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Optimizing Cooling Tower Length Fan Blade Standardization in Biodiesel Plants: Approach to Cost Savings and Efficiency Improvement

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Abstract

Cooling towers play a crucial role in dissipating heat from industrial processes, especially in biodiesel plants where thermal management is essential. However, the diversity of fan blade lengths currently in use results in increased maintenance complexity, higher inventory costs for spare parts, and inconsistent energy performance. This study addresses the challenge of optimizing cooling tower fan blade design by proposing a standardized blade length that can deliver a balance between operational efficiency and cost-effectiveness across biodiesel facilities. The main objectives of this research are to investigate the performance of standard cooling tower designs, to develop a new blade length configuration, and to evaluate its efficiency compared to existing setups. To achieve these goals, three different blade lengths 0.7 m, 1.0 m, and 1.5 m were analyzed using Computational Fluid Dynamics (CFD) simulations conducted in ANSYS Fluent. The simulations measured critical parameters such as generated torque, airflow velocity, and energy consumption under constant rotational speed (500 RPM). A systematic comparison was made to determine the best-performing design in terms of both energy output and cost savings. Results indicated that the 1.5 m blade length demonstrated the highest efficiency with the lowest cost per unit airflow, generating a torque of 8107.30 Nm and a power consumption of 424.42 kW. Conversely, the 0.7 m and 1.0 m blades offered reduced torque and airflow, but showed potential for further optimization through aerodynamic enhancements. Despite its superior performance, the longer blade increases operational and material costs, which must be weighed against energy benefits. In conclusion, while standardizing to a 1.5 m blade offers the best performance, the study highlights the importance of balancing energy efficiency with maintenance simplicity and cost. The findings provide strategic insights for biodiesel plants seeking to streamline operations and enhance system sustainability. This research also lays the foundation for broader standardization efforts in industrial mechanical systems.

1. Introduction

A Cooling towers are essential systems used across industrial and commercial sectors to remove excess heat by cooling water or other fluids through heat exchange processes. These towers function either by evaporation or air-based cooling, depending on whether they're of the wet or dry type. Their configurations natural or induced draft determine how air is introduced into the system. Key structural components such as the basin, fan deck, and spray system work in tandem to maintain performance and ensure efficient heat dissipation. However, several issues like scaling, corrosion, dirt accumulation, and foaming can compromise their efficiency. These challenges, along with tower size constraints and airflow dynamics, highlight the importance of optimizing fan components, especially in energy-intensive operations like geothermal or biodiesel power stations. By examining different fan blade lengths and standardization possibilities, it becomes possible to identify strategies that balance cooling performance, energy consumption, and maintenance costs.

Axial fans, frequently employed in cooling systems, are valued for their ability to deliver large volumes of air with low energy expenditure. Their performance, however, can be affected by several factors such as blade geometry, air density, and operational environment. In critical cooling environments like data centers and biofuel power plants, ensuring optimal fan performance is vital. Reducing blade lengths to cut costs, for instance, may diminish airflow efficiency and compromise system reliability. As such, this research seeks to assess the performance of a standard cooling tower design, propose a redesigned blade suited for the suction zone, and evaluate this new design's effectiveness. The goal is to develop a fan configuration that maintains thermal performance while reducing operational and maintenance costs through smart design adjustments.

2. Method

To perform an ANSYS simulation of a cooling tower fan blade, the process begins with defining the objective and understanding the operating conditions. The geometric model of the fan blade is then designed using CAD software, ensuring accuracy in blade profile and dimensions. This model is saved in IGES format and imported into ANSYS for further processing. Material properties, boundary conditions, and analysis type such as structural, modal, or CFD are configured to reflect real world performance. Next, the model is meshed with appropriate density for simulation precision. The solver executes numerical calculations to evaluate stress, deformation, and other physical responses. If the results meet performance expectations, the simulation moves forward; otherwise, parameters may be adjusted and reanalyzed. Finally, simulation results are validated through comparisons with experimental or theoretical benchmarks, ensuring the blade design is reliable and optimized before concluding the analysis.

