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INSTITUTE OF ENGINEERING  
PULCHOWK CAMPUS**

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**Design Simulation and Experimental Verification of Optimized Savonius Wind  
Turbine Profile**

**by**

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**A THESIS**

**SUBMITTED TO THE DEPARTMENT OF MECHANICAL AND  
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REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN  
RENEWABLE ENERGY ENGINEERING**

**DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING  
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**June, 2024**

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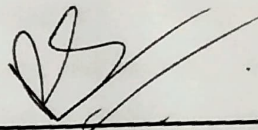
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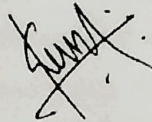
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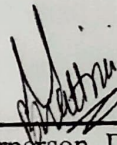
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## ABSTRACT

Nepal possesses significant hydropower potential but has not fully harnessed this resource, leading to limited power production capacity. To bridge the gap between energy demand and generation, Nepal can leverage wind energy, which can produce up to 3000 MW, with 448 MW readily and commercially exploitable. Historically, Nepal has focused on horizontal axis wind turbines (HAWTs), with minimal exploration of vertical axis wind turbines (VAWTs). VAWTs offer several advantages over HAWTs, such as lower mounting height, omni-directional capability, and efficiency at low wind speeds. The Savonius wind turbine was selected for its simple design and effective performance in low wind speeds and turbulent airflow. The report details the design process, including material selection, dimensions, and assembly process, with the use of SOLIDWORKS 17. A model was simulated, fabricated, and tested to obtain experimental data. The maximum rotational speed, torque and angular velocity generated were experimentally determined to be 266 rpm, 0.305 Nm and  $27.841 \omega$ , respectively, at wind velocities of 6.3 m/s. Theoretical maximum rotational speed, torque and angular velocity generated were calculated and found to be 214.9 rpm, 0.377 Nm and  $22.5 \omega$ , respectively, at the same wind speed. The mean absolute errors between the experimental and theoretical torque, experimental and simulated torque, experimental and theoretical rotational speed were determined to be 18.85%, 6.35% and 15%. The report concludes by suggesting ways to improve the turbine's efficiency and scalability, such as the use of more advanced materials like carbon fiber. As Nepal continues to explore alternative sources of energy, wind power, and the innovative use of technologies like the Savonius wind turbine, offer a promising solution for meeting the country's energy needs while reducing environmental impact

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## LIST OF SYMBOLS

$P$	Power of turbine
$P_{\omega}$	Wind power
$\omega$	Angular velocity
$C_{ps}$	Power coefficient of savonius rotor
$\rho$	Density of air
$H$	Height of blade
$e$	Eccentricity
$d$	Diameter of blade profile
$D$	Diameter of blade
$\lambda$	Tip speed ratio
$A$	Swept area
$\eta$	Efficiency

## CHAPTER ONE : INTRODUCTION

### 1.1 Background

As alternative energy becomes more widely discussed, it has become a much more popular topic. Due to the growing technology, people are now looking for new and renewable sources of energy to replace conventional energy sources. The generation of electricity can take place through a variety of methods. As a term, renewable energy refers to a wide range of sustainable sources of energy, including photovoltaics, solar concentrators, hydroelectricity, biomass, geothermal, and wind. Energy generation from back wind pressure using wind turbines is a concept that has been around for several decades. The idea of using the back wind pressure on the blades of a wind turbine to generate energy was first proposed by French engineer Georges Darrieus in the early 20th century. Darrieus designed a vertical-axis wind turbine that used the lift force generated by the blades as they rotated to generate energy.

Over the years, the design of wind turbines has evolved and become more efficient. Today, most wind turbines use a horizontal-axis design, where the blades are mounted on a horizontal axis and face into the wind. As the wind blows over the blades, it creates lift, which turns the rotor connected to a generator, producing electricity.

Wind turbines have become an important source of renewable energy around the world, with the installed capacity of wind power growing rapidly in recent years. Wind energy is now one of the most cost-effective sources of electricity and is being used to power homes, businesses, and entire communities.

The technology behind wind turbines has continued to evolve, with ongoing research focused on improving their efficiency, reducing their cost, and increasing their reliability. Today, wind turbines are used in a wide range of settings, from small-scale applications in remote areas to large-scale wind farms in open fields and offshore locations.

