

Computational Fluid Dynamics (CFD) Analysis and Performance Comparison of Archimedes, Savonius, and Helical Savonius Wind Turbines

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Abstract

Windmills, or wind turbines, generate wind energy and serve as a viable substitute for fossil fuels. This study mainly focuses on the Archimedes wind turbine, a novel horizontal-axis wind turbine design inspired by Archimedes' screw pump. Computational Fluid Dynamics (CFD) analysis plays a crucial role in enhancing the turbine's effectiveness, providing insights into its performance. This study investigated the performance of the Archimedes wind turbine with respect to pitch, opening angle, and wind speed variation, utilizing SolidWorks for three-dimensional modeling and ANSYS Fluent for CFD analysis. Additionally, wind turbine comparative analysis was conducted to evaluate the power and torque coefficients of the Archimedes wind turbine against the Savonius and Helical Savonius wind turbines at various wind speeds. Essentially, the study's results showed that increasing the pitch and opening angle of the Archimedes wind turbine positively impacted the power coefficient and torque coefficient, resulting in improved turbine performance. When increasing the pitch from 600 mm to 2000 mm, the maximum C_p and C_t achieved were 0.2013 and 0.2577, respectively, at 1400 mm pitch. Furthermore, when increasing the opening angle from 15° to 75°, the maximum C_p and C_t achieved were 0.2290 and 0.2937, respectively, at a 60° opening angle. The Archimedes turbine consistently outperformed the Savonius and Helical Savonius wind turbines, indicating its potential for wind energy applications. However, the Helical Savonius has approximately similar performance to the Archimedes wind turbine. Therefore, this study provided valuable insights into the performance of the Archimedes wind turbine through CFD analysis. The findings contributed to the development of more efficient wind energy technology, addressing environmental concerns and promoting sustainable energy solutions.

1. Introduction

Wind energy is the mechanical power or electrical energy produced from harnessing the wind through windmills or wind turbines. Today, the demand for alternative energy sources has been growing and increasing globally. This is due to the growing concerns about climate change that are mainly contributed from non-renewable energy sources such as fossil fuels [1]. This results in the urgent need to transition towards cleaner energy sources and more sustainable energy technologies, such as wind turbines. Wind turbines are seen as one of the solutions for reducing greenhouse gas emissions and reducing climate change [2]. Generally, there are various designs of wind turbines. A type of horizontal axis wind turbine (HAWT) that emerged as an innovative solution is the newly developed Archimedes wind turbine. This type of wind turbine comes with unique characteristics and advantages.

The Archimedes screw pump served as the inspiration for the creation of the Archimedes wind turbine. Its helical shape design, which rotates around a horizontal axis and consists of three circular blades wrapped around each other, effectively and efficiently draws wind into the turbine to generate electricity [3]. Furthermore, Archimedes wind turbines operate at high efficiency with relatively low noise levels, making them suitable for residential buildings and other similar structures [4]. The Archimedes wind turbine operates by following both the lift and drag principle [5]. As a result, researchers have conducted numerous investigations to examine the power coefficient and other parameters of the Archimedes wind turbine. In 2012, Kim et al. conducted a CFD simulation of a full-scale 0.5 kW and 1.5 m diameter model to forecast the performance of the Archimedes wind turbine, obtaining a power coefficient of $C_p = 0.29$. Jang et al. [7] analyzed the performance of Archimedes through CFD simulation to obtain the power coefficient and tip speed ratio, λ . They obtained a maximum $C_p = 0.29$ at $\lambda = 2.19$ and a wind speed of 12.73 m/s. In 2019, Sapkota *et al.* [8] assess the geometrical aspects that influence the turbine performance at 3.5 m/s wind speed while altering the pitch and opening angle. According to their study, turbines with a 60° blade opening angle generate a maximum of $C_p = 0.25$ and $\lambda = 1.5$.

The literature review indicates that the investigation of Archimedes wind turbines, considering variations in pitch, opening angle, wind speed, and performance comparisons with other wind turbines like Savonius and Helical Savonius, has not been extensively pursued. This study examines the influence of pitch, opening angle, and wind speed on the performance of the Archimedes wind turbine, and subsequently compares it with the Savonius and Helical Savonius wind turbines.