2.1 Setup in ANSYS Fluent

Table 1 *Setup in ANSYS Fluent*

No.	Steps	Description
1	Geometry Modelling	The cooling tower, including fan blades of various length, is modeled to replicate the physical setup.
2	Meshing	A detailed mesh is generated to ensure accurate resolution of airflow and heat transfer within the cooling tower system
3	Boundary Conditions	Inlet air velocity, and ambient temperature are applied to simulate actual operating conditions.
4	Solver	Appropriate solver suitable numerical are choosed
5	Simulation runs	Multiple simulations are conducted with different blade lengths to assess their impact on airflow, cooling efficiency, and energy consumption.
6	Post Processing	Temperature distribution and energy consumption are analyzed to identify the optimal fan blade length for potential standardization

3. Result and Discussion

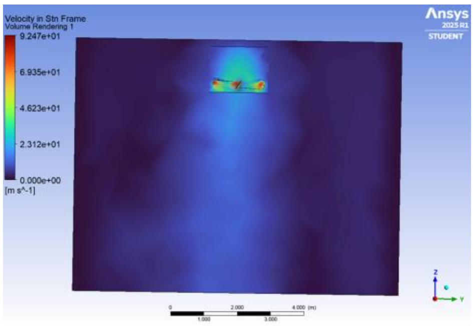
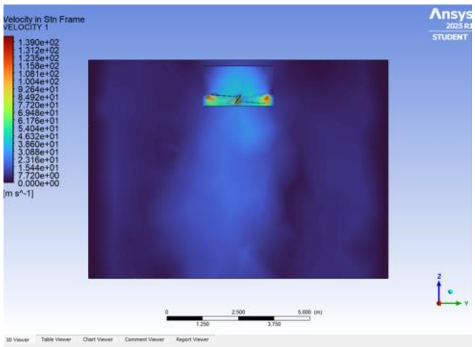
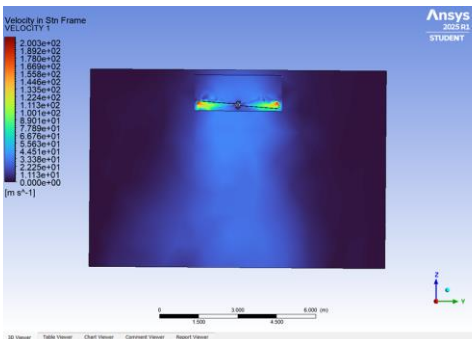
In this chapter, the results of the airflow, temperature and velocity collected once the simulation is done. In order to identify the pattern of the air flow towards variety of fan blade length the simulation graph, flow rate and colour contour is obtained. This approach are obtained by using the same parameter but difference fan blade length.

From this research, comparison of performance of a standardized blade designed for a 1.50 m, 1.00 m, and 0.70 m data to be collected will be velocity, temperature reduction and energy consumption. By collecting these data, will help to identify the best fan blade design for cooling towers and help create a more efficient and cost-effective cooling system for biodiesel plants.

3.1 Contour Colour

In this study, ANSYS Fluent was used to simulate the airflow behavior and thermal performance around a cooling tower fan blade. One of the key outputs of this computational fluid dynamics (CFD) analysis is the contour visualization, which illustrates critical flow characteristics such as velocity, pressure distribution, and temperature gradients across and around the fan blade geometry. These contour plots provide valuable insight into the aerodynamic behavior of the blade, revealing areas of high and low pressure, turbulence intensity, and potential zones of inefficiency. By analyzing these results, the performance of the blade under operational conditions can be evaluated, allowing for design improvements that enhance cooling efficiency, reduce energy consumption, and mitigate mechanical stress. This introductory section aims to present the significance of these contour results in understanding and optimizing cooling tower fan blade performance.