Wind energy is a renewable energy source that can be converted into mechanical energy by mechanical equipment such as a wind turbine, which turns the kinetic energy of the wind into mechanical energy. Currently, it is the most rapidly growing source of clean energy on the planet. There is a major issue with the technology due to fluctuation in the wind source. Highways are a near constant source of wind power due to rapidly moving vehicles. The purpose of this research is to contribute in a feasible way to the global trend towards clean energy.

## **1.2 Importance and Significance**

The Savonius wind turbines, which have vertical axis, can be used at this low level. Because the VAWT (Vertical Axis Wind Turbine) design allows the turbine to absorb wind from any direction, it is ideal for highway applications where wind blows from both sides of the road. The turbine does not need to be facing the wind. Furthermore, VAWTs are less noisy than horizontal axis wind turbines, making them suitable for usage on highways that traverse urban areas. Savonius generates significant torque with low rotational speed, high self-start, and low power efficiency by utilizing drag forces. Wind turbines are important and significant for several reasons:

- **Renewable Energy Source:** Wind turbines generate electricity from wind, which is a renewable energy source. This means that they do not consume fossil fuels, emit greenhouse gases or pollutants, and contribute to climate change.
- **Clean Energy:** Wind turbines provide a clean source of energy that can reduce our reliance on fossil fuels, and help to mitigate the impacts of climate change..
- **Energy Independence:** Wind turbines can provide communities with energy independence by generating their own electricity, reducing reliance on centralized energy sources, and promoting local control over energy resources.
- **Sustainable Development:** Wind turbines can support sustainable development by providing clean energy, creating local jobs, and reducing greenhouse gas emissions.

In summary, wind turbines are important and significant because they provide a clean, renewable, low-cost source of energy, create job opportunities, promote energy independence, and support sustainable development.

## **1.3 Types of Wind Turbine**

There are two basic types of wind turbine. They are:

### **a) Horizontal Axis Wind Turbine:**

In a horizontal axis wind turbine (HAWT), the rotor rotates parallel to both ground and wind stream. The majority of HAWTs in use today have double or triple blades, while some may have more or less. The airfoil-shaped blade functions best when the wind travels over both of its sides at a quicker speed on the upper side, inducing lower-pressure area above airfoil. An aerodynamic lift is created by the pressure difference between the top and bottom surfaces. The lift force generates rotation around the hub because the wind turbine blades are confined to travel in plane with a hub at its center.

Rotor rotation is hampered by the drag force, which is perpendicular to the lift force.

Some of the examples of horizontal axis wind turbine are:

- Upwind turbine
- Downwind turbine

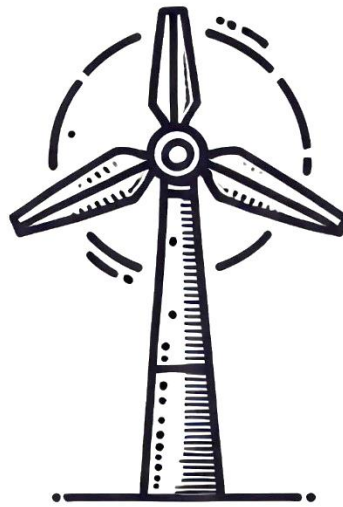


Figure 1.1 : Horizontal Axis Wind Turbine

[1]

#### **b) Vertical Axis Wind Turbine:**

The VAWT is a turbine with a rotor axis that is perpendicular to both the wind stream and the earth. VAWTs work closer to the ground, allowing heavy equipment like as the gearbox and generator to be installed closer to the ground rather than in the nacelle. Winds are lower near ground level, hence less power is generated for a given wind and capture area. Another advantage of a VAWT is that it does not require a yaw mechanism because it can harness wind from any direction. Here are some instances of VAWT:

- Darrius Turbine
- Savonius Turbine
- **Darriues Turbine**

The Darrius wind turbine is a vertical axis wind turbine that generates power from wind pressure. The reverse wind pressure on the Darrius turbine's blades can be used to generate rotational energy, which is subsequently converted into electricity.

The Darrius turbine has a vertical axis and curved blades that mimic the shape of egg beater. As the wind blows past the blades, the back pressure on the concave side forces

the blades to turn. This rotation is transformed into power using a generator attached to the turbine's axis.