2. Methodology

This study is being conducted using Computer Fluid Dynamics (CFD) analysis, which requires the usage of a few computer programs, including SolidWorks 2021 for wind turbine sketching and ANSYS for model analysis.

2.1 Modeling Process

The research commenced with the design and modeling of the Archimedes wind turbine. The task is executed using SolidWorks 2021 software. Wind turbines typically possess three interconnected blades. The chosen radius for all geometries in this study is 0.75 m, encompassing both the Savonius and Helical Savonius wind turbines.

2.1.1 Blade Pitch

Fig. 1 shows the blade pitch geometry profile that is described as the axial distance measured when the blade makes one full rotation. One crucial factor in the turbine's design is the pitch of the wind turbine blade. It regulates and limits the turbine's rotational speed in response to variations in wind speed. The simulation process involves varying and studying the pitch.

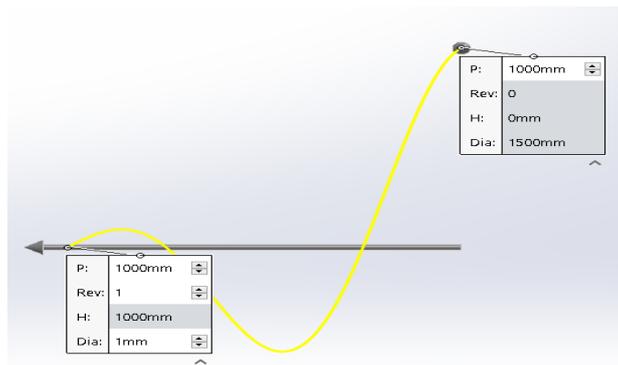


Fig. 1 Geometrical measurement for blade pitch

2.1.2 Opening Angle

The opening angle is the angle at which air exits the turbine with respect to incoming air. It also establishes the tip vortex that forms at the turbine blade's end. Similarly, a change in opening angle also affects the pressure differential that is created along the turbine's blades. The simulation process involves varying and studying the opening angle.

2.2 Simulation

This research employed ANSYS software for simulation purposes. ANSYS is a robust simulation software extensively utilized for engineering study. This simulation comprises multiple stages: Geometry, Mesh, Setup, Solution, and Results.

2.2.1 Geometry

Fig. 2 shows the geometry of Archimedes, Savonius, and Helical Savonius wind turbines. The Archimedes wind turbine features three 0.75 m radius blades at a 120° angle, which are attached to a shaft. The turbines were drawn using computer-aided design, which is SolidWorks 2021 software. We created 3D geometries of various dimensions to simulate the Archimedes wind turbine with different parameters.

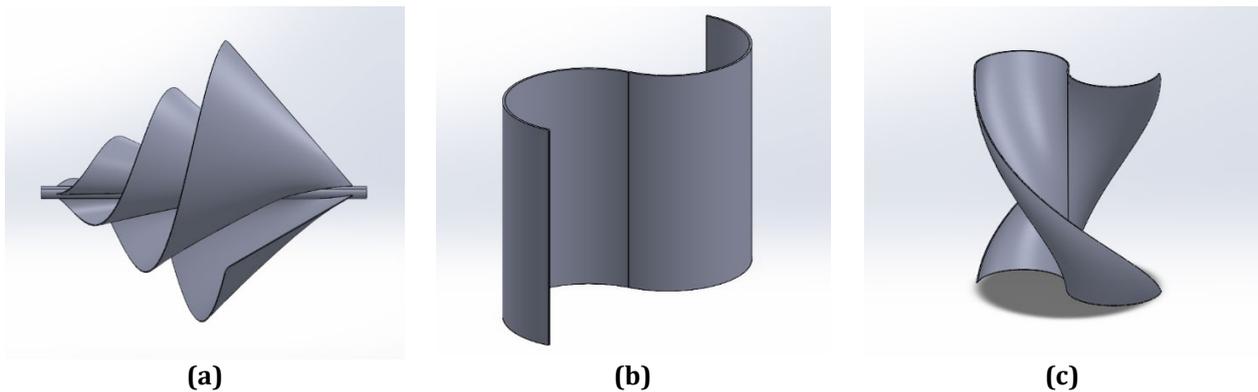


Fig. 2 Geometry of (a) Archimedes wind turbine (b) Savonius wind turbine (c) Helical Savonius wind turbine