Table 1 *Contour Colour Result*

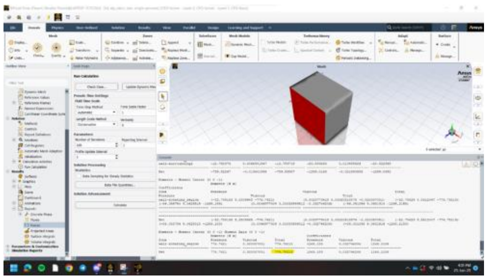
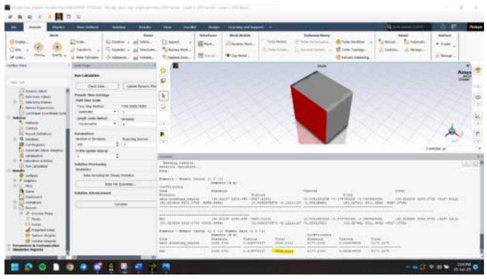
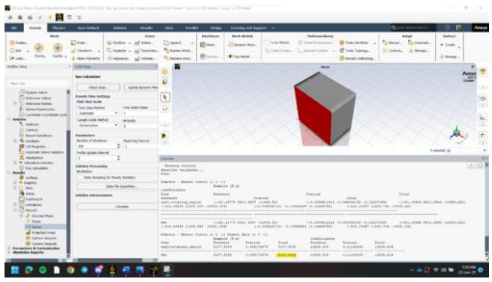
<table>
<tr><td>Length Blade (meter)</td><td>Contour Colour</td></tr>
<tr><td>0.7</td><td>
</td></tr>
<tr><td>1.0</td><td>
</td></tr>
<tr><td>1.5</td><td>
</td></tr>
</table>

The velocity contour plots from the ANSYS simulations for 0.7 m, 1.0 m, and 1.5 m fan blades reveal distinct airflow patterns and aerodynamic behaviors. The 0.7 m blade demonstrates effective upward airflow along the Z-axis, with high velocities concentrated near the blade and gradual dispersion through the tower. The 1.0 m blade shows intensified flow acceleration around the blade surface and wake, indicating stronger aerodynamic interactions within a 5 meter domain. The 1.5 m blade produces the highest velocity (up to 200.3 m/s), particularly along the leading and trailing edges, suggesting enhanced lift and torque generation. Collectively, these results highlight how blade length influences airflow distribution, velocity magnitude, and aerodynamic performance critical insights for optimizing cooling tower efficiency.

3.2 Generate Torque from ANSYS

In this thesis, torque generation analysis was conducted using ANSYS Fluent to evaluate the mechanical performance of axial fan blades in a cooling tower environment. Torque, as a critical parameter in rotating machinery, reflects the blade's ability to transfer aerodynamic force into rotational motion and is directly linked to power consumption and fan efficiency. Through computational fluid dynamics (CFD) simulation, pressure and velocity fields around the rotating blades were captured and used to compute torque values under steady-state conditions. These results provide insight into the aerodynamic loading on the blades and serve as a foundation for assessing the energy efficiency and structural demands placed on the motor and blade assembly. This section presents the methodology and key findings from the torque analysis, offering a basis for comparative performance evaluation across different blade designs.

Table 2 *Generate Torque from ANSYS Result*

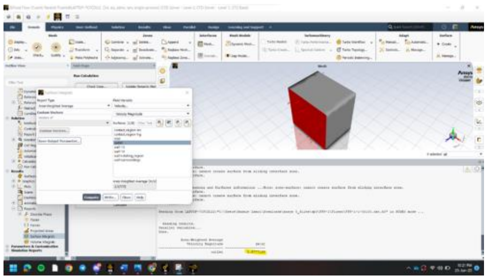
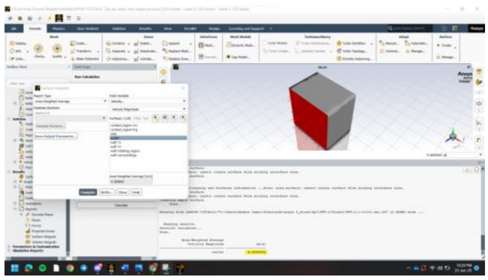
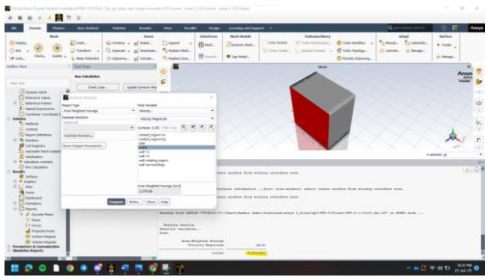
Length Blade (meter)	Generate Torque from ANSYS
0.7	
1.0	
1.5	

The torque analysis from ANSYS Fluent simulations for cooling tower fan blades of varying lengths reveals a clear trend in aerodynamic performance. For the 0.7 meter blade, the torque output was 776.782 Nm, with flow characteristics assessed using area-weighted average velocity to validate performance. The 1.0 meter blade simulation yielded a significantly higher torque of 2558.515 Nm, supported by a well-defined fluid-structure interaction setup. Meanwhile, the 1.5 meter blade produced the highest torque value of 8107.303 Nm, confirming a strong correlation between blade length and torque generation. These findings demonstrate that increasing blade length enhances aerodynamic force and rotational output, which is critical for optimizing cooling tower efficiency.