The Darrieus turbine is a type of VAWT that has several advantages over other types of wind turbines. Firstly, the Darrieus turbine is highly efficient at low wind speeds, which makes it ideal for locations with low wind speeds. This is due to its unique design, which allows it to start rotating at low wind speeds and generate power. Secondly, the Darrieus turbine can generate power from wind coming from any direction, unlike other wind turbines that need to face the wind. This makes it more efficient and versatile, especially in areas where wind direction changes frequently. Thirdly, the Darrieus turbine produces lower levels of noise pollution compared to other types of wind turbines. This makes it a suitable option for use in urban areas or areas with noise pollution regulations. Fourthly, due to its small footprint and unique design, the Darrieus turbine has a low visual impact and blends well with the environment. This makes it less obtrusive and more aesthetically pleasing than other types of wind turbines. Fifthly, the Darrieus turbine requires less maintenance compared to other wind turbines due to its simple design with fewer moving parts. This reduces the cost of maintenance and increases the reliability of the turbine. Finally, the Darrieus turbine has a proven track record of reliability and can withstand extreme weather conditions, making it a good choice for use in remote locations. Overall, the Darrieus turbine is an efficient, reliable, and low-maintenance wind turbine that has several advantages over other types of wind turbines, particularly in low wind speed locations and urban areas.

However, Darrieus turbines also have some disadvantages, such as requiring a higher starting wind speed to begin rotating and being less efficient than horizontal axis turbines.

Overall, the back wind pressure on the Darrieus turbine's blades can be utilized to generate energy and provide a source of renewable electricity.

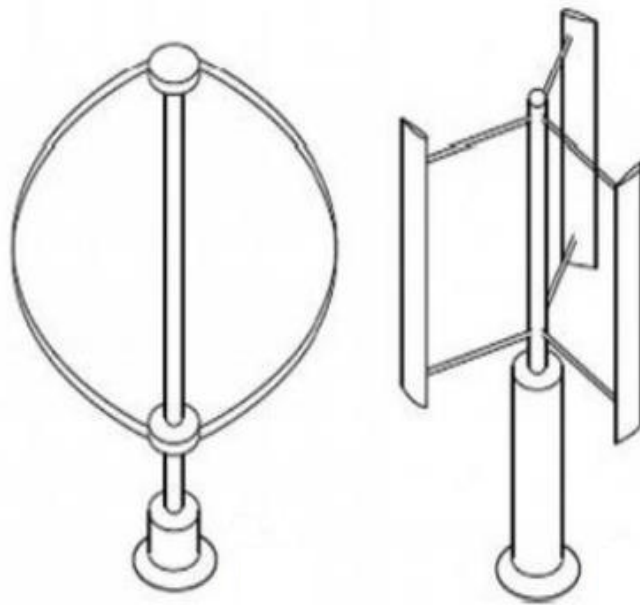


Figure 1.2 : Vertical Axis Darrieus Wind Turbine

- **Savonius Turbine**

The Savonius wind turbine is a vertical axis wind turbine developed by Sigurd Savonius in 1922 who was a Finnish engineer. Unlike standard horizontal axis wind turbines, Savonius turbines may generate electricity from wind blowing in any direction, including the backside of the rotor blades.

When wind flows across a Savonius turbine's curved blades, it causes a pressure difference on the two sides of the blade, forcing it to rotate. The rotor blades move, driving a shaft that is attached to a generator, which turns mechanical energy into electricity.

The back wind pressure is an important aspect of the Savonius turbine's design, as it allows for more efficient energy generation from wind blowing in any direction. The back pressure creates a resistance against the rotation of the rotor blades, which helps to slow them down and prevent over seeding. This can increase the lifespan of the turbine and also prevent damage to the generator.

Savonius turbines are often less efficient than horizontal axis wind turbines. This is due to their lower rotational speeds and less efficient blade design. As such, they are typically used for smaller-scale energy generation, such as for powering small electronic devices or charging batteries.

Overall, the use of back wind pressure in the design of Savonius turbines allows for energy generation from wind blowing in any direction, making them a versatile option for certain applications.

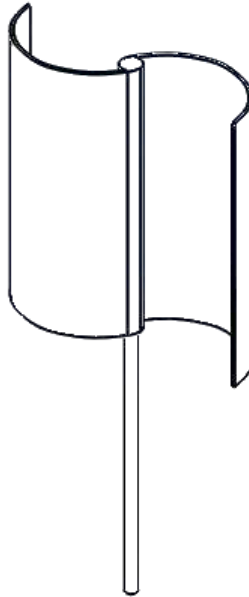


Figure 1.3: Vertical Axis Savonius Wind Turbine

#### **1.4 Problem Statement**

Fluctuations in wind energy sources are a significant impediment to its progress. Highways, high altitude hilly areas (high wind velocity), and low altitude hilly areas (low wind velocity) all appear to be a reliable source of potential wind energy. An in-depth investigation of fluid flow due to low wind velocity is required to get boundary limitations for the wind turbine design. The turbine must be capable of producing energy for use when wind velocity is low. The design must be sustainable and eco-friendly.