2.2.2 Mesh

The geometry created in SolidWorks 2021 was imported into ANSYS Mesh. The ANSYS Mesh integrates the turbine between rotating and stationary cylindrical domains, each possessing a radius five times greater than that of the turbines. Fig. 3 illustrates the domains constructed around the turbine shape. They typically offer the advantages of a dense mesh encircling the turbine.

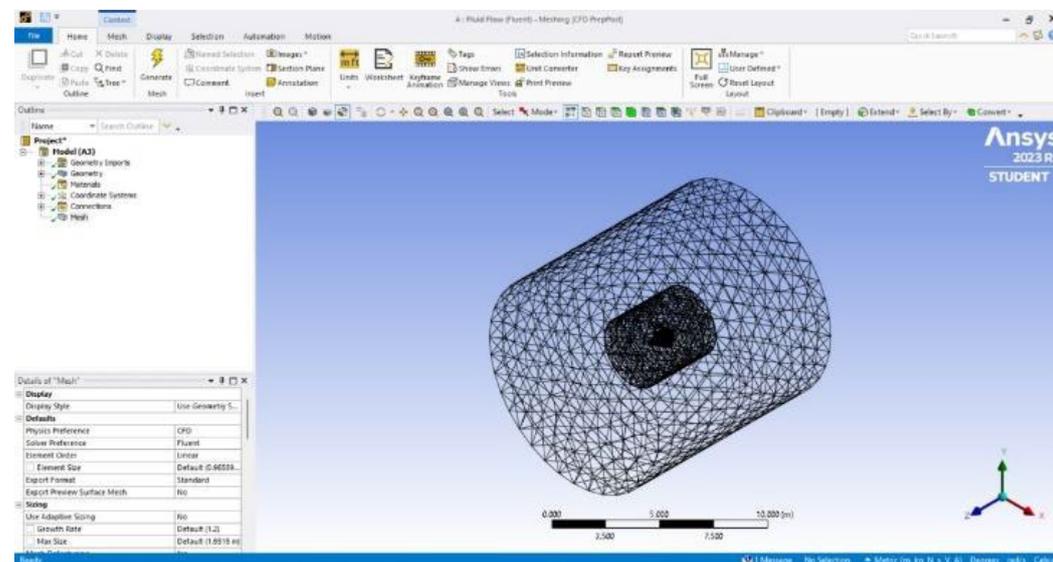


Fig. 3 Meshing

2.2.3 Setup

The configuration and boundary conditions implemented in the ANSYS simulation are presented in Table 1. This study is focused on transient time. Furthermore, in conjunction with the additional details provided below, the k- ω Shear Stress Transport (SST) model utilizing 2 equations has been chosen for the flow analysis in this study. This model is well-suited for wind turbine simulations, as it effectively predicts the complex aerodynamic phenomena related to turbine blades and rotor flows, including the impact of turbulence on the flow surrounding the blades. Simultaneously, the RPM is set to 50 to simplify the boundary conditions and guarantee numerical stability in the simulations.

Table 1 Setup and boundary conditions

Subject	Value
Velocity Formulation	Absolute
Solver	Pressure-based
Time	Transient
Turbulence Model	k- ω (SST) - 2 equations
Material	Air
Density (kg/m ³)	1.225
Viscosity (kg/m s)	1.7894e-5
Ambient Pressure (kPa)	101.325
Gauge Pressure (kPa)	0
Temperature (K)	288.15
RPM	50
Slip Condition	None

2.2.4 Solution

The solution component involves solving the mathematical equations governing the problem's physics. To determine how the system will behave under the given circumstances, this step uses numerical methods. Up until it converges to a reliable and accurate result, the solver iteratively improves the solution. Table 2 shows the calculation parameters in the physics simulation.