3.3 Generate Average Velocity from ANSYS

In this thesis, the average velocity across the surface of cooling tower fan blades was determined using ANSYS Fluent to evaluate aerodynamic performance under operational flow conditions. Average velocity serves as a key indicator of the airflow characteristics induced by blade geometry and rotation, providing insights into flow uniformity, effectiveness of air induction, and potential areas of aerodynamic loss. Through the use of surface integrals within the simulation environment, area-weighted velocity values were extracted over selected blade surfaces for each blade length. These values not only support the validation of flow behavior observed in velocity contour plots but also complement torque data by linking fluid dynamic inputs with mechanical output. This section outlines the methodology for capturing average velocity and discusses its implications for fan blade design and cooling efficiency.

Table 3 *Generate Average Velocity from ANSYS Result*

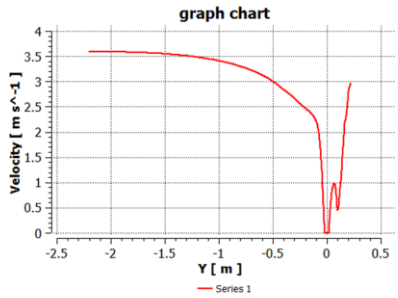
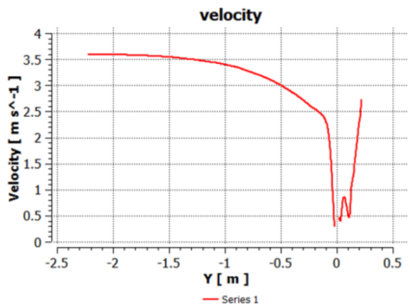
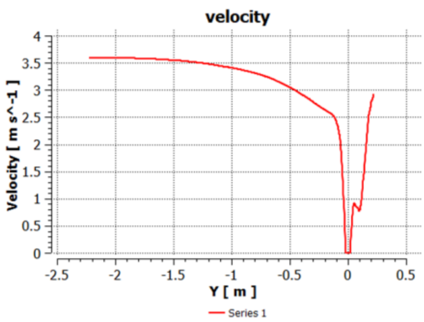
Length Blade (meter)	Generate Average Velocity from ANSYS
0.7	
1.0	
1.5	

The average velocity analysis using ANSYS Fluent revealed distinct airflow behavior across fan blades of varying lengths. For the 0.7-meter blade, the area-weighted average velocity was 2.577 m/s, serving as a baseline for aerodynamic assessment. The 1.0-meter blade exhibited the highest average velocity at 4.389 m/s across the inlet, outlet, and blade surfaces, suggesting superior flow induction. In contrast, the 1.5-meter blade showed a moderate average velocity of 3.270 m/s, despite its larger surface area, indicating a more distributed flow pattern. These results demonstrate how blade length influences airflow dynamics and validate the consistency between velocity profiles and torque outputs in the cooling tower simulation.

3.4 Air Velocity Analysis Graph

In this study, air velocity analysis graphs were generated from ANSYS Fluent simulations to investigate the airflow behavior around various cooling tower fan blade configurations. These graphs provide a quantitative representation of velocity variations along selected spatial paths or surfaces, offering insights into the flow distribution, acceleration zones, and regions of turbulence or stagnation. By examining the velocity trends corresponding to different blade lengths, the analysis supports a deeper understanding of how fan geometry influences airflow efficiency and cooling effectiveness within the tower. These visual data plots serve as essential tools for validating contour results and correlating airflow characteristics with torque and performance outcomes.