#### **1.5 Main Objective**

- To design, simulate and analyze the performance of Savonius wind turbine

#### **1.6 Specific Objectives**

- To fabricate optimized wind turbine profile, design stable structure to hold turbine and simulate the profile by following standard conditions from literature review.

- To perform experiment and observe experimental data under different wind speed and velocity to measure rotational speed of turbine shaft
- To validate and analyze theoretical, experimental and simulation result with each other

## CHAPTER TWO : LITERATURE REVIEW

The global demand for electricity is increasing on a daily basis, so renewable energy sources such as solar and wind can assist address the present electricity shortage. While horizontal axis wind turbines (HAWT) are efficient, they require high elevations and strong winds to perform properly. In contrast, VAWT can create power at lower heights, making it an attractive wind energy technique.

One innovative application of VAWTs is in harnessing wind energy from moving vehicles. VAWTs installed on highway medians can catch short-range, high-velocity wind flow generated by automobiles and convert the rotational energy into electrical energy. The goal of this project is to develop a new Savonius type vertical axis wind turbine capable of efficiently capturing wind energy from moving vehicles.

The concept of installing wind turbines on highways is not new. In truth, multiple examples exist of wind turbines being used to power highway street lights. Among different wind turbine designs, the Savonius wind turbine is a basic, simple design that has been utilized for a variety of applications, including sailing, water pumping, ventilation, and air and water power generation. Sigurd Savonius, a Finnish naval engineer, proposed the Savonius wind rotor design in the early twentieth century, and various changes have subsequently been made to increase its efficiency.

The shape, overlap ratio, aspect ratio, stage number, and blade number all play a significant role in the performance of Savonius type turbines. Hence, there have been various numerical and experimental studies from different perspectives to investigate the aerodynamic characteristics of these turbines and improve their efficiency. Overall, VAWTs like the Savonius wind turbine hold great potential for generating clean energy and reducing reliance on non-renewable sources of energy. Some of the researchers only did the numerical studies to analysis the aerodynamics behaviour.

Danao, L.A. et.al [3] suggested in their article named “A Numerical Study of Blade Thickness and Camber Effects on Vertical Axis Wind Turbines” that, the results of a two-dimensional computational study on how camber and rotor blade thickness affect a 5kW vertical axis wind turbine's performance. Validation is based on experimental results for a pitching aerofoil with dynamic stall phenomenon. Plotting the turbine's performance for a range of tip speed ratios is done, and in-depth studies are presented to explain how and—more importantly—why the turbine performs differently depending on thickness and camber.

N.H. Mahmoud [4], et al performed an experimental investigation utilizing a wind tunnel experimental setup and the results suggest that double-bladed Savonius rotors are more efficient than triple- and quadruple-bladed Savonius rotors. In comparison to a rotor without end plates, one with end plates has a higher efficiency. When it comes to performance, blades with overlap ratios outperform those without. As the Aspect Ratio increases, so will the Coefficient of Performance ( $C_p$ ).

Mohammed Hadi presented research paper on savonius wind turbine of double and triple Blades at lower wind velocity [5]. The experiment technique was carried out and tested in the wind tunnel, and the necessary measurements were gathered to investigate the performance of the two blades and three blades savonius wind turbines and compare them to determine which one performed better. In terms of starting acceleration and maximum no-load speed, the performance [power coefficient ( $C_p$ ) and torque coefficient ( $C_t$ )] was investigated as a function of the dimensionless parameter tip speed ratio ( $\lambda$ ) at low wind speeds.

The study was carried out by Md Aminul Hassan and Dr. C B Vijaya Vitala [6]. The study was conducted to investigate the possibility for energy extraction from wind on roadways. The study found that at a height of 120 cm, the maximum potential for impact wind energy was accessible. The aspect ratio is an important component to consider when designing VAWT.