Table 2 Calculation parameters

Parameters	Value
Number of Time Steps	300
Time Step Size (s)	0.1
Max Iterations / Time Step	20

2.2.5 Mathematical Formula

The mathematical formula used in this study to calculate the result from the simulation:

Power coefficient:

$$P = T\omega \quad (1)$$

$$C_p = \frac{P}{0.5\rho Av^3} \quad (2)$$

Tip speed ratio:

$$TSR = \frac{R\omega}{v} \quad (3)$$

Torque coefficient:

$$C_t = \frac{C_p}{TSR} @ \frac{T}{0.5\rho ARv^2} \quad (4)$$

3. Results and Discussion

This research utilized Computational Fluid Dynamics (CFD) analysis to assess the performance of three wind turbine designs: Archimedes, Savonius, and Helical Savonius turbines. Simulations utilizing ANSYS Fluent were performed to assess the variations in power and torque resulting from variations in blade pitch, opening angle, and wind speeds. A comparative analysis of the Archimedes, Savonius, and Helical Savonius turbines is presented to better understand performance differences among these wind turbine types.

3.1 Variation of Pitch

Table 4 and Fig. 4 show the power and torque coefficients obtained from simulations in a range of blade pitches from 600 mm to 2000 mm. All the developed Archimedes wind turbines maintain the same opening angle of 45° , regardless of pitch variations. Data obtained from simulation and calculation depicts that the power coefficient increases as pitch increases. The torque coefficient exhibits a similar outcome. However, progressively increasing the pitch causes a decrease in both power and torque coefficients. Therefore, we observe the maximum power and torque coefficients at a pitch of 1400 mm.

Table 3 Pitch vs C_p and C_t

Pitch (mm)	C_p	C_t
600	0.1797	0.2301
800	0.1881	0.2410
1000	0.1943	0.2488
1200	0.1986	0.2543
1400	0.2013	0.2577
1500	0.1960	0.2508
1600	0.1925	0.2464
1800	0.1880	0.2405
2000	0.1822	0.2331

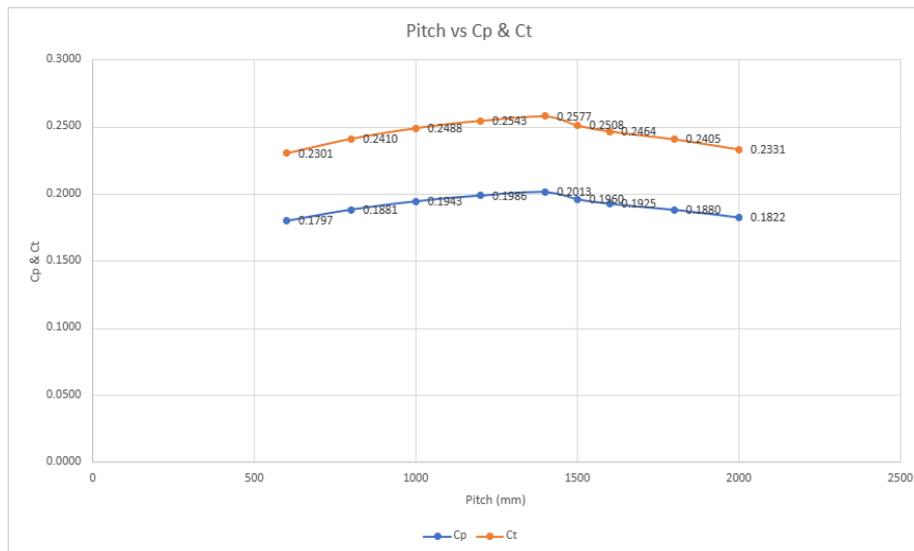


Fig. 4 Graph of C_p and C_t against pitch

3.2 Variation of Opening Angle

Table 4 and Fig. 5 present the results of simulations with a constant blade pitch of 1000 mm and varying opening angles. The Archimedes wind turbines were developed to have varied opening angles ranging from 15° to 75°. Simulation results showed that an opening angle of 60° yielded the highest C_p and C_t values, which then decreased as the opening angle increased.

