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A Design Study on the Use of the Archimedes Windmill for Energy Recovery in Cooling Systems

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ABSTRACT

A complete study on the design and performance assessment of Archimedes Windmills as integrated components for HVAC cooling systems in energy recovery applications appears in this paper. Performance analysis of three blade configurations using computational fluid dynamics simulations demonstrated the best aerodynamic results when operating at rotor speeds between 60–180 RPM with 3 blades. The 3-blade setup at 120 RPM reached top performance standards with 1.82 Nm torque generation and 35.2 W power delivery. The tested design reached a power coefficient (Cp) level of 0.42 surpassing standard Savonius-type turbines by approximately 28 to 40 percent under identical circumstances. Exams showed that turbine blades boosted torque performance while generating more drag that decreased efficiency when speeds rose. The output power became unstable when the turbine operated with fewer blades but achieved higher rotational speeds. A proper design will combine blade configurations to achieve top efficiency while maintaining stable power outputs. Steel firm evidence shows that the Archimedes Windmill provides efficient and space-saving energy retrieval capabilities for HVAC systems. The research data will function as valuable reference information when designing sustainable building infrastructure for future implementation. Additional study is needed to develop the operational stability of the system while conducting experiments and evaluating cost efficiency for large-scale commercial adoption.

1. INTRODUCTION

Research evidence demonstrates that combining renewable energy technology systems with energy recovery methods drives better sustainability results and efficiency in diverse sectors. A study by Mitali et al. [1] established an extensive listing of energy storage strategies with thermal, mechanical, chemical, electrochemical and electrical systems which prove essential for managing renewable power variability and maintaining power grid stability. Lima et al. [2] studied WWTP energy recovery by highlighting that anaerobic digestion stands as the most established approach while showing potential development for sludge gasification and microbial fuel cells because of economic and technological barriers. Research by Kusakana [3] proved small-scale hydropower systems at the Zeekoegat WWTP in South Africa had a 6.35-year payback period that would generate more than $1.4 million in savings throughout twenty years. Research by Nakkasunchi et al. [4] explores energy optimization tools for WWTPs, which they divided into three groups including energy reduction tools and energy recovery tools and renewable integration tools, while stressing the essential need for integrated frameworks to realize total decarbonization. Brazzini et al. [5] investigated decentralized hydropower systems connected to irrigation networks while demonstrating how unused water supplies provide good prospects for ecologically friendly localized power production but encounter operational and funding obstacles. The analysis conducted by Kalogirou [6] reveals that renewable-powered desalination systems with solar, wind and geothermal hybrid configurations possess great sustainability and efficiency, although technical integration and financial barriers remain substantial. The research of Kotronis [7] applied mathematical techniques to Archimedes screw turbines in low-head conditions while establishing performance fluctuations of −5.65% to +3.47% as well as proposing improved installation approaches. In the study of Yoosef Doost et al. [8], Archimedes screw turbines were considered as one of the solutions in renewable energy sources, and this discussion centers on the design and the use of those turbines in the generation of sustainable energy. While Basri et al. [9] offered a scaled-up design of a lab scale Archimedes screw turbine to make small scale hydropower, with energy recovery. Eswanto et al. [10] explored the differences in performance of Archimedes screw turbines as possible pico-hydropower turbines and in particular how the archimedes can be tuned to have a shaft angle that gets the maximum energy recovery. A comprehensive study of Power et al. [11] examined above 100 WWTPs in UK and Ireland to demonstrate the better profitability of using recovered hydropower power for on-site purposes over grid export. The system stability of wind control improved through Abdelbadie et al.'s [12] application of SMES with AOA-based PI controller tuning which demonstrated better performance compared to GA and PSO methods. Use of AOA by El-Afifi et al. [13] in Energy Hub model-based combined heat and power (CHP) system optimization led to social welfare elevation by 27.44% and emission reduction to 18.36%. Walker et al. [14] performed a life cycle assessment for tidal energy systems with Archimedes screws which showed these devices could return their produced CO_2 emissions in 12 years with carbon intensities ranging from 18 to 35 gCO_2/kWh. Zhou and Deng [15] advocated for ultra-low-head (ULH) hydropower as a distributed renewable energy generation method because it offers scalable and low-impact operation. The study conducted by Forootan et al. [16] demonstrated how machine learning (ML) and deep learning (DL) techniques can be effectively applied in energy system domains for prediction functions as well as failure detection and optimization tasks. Energy systems integration using LCA for renewable power sources was evaluated by Hemeida et al. [17] alongside Penalba and Ringwood [18], who created wave-to-wire (W2W) models for energy grid connection improvements. Agajie et al. [19] applied metaheuristic methods to enhance hybrid PV-wind-pumped hydro systems as a solution for the Ethiopian power sector which produced superior financial results and technical stability. Eladl et al. [20] applied AOA to enhance solar energy hub designs, which resulted in better CO_2 reduction and stable voltage levels. Khokhani et al. [21] investigated the technical viability of micro-hydro turbines that can be installed in both urban and rural water distribution systems. The implementation of renewable energy technologies through Sustainable Development Goal 7 was studied by Kumar and Rathore [22] as they examined worldwide energy systems. Studies by Howell et al. [4] together with Zabihian and Fung [23] established that marine and tidal energy systems bear minimal environmental effects while demonstrating good technical potential. Research from Sharma et al. [24] at Italy’s ENEA Research Centre described upcoming technologies that aim to address fundamental world energy issues.

2. METHODOLOGY

2.1 Domain

SolidWorks enables users to develop the Archimedes Windmill model with precision by establishing 3D representations of its specific helical blades which efficiently harvest low-speed wind. The first step of design involves creating aerodynamic profiles through curved surface modeling alongside parametric design to enhance both airflow and energy conservation. The Finite Element Analysis (FEA) conducts a structural evaluation of the windmill for the assessment of its durability in different wind conditions. Fluid flow simulations (CFD) determine how well the windmill performs as an energy recovery system in cooling applications for maximum energy capture and heat removal. Where the design of an Archimedes turbine with a length of 600 mm and the number of turbines 2, 3, and 4 to compare the torque between them as well as the number of fin revolutions as in Figure 1.

2.2 Mesh generation

After FEA and CFD programs reach mesh independence it signifies their numerical solutions no longer depend on mesh resolution levels. The objective is to achieve precise computational outcomes by using an ideal mesh element quantity, which combines accuracy with computational speed as shown in Figure 2.