K.K. Sharma, et al [7] has looked into how well a two-stage, double-bladed Savonius rotor performs. The team conducted experiments in a subsonic wind tunnel. Overlap, tip speed ratio, power ( $C_p$ ) and torque coefficient ( $C_t$ ) are among the variables examined. In order to achieve optimal rotor performance, an overlap ratio optimization was implemented. According to the investigation, a 9.37% overlap condition was reached, resulting in a maximum  $C_p$  of around 0.52. Similarly, when overlap rises to 19.87% (previously it was 9.37%), the power and torque coefficients decrease.

Ahmed Y., et al [8] has devised a model with three frames along with cavity vanes, which was fabricated and tested in low velocity wind tunnel. This model exhibited a high drag coefficient because the vanes shut the frame on one side while moving in the direction of the wind, capturing the wind efficiently. On the other side, the frame rotates in the opposite direction of the wind, allowing the wind to pass through with no resistance. The model was subjected to test in a wind tunnel at varying wind speeds.

This new model provides a higher power coefficient of around 0.32 (wind velocity of around 8.2 m/s and ratio of tip speed of nearly 0.31).

The experimental investigation presented in the work of Fred W., et al [9] intends to evaluate the effect of blade number on the performance of a Savonius type wind turbine model. The studies compared two, three, and four blade wind turbines to demonstrate how tip speed ratio, torque, and power coefficient are related to wind speed. A simulation of wind turbine pressure distribution will be performed using the ANSYS 13.0 software. The study found that the number of blades influences the performance of a wind turbine. The Savonius type with three blades provides the highest performance at high tip speed ratios. The maximum tip speed ratio is 0.555 at a wind speed of 7m/s.

Prof. Vaibhav Bankar and Ashwin Dhote [10] presented research paper on “Design, Analysis and Fabrication of Savonius Vertical Axis Wind Turbine”.

The following are the same results drawn from this research:

- [1] This setup can provide at least 10% of the power consumption.
- [2] A multistage generator is a double generation concept that uses the same size rotor.
- [3] When the wind speed is low, the gear configuration might increase the number of rpms.
- [4] This turbine is normally ideal for a height of 8 to 10 meters above ground level. Because air has a low velocity at ground level.
- [5] Combining an alternator with a gear system can enhance output, but it will unnecessarily increase the cost of the machine.
- [6] From an all-weather standpoint, the material used should be non-corrosive.
- [7] Reinforced glass fiber is an alternative material for turbine blades since it is more elastic, but it is more expensive than aluminum alloy.

Research performed by Vinit. V. Bidi and team [11] VAWT was used to evaluate the possibility for generating power for highways. The primary goal of the research was to commercially produce the turbine at the lowest possible cost utilizing readily available materials. The turbine, which generated 100-105 watts of power, was tested at the highway median [12]. The turbine rotated nearly around 340 rpm at minimum speed of between 12 m/s to 13m/s.

The study carried by [13] We investigated the relationship between aspect ratio and turbine performance. The study discovered that turbines with smaller aspect ratios have a greater power coefficient. A thicker blade resulted in increased in-service stability.

## **CHAPTER THREE : RESEARCH METHODOLOGY**

### **3.1 Theoretical Consideration**

#### **3.1.1 Working Principle**

The working principle of the system describes involved several components working together to convert wind energy into electrical energy, which can then be used to power a light bulb.

First, the turbine is the primary component responsible for capturing wind energy. The turbine blades are designed to be concave and convex, which creates a differential force when wind flows over them. This differential force causes the turbine to rotate.

As the turbine rotates, it is connected to a shaft, which rotates a pulley at a certain RPM. The shaft is connected to a motor (used as generator), which converts the mechanical energy generated by the rotating shaft into electrical energy and voltage is generated.

Overall, the system described takes advantage of the kinetic energy of the wind to generate electrical energy, which can then be stored and used to power various devices.

The law used in the project of generating energy using Savonius wind turbine is the law of conservation of energy, which states that energy cannot be created or destroyed, only transferred or converted from one form to another. In this case, the kinetic energy of the moving vehicle is converted into mechanical energy by the Savonius wind turbine, and then to electrical form of energy with help of the generator.

#### **3.1.2 Betz Law**

A key idea in the realm of wind energy is the Betz law, which establishes the upper bound on a wind turbine's theoretical efficiency. It was developed in 1919 by German scientist Albert Betz and is predicated on the ideas of mass, momentum, and energy conservation. The greatest power that a wind turbine can take from the wind is 59.3% of the wind's total kinetic energy, as expressed by the Betz law.

