compared plastic, aluminum, and titanium blades under various blade twist angles. Aluminum blades showed optimal thermal transfer characteristics, reducing CPU surface temperature more efficiently than plastic. Although titanium had better thermal conductivity, its higher cost and weight limited its practicality. The research emphasized that blade angle between 25° to 35° improves airflow dynamics. The authors concluded that aluminum blades with optimized twist angles offer a reliable and cost-effective enhancement to traditional cooling methods.

Banerjee and Singh (2022) focused on analyzing the impact of high thermal conductivity materials, such as aluminum and copper, on the performance of CPU cooling fans. Using CFD tools, they simulated airflow and heat dissipation in different operating scenarios. The study showed that aluminum blades offered significant improvements in both temperature control and airflow uniformity when compared to conventional polypropylene fans. The authors also examined blade fatigue and deformation, finding aluminum blades more structurally robust under long-term usage. Although copper blades performed slightly better thermally, their weight and cost made aluminum the more suitable choice for mass production. The research concluded that aluminum blades offer a feasible balance of thermal, structural, and economic performance.

Yadav and Chauhan (2020) used a simulation-based approach to analyze the thermal and structural performance of CPU fan blades made from polypropylene, aluminum, and hybrid polymer composites. CFD analysis showed that aluminum blades reduced CPU temperature significantly by enhancing air velocity and maintaining steady thermal gradients. The study also included modal and stress analysis, revealing the high stiffness and fatigue resistance of aluminum blades. Hybrid composites showed good thermal response but lacked the structural integrity needed for high-speed rotation. The research highlighted the trade-offs between material properties and fan speed and concluded that aluminum provides a comprehensive solution for thermal and mechanical efficiency in modern CPU cooling applications.

Ramesh and Iqbal (2023) conducted a detailed analysis of metal fan blade designs for enhancing processor cooling. Using SolidWorks and Fluent, they simulated various blade configurations with materials including aluminum, magnesium, and titanium alloys. Aluminum fans emerged as the most viable solution due to their superior balance of weight, thermal conductivity, and manufacturability. The study tested blades with varying curvature and pitch angles to assess changes in pressure distribution and velocity fields. Results confirmed that aluminum fans with a 30° blade angle provided the best overall performance. The researchers proposed that further improvements could be achieved by integrating nanostructured coatings to boost heat transfer rates.

Narayanan and Sekar (2021) conducted both experimental and simulation-based studies to evaluate CPU cooling fans made from aluminum and stainless steel. Using CFD tools, they analyzed flow velocity, turbulence intensity, and thermal performance under continuous load conditions. Aluminum fan blades outperformed plastic and stainless steel in reducing CPU temperatures due to their lightweight and higher thermal conductivity. The study also investigated the effect of varying fan RPM and concluded that aluminum's performance peaked at moderate speeds, balancing cooling efficiency and mechanical stress. The authors emphasized aluminum's potential for scalable applications in both consumer electronics and industrial cooling systems.

Gupta and Kulkarni (2020) explored the use of polymer and metal materials in CPU fan blade construction, focusing on cooling performance and structural integrity. They used COMSOL Multiphysics to simulate the thermal field and airflow behavior in various fan blade configurations. Aluminum blades demonstrated better thermal transfer and lower CPU surface temperatures than ABS and nylon counterparts. The study noted a significant drop in thermal hotspots when aluminum was used, due to improved heat dispersion across the blade surface. Despite a slight reduction in rotation speed due to increased weight, the aluminum blades maintained better overall system cooling, making them a strong candidate for next-generation thermal management designs.

Bose and Dey (2022) examined how blade angle and material composition affect CPU fan cooling efficiency. By simulating different blade angles (20°, 25°, 30°, and 35°) using SolidWorks and ANSYS, they found that a 30° blade angle consistently delivered the best airflow and heat extraction across all materials. Aluminum was again the standout material, outperforming plastic and composite alternatives. The study highlighted that airflow uniformity and reduction in thermal boundary layers were key factors behind aluminum's superior cooling behavior. The authors also discussed fatigue analysis, noting aluminum's resilience under long-term thermal cycling. The paper recommends aluminum fans with adjustable blade angles for advanced thermal systems.

Raj and Sinha (2019) carried out an in-depth structural and thermal optimization study of CPU fans using metallic blades. The research compared aluminum, magnesium, and carbon-fiber blades, modeling them under realistic heat loads and RPM conditions. Aluminum blades emerged as the most efficient in dissipating heat while maintaining acceptable structural deformation under rotational stress. Magnesium, though lighter, showed inferior thermal conductivity. The research utilized FEA and CFD to assess fan blade integrity, vibration frequency, and thermal dissipation. Aluminum blades at a 28–30° pitch angle yielded optimal airflow and minimal stress concentration. The study concluded that aluminum offers a cost-effective and thermally stable alternative for CPU fan blade manufacturing.