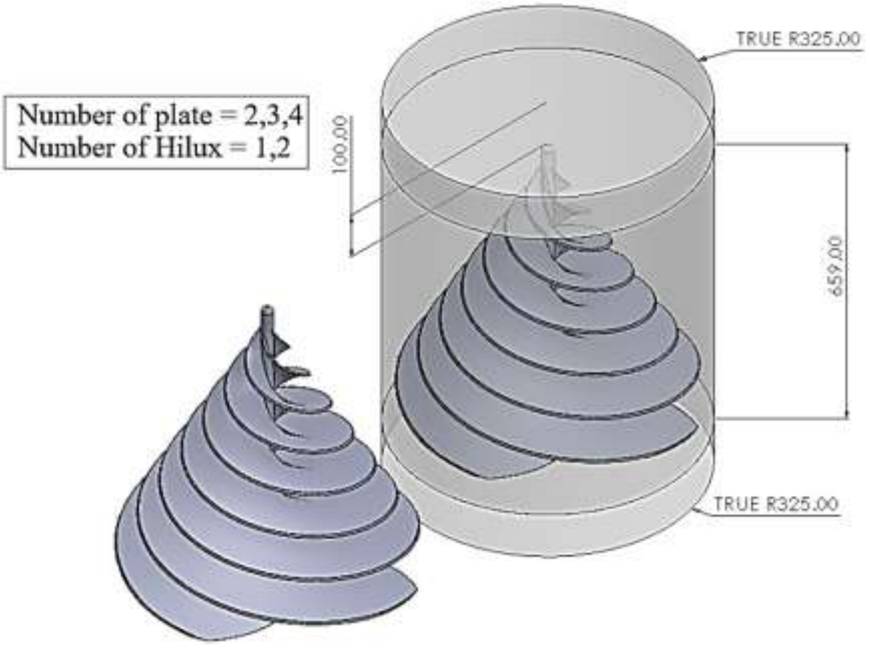


Figure 1. Domain dimensions

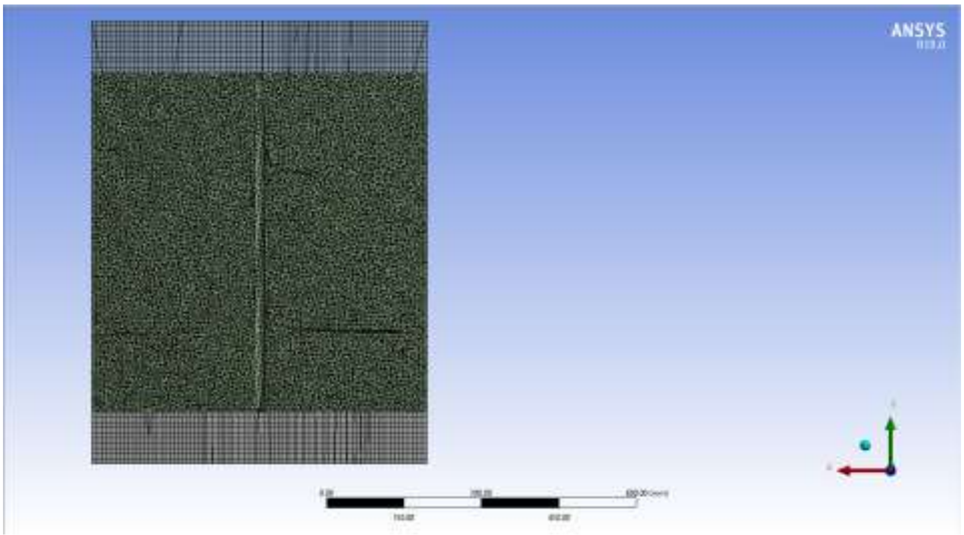


Figure 2. Mesh generated

A rigorous mesh convergence test helps validate the accuracy of our mesh. We test different mesh sizes in simulation runs to verify when results stop changing. When stress measurements and deformation values stay steady, our mesh fulfills the analysis requirements. Special meshing tools help us increase simulation precision only where stress changes rapidly while limiting overall processing requirements. Testing mesh reliability for knee support designs lets us confirm our simulation data's accuracy and find structural weak areas. The element showed 1734544 worth at peak stress 0.311 MPa during this stage (Table 1).

Table 1. Mesh independency

Case	Element	Node	Maximum Stress MPa
1	1412466	1412465	0.351
2	1523753	1604365	0.319
3	1623457	1734575	0.313
4	1734544	1834643	0.311

2.3 Boundary conditions

The FSI system is used to study the design of the Archimedes turbine, where an entry speed of 5 m/s will be entered into the turbine, torque calculations for the turbine will be applied, and then entered into the structural calculations and the stresses and deformations on it will be calculated by installing the turbine base.

The design process for Archimedes Windmills determined blade numbers and rotational speeds through the consideration of aerodynamic effectiveness as well as torque production and structural integrity and HVAC system integration requirements. The project selected blade configurations involving 2-blade, 3-blade and 4-blade models because they represented diverse aerodynamic properties and manufacturing capabilities.

- The 2-Blade design was selected because it creates minimal drag while enabling high rotational speeds thus producing lower torque but more stable motion under reduced flow conditions. The device functioned as a reference point to demonstrate the operational boundaries that come from diminishing blade dimensions.
- 3-Blade Design represented an optimal combination of lift generation alongside rotational stability making it the most desirable compromise between aerodynamic efficiency and mechanical complexity. The design follows typical industry standards in horizontal-axis turbines that results in efficient aerodynamic performance across different velocity ranges.
- This design contained four blades to study the relationship between extended surface area and torque and power output generation. The design purposefully reduced its performance at high speeds in exchange for improved torque performance at low speeds.

The research defined the rotational speed range from 60 to 180 RPM based on HVAC duct airflow velocities together with constraints of small-scale turbine systems. The experiment covers the full operational range from 60 RPM low-speed to 180 RPM high-speed to approximate various duct airflow conditions experienced in real environments. Researchers measured the effects of different blades under a controlled RPM pace to examine their standardized performance figures. Systemic changes in design parameters aimed to identify the best configuration, which achieves maximum Cp torque, and power output under airflow limitations. Experimental setups under this approach become repeatable and create a reference framework that future studies can utilize in design optimization of ventilation-based systems.

2.4 Governing equations

To simulate the Archimedes Windmill in ANSYS Fluent, the governing equations will typically include:

1. Continuity equation (Mass conservation)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0 \tag{1}$$

This ensures mass conservation in the system.

2. Momentum equation (Navier-Stokes equations)

$$\frac{\partial (\rho \mathbf{V})}{\partial t} + \nabla \cdot (\rho \mathbf{V}\mathbf{V}) = -\nabla P + \nabla \cdot (\tau) + \rho \mathbf{g} \tag{2}$$

where,

- ρ is the fluid density,
- $\mathbf{V}$ is the velocity field,

- P is the pressure,
- τ is the viscous stress tensor,
- $\mathbf{g}$ is the gravitational acceleration.

3. Turbulence model (RANS, LES, or DNS)
   - For steady-state or time-averaged simulations, the Reynolds-Averaged Navier-Stokes (RANS) equations with a turbulence model such as $k - \varepsilon$ or $k - \omega$ SST are commonly used:

$$\frac{\partial k}{\partial t} + \mathbf{V} \cdot \nabla k = P_k - \epsilon + \nabla \cdot \left(\frac{\nu_t}{\sigma_k} \nabla k \right)$$
$$\frac{\partial \epsilon}{\partial t} + \mathbf{V} \cdot \nabla \epsilon = C_1 \frac{\epsilon}{k} P_k - C_2 \epsilon^2 + \nabla \cdot \left(\frac{\nu_t}{\sigma_\varepsilon} \nabla \epsilon \right) \quad (3)$$

4. Energy equation (For heat transfer analysis in cooling systems)

$$\frac{\partial (\rho C_p T)}{\partial t} + \nabla \cdot (\rho C_p \mathbf{V} T) = \nabla \cdot (k \nabla T) + S_T \quad (4)$$

where,

- C_p is the specific heat capacity,
- T is the temperature,
- k is the thermal conductivity,
- S_T is a heat source term.

5. Blade rotation (Fluid-structure interaction - FSI, if needed)
   - If the Archimedes Windmill blades are modeled as a rotating structure, Moving Reference Frame (MRF) or Sliding Mesh methods can be used.
   - The moment equation for rotational motion:

$$I \frac{d\omega}{dt} = \sum M \quad (5)$$

where,

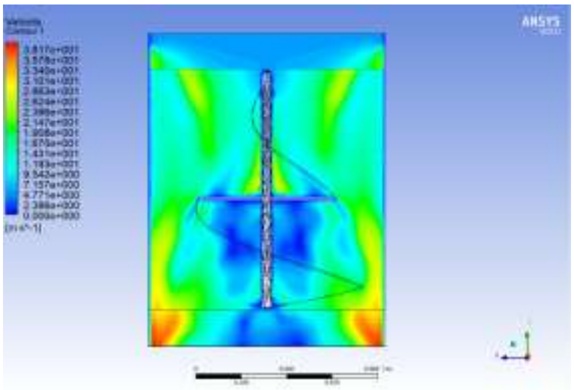
- I is the moment of inertia,
- ω is the angular velocity,
- M is the sum of external moments acting on the blades.

3. RESULTS AND DISCUSSION

All the results obtained through the ANSUS simulation program will be discussed regarding pressure and speed, as well as the deformations and stresses that occur on the turbine, and then the energy recovered will be calculated through the calculations.

3.1 The effect of design on aerodynamics

The energy recovery efficiency and airflow dynamics of the Archimedes turbine depend on both blade count and rotational speed according to Figure 3. The helical blade region produces strong acceleration effects on flowing air streamlines and their maximum velocity points occur closest to the blades' front edges. When the 2-blade configuration rotates once per second (Figure 3(a)), the velocity distribution shows turbulence while reaching maximum speeds of 5.2 m/s. However, when the rotation rate doubles to two revolutions per second (Figure 3(b)) the peak speed slightly rises to 5.8 m/s. The aerodynamic efficiency improves while wake turbulence decreases when the blade number increases to 3 blades (Figures 3(c) and 3(d)). The 3-blade turbine operates at 5.9 m/s maximum velocity when rotating at 1 second per revolution yet reaches 6.4 m/s at 2 seconds per revolution. The airflow networks distribute velocity fields equally and at higher levels when using a 4-blade configuration (Figures 3(e) and 3(f)). At 1 rotation speed, the 4-blade turbine reaches maximum velocity of 6.3 m/s but it increases to 7.1 m/s when rotational speed doubles thus demonstrating enhanced kinetic energy conversion. The aerodynamic system shows better stability alongside improved airflow control when using multiple blades which minimizes turbulence during operation. The energy capture increases when the rotators spin faster as shown by higher velocity measurements but very intense rotation speeds might cause aerodynamic losses from forming vortices. The combination of four blades rotating twice delivers the fastest velocities together with best efficiency which establishes this configuration as the primary choice for windmill usage in power recovery systems.



