Computational Analysis and Aerodynamic Optimization of a Savonius Wind Turbine

A Project Report

Submitted by

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Abstract

This study uses Computational Fluid Dynamics (CFD) to analyze the aerodynamic performance optimization of a Savonius Vertical Axis Wind Turbine. The primary goal is to determine how differences in blade arc angle effect turbine efficiency while keeping a fixed overlap ratio (OR) of 0.4 and a tip speed ratio (TSR) of 1. SolidWorks was used to create blade geometries with arc angles ranging from 110° to 150° (in 10° increments) and then analyzed in ANSYS Fluent under steady-state conditions. Using the SST (Shear Stress Transport) k-ω turbulence model to accurately simulate turbulent flow characteristics. All simulations were carried out using a constant inlet air velocity of 8 m/s, a time step of 0.0001 s, and a total of 8160 steps. The performance indicators analyzed include maximum power output (P_{max}) and power coefficient (C_p). Results show that P_{max} and C_p rise with blade arc angle, peaking at 130° with 45.52 W and C_p of 0.292. Beyond this angle, performance degrades due to greater flow separation and aerodynamic loss. The data demonstrate that blade arc angle has a considerable influence on drag-induced torque and total turbine efficiency. This study emphasizes the significance of geometric optimization in improving Savonius turbine performance, especially for small-scale applications in low-wind or urban settings. The findings establish a solid platform for future experimental validation and multi- parameter optimization research.

Introduction

1.1 BACKGROUND

As the globe becomes increasingly concerned about climate change and fossil fuel depletion, there is a greater demand for clean and renewable energy sources. Wind energy is one of the most promising and extensively used kinds of renewable power. While horizontal axis wind turbines (HAWTs) dominate large-scale power generation, vertical axis wind turbines (VAWTs) have advantages in some situations, such as urban or low-wind areas. The Savonius wind turbine is well-known among VAWTs due to its simple design, inexpensive production costs, and ability to operate in omnidirectional and low wind situations. Rotational motion is produced by using drag forces caused by the wind acting on its curved blades. This makes it suitable for small-scale and off-grid applications. The main disadvantage of the Savonius turbine is its low efficiency when compared to lift-based systems such as HAWTs or Darrieus turbines. To solve this constraint, researchers investigated numerous modifications to increase the aerodynamic performance of the Savonius turbine, such as changes in blade design, number of blades, and overlap ratios. In this effort, Computational Fluid Dynamics (CFD) has emerged as an effective technique for studying and optimizing wind turbine designs. CFD enables for thorough simulation of airflow patterns, pressure distribution, and turbulence effects, providing valuable insight into the aerodynamic behavior of various configurations without the need for expensive physical prototypes.

This study uses CFD simulation to design and optimize a Savonius wind turbine. By analyzing various blade geometries and operational parameters, the goal is to identify configurations that enhance efficiency and performance. The findings of this research could support the broader application of Savonius turbines in sustainable, decentralized energy systems, particularly in areas where conventional turbines are less effective.

1.2 WIND ENERGY

The use of renewable energy sources has grown in popularity over the last several decades. In particular, wind and solar energy are becoming the primary renewable sources as technology advances. In contrast, wind energy has become a well-known renewable technology. 743 GW of wind power has been installed overall, according to GWEC historical data, with 93 GW of new wind power installations in 2020 compared to 2019 [1].

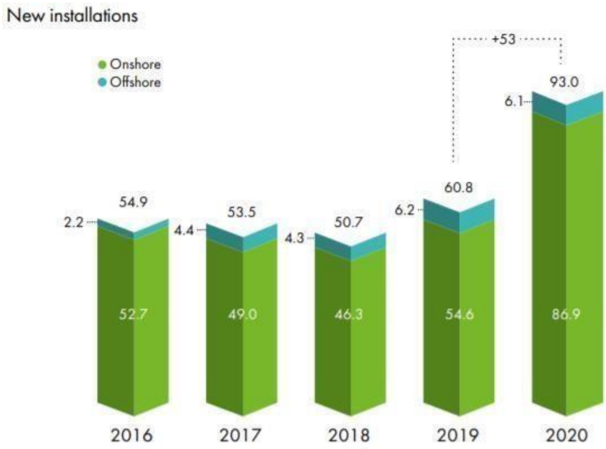


Figure 1.1: Trend of global new wind energy installations [1]

Research and technical developments on onshore and offshore wind turbines have exploded in the past few years. The two main types of wind turbines are horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT). HAWTs are more effective than the other two because of their sophisticated technology. The two main types of VAWTs are Savonius wind turbines and Darrius wind turbines. The past ten years have seen a large number of studies on various VAWT. Performance of the Savonius wind turbine has been shown in conditions of turbulent flow.

It is mostly positioned in remote areas without grid access because to its robust and simple construction. To date, a number of savonius designs have been developed and examined. This technology will be unable to make a substantial contribution to the installed power of the world because of its major focus on modest applications. A brief synopsis of Savonius and other VAWTs is included in the theory section. VAWT's main advantage is that it can absorb wind independent of the horizontal wind's direction, negating the requirement for a yaw control device. One significant advantage of VAWT is that it requires less starting torque due to its small design. In addition, VAWTs are robust and have a simple design. Important VAWT components are placed on the ground to assist turbine maintenance [2]. The maintenance and commissioning of large-scale HAWTs is more complex than that of small- scale VAWTs. These days, small-scale off-grid applications are more likely to use hybrid wind and solar energy sources [3]. In this case, VAWT could be used to produce electricity. Recent developments in wind power technology have enabled a wide range of options for both vertical and horizontal wind turbines. The market currently offers wind turbines with ratings ranging from a few kW to 10 MW. Due to their efficiency and advanced technology, HAWTs are the market leaders in this broad spectrum of generation capacity. VAWTs are equally well-known for their small-scale applications, though. More information regarding the many types of VAWT will be included in the theory section of this project.

By the year 2000, almost 70% of all wind power installations globally were in Europe, which has a fantastic reputation for encouraging renewable energy. In 2009, the Swedish Parliament set the goal that by 2020, at least 50% of the nation's energy would originate from renewable sources.[4] Sweden more than doubled its wind power installations between 2018 and 2019, and 15% of its electricity was generated by wind power in 2019 [5], according to data from Wind Europe. One country that prioritizes minimizing its environmental impact and invests in wind power is Sweden, without a question. It has been demonstrated that small-scale renewable energy generation is more economical since it efficiently utilizes the natural resources of the local community. Moreover, it would promote the decentralization of electricity and reduce environmental degradation [6]. As was previously shown, the SSWT can be a useful tool for expanding the wind energy sector and the country's potential to generate wind power. While a variety of blade designs can be used to generate the SSWT, those designs need to be tuned to produce a Savonius rotor that is both efficient and daily use [7].

1.3 THEORY

In this section the fundamental theory of vertical axis wind turbine, fluid mechanics, computational fluid dynamics are discussed in brief. Different blade geometries and essential concepts of simulation setup are also presented along with turbine theory.

1.3.1 Different Types of VAWT

Mainly VAWTs are divided into two major types:

1: Savonius- drag driven

2: Darrius- lift driven

From design point of view, Savonius turbines are simple compared to Darrius turbines. Savonius turbines contains two semi-cylindrical cups attached to the vertical shaft in such a way that it can create drag forces and rotate around the vertical axis. Figure 2(a) shows the design of the Savonius wind turbine, followed by the Darrius-rotor figure 2(b).

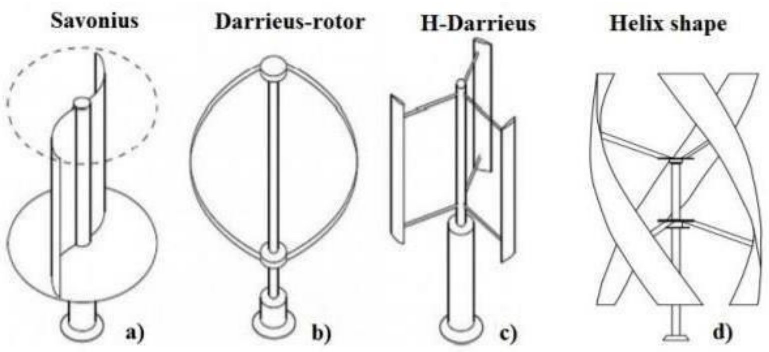


Figure 1.2: Types of VAWT rotor (a)Savonius (b)Darrieus (c)H-Darrieus (d)Helix shape [7]

Figure 2 (b-d) depicts the various types of Darrius turbine profiles. Figure 2(b) was designed to lessen centrifugal stresses, 2(c) to increase cross-sectional area, which makes it easier to build and enables for a higher tower height, and 2(d) to reduce torque and thrust oscillations. According to prior studies, the Savonius Turbine is less efficient than the Darrius Turbine. Savonius turbines are employed where cost and dependability are the most important considerations [6]. Savonius turbines are suitable for tiny sizes, with power scales of $R2$ and mass scales of $R3$.

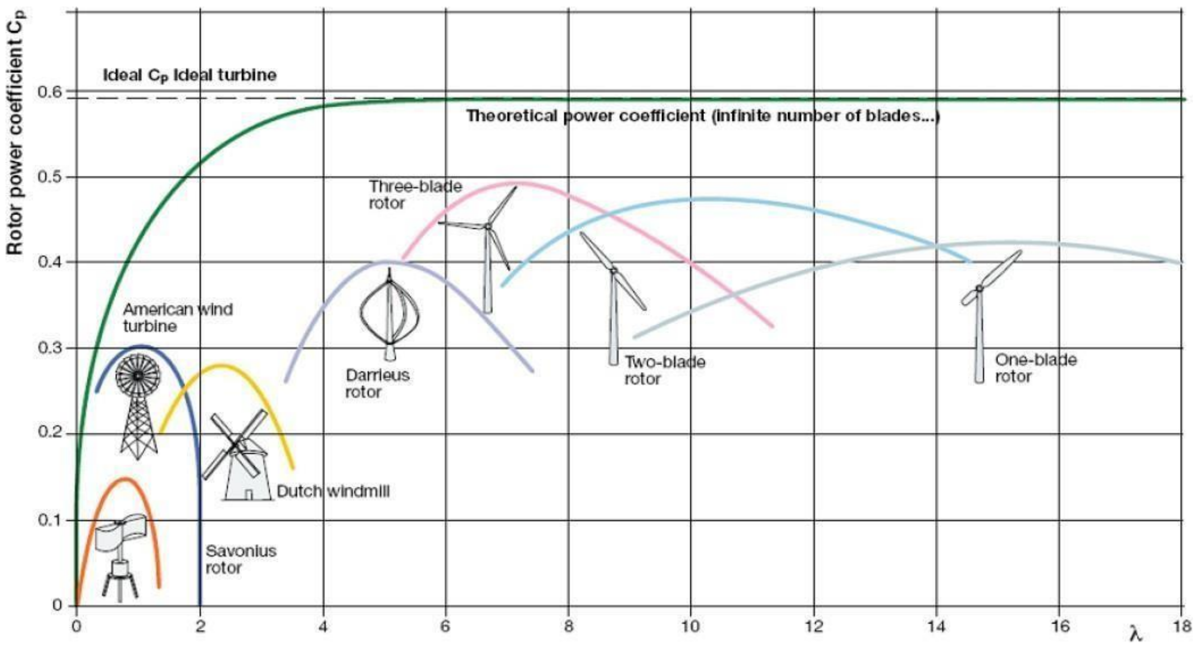


Figure 1.3: Cp curve of different designs averaged to tip speed ratio [10]

The tip speed ratio (TSR), which is useful for examining the turbine performance at various rotational velocities, is another crucial statistic. The tip speed ratio, denoted by λ, can be expressed mathematically as the ratio of the blade's tip speed to the input wind velocity. Plotting the turbine power curve against the TSR is standard practice. The efficiency of each

TSR turbine varies. All of the simulations in this thesis are run at TSR 1, with the exception of the validation section.