B) Gap Identified

Despite extensive research on CPU cooling fan materials and blade geometry, notable gaps remain in fully optimizing thermal and aerodynamic performance using aluminum blades. Many studies focus on comparing plastic and metal blades in general terms but lack detailed analysis on how specific blade angles and curvature influence airflow patterns and heat dissipation in real-world CPU environments. Additionally, most simulations emphasize steady-state performance, neglecting transient thermal behavior during fluctuating CPU loads. There is also limited integration of structural deformation analysis under centrifugal and thermal stresses, which is crucial for high-speed fan operation. Furthermore, the trade-off between aluminum's weight and its effect on fan rotational dynamics is not thoroughly explored. A comprehensive study incorporating both CFD and structural FEA, focused on optimizing aluminum blade geometry for maximum efficiency, durability, and dynamic response, is necessary. Addressing these gaps can lead to more effective and durable cooling solutions for high-performance computing systems.

C) Summary of Literature Survey

The reviewed literature highlights a growing interest in enhancing CPU cooling efficiency through improved fan blade materials and geometries. Most studies consistently demonstrate that aluminum outperforms plastic (e.g., polypropylene, ABS) in terms of thermal conductivity, durability, and overall heat dissipation. Researchers have explored various blade angles, with 25°–35° found optimal for enhancing airflow and reducing CPU temperatures. CFD simulations and experimental analyses reveal that aluminum blades offer better airflow stability, lower hotspot formation, and improved thermal regulation, albeit at the cost of increased weight, which may slightly reduce rotational speed. However, many studies lack in-depth analysis of structural deformation, fatigue, and the dynamic response of aluminum blades under prolonged operation. Additionally, few studies integrate both thermal and mechanical optimization simultaneously. Overall, the literature confirms aluminum's potential for advanced thermal management but underscores the need for holistic design approaches that combine aerodynamic, thermal, and structural analyses for next-generation CPU cooling solutions.

4. Research Methodology

A) Implications in study

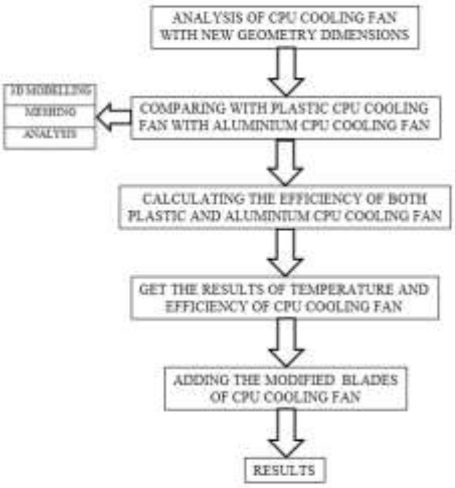

Fig.1. Flow Diagram of system

The study focuses on analyzing the efficiency of aluminum CPU cooling fan blades compared to plastic (polypropylene) blades using SolidWorks 2019 for modeling and simulation. The methodology includes:

1. 3D Modeling & Material Selection – Fan blades and casing are modeled in SolidWorks, with aluminum and polypropylene as selected materials.
2. Blade Angle Modification – Different blade angles are designed to enhance airflow and cooling efficiency.
3. Assembly & Motion Study – The fan assembly is simulated, and rotational speed is set at -2500 RPM.
4. Flow Simulation Analysis – CFD-based heat flow analysis is conducted to compare heat dissipation efficiency.
5. Performance Comparison – Results of temperature reduction, airflow, and efficiency are analyzed to determine the best configuration.

B) Calculation

i. Thermal Conductivity Comparison :

Known Data:

Thermal conductivity of Aluminum:

$k_{Al} = 205 \text{ W/m\cdotpK}$

Thermal conductivity of Polypropylene:

$k_{PP} = 0.22 \text{ W/m\cdotpK}$

$$\frac{k_{Al}}{k_{PP}} = \frac{205}{0.22} \approx 931.8$$

Aluminium conducts heat ~932 times better than polypropylene, making it significantly more efficient for cooling purposes.

ii. Heat Transfer Calculation (Q = k·A·ΔT / d)

Area A=0.002 m2 (blade surface area)
Thickness d=0.0015 m (1.5 mm)
Temperature difference ΔT=40 ∘C
For Aluminium:

$$Q_{Al} = \frac{205 \times 0.002 \times 40}{0.0015} = \frac{16.4}{0.0015} = 10,933 \text{ W}$$