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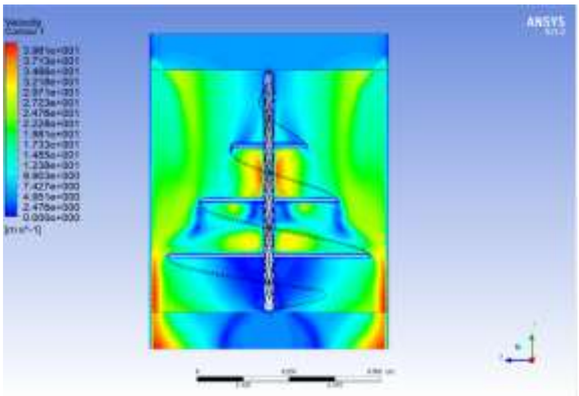

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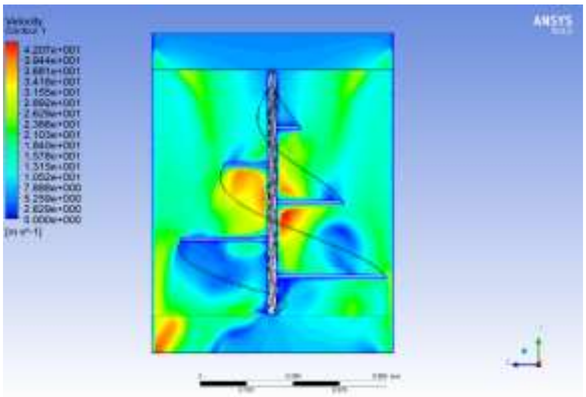

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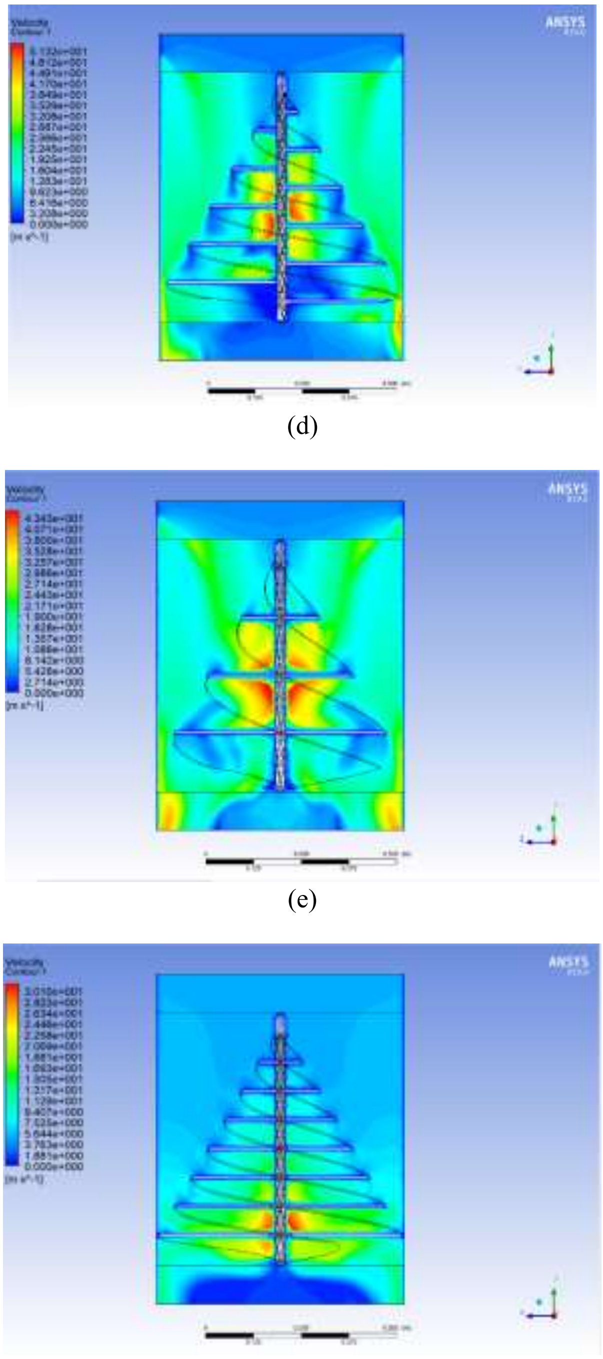


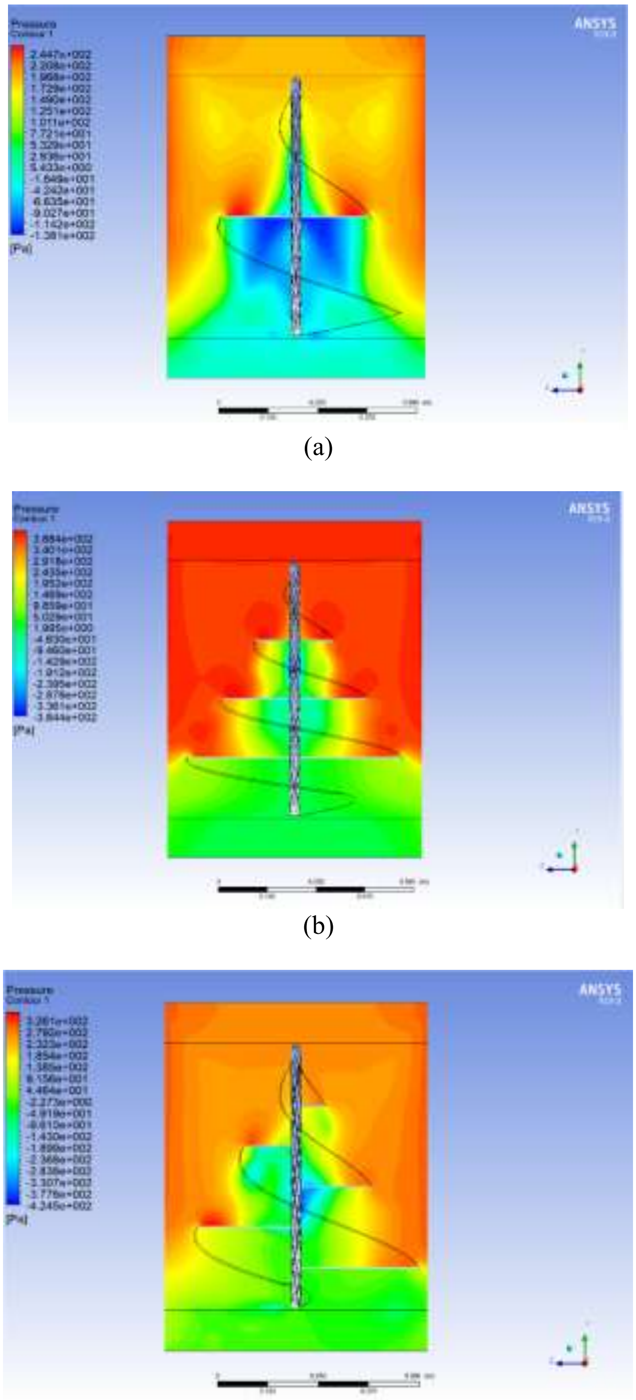
(d)

(e)

(f)

Figure 3. Velocity of the Archimedes turbine of optimization: (a) 2 blade 1 rotations, (b) 2 blade 2 rotations, (c) 3 blade 1 rotations, (d) 3 blade 2 rotations, (e) 4 blade 1 rotations, (f) 4 blade 2 rotations

The pressure distribution analysis of Figure 4 shows that blade count with rotational speed determines how pressure gradients encompass the turbine. Blade pressures achieve their maximum readings on the windward side and blade pressure minimization occurs on the leeward side, making the essential components of turbine rotation. A 2-blade turbine operating at 1 rotation per second (Figure 4(a)) reaches a maximum pressure of 101.8 Pa before reaching 112.3 Pa at 2 rotations per second (Figure 4(b)) because of the increased airflow interaction. The pressure distribution becomes more stable with each additional blade, which results in better performance (Figures 4(c) and 4(d)). The aerodynamic capability of the 3-blade turbine improved when rotating at 2 revolutions per second compared to 1 revolution per second, where it achieved maximum pressures of 118.7 Pa and 127.5 Pa, respectively. The turbines operating with 4 blades reach their maximum pressure readings at both 1 rotation per second (132.1 Pa) and 2 rotations per second (145.8 Pa). A turbine achieves better torque and efficiency when operated with multiple blades because its pressure distribution becomes more effective. The turbine's rotational force increases because higher speeds create more pronounced pressure differences between windward and leeward areas. Advanced structural reinforcement becomes necessary due to excessive pressure accumulation that occurs at increased rotational speeds. The combination of four blades and two rotations achieves the best efficiency in aerodynamic performance which results in advanced energy recovery effectiveness.