1.3.2 Different Savonius Blade Profiles

The various blade profiles and the rationale behind them will be covered in this section. The classic Savonius rotor, which depicts all of the dimensions of a two-bladed Savonius rotor, is shown in Figure 4.

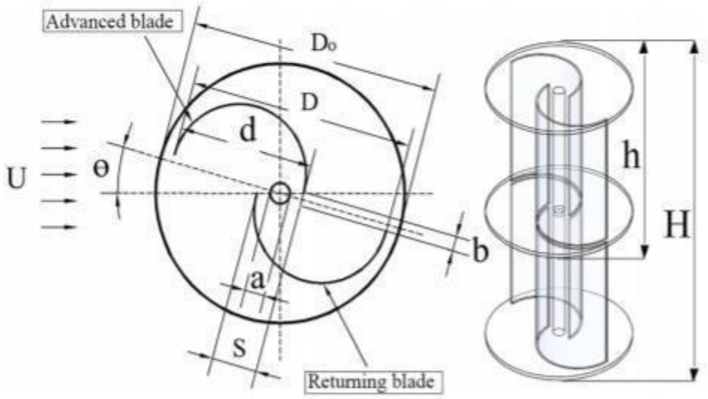


Figure 1.4 : Traditional Savonius Rotor [11]

For various investigations, several researchers have created a variety of blade profiles based on the classic Savonius rotor. Roy and Saha conducted a study using four distinct blade profiles, which are depicted in Figure 5. Classical semi-elliptic and semi-circular Savonius profiles Roy and Saha's work has a comparison of Figure 5(a,b) [13]. However, Benesh AH created Figure 5(c) in 1996, and at the time, it was regarded as one of the best small-scale

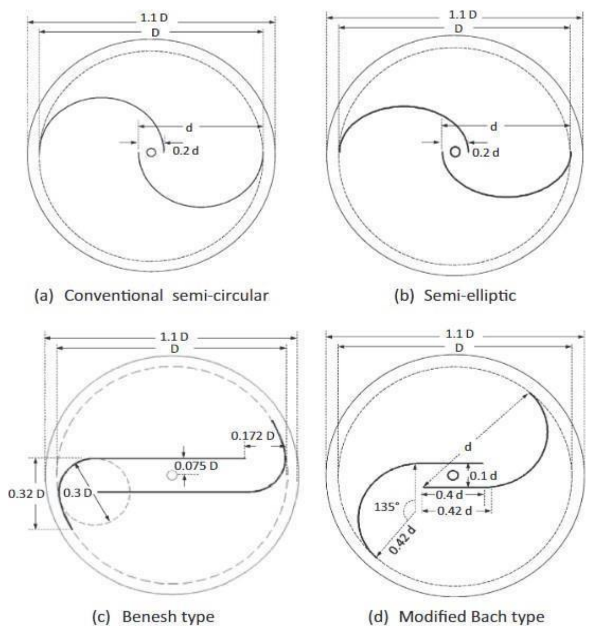


Figure 1.5: Various blade profiles generated by Roy and Saha [13]

wind turbines (SSWT). Many studies on the Savonius turbine have been conducted in the past 20 years, and many researchers are now very interested in the Bach type profile. In this thesis, the Modified Bach type profile created by Lundberg, Manousidou, Solhed, and Sundberg is chosen for additional research and design optimization based on efficiency [5].

Chapter 2

OBJECTIVES

1: To design and simulate Savonius wind turbine models with varying blade angles using CFD.

2: To analyze the effect of blade angle on power output and coefficient of performance (Cp).

3: To determine the optimal blade angle that maximizes aerodynamic efficiency and energy capture.

2.1 SCOPE AND LIMITATIONS

2.1.1 Scope:

This research focuses on the design and performance analysis of a Savonius vertical axis wind turbine (VAWT) using Computational Fluid Dynamics (CFD). The primary goal is to determine the effect of different blade angles on the turbine's aerodynamic performance, specifically its power output and coefficient of performance (Cp).The scope comprises developing 3D turbine models with various blade angles, which are subsequently simulated under steady-state wind conditions with CFD software. The analysis is limited to drag-based Savonius rotor designs and excludes other VAWT types, such as lift-based Darrieus turbines. The study explores a variety of blade angles to find which configuration produces the best aerodynamic performance. Wind speed is kept constant throughout the simulations to isolate the impact of blade angle on performance. Environmental elements such as topography effects, wind direction fluctuation, and turbulence intensity are ignored. This study does not address structural design, material selection, cost analysis, or experimental validation. All conclusions are based on simulation results and compared to existing literature to confirm trends and performance outcomes. No physical prototypes are built. By focusing on CFD analysis and blade angle optimization, this study hopes to provide practical insights for enhancing the design of Savonius turbines, particularly for small-scale applications in urban or low-wind-speed settings. The findings can inform future development of more efficient, compact wind energy systems for decentralized renewable energy generation.

2.1.2 Limitations:

This study focuses on the investigation of a Savonius vertical axis wind turbine using Computational Fluid Dynamics (CFD) simulations. The results are entirely based on numerical modeling and have not been confirmed through actual experimentation. As a result, real-world factors like material flaws, assembly tolerances, wear and tear, and mechanical losses are not taken into account. One significant constraint is the assumption of consistent, uniform wind flow at a constant velocity. In fact, wind conditions vary greatly in terms of speed, direction, and turbulence intensity. These dynamic impacts are not captured in the current simulation configuration. The environment is also expected to be devoid of obstacles and terrain impacts. The research focuses solely on the impact of blade angle on aerodynamic performance. Other design factors, including blade number, overlap ratio, rotor aspect ratio, and shaft losses, remain constant. Furthermore, the simulations use an incompressible, isothermal fluid (air), with no heat transfer or humidity effects. While these assumptions and restrictions help to simplify the study and focus on specific objectives, they also point to the necessity for additional experimental and multivariable research to fully evaluate performance.

Chapter 3

Project Methodology

3.1 INTRODUCTION

To analyze and optimise the aerodynamic performance of a Savonius wind turbine, a structured research technique is required. This study employs Computational Fluid Dynamics (CFD) simulations to investigate the influence of different blade angles on turbine performance. The methodology is intended to rigorously analyze, evaluate, and assess the effect of blade angle on important performance metrics such as power output and coefficient of performance (Cp). The research method begins with the geometric design of the turbine in CAD software, followed by mesh production to prepare the model for simulation. To recreate realistic wind flow settings, CFD simulations are carried out in ANSYS Fluent with regulated boundary conditions. Each simulation considers a particular blade angle while keeping all other variables constant in order to isolate its influence. The data is then examined to uncover trends in aerodynamic performance, which leads to the discovery of an ideal blade design.

This methodology guarantees a rigorous, consistent, and data-driven approach to performance analysis while also providing quantitative evidence to support design decisions.

3.2 ASSUMPTIONS AND BOUNDARY CONDITIONS

3.2.1 Assumptions

1: All simulations are two-dimensional (2D) to reduce computational load and time.

2: Incompressible flow is assumed for the fluid (air).

3: Wind velocity is constant at 8 m/s throughout all simulations.

4: The flow is uniform at the inlet with zero shear applied to side walls.

5: Simulations are performed using the RANS (Reynolds-Averaged Navier-Stokes) equations with the k-ω Shear Stress Transport (SST) turbulence model. Turbulent model constant $C\mu = 0.09$.

6: No turbulence study or modeling of turbulent imperfections in power output was considered.

7: Simulation time step is fixed at 0.0001 seconds, and simulations are run for 8160 time steps.

8: No-slip conditions are not applied; instead, side walls have zero shear to simulate free field conditions.

3.2.2 Boundary Conditions

1: Inlet Boundary

Velocity inlet, with uniform velocity of 8 m/s.

Inlet velocity is in x-direction with 0-gauge pressure.

2: Outlet Boundary

Default outlet values used (likely pressure outlet with 0 Pa gauge pressure in ANSYS).

3: Walls (Side Domain Boundaries)

Zero shear condition applied (i.e., effectively simulating free field condition).

No physical walls exist in reality, so domain walls are assumed frictionless.

4: Blade Walls

Treated as moving walls with specified angular velocity (ω).

15-layer inflation layers are applied on blade walls for boundary layer resolution.

5: Mesh Interface

A rotating region is used for the rotor with sliding mesh technique to simulate blade rotation.

6: Solver and Model Settings

Pressure-based transient solver used.

Absolute velocity formulation.

Single precision to reduce computational cost.

Second-order upwind scheme for pressure, momentum, turbulent kinetic energy, and specific dissipation rate.