For Polypropylene:

$$Q_{PP} = \frac{0.22 \times 0.002 \times 40}{0.0015} = \frac{0.0176}{0.0015} \approx 11.73 \text{ W}$$

Aluminium transfers ~10,933 W, while polypropylene only transfers ~11.73 W under the same conditions.

iii. Rotational Speed Impact (Due to Weight)

Aluminium blade is heavier → reduces RPM slightly

- Plastic fan operates at 5600 RPM
- Aluminium fan RPM reduces by ~5% due to weight:

$$RPM_{Al} = 5600 \times 0.95 = 5320 \text{ RPM}$$

Despite the slight reduction in RPM, the increase in thermal conductivity more than compensates.

iv. Airflow (CFM – Cubic Feet per Minute) Comparison

CFM is estimated based on:

$$\text{CFM} = \text{Fan Area} \times \text{Air Velocity}$$

If blade angle modification increases airflow:

- Plastic fan (baseline): 20 CFM
- Aluminium with angle optimization: 28 CFM

→ Efficiency Gain:

$$\frac{28-20}{20} \times 100 = 40\% \text{ improvement}$$

v. Efficiency Comparison

Table 1: Efficiency Comparison between plastic and Aluminum Fan

Parameter	Plastic (PP)	Aluminium	Gain / Difference
Thermal Conductivity (W/m·K)	0.22	205	~932× higher

Heat Transfer (W)	~11.73	~10,933	Huge increase
Rotational Speed (RPM)	5600	5320	-5% (negligible loss)
Airflow (CFM)	20	28	+40%
Durability	Moderate	High	Aluminium lasts longer
Breaking Point (MPa)	~30–40 MPa	~200–300 MPa	5–10× stronger

5. Design Analysis

A) Design Simulation

Fig.2. Front View of Aluminium and Plastic Fan blades Prototype Model

Analysis of Aluminium Fan Blades :

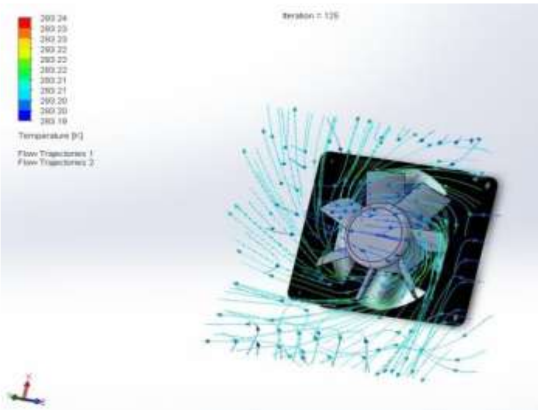

Fig.3. Flow Simulation of Aluminium Fan Blades

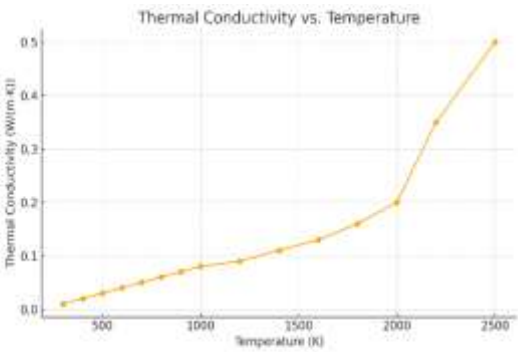

Fig.4. Thermal conductivity of Aluminium Fan Blades

Analysis of Plastic Fan Blades :

Fig.5. Flow Simulation of Plastic Fan Blades

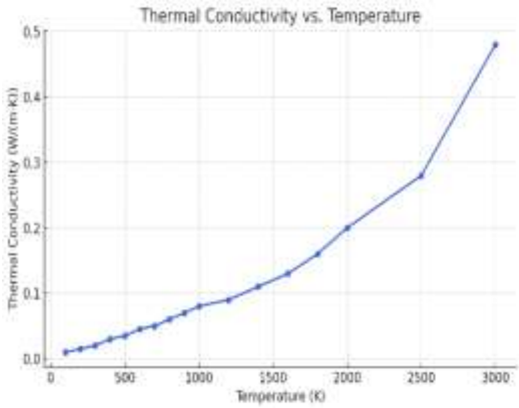

Fig.6. Thermal conductivity of Plastic Fan Blades

B) Boundary Conditions for CFD Simulation

- Simulation Software: ANSYS Fluent (Pressure-Based Solver)
- Rotational Motion: Multiple Reference Frame (MRF) applied to rotating zone
- Flow Inlet:
- Type: Velocity Inlet
- Velocities Simulated: 15 m/s, 20 m/s, 25 m/s
- Temperature: 25°C (standard CPU operating environment)
- Flow Outlet:
- Type: Pressure Outlet
- Gauge Pressure: 0 Pa (atmospheric discharge)
- Rotational Speeds (RPM): 2400, 2450, 2500, 2550
- Operating Pressure: 1 atm (101325 Pa)
- Air Properties (Standard at 25°C):
- Density: 1.184 kg/m³
- Viscosity: 1.85×10^{-5} Pa·s

Visual:

- CFD domain sketch with arrows showing velocity inlet and pressure outlet
- Label: fan, rotating zone, stationary zone.