Table 4 Opening angle vs C_p and C_t

Opening Angle	C_p	C_t
15°	0.0725	0.0926
30°	0.1514	0.1937
45°	0.1966	0.2518
60°	0.2290	0.2937
75°	0.1898	0.2434

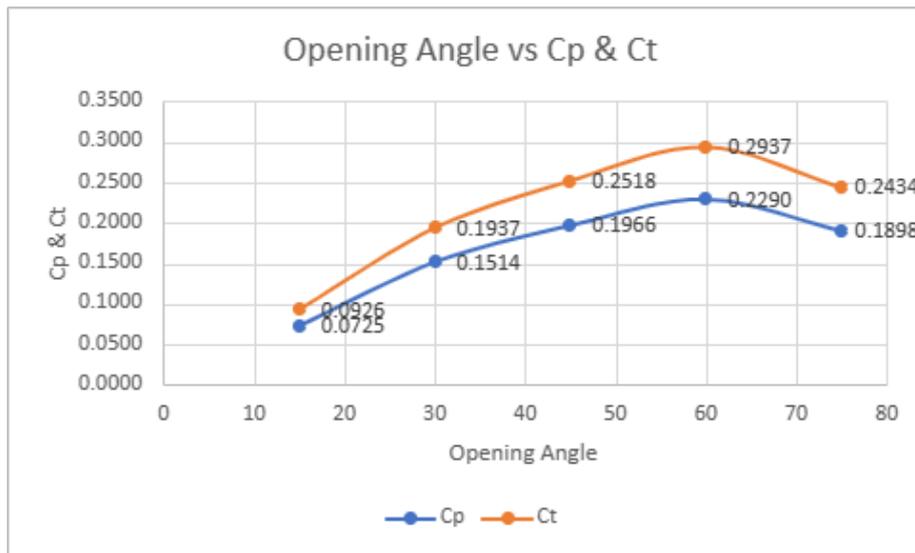


Fig. 5 Graph of C_p and C_t against opening angle

3.3 Variation of Wind Speed (Archimedes)

Simulation results for the Archimedes wind turbine, featuring a 1000 mm pitch and 45° opening angles, are presented in Table 5 and Fig. 6. Simulations conducted included a range of wind speeds from 3 m/s to 9 m/s. The results indicate a reduction in C_p despite an increase in power. Several factors may contribute to this, including increased aerodynamic losses, constraints in wind turbine design, turbulence resulting from high wind speeds, among others. However, the value of C_t rises with increasing wind speed.

Table 5 Wind speed vs C_p and C_t

Wind Speed (m/s)	C_p	C_t
3	0.2334	0.1793
5	0.1966	0.2518
7	0.1617	0.2899
9	0.1370	0.3159

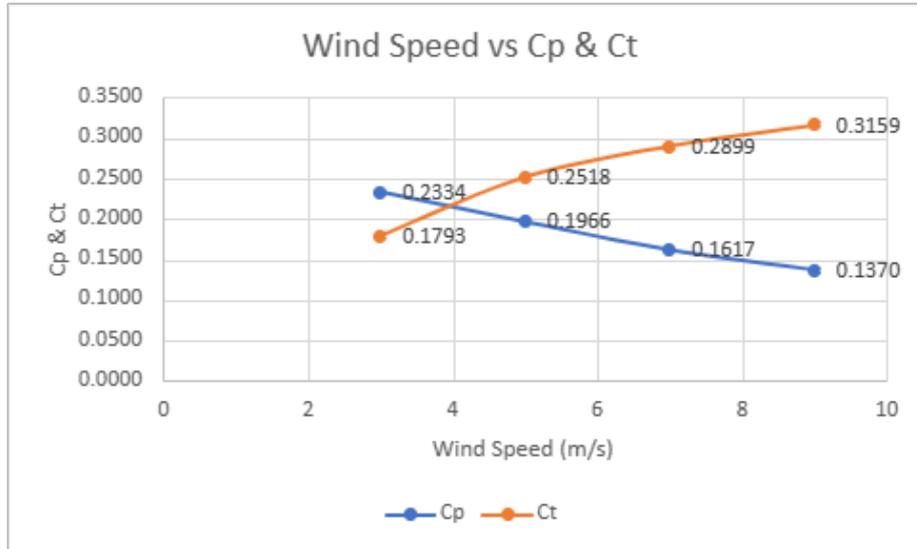


Fig. 6 Graph of C_p and C_t against wind speed

3.4 Variation of Wind Speed (Savonius)

A CAD model of the Savonius wind turbine was developed, maintaining a radius of 0.75 m, consistent with that of the Archimedes wind turbine. The simulation employed the model for a valid comparison with Archimedes, owing to its comparable dimensions. The data presented in Table 6 and Figure 7 indicate that both C_p and C_t exhibit an increase as wind speed rises.