3.3 OUTLINE OF METHODOLOGY

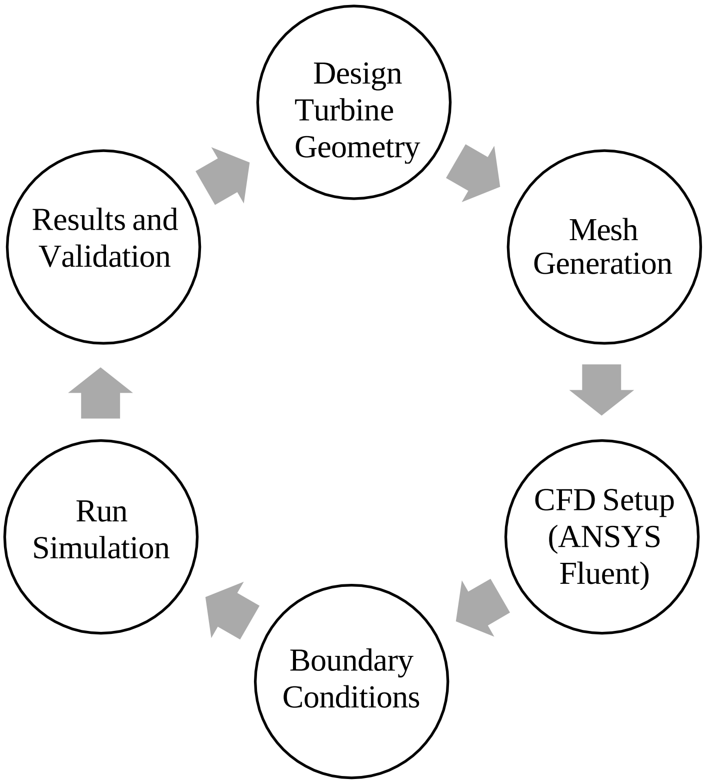


Figure 3.1: Automated Simulation Cycle

3.3.1 Design Turbine Geometry

In this work, a modified Bach-type Savonius wind turbine blade is used to increase aerodynamic efficiency over the usual semi-cylindrical design. The change entails redesigning the blade profile to form a circular arc with blade angles ranging from 110° to 150° in 10° increments, allowing for a systematic examination of curvature effects. The Bach-type design combines a more streamlined inner surface and a sharper leading edge in order to lessen the negative torque generated by the returning blade and improve flow redirection onto the advancing blade. The rotor has a diameter of 240 mm and a blade height of 100.8 mm, with a consistent overlap distance of 96 mm, for an overlap ratio of 0.4. To ensure optimal interaction with the entering airflow, the blades are spaced 24 mm apart. The turbine is built with a tip speed ratio (TSR) of one to represent its drag-based operational characteristics. The modified Bach-type profile is designed to increase self-starting behavior and rotational speed in low wind situations, making it ideal for decentralized, small-scale wind energy applications.

The entire rotor geometry, including blades, shaft, and overlap configuration, was created using SolidWorks 3D CAD software. The blade arc was sketched for each blade angle variation with the Centerpoint Arc tool, and parameters were properly set to ensure consistent rotor diameter, overlap, and gap. Each blade design was extruded to a height of 100.8 mm, and the Modified Bach contour was modified with spline tools and tangent constraints to smooth the trailing edge. A central shaft with a diameter of 10 mm was installed and aligned with the blades. The blades were mirrored and printed to create symmetrical rotor profiles. Each variation (110°, 120°, 130°, 140°, and 150°) was stored as a separate SolidWorks part file to ensure constant boundary conditions for performance measurement. These models served as the foundation for future CFD study and simulations of aerodynamic behavior.

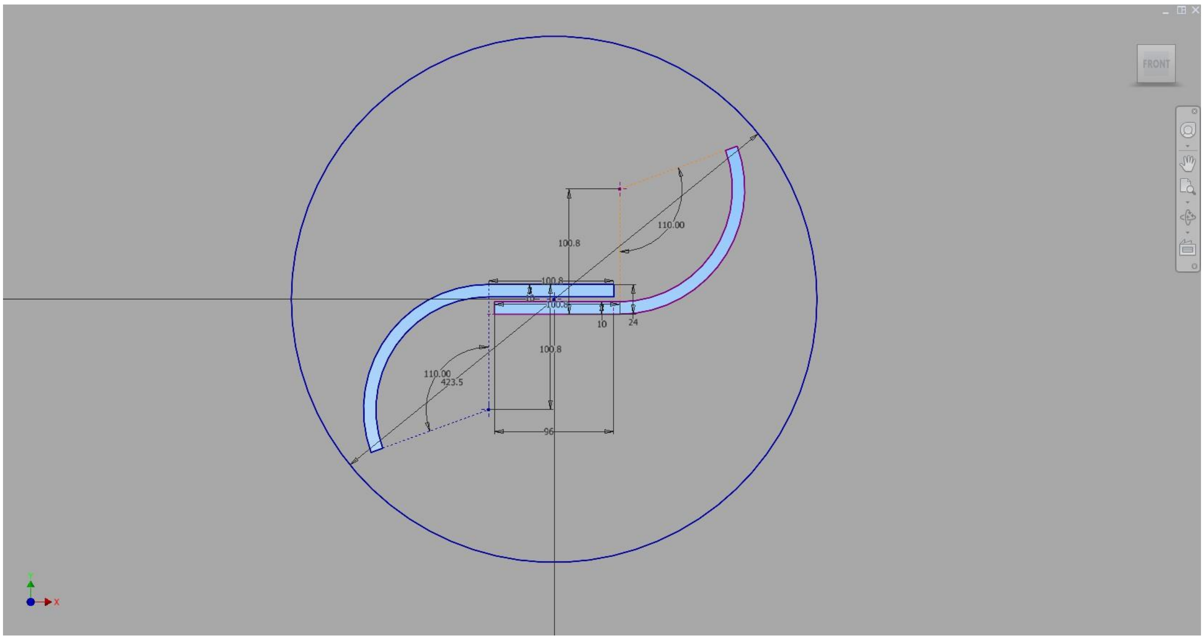


Figure 3.2: Blade Design with 110 degrees.

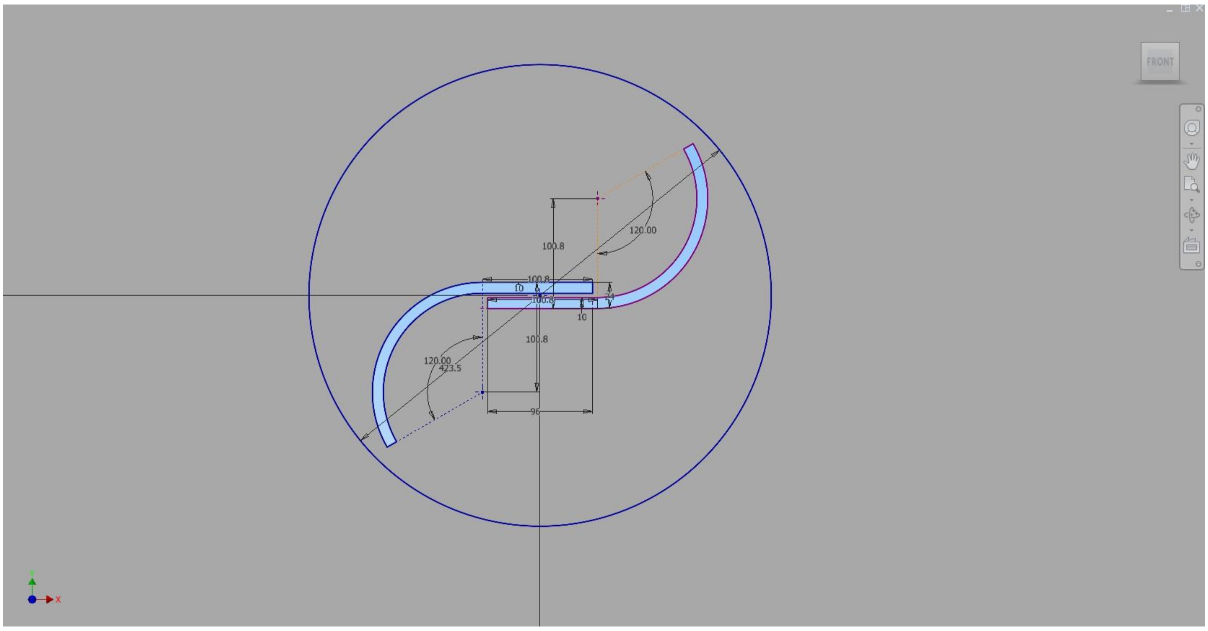


Figure 3.3: Blade Design with 120 degrees.

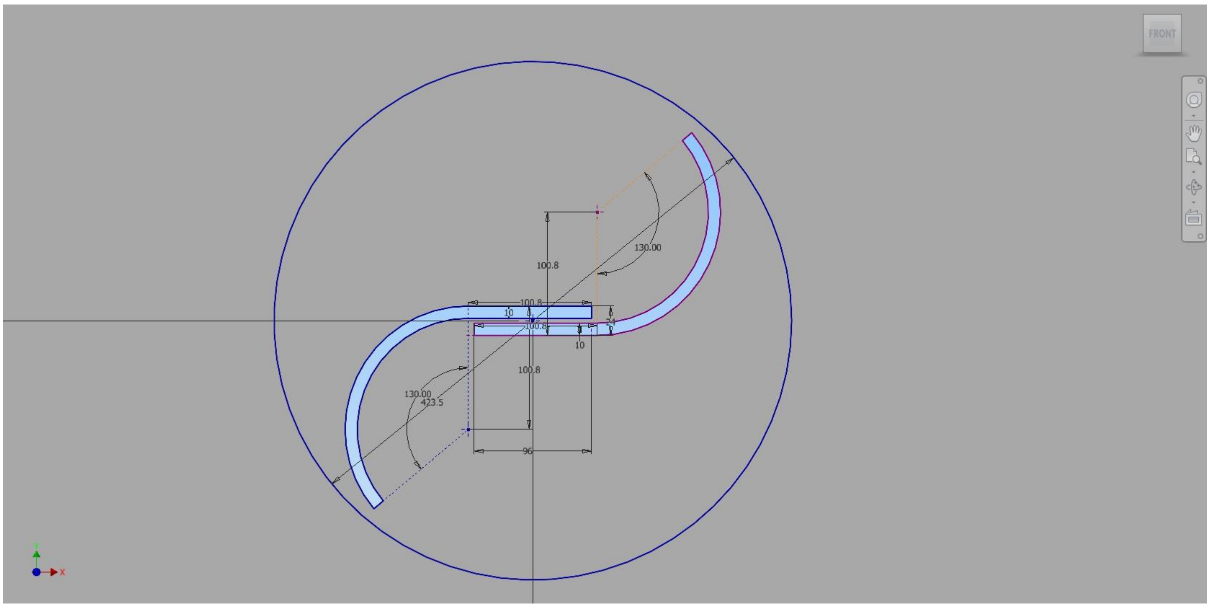


Figure 3.4: Blade Design with 130 degrees.