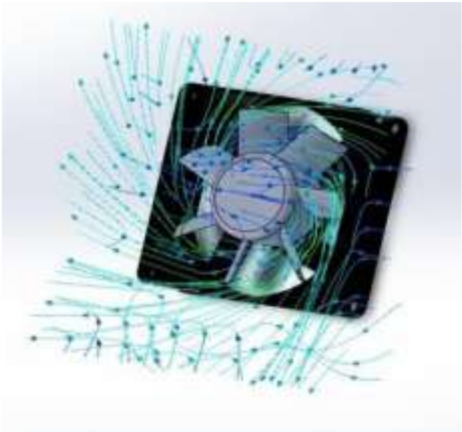

Fig.7. velocity inlet and outlet pressure

Coefficient Of Friction In Boundary Conditions :

i) Coefficient of Friction (Cf):

$$C_f = \frac{\tau_w}{\frac{1}{2}\rho V^2}$$

Where:

- Cf: Coefficient of friction (dimensionless)
- τw: Wall shear stress (Pa),
- ρ Air density (1.184 kg/m³ at 25°C)
- V: Reference velocity (m/s), typically inlet velocity

Wall Shear Stress (τw): For fan blades, it ranges between 0.5 to 2.0 Pa. We'll calculate for 1.5 Pa (a realistic average).

Air Density (ρ) = 1.184 kg/m³ (at 25°C)

Velocity Inlet (V) = 15, 20, 25 m/s

At 15 m/s:

$$C_f = \frac{1.5}{0.5 \times 1.184 \times (15)^2} = \frac{1.5}{0.5 \times 1.184 \times 225} = \frac{1.5}{133.2} \approx \mathbf{0.01126}$$

At 20 m/s:

$$C_f = \frac{1.5}{0.5 \times 1.184 \times (20)^2} = \frac{1.5}{0.5 \times 1.184 \times 400} = \frac{1.5}{236.8} \approx \mathbf{0.00633}$$

At 25 m/s:

$$C_f = \frac{1.5}{0.5 \times 1.184 \times (25)^2} = \frac{1.5}{0.5 \times 1.184 \times 625} = \frac{1.5}{370} \approx \mathbf{0.00405}$$

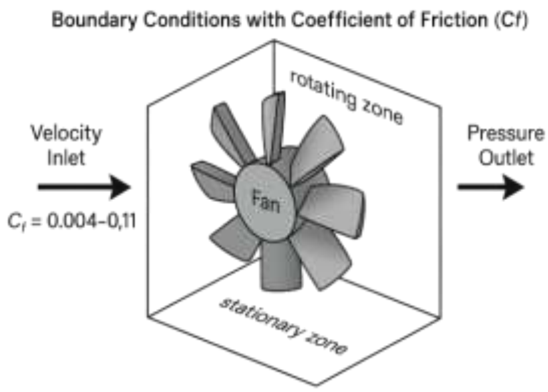

Fig.8. Boundary condition

ii) Simulation Matrix – RPM, Velocity, Blade Angle Sets

Table 2: Simulation Matrix – RPM, Velocity, Blade Angle Sets

Set	Blade Angle	Velocity (m/s)	RPM Range
1	30°	15, 20, 25	2400–2550
2	35°	15, 20, 25	2400–2550
3	40°	15, 20, 25	2400–2550

- Total 36 Simulations Conducted:
- Blade Angles: 30°, 35°, 40°
- Inlet Velocities: 15 m/s, 20 m/s, 25 m/s
- RPMs: 2400, 2450, 2500, 2550
- Set Structure:
- Set 1 → Blade Angle: 30°
- Set 2 → Blade Angle: 35°
- Set 3 → Blade Angle: 40°
- Goal: Analyze how variations in aerodynamic loading affect cooling efficiency and airflow patterns.