The law states that as the wind flows through the rotor of the wind turbine, its velocity is reduced, and its kinetic energy is converted into mechanical energy that drives the generator. However, the wind cannot be fully converted into mechanical energy, as some energy is lost due to the conservation of momentum and the law of mass conservation. As a result, the wind will always exit the turbine with some residual velocity.

The Betz law is a theoretical limit, and it assumes that the wind turbine operates in ideal conditions, with no friction or other losses. In reality, wind turbines face various

practical limitations that prevent them from achieving the maximum theoretical efficiency. These limitations include aerodynamic losses, mechanical losses, and the variability of the wind speed and direction.

Despite its limitations, the Betz law provides a useful benchmark for the performance of wind turbines and helps in the design of wind energy systems. To design a wind turbine, the following salient parameters are considered:

### 3.1.3 Salient Design Parameters

#### i. Power Coefficient ( $C_{ps}$ )

In the wind power sector, the Power Coefficient ( $C_{ps}$ ) is a regularly used metric of Savonius wind turbine efficiency. It is the proportion of actual electricity produced by a wind turbine to the total amount of wind energy entering the rotor blades at a specific wind speed. The wind turbine is more efficient the higher the  $C_{ps}$  number.

$$\text{Power coefficient, } C_{ps} = P_{\text{rotor}} / P_{\text{wind}} \dots\dots\dots (3.1)$$

#### ii. Tip speed ratio ( $\lambda$ )

The ratio of the wind speed to the speed of the blade tips is known as the tip speed ratio ( $\lambda$ ). The tip speed ratio affects the turbine's efficiency. Low  $C_{ps}$  is caused by insufficient energy extraction from the wind, which is shown by a low tip speed ratio. Conversely, a high tip speed ratio may result in high blade stresses and low  $C_{ps}$ . Consequently, in order to enhance efficiency, the tip speed ratio must be optimized. Tip speed ratio ( $\lambda$ ) is calculated using the following formula:

$$\lambda = \text{Velocity of blade tip} / (\text{Free stream velocity}) \dots\dots\dots (3.2)$$

#### iii. Forces Involved

Wind turbines rotate due to two different types of forces: drag and lift.

Lift forces are perpendicular to the direction of the flow, whereas drag forces follow the direction of the fluid flow (wind). The rotating motion of a turbine can be produced via lift or drag, depending on the kind of blades employed. The Savonius rotor uses drag force in this situation.

#### iv. Wind Power

Wind power is the energy per unit time of the air moving at a certain speed. The computation involves multiplying the air density, blade area, and wind speed cube. The mechanical energy produced by the wind power entering the turbine blades is transformed into electrical energy. The formula determines the wind's power.

$$\text{Power of the wind } (P_w) = (\rho * A * v^3) / 2 \dots\dots\dots (3.3)$$

### v. Turbine Angular Speed, Rotational Speed, Efficiency and Torque

$$\text{Angular speed } \omega = (\lambda * v) / R \dots\dots\dots (3.4)$$

$$\text{Rotational Speed, } N = (\omega * 60) / 2\pi \dots\dots\dots (3.5)$$

$$\text{Turbine Efficiency, } \eta = P / P_w \dots\dots\dots (3.6)$$

$$\text{Torque, } T = P / \omega = (R * C_{ps} * \rho * A * v^2) / 2 \dots\dots\dots (3.7)$$

where  $V$  is the wind speed,  $A$  is the area the turbine's blades sweep,  $\rho$  is the air density, and  $C_{ps}$  is the turbine's power coefficient.

### vi. Power of a Wind Turbine

The quantity of electrical power that a wind turbine generates is known as its power, and it depends on both the turbine's specifications and the wind speed. The following formula can be used to determine the power output of a wind turbine:

$$\text{Turbine Power, } P = T * \omega \dots\dots\dots (3.8)$$

### vii. Swept Area

The area of air that surrounds the turbine during its motion is known as the swept area.

$$\text{Swept Area, } A = H * D \dots\dots\dots (3.9)$$

Where,

$$A = \text{Swept Area (m}^2\text{)}$$

$$H = \text{Height of Savonius Blade (m)}$$

$$D = \text{Diameter of Savonius turbine (m)}$$

### viii. Number of Blades

The number of blades in a vertical axis wind turbine (VAWT) affects its performance, efficiency, and smoothness of operation. Two or three blades are typically more suitable for VAWTs, as they can provide better aerodynamic efficiency and smoother operation compared to turbines with more blades. This is because with fewer blades, there is less interference between them, resulting in less turbulence and better performance. However, the optimal number of blades also depends on other factors such as the size and design of the turbine, wind speed, and application.