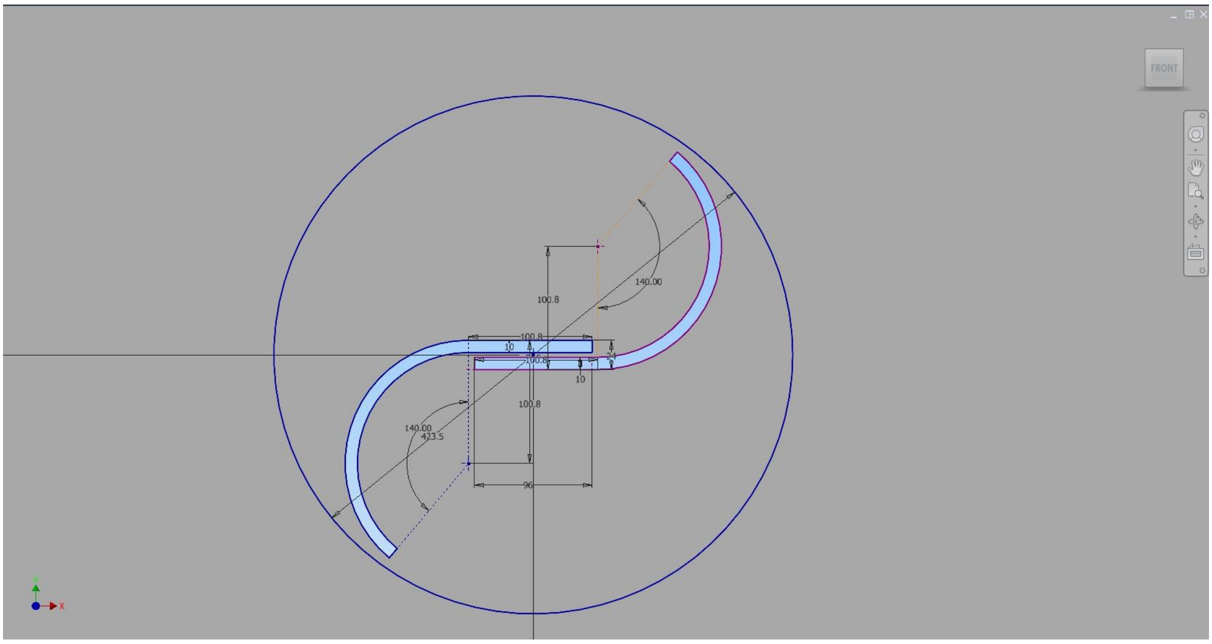


Figure 3.5: Blade Design with 140 degrees.

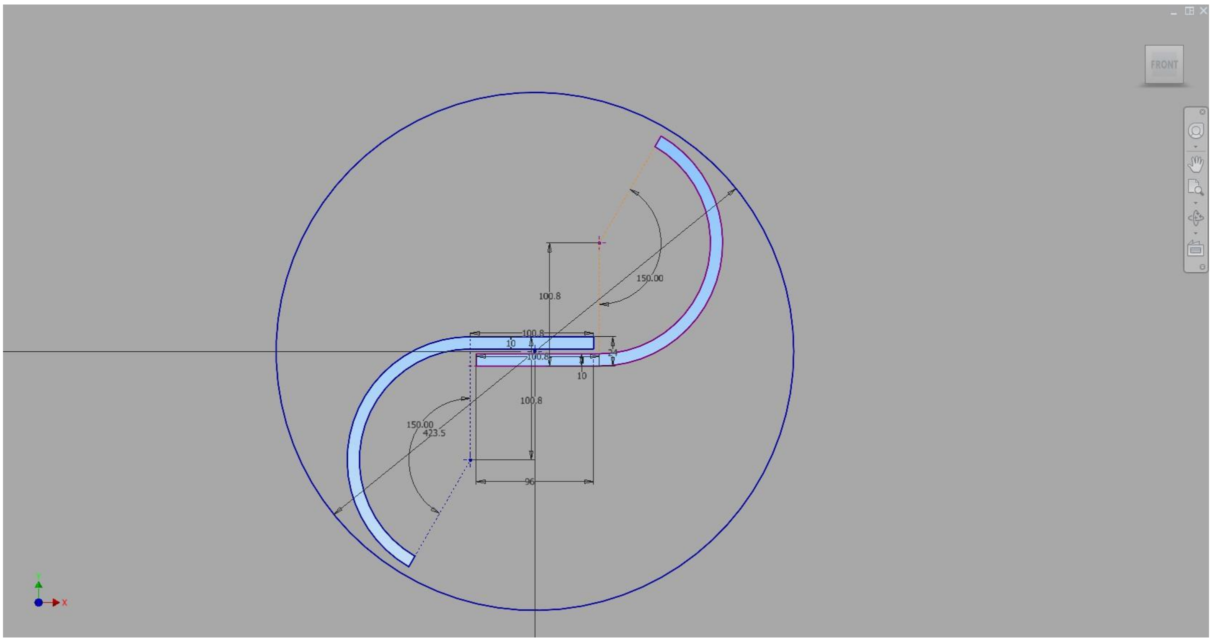


Figure 3.5: Blade Design with 150 degrees.

3.3.2 Meshing

Meshing is the second stage after establishing the geometry and refinement regions. Correct meshing is necessary for an efficient solution that yields accurate results. Ansys offers three meshing methods:

I. Quadrilateral Dominant.

II. Triangles.

III. Multizone Quad/Tri.

According to Ansys' meshing standards, each has a distinct advantage. A quadrilateral approach is more efficient than a triangular one, and the third way combines the two; it is employed for a specific problem that requires compact meshing to investigate the many dependent parameters. The mesh method used will be determined by the application. The fundamental advantage of an unstructured mesh is that it can accommodate curvature boundaries of any shape. Interfaces are constructed on each refinement zone to facilitate the movement from one refinement to the next. Different rectangular sections symbolize each refinement. The modifications are used to reduce simulation time and improve solution accuracy. A brief explanation is provided in the simulation setup section.

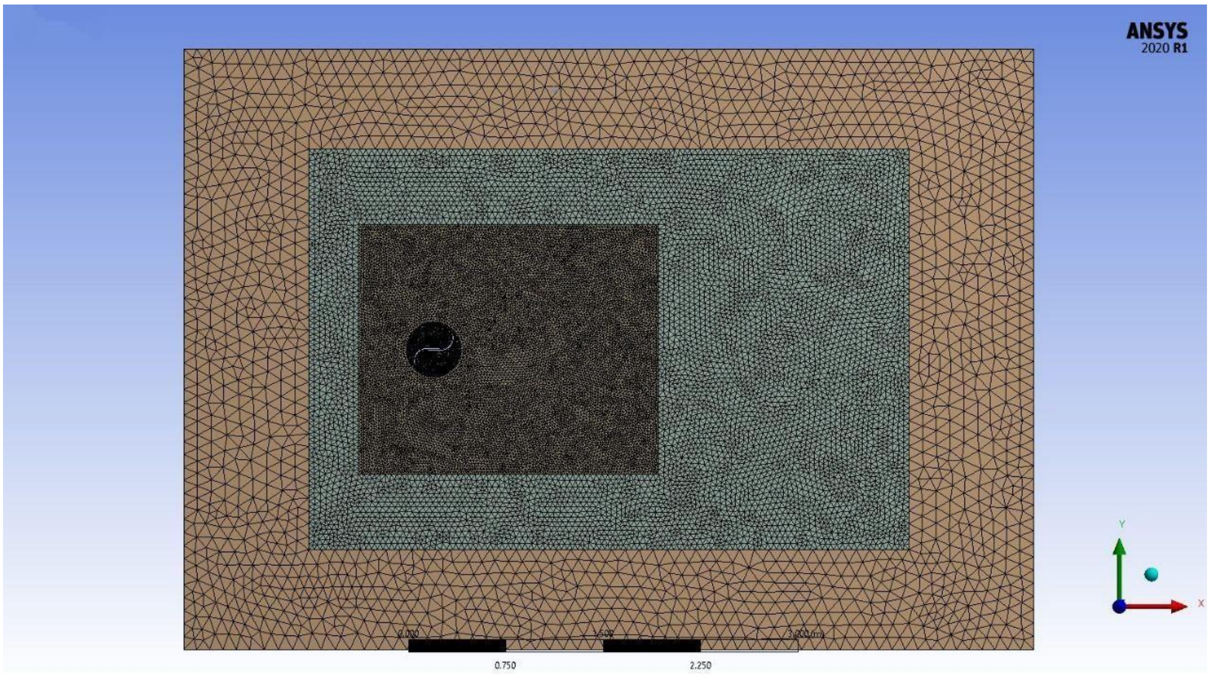


Figure 3.6: Meshing used for Simulation.