Table 6 Wind speed vs C_p and C_t

Wind Speed (m/s)	C_p	C_t
3	0.0809	0.0612
5	0.1115	0.1405
7	0.1120	0.1976
9	0.1189	0.2698

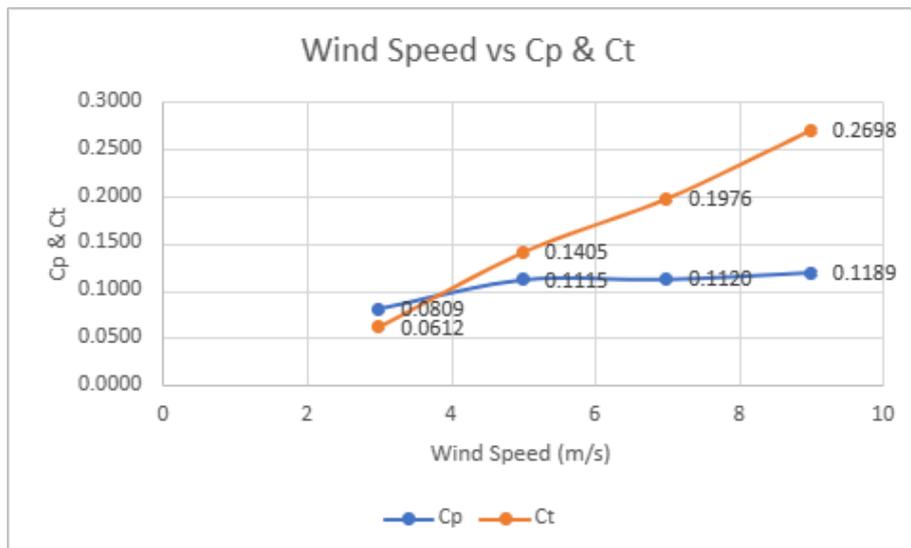


Fig. 7 Graph of C_p and C_t against wind speed

3.5 Variation of Wind Speed (Helical Savonius)

By using the same radius of 0.75 meters, a computer-aided design (CAD) model of the Helical Savonius wind turbine was constructed. The model is compared to the Archimedes and Savonius wind turbines in the simulation. Both C_p and C_t are shown to rise with increasing speed, as demonstrated by the findings presented in Table 7 and Fig. 8.

Table 7 Wind speed vs C_p and C_t

Wind Speed (m/s)	C_p	C_t
3	0.1619	0.1223
5	0.1823	0.2295
7	0.1944	0.3426
9	0.1983	0.4493