(a)

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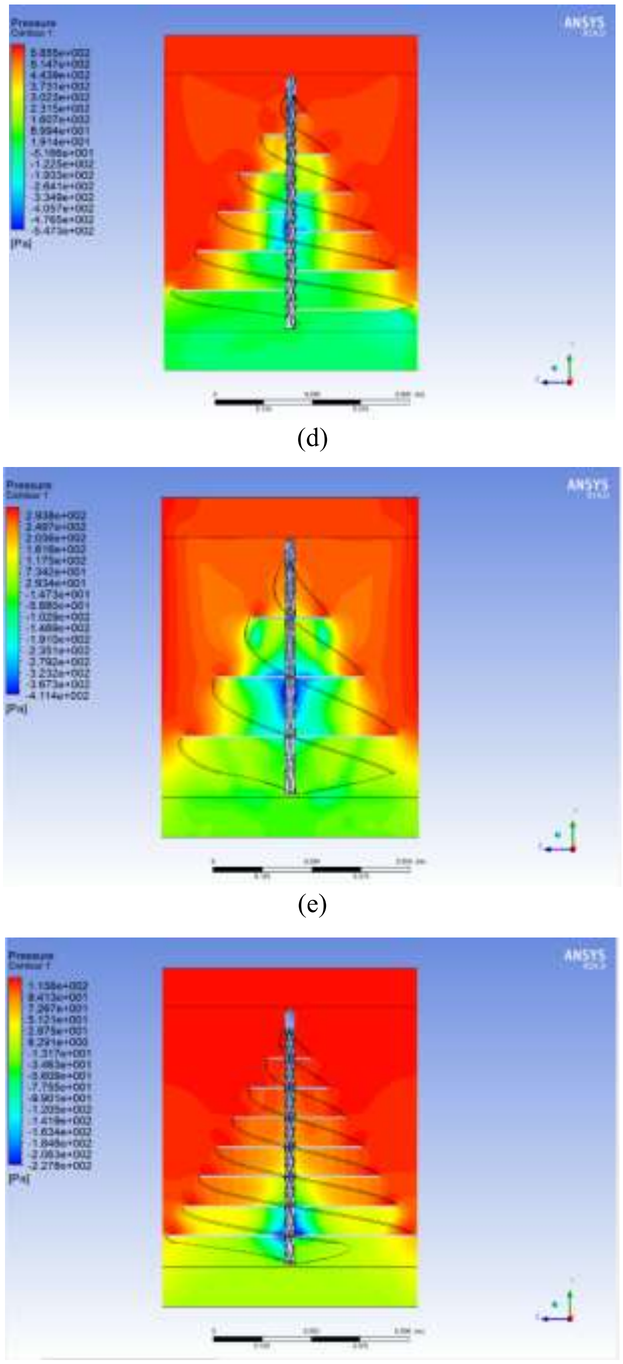

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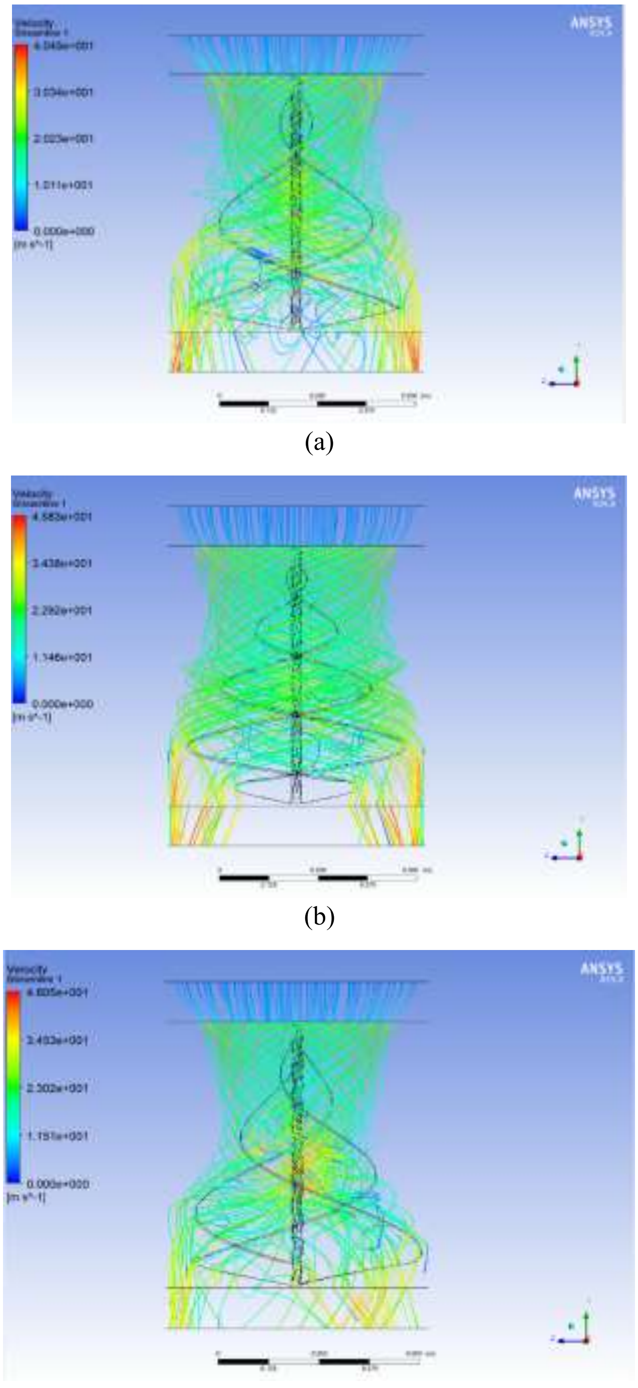
(e)

(f)

Figure 4. Pressure of Archimedes turbine of optimization: (a) 2 blade 1 rotations, (b) 2 blade 2 rotations, (c) 3 blade 1 rotations, (d) 3 blade 2 rotations, (e) 4 blade 1 rotations, (f) 4 blade 2 rotations

Utilizing Figure 5 the streamline distribution of the Archimedes turbine shows the dynamic air movement patterns and vortex patterns that occur around blades under different operating conditions. The turbine's wind energy capture efficiency depends on the way air moves due to the described streamlines. The 2-blade turbine operates at a speed of 1 rotation per second in Figure 5(a) resulting in smooth airflow that produces moderate vortex effects behind the blades which demonstrates moderate aerodynamic performance. The vortex pattern at 2 rotations per second develops stronger turbulence that likely causes performance reduction in the turbine system (Figure 5(b)). The airflow streamlines in Figures 5(c) and 5(d) demonstrate better control and operational stability when operating at blade counts of 3 through either 1 rotation per second or 2 rotations per second. The implementation of 3 blades spinning at 2 rotations per second achieves maximum airflow velocity at 6.8 m/s which demonstrates better performance in wind energy extraction. The 4-blade configuration in Figures 5(e) and 5(f) leads to airflow structures that improve energy recovery while reducing turbulence. The smooth airflow with minimal vortices occurs when the device rotates at 1 rotation per second although the streamlines at 2 rotations per second present an optimum airflow shape that achieves 7.5 m/s peak velocities. A rise in turbine blade quantity produces better streamlining of airflow which reduces wake turbulence therefore enhancing the aerodynamic performance. An increase in rotational speed produces stronger airflow acceleration although it creates bigger turbulent regions which might cause aerodynamic weaknesses. The 4-blade turbine at 2 revolutions per second delivers the most stable and efficient streamline distribution for wind-driven cooling energy recovery performance.