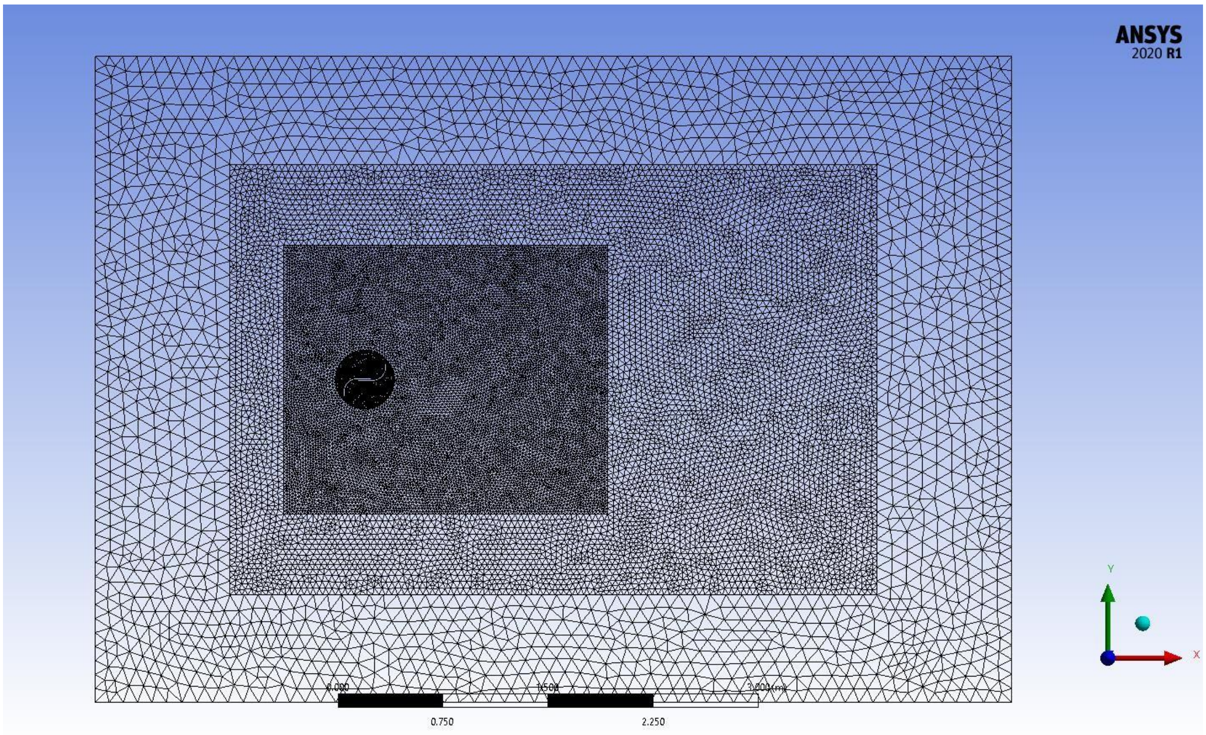
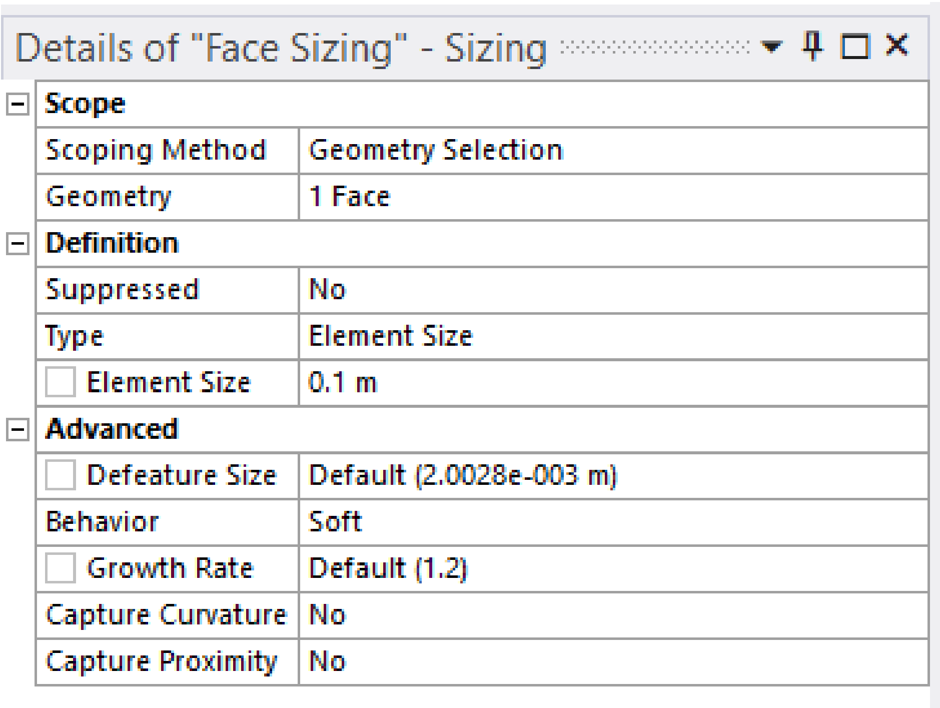


Figure 3.7: Transparent Meshing.



Details of "Face Sizing" - Sizing

Scope	
Scoping Method	Geometry Selection
Geometry	1 Face
Definition	
Suppressed	No
Type	Element Size
Element Size	0.1 m
Advanced	
Defeature Size	Default (2.0028e-003 m)
Behavior	Soft
Growth Rate	Default (1.2)
Capture Curvature	No
Capture Proximity	No

Figure 3.8: Outer Region Sizing.

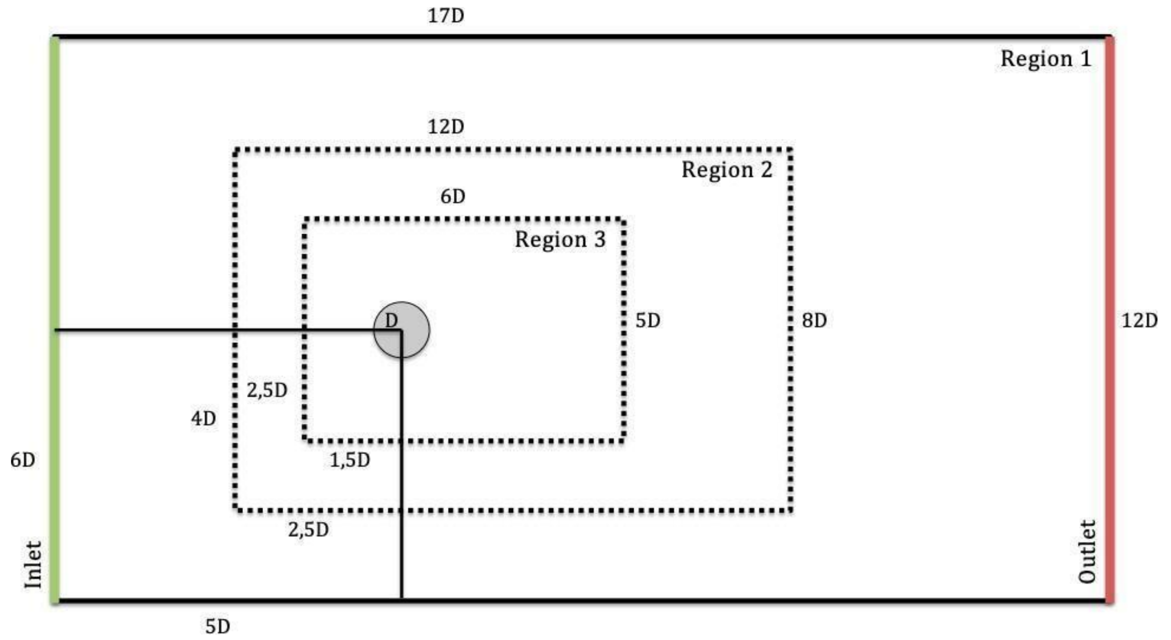


Figure 3.9: Dimension of simulation domain in terms of turbine diameter [5]

Refinements	Method	Mesh size (m)
Region 1	Triangular	0.1
Region 2	Triangular	0.04
Region 3	Triangular	0.02
Rotating Region	Triangular	0.01
Turbine blades	Triangular	0.005

Table 3.1: Selected meshing size of refinements and rotor face

3.3.3 Simulation Setup

Geometric modeling is the first step in the methodical simulation setup process, which then moves on to meshing, applying boundary conditions, and CFD analysis. The purpose of this configuration is to assess the Savonius wind turbine's aerodynamic performance at different blade angles. SolidWorks is used to generate the Savonius wind turbine models. Multiple blade angle configurations (such as 110,120,130,140, and 150 deg) are represented in the blade geometry model while keeping the rotor height, diameter, and overlap ratio constant. ANSYS Meshing is used to mesh the 2D geometry once it has been loaded into ANSYS Workbench. In order to precisely capture boundary layer effects and flow separation, a structured or hybrid mesh is used, with fine-grained mesh zones around the rotor. To guarantee the accuracy of the answer, mesh independence tests are carried out.

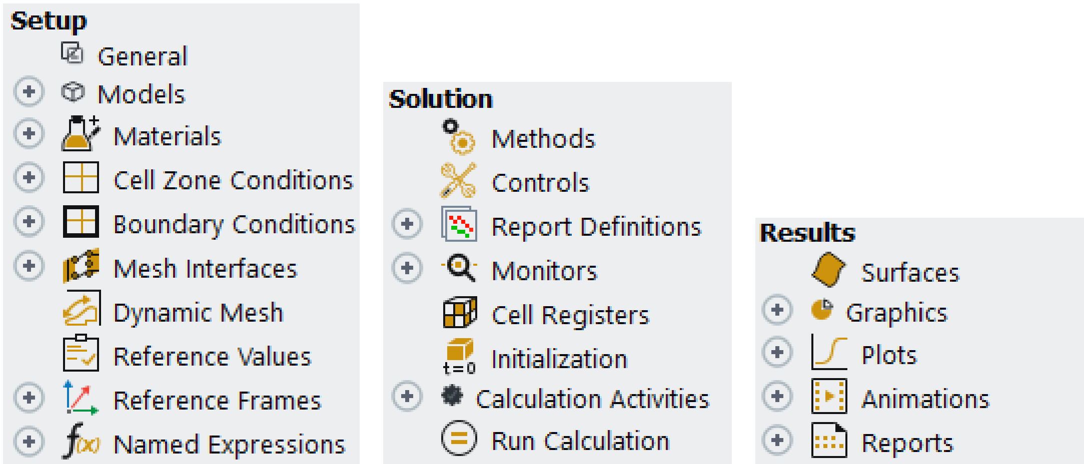


Figure 3.10: Different phases of Fluent setup

The various design geometries used in this study have distinct meshing requirements. Meshing is done using a scripting technique to reduce time and effort. The generic Python script specifies the meshing size, refinement zones, interfaces, faces, and bodies. The meshes that are generated will automatically update in Fluent before being exported to the Fluent setup. The fluid arrangement is changed, and Single Precision is chosen as the precision setting because it is less time-consuming and adequately accurate. Precision selection is followed by the selection of a number of processes based on system capacity. For more thorough results, a Pressure-Based solver with absolute velocity formation and a transient simulation setup is then employed. The Viscous (SST k-omega) turbulence model is used with preset model constants. Following model selection, materials with predetermined densities and viscosities have been chosen, both solid and fluid. Boundary conditions include an input velocity of 8 m/s, blade walls chosen to move at an angular velocity (ω) determined in a parameter set (figure 19), and shear set to zero for the domain's sidewalls. In the simulation, we assume an equal flow with no shear from the walls, even if there aren't any such barriers in reality. A quick overview of the boundary conditions is provided in Section

3.2.2. The coupling algorithm provides a substitute for the pressure-density based segregated method with SIMPLE type pressure-velocity coupling, according to Ansys user recommendations. In spatial discretization settings, the gradient is solved using a least square cell-based approach. As a second-order upwind scheme, pressure, momentum, turbulent kinetic energy, and a particular dissipation rate are adjusted. Choosing the second-order upwind strategy has the advantage of being more accurate than the first order and utilizing two upstream locations for computation. The report definition is extracted based on the data requirements when the method has been chosen. Choosing a suitable output type is the first step in defining the report definition. The present investigation involved the extraction of lift force, drag force, moment data, $y+$, and CFL data. The power coefficient is computed using the output file and graphic representation that are gathered. Initializing the flow in the simulation domain is required prior to beginning any simulation. Given the sliding meshes in the problem (the innermost refinement meshing and the rotating section, figure 10), the reference frame is chosen in relation to the cell zone. Additionally, the Initialization window's gauge value is set to zero and the starting velocity in the x-direction is set to 8 m/s. Lastly, the time steps and time step size are set. Since CFL values are dependent on the time step size, the time step size can be assumed by running a few simulations. All of the simulations in this study are run at a time step size of 0.0001 seconds for 8160 time steps. In comparison to the previous study, which employed 10000 to 15000 time-steps, it was discovered that 5000 to 7000 time-steps were providing somewhat worse results when employing higher and lower time stepped analysis. To put it briefly, an average figure that has more time-steps will be more accurate. Therefore, a smaller number of time-steps are selected while taking into account the time and available computing resources.