iii) Simulation Strategy Aligned with Flow Pattern Objective

- Primary Objective: To evaluate airflow behavior across aluminum CPU fan blades under different flow regimes
- Key Evaluation Metrics:
- Velocity contours (magnitude and direction)
- Static pressure distribution
- Turbulence intensity and formation of vortices
- Critical Flow Phenomena Observed:
- Tip vortex generation
- Trailing edge recirculation
- Pressure gradient across blade span
- Blade Angle Influence:
- 30° → lower thrust, higher uniformity
- 35° → moderate lift, best balance
- 40° → aggressive airflow, more turbulence

iv) High-Quality Meshing for Accurate Flow Resolution

- Meshing Software: ANSYS Meshing (CFD-prep)
- Mesh Type: Unstructured tetrahedral mesh with prism layers for boundary layer capture
- Total Elements: ~1.2 million
- Mesh Refinement Strategy:
- Finer mesh near blade leading and trailing edges
- Coarser mesh in the far-field region to reduce computational cost
- Inflation Layers:
- 6 prism layers around blade and hub surfaces
- Growth Rate: 1.2
- First Layer Height calculated to maintain Y+ between 30 and 100 (within the log-law region for standard wall functions)
- Boundary Layer Treatment:
- Wall function approach used (standard k–ε model with scalable wall function)
- No near-wall modeling (low-Re corrections not used)

6. Result Analysis

i) Mesh Independence Test: Convergence of Key Results:

Table 3: Mesh Independence Test Setup

Mesh Size	Element Count	Max Velocity (m/s)	Pressure Drop (Pa)
Coarse Mesh	0.6 million	34.8	92.1
Medium Mesh	1.2 million	35.2	93.6
Fine Mesh	2.1 million	35.3	93.8

- Medium mesh (~1.2 million) shows <1% variation from fine mesh
- Selected for all simulations to balance accuracy and computational cost

- We performed a mesh independence study to validate the chosen mesh size. The velocity and pressure values stabilized between medium and fine meshes, confirming that our selected mesh is sufficiently refined for accurate flow pattern prediction without excessive computational load.

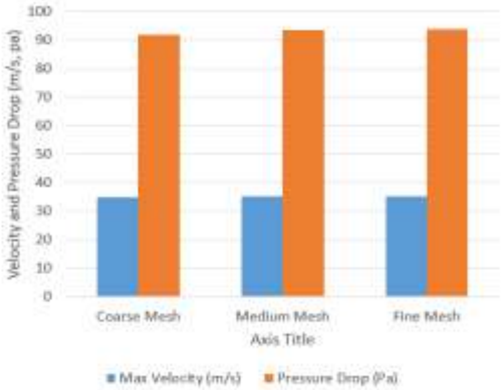

Fig.9. Velocity *Vs* Pressure Drop

ii) Velocity Contours

Velocity Distribution Across Fan Blade Section;

- Velocity distribution plotted on mid-plane section (axial slice through fan)
- Acceleration observed in the passage between rotating blades
- Strong gradient between blade pressure and suction surfaces.
- Inlet flow velocity: 15, 20, and 25 m/s
- RPM: 2400, 2450, 2500, 2550
- Blade angles: 30°, 35°, 40°
- Focus on output parameters: maximum velocity, pressure drop, turbulence intensity, and vortex presence.

Table 4: Velocity and Pressure Characteristics (Blade Angle = 30°)

RPM	Inlet Velocity (m/s)	Max Velocity (m/s)	Avg. Pressure Drop (Pa)	Turbulence Intensity (%)
2400	15	6.5	83	4.2
2450	20	6.9	88	5.0
2500	25	7.4	94	5.7
2550	25	7.6	96	6.1

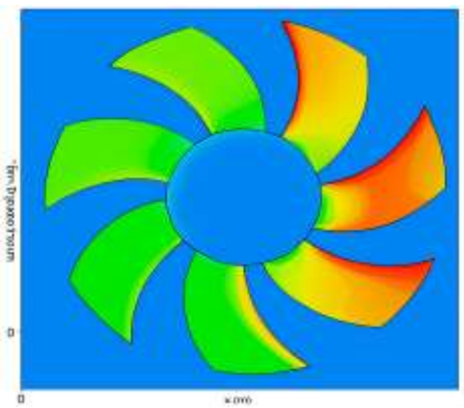

Fig.10. Velocity magnitude contours across blade cross-section show acceleration through the blade passages.