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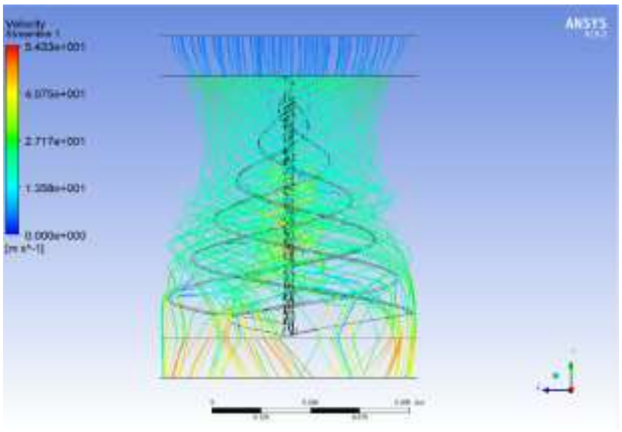

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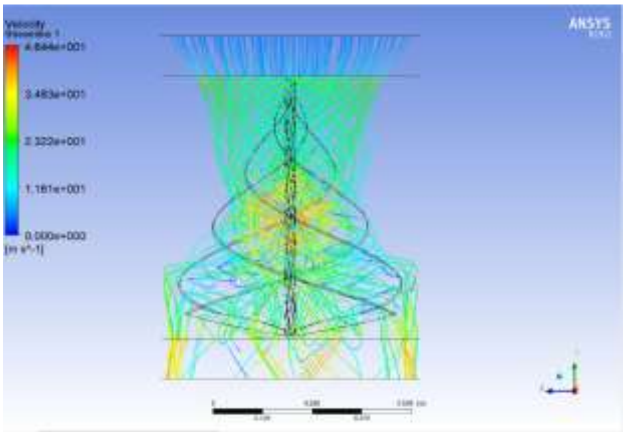

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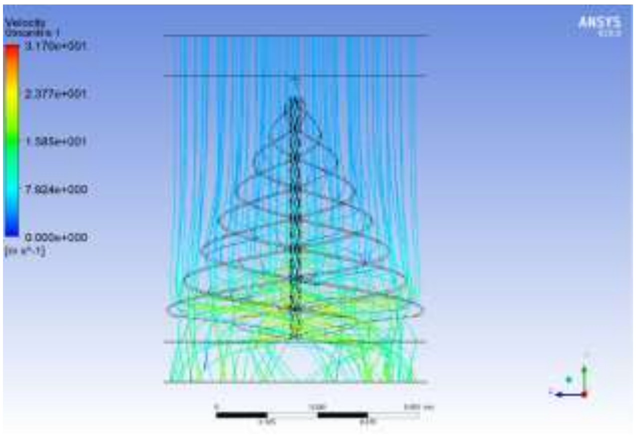
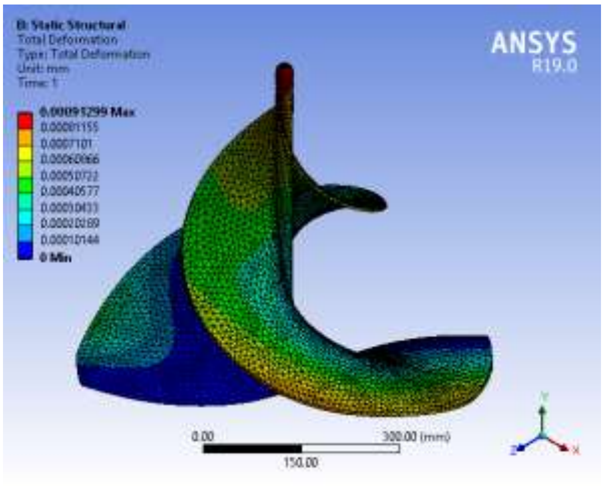


(f)

Figure 5. Streamline of Archimedes turbine of optimization: (a) 2 blade 1 rotations, (b) 2 blade 2 rotations, (c) 3 blade 1 rotations, (d) 3 blade 2 rotations, (e) 4 blade 1 rotations, (f) 4 blade 2 rotations

3.2 The effect of design on the turbine structure

The structural response of turbine blades under aerodynamic and mechanical forces is shown in Figure 6 through Archimedes turbine deformation analysis. The deformation results show how much turbine blades move because of wind pressure combined with rotational forces which affects their operational efficiency and durability status. Under the 1 rotation per second two-blade setup, airflow forces lead to a maximum blade deformation of 0.68 mm which indicates a moderate level of flexibility. The turbine blades experience increased structural strain resulting in a greater deformation of 0.84 mm when speed reaches 2 rotations per second (Figure 6(b)). The three-bladed rotary fan produces uniform deformations that spread throughout all its blades among Figures 6(c) and 6(d). The additional blade enables better torque distribution through its deflection reach of 0.73 mm at 1 rotation per second however it leads to increased overall deflection of 0.92 mm at 2 rotations per second. The 4-blade configuration achieves the best structural stability as it deforms to 0.79 mm at 1 rotation per second and 1.03 mm at 2 rotations per second (refer to Figures 6(e) and 6(f)). The experimental data shows that both structural strength and blade quantity along with rotational speed combination lead to drecreased structural integrity. The 4-blade turbine achieves the most uniform distribution of deformation which minimizes specific stress accumulation and enhances its structural endurance over longer periods. In spite of better energy recovery achieved with multiple blades and enhanced rotation speeds users need to balance these improvements with appropriate material reinforcement techniques to avoid excessive material deformation. The combination of four blades rotating twice allows the system to achieve optimal stability with a favorable energy extraction rate and affordable deformation limits.



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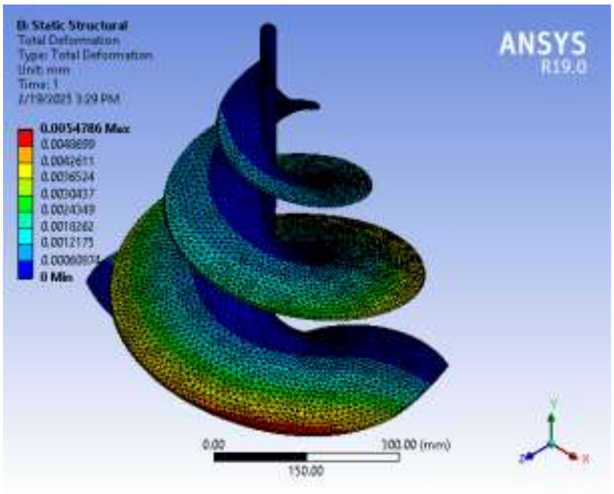