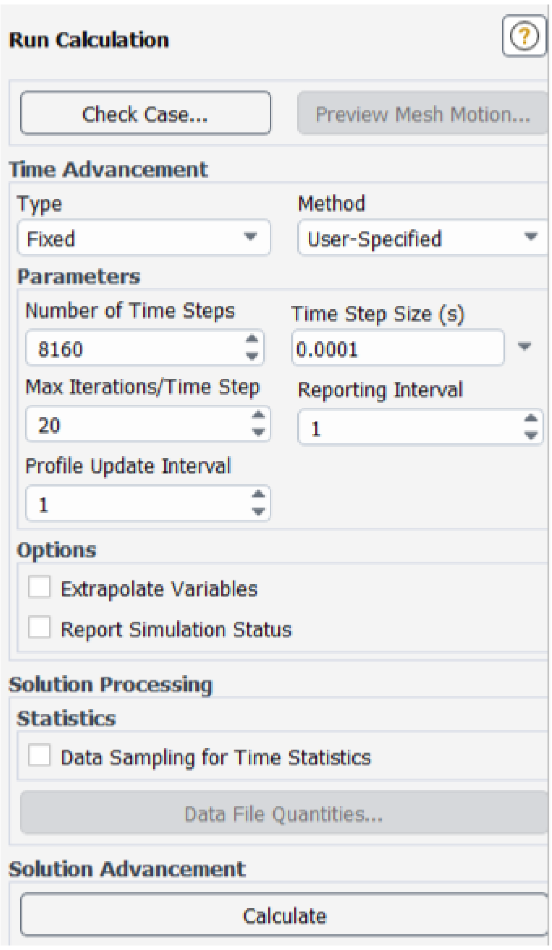


Figure 3.11: Number of Time Steps and Time Step size.

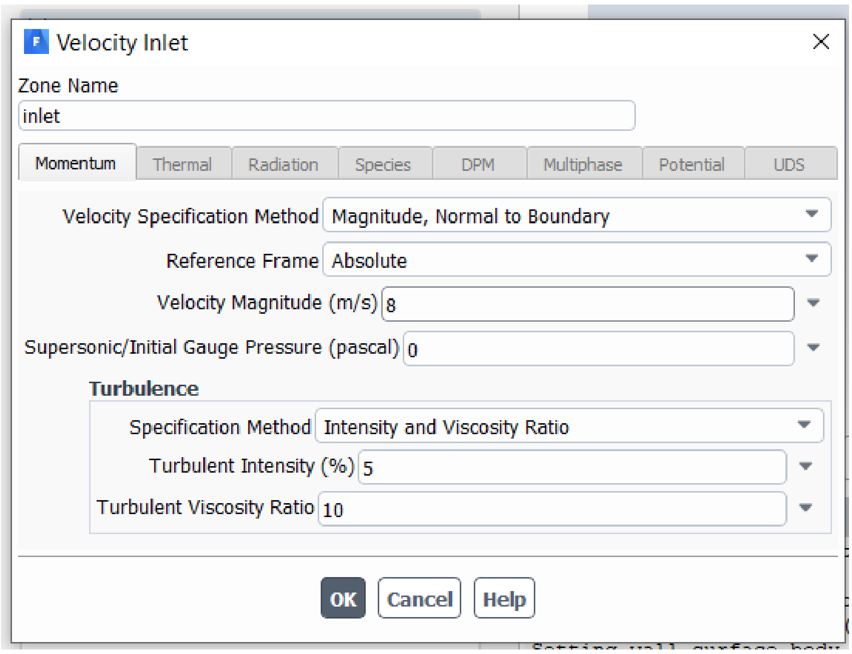


Figure 3.12: Inlet Velocity Boundary Condition.

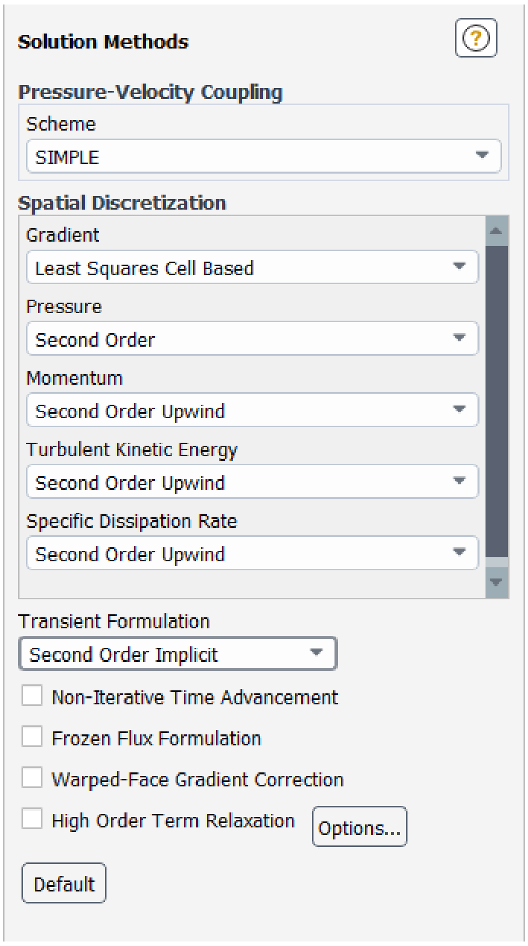


Figure 3.13: Solution Method

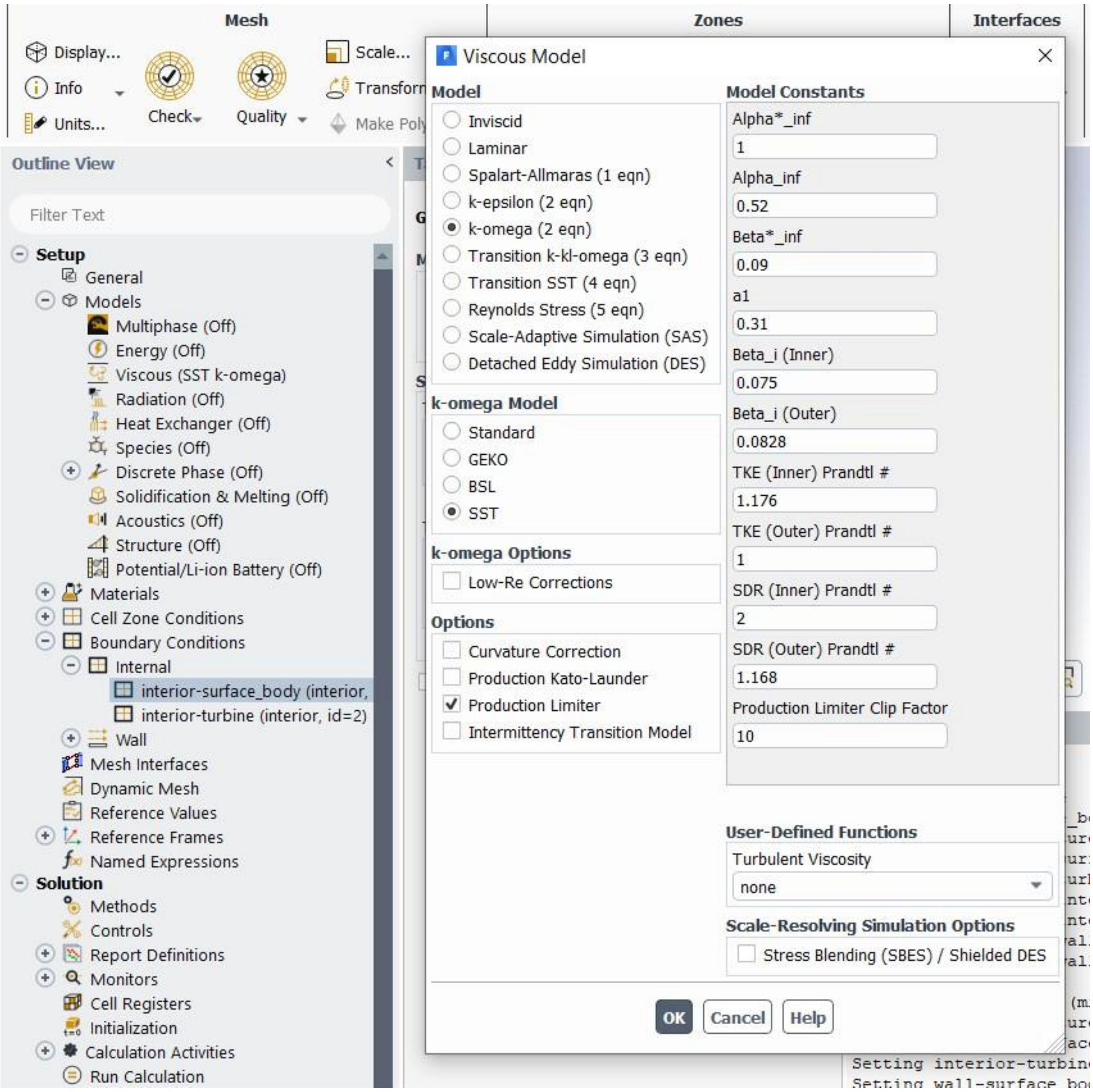


Figure 3.14: Viscous Modelling.