### 3.2 Design Considerations

Zhang, Baoshou et al [14] produced a complex blade with a bent quadratic polynomial curve describing it. The Savonius blade's ideal profile had the shape of a "hook" and had design values of  $a_2 = 0.0179$  and  $a_1 = 0.0392$ . The design parameters were taken into consideration with reduction scale of 0.5 for simulation analysis and experimental verification.

$$\text{Optimal Savonius: } y = 0.0179x^2 - 0.0392x + 0.2059$$

Where,  $x$  = angle in radian,  $y$  = distance from center to edge of profile

### 3.2.1 Material and Dimensions

A range of materials, such as ABS plastic, carbon fiber reinforced epoxy, glass fiber reinforced polyester resin, glass fiber reinforced epoxy with mineral fillers, wood, and polycarbonate sheet, can be used to make wind turbine blades. The intricate geometry of the blade, the absence of close fabrication equipment, and the accessibility of appropriate materials are some of the factors that will be taken into account while selecting polycarbonate sheets for the Savonius blades.

The materials and dimensions which are used in the project are as follows:

Table 3.1: Material and Dimensions

S.N.	Parts Name	Materials
1	Shaft	Mild Steel
2	Nuts and bolts	Mild steel
3	Savonius blades	Aluminum Sheet
4	Bearings	Steel
5	Stand	Mild Steel

### 3.2.2 Blade Design

Table 3.2: Blade Dimension

Blade Diameter(d)	250 mm
Eccentricity(e)	40 mm
Height(H)	460 mm
No. of Stages	Single Stage
Thickness	2 mm
Aspect Ratio (AR)	1 H/D

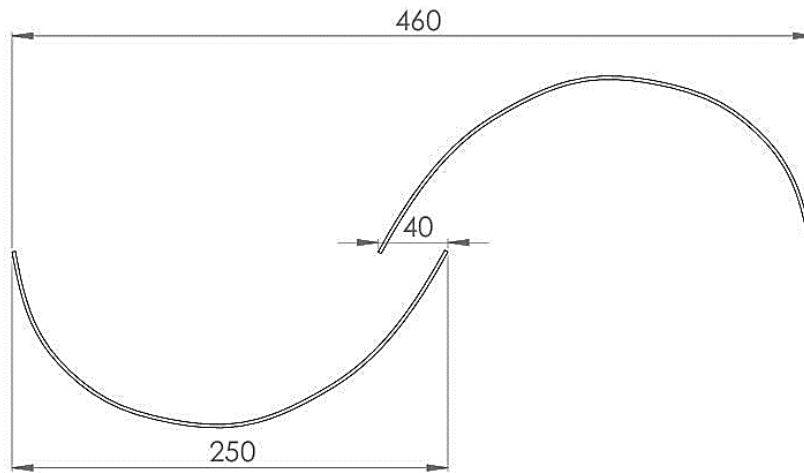


Figure 3.1: Design of Blade Profile

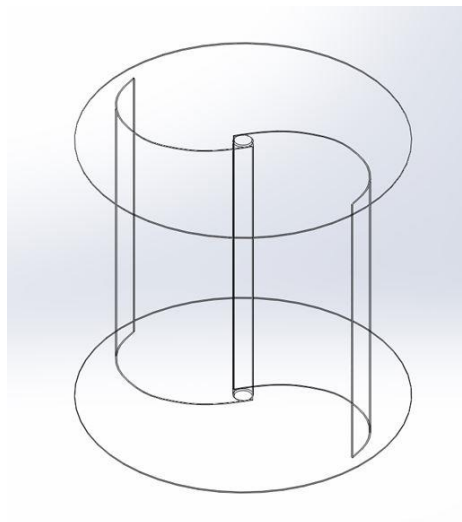


Figure 3.2: Wireframe View of Turbine

### 3.2.3 Design of Shaft

Shaft is kept in between the profile of two blades. For the designing of shaft following parameters are assumed.