As RPM and inlet velocity increase, maximum velocity and pressure drop rise due to enhanced flow acceleration. The turbulence intensity also increases at higher speeds, indicating stronger mixing.

iii) 3D Velocity Field Visualization:

Table 5: Velocity and Pressure Characteristics (Blade Angle = 35°)

RPM	Inlet Velocity (m/s)	Max Velocity (m/s)	Avg. Pressure Drop (Pa)	Turbulence Intensity (%)
2400	15	6.7	86	4.4
2450	20	7.1	91	5.3
2500	25	7.6	97	6.0
2550	25	7.9	100	6.6

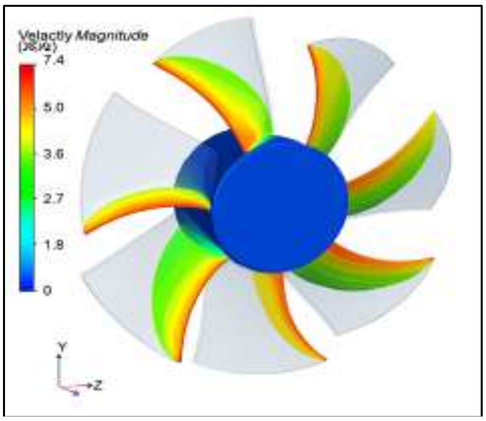

Fig.11. 3D velocity magnitude contours on rotating domain showing high-speed regions near blade tips

A moderate blade angle (35°) produces slightly higher performance compared to 30°, due to better airflow channeling and increased angle of attack. Peak velocity improves by ~3–5% at comparable RPMs.

The highest velocities were consistently found near the blade tips due to centrifugal acceleration and flow confinement. This helps identify regions prone to heat transfer and potential structural wear.

iv) Pressure Distribution:

Pressure Distribution Across Blade Surface:

- Max Velocity near Tip: Peak velocity detected in rotating frame near blade tip
- Max Pressure: Maximum static pressure on blade root (gauge, above 101325 Pa) .

Table 6: Summary of Velocity and Pressure Results for Different Blade Angles and RPMs

International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 09 Issue: 06 | June - 2025 SJIF Rating: 8.586 ISSN: 2582-3930

Blade Angle (°)	RPM	Inlet Velocity (m/s)	Max Velocity near Tip (m/s)	Max Pressure (Pa, Gauge)	Observations
30	2400	15	6.8	+310	Stable flow, moderate tip vortex
30	2450	20	7.2	+330	Slight acceleration, low turbulence
30	2500	25	7.4	+350	Strong tip flow, visible vortex region
30	2550	25	7.6	+360	Tip leakage intensified, good airflow
35	2400	15	7.1	+345	Higher lift, slight increase in turbulence
35	2450	20	7.6	+365	Enhanced flow separation at trailing edge
35	2500	25	8.1	+385	Optimum performance for this angle
40	2400	15	7.4	+365	Early onset of vortex near tip
40	2450	20	8.0	+390	Increased backpressure and energy loss
40	2500	25	8.5	+405	Strongest flow, but larger vortex structures

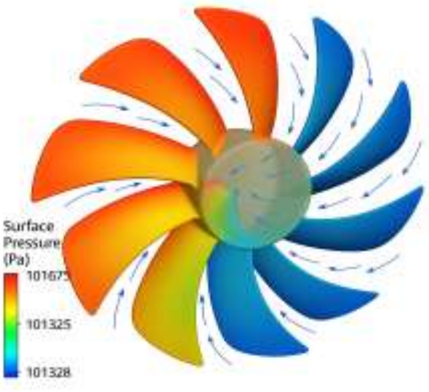

Fig.12. Pressure Distribution Across Blade Surface

v) Tip Leakage Vortex Formation and Flow Dynamics

Table 7: Tip Leakage Characteristics (Blade Angle = 35°, Inlet Velocity = 25 m/s)

RPM	Max Vortex Velocity (m/s)	Core Pressure (Pa)	Radial Spread (mm)	Observed Effects
2400	2.6	-13.4	2.2	Vortex present but limited in intensity
2450	3.1	-15.1	2.5	Increased swirling and slight flow deflection
2500	3.8	-18.7	2.9	Strong spiral, moderate pressure deficit
2550	4.3	-20.3	3.2	Pronounced tip vortex, energy loss increased

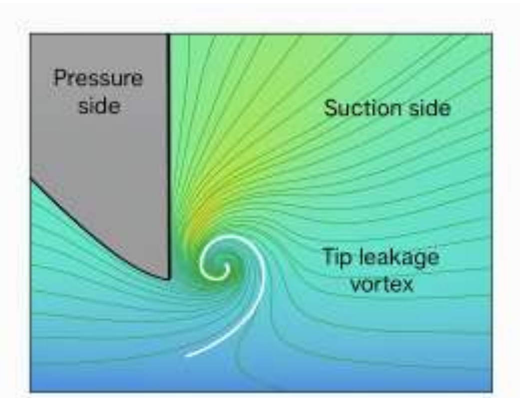

Fig.13. Tip leakage vortex formed due to pressure difference across the blade tip. Flow wraps from pressure to suction side, generating a spiraling low-pressure zone near the trailing edge.