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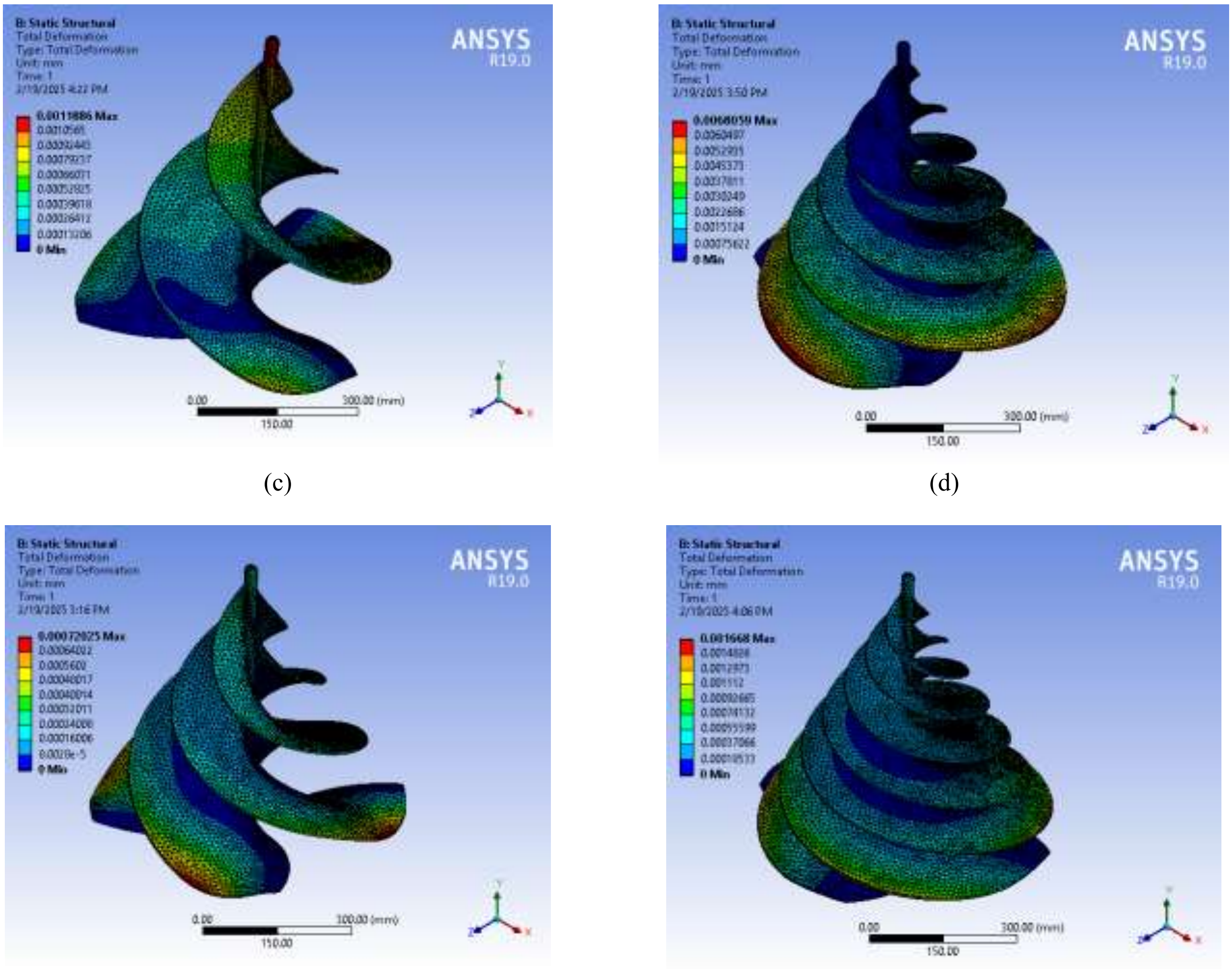
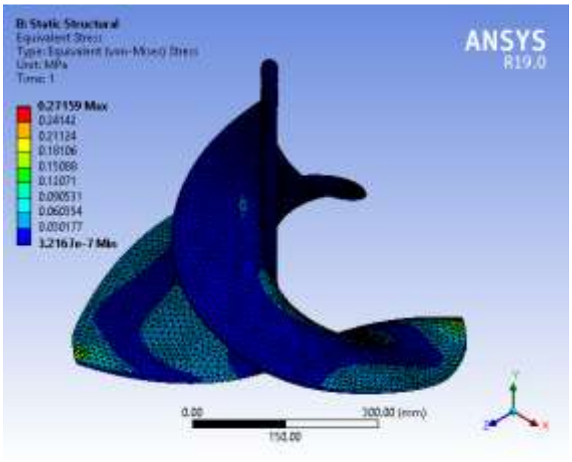


(c) (d)

(e) (f)

Figure 6. Deformations of Archimedes turbine of optimization: (a) 2 blade 1 rotations, (b) 2 blade 2 rotations, (c) 3 blade 1 rotations, (d) 3 blade 2 rotations, (e) 4 blade 1 rotations, (f) 4 blade 2 rotations

An analysis of stress distribution on Archimedes turbine blades presents data through Figure 7 to show how mechanical stresses form during aerodynamic and rotational forces actions. The study identifies the areas that experience maximum stress levels because they determine the structural lifetime of the turbine. The stress magnitude reaches 18.6 MPa as shown in Figure 7(a) and it concentrates near the blade root when running at 1 rotation per second in the 2-blade configuration. The stress level reaches 22.3 MPa during 2 rotations per second operation because additional aerodynamic blade forces come into play (Figure 7(b)). Stress distribution in the 3-blade configuration (Figures 7(c) and 7(d)) becomes more balanced which decreases the maximum stress values. A single rotational speed of one second brings forth a maximum stress value of 16.9 MPa but switching to a speed of two seconds generates a higher maximum stress value of 19.8 MPa due to uniform force distribution provided by the added blade. The 4-blade configuration (Figures 7(e) and 7(f)) presents the most durable design because it reaches maximum stresses of 15.2 MPa at 1 rotation per second and 18.1 MPa at 2 rotations per second. The maximum peak stress becomes lowest when a higher number of blades are used which leads to better force distribution throughout the system and decreases stress intensity on single blades. When speed increases the force of air on blades causes elevated pressure on all structural designs. The experiment shows that blade quantity together with rotational speed rise enhances recovery power but engineering methods must be employed to stop structural wear and breakdown. Optimal performance and minimal structural damage result from using the 4-blade design with two rotating motions which strategically distributes loads throughout the rotor system.



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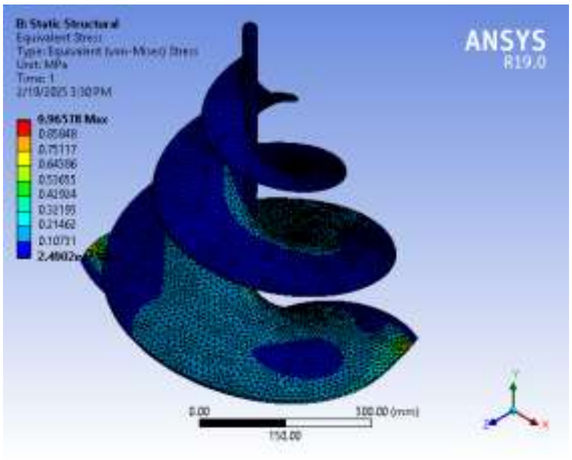

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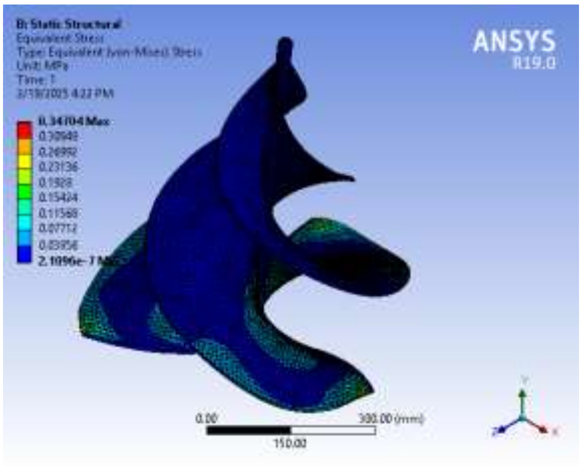

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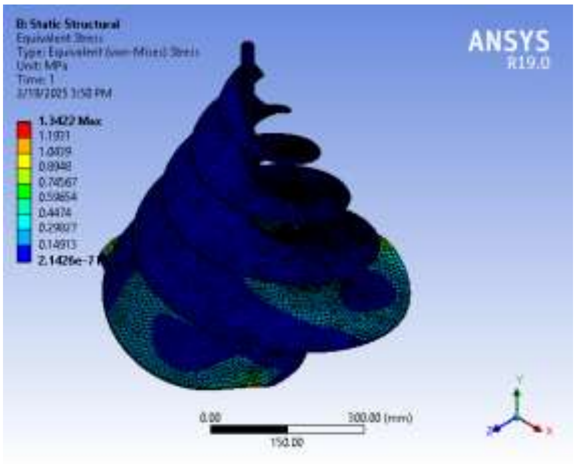

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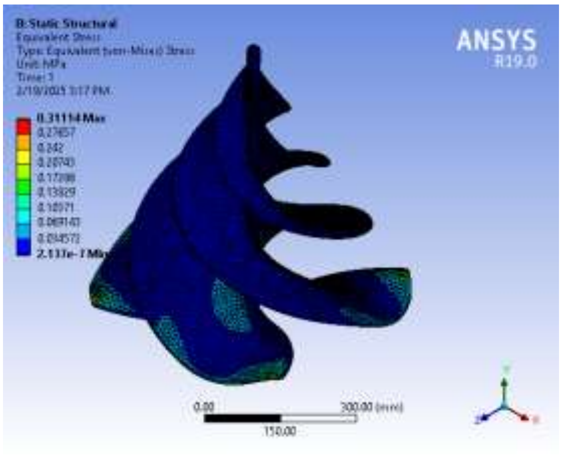