Table 4 *Air Velocity Analysis Grpah*

Length Blade (meter)	Air Velocity Analysis Graph
0.7	
1.0	
1.5	

The velocity analysis graphs from the ANSYS Fluent simulations of the 0.7 m, 1.0 m, and 1.5 m fan blades reveal consistent flow behavior trends and critical aerodynamic interactions. All three blades exhibited relatively uniform upstream velocity (3.5–3.6 m/s), followed by pronounced drops near the blade region indicating boundary layer formation and possible flow separation. The 1.0 m blade showed the steepest velocity decline and oscillation near the leading edge, suggesting strong pressure gradients and efficient force generation. The 1.5 m blade presented a sharp velocity dip around mid-span, followed by recovery, highlighting the impact of larger blade surfaces on airflow disruption and reattachment. Collectively, these profiles validate the aerodynamic response captured in contour and torque results, supporting the role of blade geometry in shaping flow efficiency.

3.5 Calculation Results

This section presents the results of torque-based power calculations derived from ANSYS simulations of three blade configurations operating at a constant rotational speed of 500 RPM. The calculated torques were used to determine mechanical power output, daily and monthly energy consumption, and total electricity cost for continuous 24-hour operation over a 30-day period. Simulation 1, using a 0.7 meter blade, yielded the lowest power consumption at 40.66 kW, while the 1.5 meter blade in Simulation 3 generated the highest at 424.42 kW. Corresponding monthly energy costs ranged from RM 13,173.84 to RM 137,512.08, based on an industrial tariff rate of RM 0.45 per kWh. Additionally, energy efficiency was evaluated through volumetric flow rate analysis, with the 1.5 meter blade demonstrating the best performance at 18.360 kW/m^3/s. These results provide critical insight into the trade-offs between blade size, airflow characteristics, and operating costs in high efficiency fan system design.

Table 5 *Result Data*

Simulation	Length of Blade (m)	Average Velocity (m/s)	Speed (RPM)	Torque (Nm)
1	0.7	2.577	500	776.782
2	1.0	4.389	500	2558.515
3	1.5	3.270	500	8107.303

3.5.1 Summary Data

Table 6 *Summary Data*

Simulation	Length of Blade (m)	Energy Consumption (kW)	Electrical Cost Per Month (RM)	Energy Efficiency (kW/m3/s)
1	0.7	40.66	13,173.84	10.252
2	1.0	133.94	43,396.56	9.712
3	1.5	424.42	137,512.08	18.360

A comparative analysis was conducted on three fan simulations with varying blade lengths (0.7 m, 1.0 m, and 1.5 m) to evaluate energy consumption, operational cost, and energy efficiency. The results indicate a direct correlation between blade length and energy consumption, where increasing the blade length significantly elevated both power usage and monthly electrical cost. Specifically, the 0.7 m blade configuration consumed 40.66 kW with a corresponding monthly cost of RM 13,173.84, while the 1.5 m configuration reached 424.42 kW and RM 137,512.08. In terms of energy efficiency measured as kW per m^3/s, the 1.5 m blade demonstrated the highest efficiency at 18.360, followed by the 0.7 m blade at 10.252, whereas the 1.0 m blade showed the lowest at 9.712. These findings suggest that although longer blades require substantially higher power input, they also yield improved volumetric efficiency. Therefore, the selection of blade length should consider the trade-off between operational cost and airflow performance, depending on the specific application requirements.

4. Equation

By Cooling tower Efficiency per unit flow:

$$\frac{\text{Power Output (W)}}{\textit{Volumetric Flow rate } (m^3/s)}$$

5. Conclusion

Simulation results confirm that increasing blade length from 0.7 m to 1.5 m significantly boosts torque from 776.782 Nm to 8107.303 Nm and mechanical power output, reaching 424.42 kW. This gain stems from greater aerodynamic interaction, but it also leads to a steep rise in energy consumption, with monthly operating costs escalating from RM 13,173.84 to RM 137,512.08. Despite improved performance, energy efficiency per unit volumetric flow rate does not scale linearly, as the 1.0 m blade recorded the lowest efficiency (9.712 kW/m^3/s) despite higher velocity. These outcomes emphasize the need to balance blade geometry, energy usage, and airflow efficiency for optimal and cost-effective cooling tower design.

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