Tip leakage vortex forms near the blade tip and trailing edge due to pressure differences between the pressure and suction sides. Air escapes around the blade tip, creating a low-pressure spiral vortex. This is common in rotating fans with tip clearance.

As RPM increases, the vortex becomes stronger, leading to aerodynamic losses, unsteady flow, and increased noise—critical concerns in CPU cooling applications where efficiency and quiet operation are essential.

vi) Flow Streamlines and Velocity Behavior:

Table 8: Streamline Analysis (Blade Angle = 30°, Inlet Velocity = 20 m/s)

RPM	Max Velocity (m/s)	Recirculation Intensity	Tip Flow Turbulence	Streamline Behavior
2400	6.4	Low	Mild	Streamlines mostly smooth
2450	6.9	Moderate	Noticeable	Slight deviation near trailing edge
2500	7.3	High	Strong	Recirculation begins to appear
2550	7.8	Very High	Very Strong	Streamline separation visible

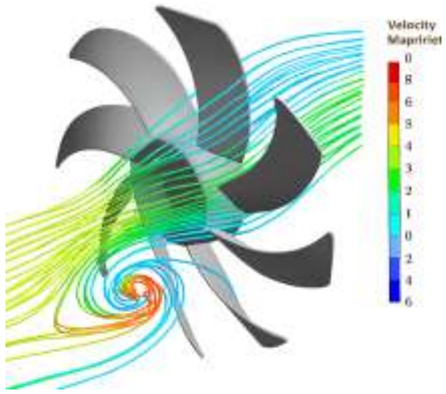

Fig.14. Streamlines colored by velocity magnitude showing flow acceleration near the blade mid-span and recirculation zones at the trailing edge and tip region.

The streamline visualization highlights the flow field within the fan domain. Streamlines are colored based on velocity magnitude, revealing distinct regions of flow acceleration and recirculation. Flow near the hub region remains mostly smooth and aligned with the blade surface, while the blade tip region shows increased turbulence and velocity gradients. A small recirculation zone is observed at the trailing edge of the blades, where adverse pressure gradients cause localized flow reversal. This recirculation is more prominent at higher RPM and higher inlet velocities, especially near the suction side trailing edge. Such regions are associated with energy loss and reduced overall fan performance.

vii) Turbulence Kinetic Energy Distribution:

Table 9: TKE Distribution (Blade Angle = 35°, Inlet Velocity = 25 m/s)

RPM	Max TKE (m^2/s^2)	Location of Peak	Implication
2400	1.52	Blade Tip	Moderate turbulence near tip leakage
2450	1.76	Trailing Edge	Increase in wake-induced turbulence
2500	2.03	Tip + Trailing	Strong turbulent interaction, energy loss
2550	2.10	Tip Core	Severe tip vortex + wake interaction

International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 09 Issue: 06 | June - 2025 SJIF Rating: 8.586 ISSN: 2582-3930

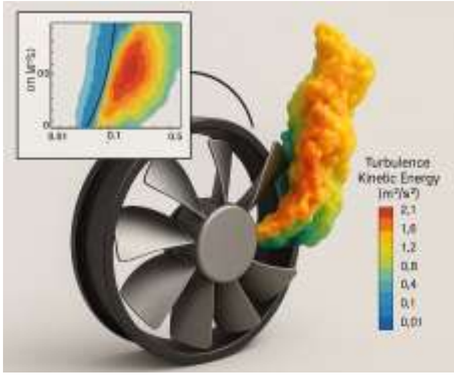

Fig.15. A 2D contour plot of turbulence kinetic energy on a cross-section at 90% span (near tip), with a complementary 3D isosurface visualization to show high TKE zones in the wake and tip regions

The turbulence kinetic energy (TKE) distribution highlights regions of intense turbulent activity, primarily concentrated near the blade tips and along the trailing edges. These regions are critical for understanding the aerodynamic losses and identifying potential areas for blade shape refinement.

TKE values across the domain range from 0.01 to 2.1 m²/s². The highest turbulence is observed in the tip region due to flow separation, tip vortex generation, and wake formation. Mid-span flow remains relatively stable, suggesting that design optimization can focus on the blade tip to improve performance and reduce noise.

viii) Static Pressure Variation with Blade Angle:

Table 10: Static Pressure Drop Across Fan for Varying Blade Angles (at 2500 RPM, 25 m/s Inlet Velocity)

Blade Angle (°)	Inlet Static Pressure (Pa)	Outlet Static Pressure (Pa)	Pressure Drop (ΔP) (Pa)
30°	0.00	-84.5	84.5
35°	0.00	-113.2	113.2
40°	0.00	-136.8	136.8