Chapter 4
Results and Discussion

4.1 INTRODUCTION

The numerical results from CFD simulations of the Savonius wind turbine with a constant overlap ratio (OR) of 0.4 and a fixed tip speed ratio (TSR) of 1 are shown in this section. The study's main objective is to evaluate the aerodynamic performance at different blade arc angles, which range from 110° to 150° in increments of 10°. To determine how blade shape affects turbine efficiency, important performance indicators like the power coefficient (Cp) and mechanical power output are assessed. To evaluate performance trends and design optimization potential, the findings are contrasted with previous research with varying overlap ratios. Important insights into the aerodynamic trade-offs related to blade angle change at constant overlap conditions are provided by discussing any observed performance differences in the context of simulation settings, design limitations, and actual flow behavior.

4.2 RESULTS

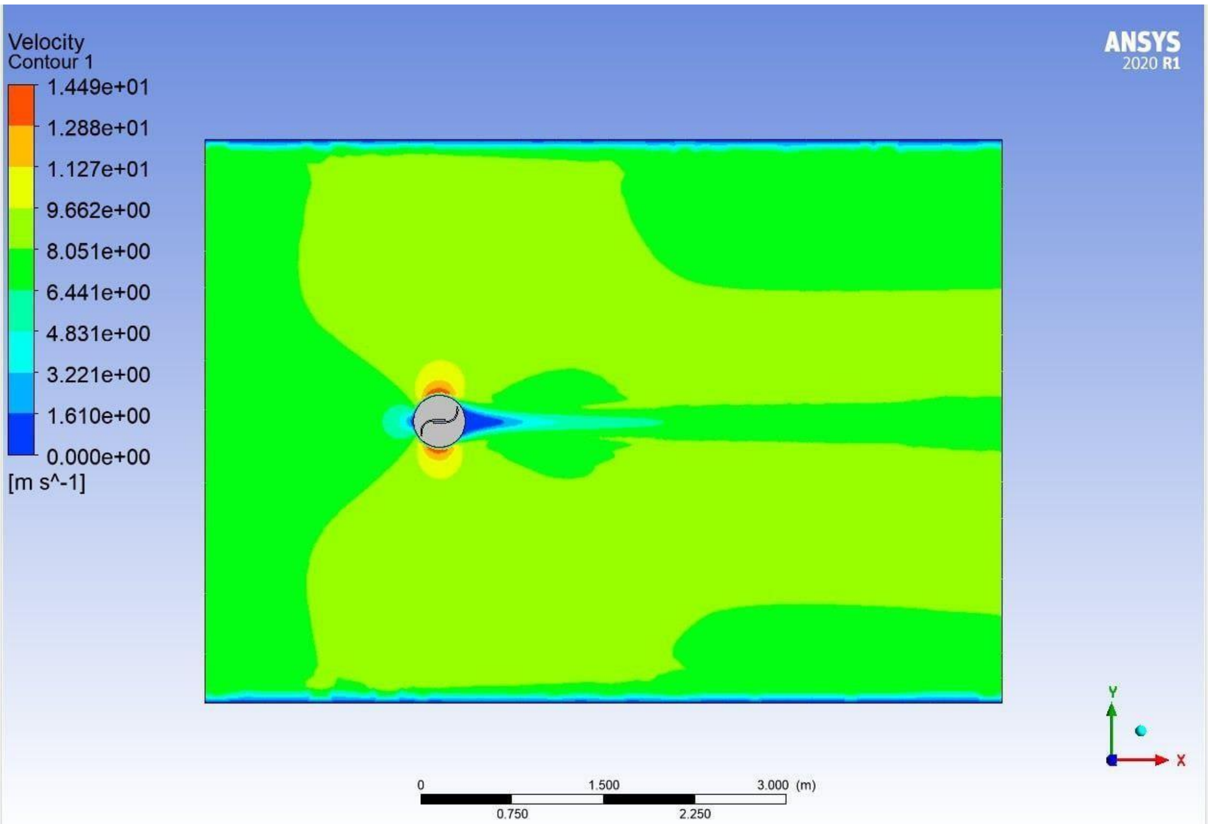


Figure 4.1: Velocity contour of Savonius turbine showing wake and flow separation.

Blade Arc Angle (Degree)	P_{Max}(W)	$C_{P,Max}$
110	40.03	0.243
120	43.96	0.267
130	45.52	0.292
140	41.43	0.274
150	41.24	0.262

Table 4.1: Variation of Maximum Power Output and Power Coefficient (Cp) with Blade Arc Angle at TSR = 1 and Overlap Ratio = 0.4

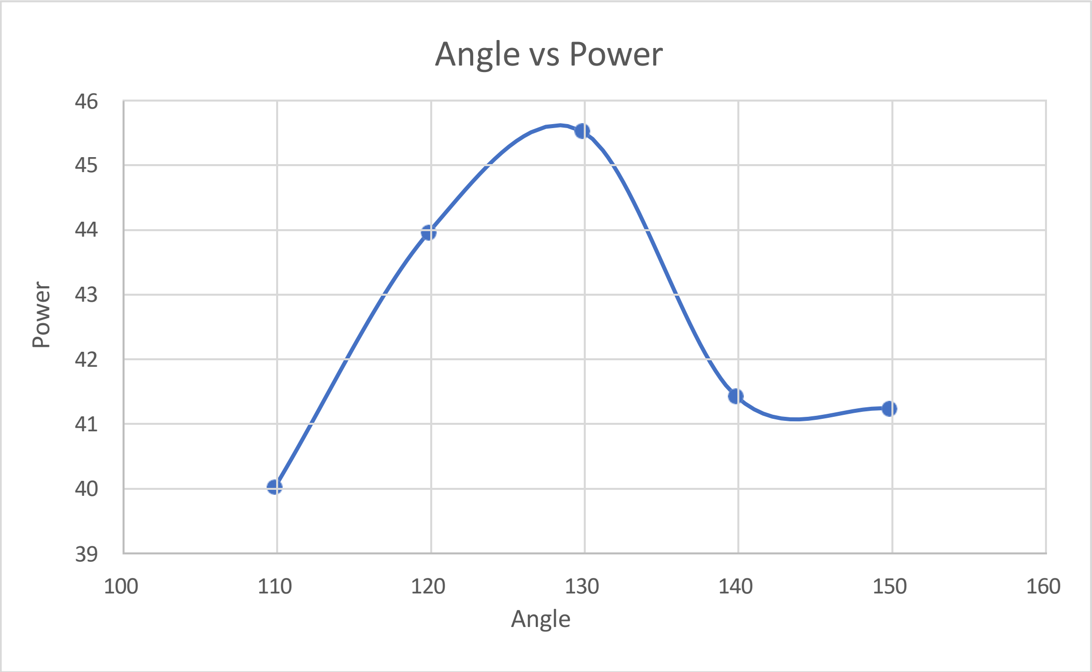


Figure 4.2: Angle vs Power

Figure 25 shows the result of the power study for five selected geometries. After looking into the results, it can be observed that as we increase the blade angle power is also increasing gradually. At a certain point, it again starts to decrease.

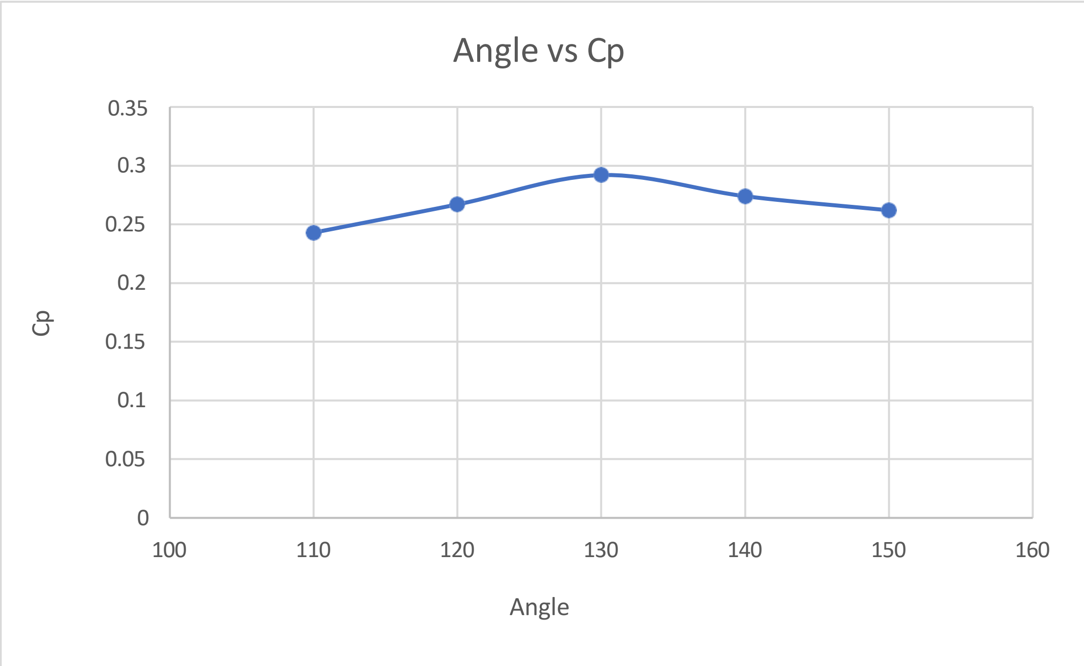


Figure 4.3: Angle vs Cp

Figure 26 shows the result of the power co-efficient study for five selected geometries. After looking into the results, it can be observed that as we increase the blade angle power co- efficient is also increasing gradually. At a certain point, it again starts to decrease.