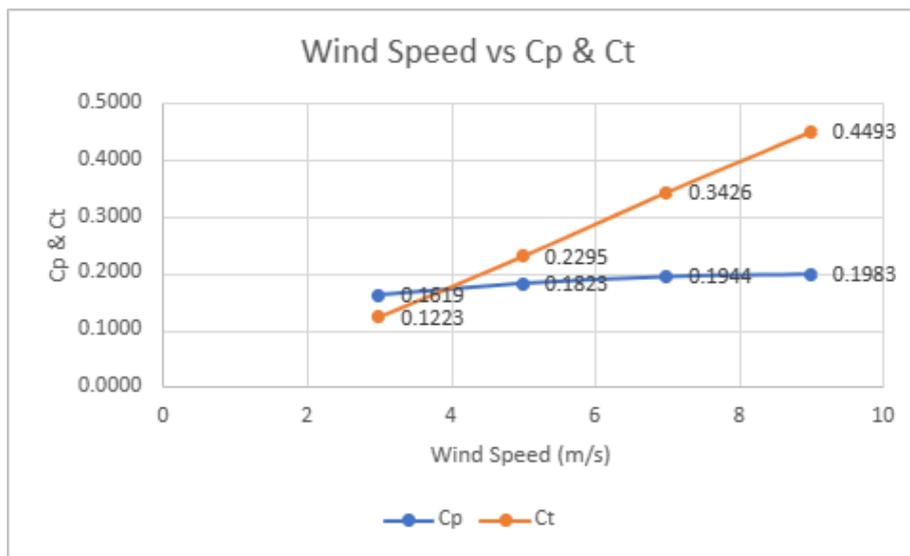


Fig. 8 Graph of C_p and C_t against wind speed

3.6 Comparison for Archimedes, Savonius and Helical Savonius Wind Turbine

The performance of the Archimedes, Savonius, and Helical Savonius wind turbines was compared and evaluated through the obtained C_p and C_t from various wind speeds. From the simulation and comparison, the Archimedes wind turbine shows better performance than the Savonius wind turbine, while approximately similar performance for the Helical Savonius and the Archimedes wind turbine.

3.6.1 Power Coefficient

Table 8 and Figure 9 present a comparison of the power coefficients for Archimedes, Savonius, and Helical Savonius wind turbines. The results indicate that the Archimedes wind turbine exhibits a higher C_p compared to the Savonius wind turbine. Despite a lower C_p value for Archimedes in comparison to Savonius, the Archimedes wind turbine achieved a higher C_p at a wind speed of 11 m/s. In comparing the Archimedes wind turbine and the Helical Savonius wind turbine, it is observed that the latter exhibits a higher coefficient of performance (C_p) at elevated wind speeds, whereas the Archimedes turbine demonstrates superior C_p at lower wind speeds.

Table 8 Comparison of C_p for Archimedes, Savonius and Helical Savonius

Wind Speed (m/s)	Power Coefficient, C_p		
	Archimedes	Savonius	Helical Savonius
3	0.2334	0.0809	0.1619
5	0.1966	0.1115	0.1823
7	0.1617	0.1120	0.1944
9	0.1370	0.1189	0.1983

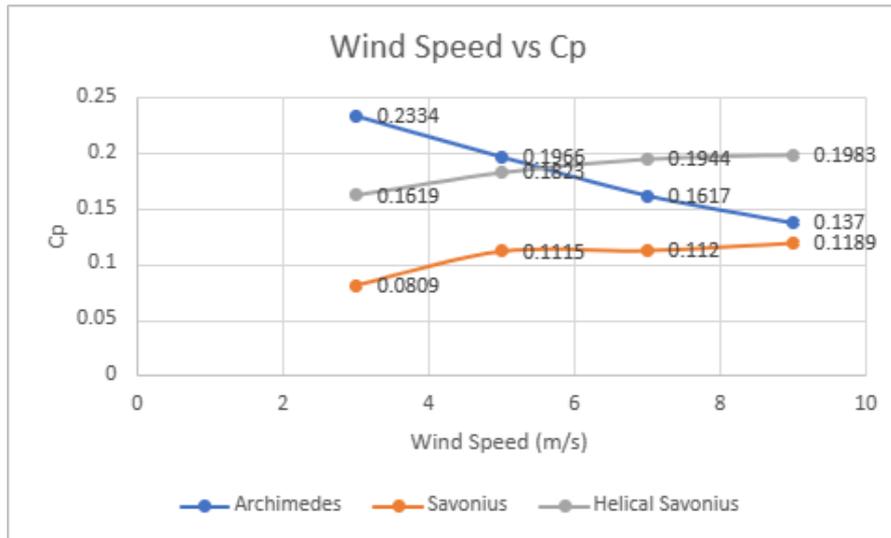


Fig. 9 Graph comparison of C_p against wind speed for Archimedes, Savonius and Helical Savonius

3.6.2 Torque Coefficient

Table 9 and Figure 10 present a comparison of the torque coefficients for Archimedes, Savonius, and Helical Savonius designs. When comparing the torque coefficients of Archimedes, Savonius, and Helical Savonius wind turbines, it is evident that all turbine types exhibit an increasing trend in C_t as wind speed increases. However, the coefficient of thrust (C_t) of the Savonius wind turbine is lower in comparison to that of the Archimedes wind turbine. Consequently, Archimedes demonstrates superior performance compared to Savonius. In comparison, the coefficient of thrust (C_t) for the Helical Savonius turbine exceeds that of the Archimedes wind turbine.