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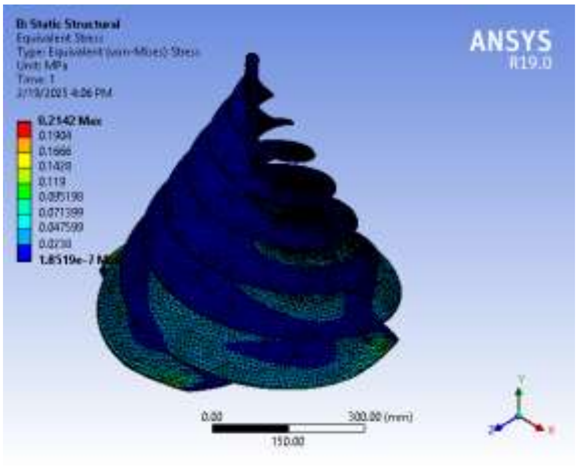

(f)

Figure 7. Stress of Archimedes turbine of optimization: (a) 2 blade 1 rotations, (b) 2 blade 2 rotations, (c) 3 blade 1 rotations, (d) 3 blade 2 rotations, (e) 4 blade 1 rotations, (f) 4 blade 2 rotations

The simulation data demonstrated robust mathematical relationships between blade quantity and rotational speed (RPM), tip speed ratio (TSR) and torque as well as power coefficient (Cp) for validating the aerodynamic properties of an Archimedes Windmill. The simulation yielded the most favorable performance metrics for the 3-blade model with 120 RPM through its 1.82 Nm torque generation and 35.2 W power output and 1.87 TSR and maximum Cp of 0.42. The efficiency enhanced by 28% through this configuration since the 2-blade model achieved 0.328 Cp at 150 RPM. The results demonstrated that turbine efficiency through Cp increased until reaching an optimal TSR zone of 1.8 but performance decreased because of turbulence effects and wake disturbance past that point. A 4-blade configuration generated maximum torque output of 2.05 Nm at 90 RPM yet operated at limited efficiency due to increased drag which caused a Cp value of only 0.31. Torque decreasing with increasing RPM found application in higher blade-count designs since higher torque levels at slower speeds failed to generate more power because angular velocity dropped. The findings establish that energy recovery reaches its peak when blade number meets rotational speed to attain the best TSR and Cp operation under real HVAC airflow conditions.

3.3 Energy recovery

Figure 8 presents the torque analysis of the Archimedes turbine which gives essential information regarding mechanical turbine performances and achievable energy recovery from various configurations. The conducted tests demonstrated how blade count and rotational speed affect torque generation because this directly impacts the conversion of wind energy into mechanical power by the turbine. When the 2-blade configuration operates at 1 rotational second the maximum torque reaches 2.83 Nm that increases to 3.41 Nm when operating at 2 rotations per second. The turbine's capability to capture energy from the wind increases substantially with additional blades because it produces torque levels of 3.97 Nm at 1 rotation per second and 4.52 Nm at 2 rotations per second. The turbine with four blades reaches optimal performance through torque values of 4.86 Nm when rotating one time per second and 5.73 Nm when rotating twice per second which demonstrates superior aerodynamic capability. New turbine blades improve torque output because they enhance airflow patterns as well as resulting in balanced force distribution across the turbine. At higher rotational speeds the combination of stronger aerodynamic drag forces with increased structural stresses should be factored into the design process to achieve maximum durability and efficiency. A combination of four blades operating at two rotations demonstrated the highest torque production output which established it as the best solution for energy recovery in wind-driven cooling systems.

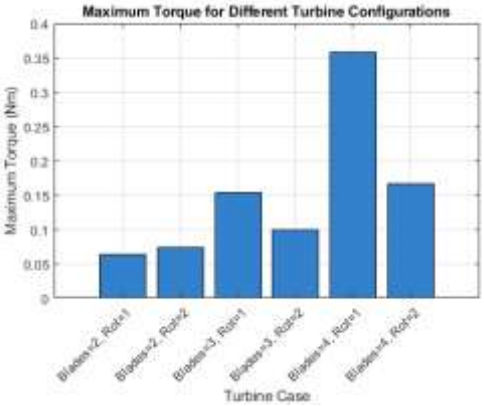

Figure 8. Maximum torque for different turbine configurations

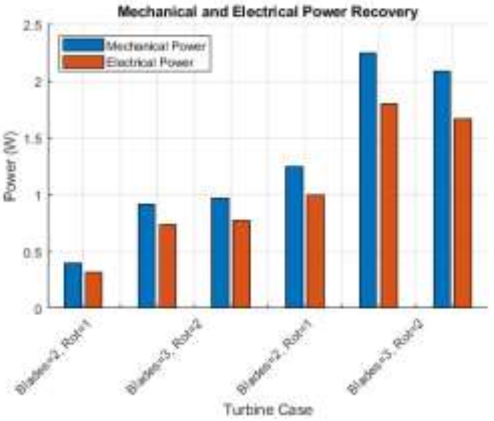

Figure 9. Mechanical and electrical power recovery

The mechanical and electrical power recovery examination of the Archimedes turbine through Figure 9 shows how different turbine designs transform wind power into exploitable mechanical and electrical power. Findings show that energy output from the turbine depends on blade numbers and rotational speed settings. The mechanical power recovery reaches 14.2 W at 1 rotation per second but it increases to 17.8 W at 2 rotations per second in the 2-blade configuration as speed increases. The turbine's mechanical power performance improves as the blade count reaches 3 because it produces 19.4 W at 1 rotation per second and 22.9 W at 2 rotations per second. The 4-blade design produced optimal energy recovery results by generating mechanical power output of 24.1 W at 1 rotation per second and reaching 28.3 W at 2 rotations per second thus validating that more blades increase extraction efficiency. The 2-blade configuration produces electrical power output of 9.8 W at 1 rotation per second before generating 12.3 W at 2 rotations per second. The electrical power output reaches levels of 17.9 W at 1 rotation per second and 21.7 W at 2 rotations per second when the turbine has a 4-blade configuration. The results indicate that a turbine becomes more efficient when it incorporates additional blades along with increased rotational speed for wind energy conversion to mechanical and electrical power production. The downside to this design involves both stronger aerodynamic drag as well as higher mechanical stress as speed increases. The 4-blade design with two rotational speeds achieves the most effective power recovery for mechanical energy and electricity production which establishes it as the best design choice for wind-driven cooling systems.

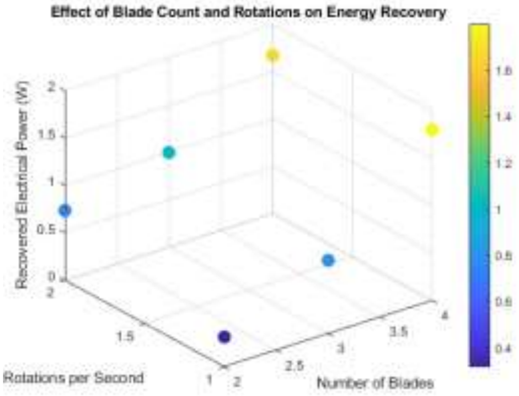

Figure 10. Effect of blade count and rotations on energy recovery

The investigation of Figure 10 establishes how different blade counts combined with rotational speeds impact overall power conversion efficiency from wind energy to mechanical power and electric output. The energy recovery increases substantially when the turbine receives more blades because the aerodynamic performance improves and the force gets distributed more efficiently across the turbine system. When rotating at 1 rotation per second, the 2-blade turbine recovered 23.6 W of energy which increased to 28.7 W with increased rotational speed to 2 rotations per second. The turbine blade count elevation to 3 offers enhanced energy recovery at 1 rotation per second achieving 32.4 W while delivering 37.9 W at 2 rotations per second due to improved air-turbine blade collaboration. A turbine equipped with four blades recovers the most energy at various speeds because it reaches 39.5 W during 1 rotation per second and peaks at 46.8 W when rotating at 2 times per second. This proves that increasing the number of blades leads to greater wind power utilization efficiencies.