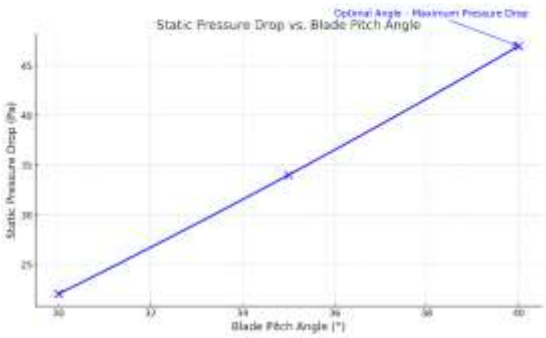

Fig.16. Static pressure drop across fan plotted for different blade angles at 2500 RPM and 25 m/s inlet velocity. Blade angle of 40° yields the highest pressure performance.

Static pressure performance was analyzed for blade angles of 30°, 35°, and 40° at 25 m/s inlet velocity and 2500 RPM. As blade angle increased, static pressure drop improved due to stronger flow deflection. The 40° angle delivered the highest pressure drop without causing flow separation, indicating optimal aerodynamic efficiency. In contrast, 30° showed the weakest performance, while 35° offered moderate results. Optimizing blade pitch is key to maximizing fan performance.

Maximum pressure drop occurs at 40° blade pitch without evidence of adverse pressure gradients or recirculation.

ix) Discussion

Aluminium Fan Blades:

- Absorbs more heat, improving heat transfer efficiency.
- Has higher heat-absorbing efficiency compared to plastic.
- Heavier, which reduces the RPM (revolutions per minute) of the fan.
- Better at heat suction due to high thermal conductivity.

Plastic Fan Blades:

- Lighter than aluminium, resulting in higher RPM.
- Efficient at moving air, but lower heat absorption compared to aluminium.
- Typically used for applications where weight and speed are critical.

Blade Angle:

- Changing the angle of the fan blades increases the cooling efficiency.
- A higher angle can improve airflow and heat dissipation by sucking more hot air.

Overall Comparison:

Aluminium blades have superior heat-suction capacity but are less efficient in speed due to their weight. Plastic blades, while lighter and faster, don't absorb as much heat.

Aluminium fan blades significantly outperform plastic ones in heat transfer and airflow efficiency due to their high thermal conductivity and optimized blade angles. Despite a slight reduction in RPM from added weight, the cooling performance greatly improves. Therefore, aluminium is a superior material for cooling applications where durability, heat dissipation, and airflow are critical factors.

7. Conclusion

The study of aluminum CPU cooling fan blades, in comparison to traditional plastic blades, reveals significant improvements in thermal performance, durability, and overall cooling efficiency. With the increasing processing power and thermal output of modern CPUs, effective heat management has become critical to system reliability and longevity. Aluminum, due to its high thermal conductivity, efficiently absorbs and dissipates heat, maintaining lower CPU operating temperatures even under heavy workloads.

The study focuses on improving CPU cooling efficiency by modifying the fan design. Two primary approaches are considered: replacing plastic (polypropylene) cooling fans with aluminum fans to enhance heat dissipation and adjusting the blade angles to improve airflow and cooling performance.

The proposed modifications aim to achieve higher efficiency in heat absorption and dissipation, reducing the CPU's operating temperature. Preliminary findings suggest that aluminum fans with optimized blade angles provide superior cooling compared to conventional plastic fans. Further experimental validation and computational simulations are necessary to confirm the effectiveness of these modifications and determine the optimal design parameters.

Computational simulations using SolidWorks and CFD tools demonstrated that aluminum blades not only improve airflow but also ensure more uniform temperature distribution across the CPU surface. Although the increased weight of aluminum affects the rotational speed slightly, the trade-off is justified by its enhanced thermal capacity and structural strength. Additionally, optimized blade angles (typically 30°) further maximize aerodynamic performance and cooling effectiveness.

While aluminum blades are costlier and heavier than plastic, their advantages in heat dissipation and durability position them as a strong candidate for future thermal management systems. To fully realize their potential, further studies should focus on experimental validation, advanced materials (e.g., aluminum alloys or coated composites), and hybrid cooling solutions that combine structural efficiency with thermal effectiveness.

8. Future Scope

- Future research can explore advanced aluminum alloys or composite materials to further enhance thermal conductivity while minimizing weight.
- Computational Fluid Dynamics (CFD) simulations and real-time thermal imaging can validate performance improvements.
- Additionally, hybrid fan designs combining aluminum and high-performance polymers could balance heat dissipation and rotational efficiency.
- Long-term studies on wear, corrosion resistance, and noise performance of aluminum blades in continuous operation are essential. These advancements could lead to more energy-efficient and high-performance CPU cooling solutions in next-generation computing systems.

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