Table 9 Comparison of C_t for Archimedes, Savonius and Helical Savonius

Wind Speed (m/s)	Torque Coefficient, C_t		
	Archimedes	Savonius	Helical Savonius
3	0.1793	0.0612	0.1223
5	0.2518	0.1405	0.2295
7	0.2899	0.1976	0.3426
9	0.3159	0.2698	0.4493

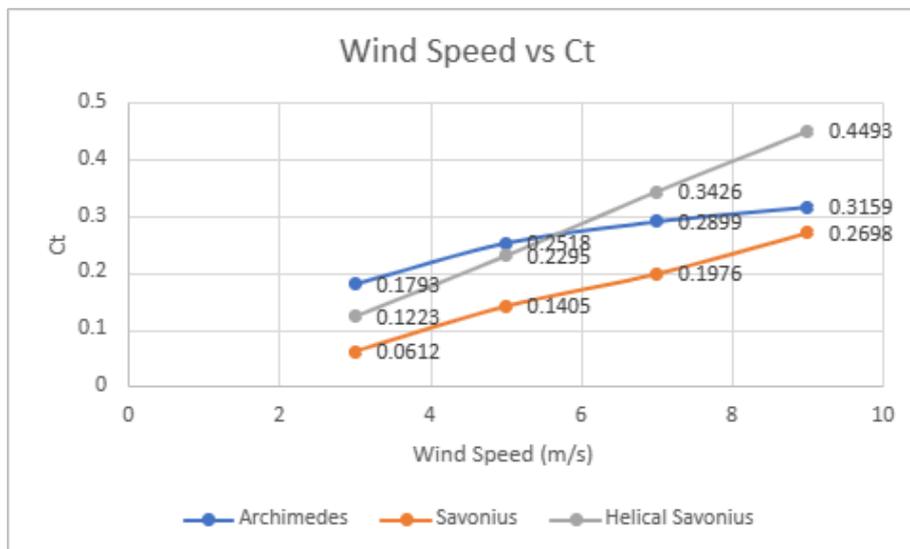


Fig. 10 Graph comparison of C_t against wind speed for Archimedes, Savonius and Helical Savonius

Conclusion

The Computational Fluid Dynamics (CFD) analysis of the Archimedes wind turbine yielded several conclusions. Notably, the optimal models were identified as the Archimedes wind turbine with a pitch of 1400 mm at an opening angle of 45°, and a pitch of 1000 mm at an opening angle of 60°. Higher wind speeds generate increased power as they enable the blades to rotate more rapidly, resulting in improved performance of the wind turbine. Thus, an increase in wind speed results in a reduction of the power coefficient, C_p , attributable to various factors. The comparison between the Archimedes wind turbine and the Savonius wind turbine indicates that the Archimedes turbine exhibits a higher coefficient of performance (C_p) of 0.1370 at a wind speed of 9 m/s, in contrast to the Savonius turbine, which has a C_p of 0.1189 at the same wind speed. It can be concluded that the Archimedes turbine outperforms the Savonius wind turbine. At elevated wind speeds, the Helical Savonius exhibits a higher coefficient of performance (C_p) compared to the Archimedes wind turbine, which demonstrates a superior C_p at lower wind speeds. Consequently, the performance of these two wind turbines is approximately comparable.

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Author Contribution

*The authors confirm contribution to the paper as follows: **study conception and design:** Mohamad Faizal Mohamad Raffi, Sofian Mohd; **data collection:** Mohamad Faizal Mohamad Raffi, Sofian Mohd; **analysis and interpretation of results:** Mohamad Faizal Mohamad Raffi, Sofian Mohd; **draft manuscript preparation:** Mohamad Faizal Mohamad Raffi, Sofian Mohd. All authors reviewed the results and approved the final version of the manuscript.*

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