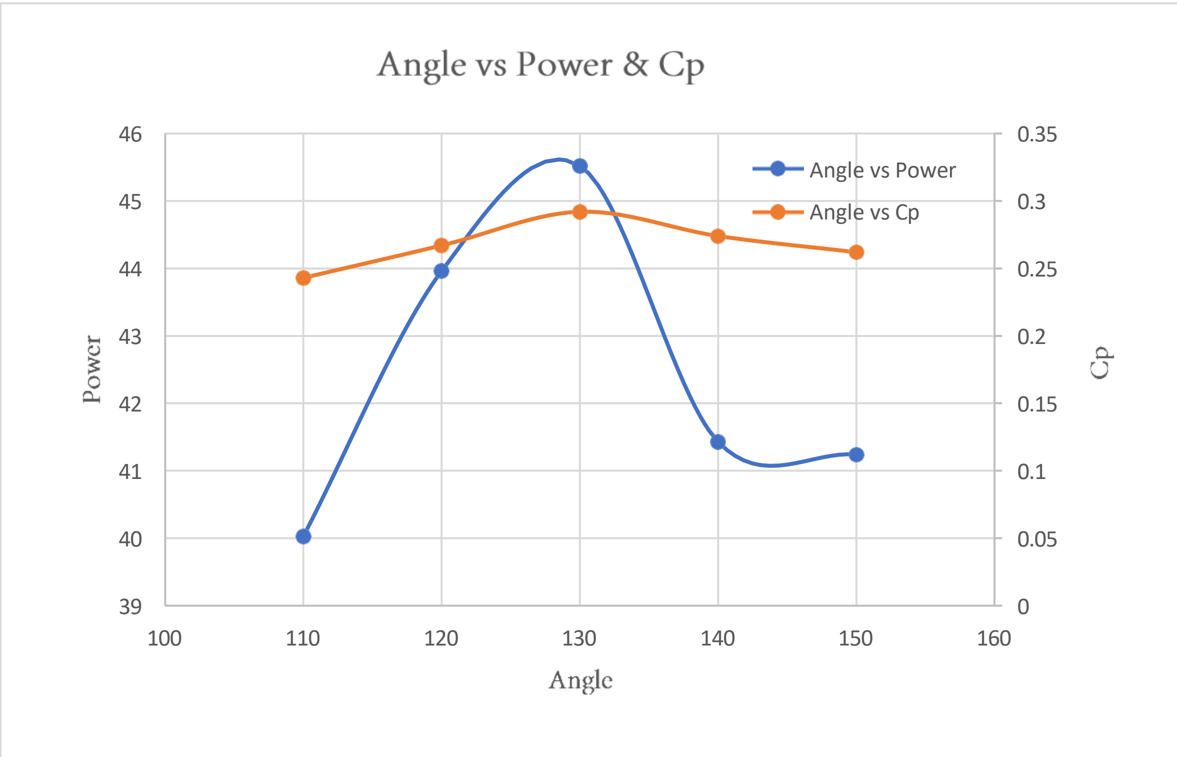


Figure 4.4: Angle vs Power & Cp

4.3 DISCUSSION

An extensive examination of the Savonius wind turbine's aerodynamic performance in relation to different blade arc angles is provided in this section. SolidWorks was used to model the blade geometries for the simulations, which were run using ANSYS Fluent. Five different configurations with blade angles of 110°, 120°, 130°, 140°, and 150° are examined in the study, all while keeping the overlap ratio at 0.4 and the tip speed ratio (TSR) at 1. To identify the ideal blade geometry in these circumstances, two important performance metrics—maximum power output and power coefficient (Cp)—were assessed and contrasted.

The turbine's maximum power output and blade angle show a non-linear connection. At 110°, the turbine produced 40.03 W; at 120°, that amount rose to 43.96 W. The power production peaked at 130°, producing 45.52 W, and then showed a discernible decrease, reaching 41.43 W at 140° and 41.24 W at 150°. According to this pattern, increasing blade curvature initially improves torque generation and wind capture. This is probably because it improves flow guidance and interaction with the approaching wind. But after 130°, performance deteriorates as the arc angle increases more. This counteracts the advantages of higher frontal area and is caused by increased drag and undesirable flow separation on the returning blade.

The power coefficient (Cp), which measures how well wind energy is converted into mechanical energy, exhibits a similar pattern. Cp was 0.2243 at 110°, 0.267 at 120°, and 0.292 at 130°—the highest value. Cp then declined marginally to 0.274 and 0.262 at 140° and 150°, respectively. The relationship between Cp and blade angle suggests that more curvature in a blade's geometry does not always translate into increased efficiency. A slight increase in arc angle enhances energy collection and flow interaction, but too much curvature can lead to unstable flow behavior, bigger wake zones, and increased aerodynamic losses.

Aerodynamic torque output and efficiency have a strong correlation, as seen by a plot of angle vs power and Cp. The best blade arrangement for the specified TSR and overlap ratio is evidently 130°, where both metrics peak. The synchronized patterns offer a strong foundation for design optimization and support the accuracy of the simulation findings. The findings highlight how crucial it is to optimize the blade arc angle in Savonius turbines. A good compromise between drag-induced torque and aerodynamic losses is achieved at an angle of 130°. Angles above 130° provide extra drag and lessen the efficiency of the returning blade, while angles below 130° might not be able to capture enough wind energy. These results are in line with earlier studies that show a range of curvatures that maximize Cp. The findings also lend credence to the idea that, although being drag-based, the Savonius turbine nevertheless gains from aerodynamic fine-tuning, especially with regard to blade spacing and shape. The trend also shows that power output and Cp are sensitive to geometrical changes, with performance being greatly impacted by simply a 10° change in blade angle.

The results of the study are wholly dependent on the simulation model, regardless of its ability to accurately represent reality, because they are totally based on simulations. Simulations will always have some degree of uncertainty, because flow cannot be precisely calculated everywhere as it is in reality. Since 2D simulations are conducted for an unlimited Savonius turbine height, a smaller Cp is anticipated in practice. Higher processing power and a more fine-tuned mesh could always be used to achieve an accurate output. This work was completed using a personal computer with little processing capability. The size of the simulation domain and the number of time steps can affect the results. Simulations are run for 8160 time steps with a time step size of 0.0001 seconds while taking the work's time frame into account. The turbulence study, which could have an impact on the manufacturer due to power output flaws, is not covered in this study.

4.4 VALIDATION

Blade Arc Angle	Tip Speed Ratio (Previously Researched)	$P_{Max}(W)$ (Previously Researched)	Tip Speed Ratio (This Researched)	$P_{Max}(W)$ (This Researched)	Increace in $P_{Max}(W)$
110	1.0	37.57	1.0	40.03	2.46
120	0.8	39.72	1.0	43.96	4.24
130	0.9	41.19	1.0	45.52	4.33
140	1.1	39.70	1.0	41.43	1.73
150	1.0	40.81	1.0	41.24	0.43

Table 4.2: Comparative Validation of Simulated and Previously Researched Results for Maximum Power Output.

Blade Arc Angle	Tip Speed Ratio (Previously Researched)	$C_{P,Max}$ (Previously Researched)	Tip Speed Ratio (This Researched)	$C_{P,Max}$ (This Researched)	Increace in $C_{P,Max}$
110	1.0	0.2396	1.0	0.243	0.0034
120	0.8	0.2533	1.0	0.267	0.0137
130	0.9	0.2627	1.0	0.292	0.0293
140	1.1	0.2532	1.0	0.274	0.0108
150	1.0	0.2603	1.0	0.262	0.0017

Table 4.3: Comparative Validation of Simulated and Previously Researched Results for Maximum Power Coefficient.

The presented table provides a comprehensive validation of the current CFD simulation results against previously published data for a range of blade arc angles (110° to 150°) on Savonius wind turbines. It compares key aerodynamic performance parameters, namely the maximum power output P_{Max} and the maximum power coefficient Cp under varying Tip Speed Ratios (TSR).

For each blade arc angle, the table juxtaposes values obtained in earlier studies with those derived from the current research conducted at a constant TSR of 1.0 for uniformity in simulation conditions. The comparison indicates consistent improvements in both power and efficiency across all angles, with the most notable gains observed at a blade arc angle of 130°, where the power output increased from 41.19 W to 45.52 W, a 10.5% increase, and the power coefficient rose from 0.2627 to 0.292, a relative improvement of 0.0293.

Similarly, for 120°, an enhancement in performance was also evident, with a power increase of 4.24 W and a Cp increment of 0.0137. Although smaller, positive gains were also recorded for angles of 110°, 140°, and 150°, demonstrating the robustness and credibility of the CFD methodology used.

These findings validate the simulation approach by showing good agreement and performance improvement over previous work. The deviations in TSR values used in earlier studies and the current work are normalized by using a fixed TSR in simulation, allowing for an effective comparison. The outcomes underline the effectiveness of optimized blade arc angles in enhancing turbine performance and support the selection of 130° as the optimal configuration in this study.

Chapter 4

Future Scopes of This Study

The present study used SolidWorks for blade modeling and ANSYS for computational simulations to show how different blade arc angles affect the performance of a Savonius Vertical Axis Wind Turbine (VAWT) at a set tip speed ratio (TSR = 1) and overlap ratio (0.4). There are still a number of directions for further research and development, even if the findings provide insightful information about aerodynamic behavior and peak performance at a blade angle of 130°:

Expanded Parametric Analysis: The study can be expanded by adjusting other factors including aspect ratio, blade curvature, overlap ratio, and TSR. The most effective design over a wider working range could be found using a multi-objective optimization technique.

Transient CFD Simulations: Only steady-state simulations were used in this investigation. Transient flow simulations would more closely depict real-time turbine behavior by capturing torque fluctuations and unstable wake dynamics.

Experimental Validation: To confirm the simulation results and guarantee their applicability, a physical prototype must be fabricated and then tested in a wind tunnel or the field.

Structural and Modal Analysis: To evaluate the long-term sustainability of blade materials under cyclic wind stress, future research should combine structural strength and fatigue life analysis.

Hybrid Turbine Designs: To capitalize on the high beginning torque of Savonius and the higher efficiency of Darrieus turbines, hybrid systems that combine Savonius and Darrieus rotors can be studied.

Urban and Rural Deployment Studies: Evaluating feasibility, economic viability, and adaptation under different wind profiles can be aided by practical assessments conducted in both urban and off-grid rural settings.

The current work can be greatly improved by following these future paths, which will result in a more reliable and flexible solution for small-scale, sustainable wind energy generation.

Chapter 6

Conclusion

This study investigated the aerodynamic performance of a Savonius Vertical Axis Wind Turbine (VAWT) by varying the blade arc angle between 110° and 150°, with a fixed tip speed ratio (TSR) of 1 and an overlap ratio of 0.4. The blade designs were modeled using SolidWorks, and Computational Fluid Dynamics (CFD) simulations were performed using ANSYS to evaluate the power output and power coefficient (Cp) across the selected range of blade angles. The results show that blade arc angle has a considerable influence on both power production and Cp. Among the examined configurations, a blade arc angle of 130° produced the best results, with a maximum power of 45.52 W and a matching power coefficient of 0.292. Beyond this angle, performance deteriorated, indicating that there is an ideal arc angle for maximizing turbine efficiency. The decrease in performance at 140° and 150° could be due to higher drag and adverse flow separation around the blades. This study indicates that careful geometric parameter selection—particularly blade arc angle—can result in significant improvements in VAWT efficiency. The findings provide a helpful design reference for improving small-scale wind turbine systems, particularly in low wind speed or urban environments where Savonius turbines are widely used. The findings will also serve as a foundation for future optimization and experimental validation studies.

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