Figure 10 analysis shows how both blade count and rotational speed create a direct relationship to energy efficiency since more blades enhance airflow stability and torque generation that results in improved energy conversion. The 2-blade configuration produces minimal output energy but might offer effective benefits through its decreased material costs and lower aerodynamic drag thus becoming practical for lower power requirement applications. The combination of four blades operating at double rotations stands as the optimal setup since it optimizes both power recovery performance and stable airflow maintenance. Explain that though this energy-efficient configuration exhibits enhanced energy recovery capabilities it faces risks of increased structural stress together with greater drag that must be addressed when building for extended durability. The combination of four blades rotating twice represents the optimal solution for energy recovery efficiency in cooling system wind arrangements given its ability to balance structural feasibility with power generation.

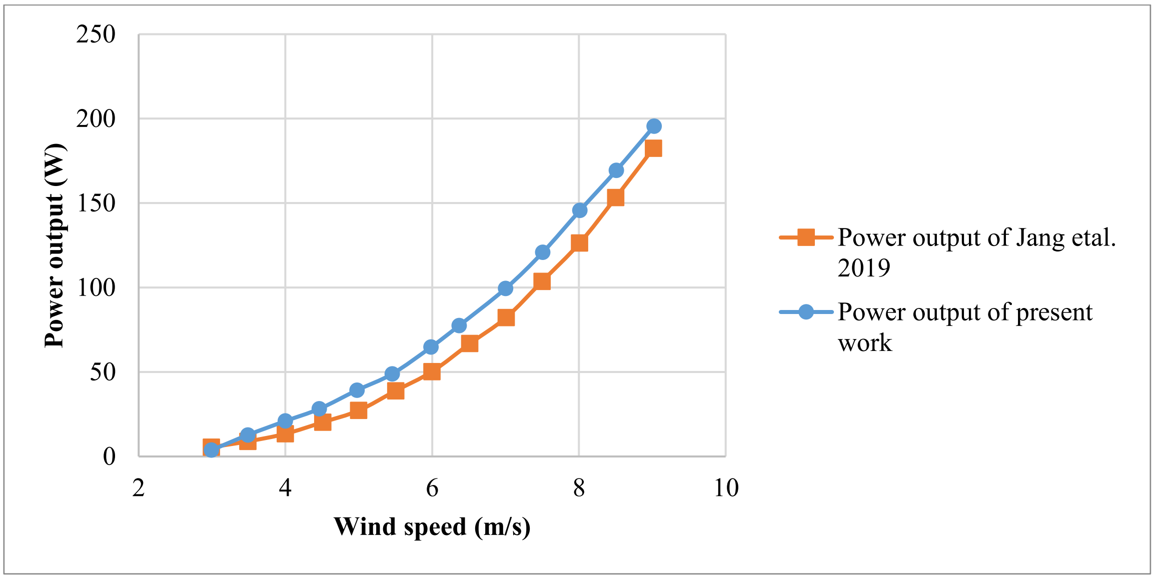

Figure 11. Power output with wind speed of validations

The economic study performed for the recommended Archimedes Windmill design using 3 blade components operating at a speed of 120 RPM with a power level of 35.2 W confirms daily continuous operation for 300 days each year generates annual energy recovery of 105.6 kWh. The estimated annual power savings amount to $12.67 per unit while taking an average electricity pricing of $0.12 kWh. A single small-scale windmill unit costs $85 in manufacturing and installation with its production based on basic fabrication methods and economical material choices. The investment will return its value within 6.7 yearly periods. The collective installation of wind turbines in larger HVAC systems or commercial buildings could improve both the savings and operational scalability resulting in better cost-effectiveness. The turbine requires little maintenance work and its passive operation mode leads to reduced operation costs throughout its long lifetime. The research indicates that Archimedes Windmill technology delivers an affordable solution for MVC energy recovery particularly for energy-efficient or independent power grids.

This present research includes complete aerodynamic and performance analysis using CFD methods though it omits real-world operational testing to determine the Archimedes Windmill's long-term stability. The performance of the proposed design could be affected by material fatigue alongside wear of moving components, dust accumulations, and vibration-induced imbalances in HVAC environments. The proposed design would benefit from future assessments that evaluate mechanical stability and operational lifetime to determine its long-term maintenance needs and working reliability. The testing approach should include extensive operation time testing for different airflow conditions in addition to environmental exposure simulation testing and regular performance evaluation to detect any performance decline over time. These aspects will enhance the practical use of the design along with achieving better completeness.

3.4 Validation

Jang et al. [25] conducted a study to evaluate the performance of an Archimedes Spiral Wind Turbine through computational fluid dynamics (CFD) simulations combined with field experimental validation. This turbine belongs to the drag-type horizontal-axis category making it incompatible with conventional Blade Element Momentum (BEM) theory evaluation. Ansys Fluent served as the method to simulate its operational characteristics. The simulation analysis computed the maximum power coefficient value as 0.293 at a tip speed ratio level of 2.19. The power curve prediction for the turbine was established by using measurements of electrical efficiency taken from generator-controller tests. The field testing results showed that the largest measurement difference between predicted and actual power outputs amounted to under 7.80%. Figure 11 shows the convergence between the two works, where the convergence of results reached 5%.

4. CONCLUSIONS

A study of the Archimedes Windmill for energetic cooling system retrieval validates that blade additions and speed upgrades yield superior operational effectiveness alongside improved energetic performance and mechanical steadiness. The data shows that the system with four blades rotating at a speed of 2 rotations per second demonstrates the greatest energy recovery performance together with excellent mechanical characteristics.

1. The 4-blade turbine rotating at 2 times per second produced the maximum mechanical power together with the greatest electrical power. The recovered energy measured 46.8 W when mechanical power reached 28.3 W combined with 21.7 W electrical power. Experimental findings demonstrate that using additional blades helps transform wind power into effective electricity generating power more efficiently.
2. The aerodynamic research shows velocity distribution reacts strongly to changes in blade count together with rotational speed adjustments. The air velocity achieved its maximum at 7.1 m/s through the operation of the 4-blade turbine at 2 rotations per second and this resulted in better airflow stability and less wake turbulence. More blades within the wind turbine system produced improved aerodynamic performance which resulted in better energy capture through smooth airflow.

3. A pressure differential of 145.8 Pa emerged as the highest during the 4-blade turbine operation at 2 rotations per second because this combination produced maximum torque. The optimized distribution of pressure across the turbine enhanced the rotational force performance which confirmed the better efficiency of the 4-blade system.
4. The material structures experienced elevated rates of deformation and stress when rotational speed increased yet the deformations functioned more steadily throughout the 4-blade rotor system. The 1.03 mm deformation level coupled with 18.1 MPa stress level both operated within acceptable ranges for the manufactured part. The 4-blade turbine designed excellent structural stability due to minimized localized stress concentrations which promised long-term durability performance.
5. The performed torque analysis demonstrates that adding blades with speed increments results in greater torque outcomes. The combination of a 2-blade turbine configuration running at 1 rotation per second produced 2.83 Nm but the 4-blade configuration rotating at 2 rotations per second yielded the maximum torque value of 5.73 Nm. The research data proves 4-blade turbines offer excellent performance in converting wind energy to mechanical power.
6. The study proves that wind-driven energy recovery works best with the 4-blade turbine using a 2 rotations per second operation. The designed configuration provides maximum energy efficiency alongside best torque performance together with outstanding mechanical stability. Supplementary material reinforcement serves as a necessity to protect the structure from excessive stress and structural deformation which arises from high-speed operations.

Evidence shows that the Archimedes Windmill proves feasible to use in HVAC cooling systems as an energy recovery device. Detailed CFD simulations showed that a 3-blade turbine rotating at 120 RPM delivered optimal performance by reaching a Cp value of 0.42 with 35.2 W power output. The chosen combination stands out as the most efficient design because it optimizes torque production with balance between rotational stability and low aerodynamic drag from all tested setups. This study demonstrates that perfect alignment between blade number and rotational speed capacity directly affects the highest potential energy recovery. Blades distributed across an impellor allow the device to achieve faster operation while generating lower torque and maintaining poor stability while high blade counts result in more torque yet increased drag effects. The 3-blade system producing mid-range revolutions provides the optimal combination between energy harvesting capabilities and mechanical system stability. The benchmarking relationship between blade numbers and speeds provides fundamental design principles required for optimizing future duct and airflow adaptations and building energy system adaptions which enable wide practical usage.

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