#### Assumed Parameters:

Table 3.3: Assumption of Parameters

S.N	Parameter	Values
1	Power coefficient of Savonius Rotor ( $C_{ps}$ )	0.262
2	Density of Air ( $\rho$ )	1.225 kg/ m <sup>3</sup>
3	Tip Speed Ratio ( $\lambda$ )	1

### 3.2.4 Power Calculation

Since the maximum efficiency for Savonius turbine is at aspect ratio (AR) = 1,

So, assuming

Aspect ratio (AR) = H/D

Height of Blade (H) = 460 mm

Eccentricity (e) = 40 mm

Diameter of blade profile (d) = 250 mm

So, Diameter of blade (D) = 2d-e = 460 mm

Now, the power of the wind is given by the formula

Power of the wind ( $P_w$ ) =  $(\rho * A * v^3) / 2$

For savonius turbine, The torque generated by the turbine can be calculated using the following formula:

Torque,  $T = P / \omega = (R * C_{ps} * \rho * A * v^2) / 2$

Angular speed,  $\omega = (\lambda * v) / R$

$N = (\omega * 60) / 2\pi$

Turbine power,  $P = T * \omega$

$\eta = P / P_w$

Where,  $\rho$  = Density of air, kg/ m<sup>3</sup>, v = Wind velocity, m/sec,  $\lambda$  = Tip speed ratio

R = Radius of turbine, N = Rotational speed, rpm,  $\eta$  = Efficiency

A = Swept Area(m<sup>2</sup>) = H\*D = 0.46\*0.46 = 0.2116m<sup>2</sup>

### 3.3 Methodology

This study uses a Savonius wind turbine to investigate the energy produced by the rear wind pressure of a moving vehicle at comparatively lower wind speeds. The following is a list of the several steps in the research methodology;

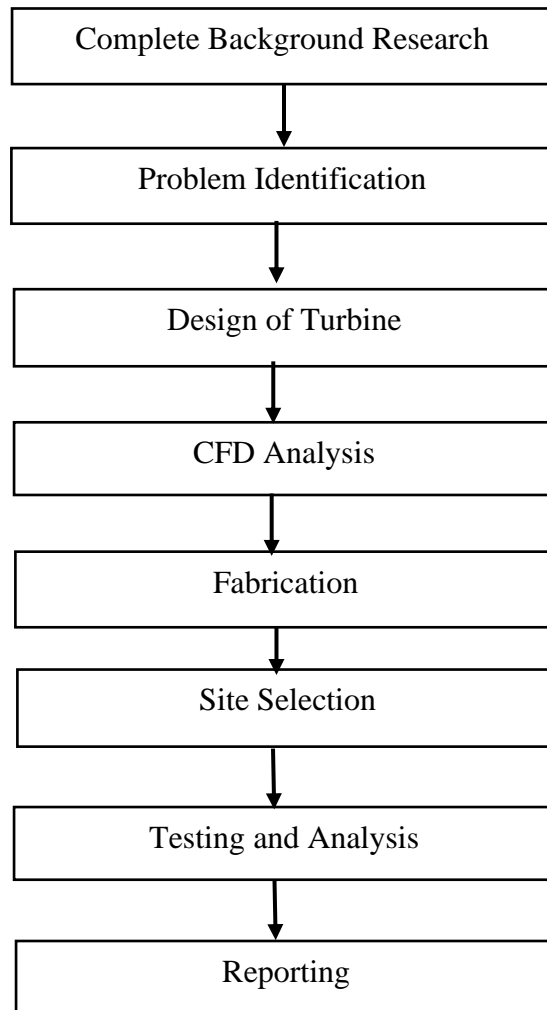


Figure 3.3: Flow Chart of Methodology

The steps mentioned above are described as follows:

#### 3.3.1 Complete Background Research

This required reading relevant literature on helical wind turbines, looking over research papers, and reviewing earlier studies on the subject of helical wind turbines by different people. A strong basis for the project's advancement was created by this research.

#### 3.3.2 Problem Identification

The problem identification step is critical to the success of any project, including a Savonius turbine project. By carefully defining the problem and understanding the

objectives of the project, a plan would be developed that is more likely to succeed and deliver the desired results.

### 3.3.3 Design of Turbine

The turbine had been selected according to the aspect ratio, overlap ratio and its material nature. The aspect ratio was taken as one and the overlap ratio was taken as 0.15. Once the background research was completed, the gathered information was carefully analyzed.

### 3.3.4 CFD Analysis

The following comprehensive, step-by-step simulation process makes up the CFD analysis for Savonius turbine:

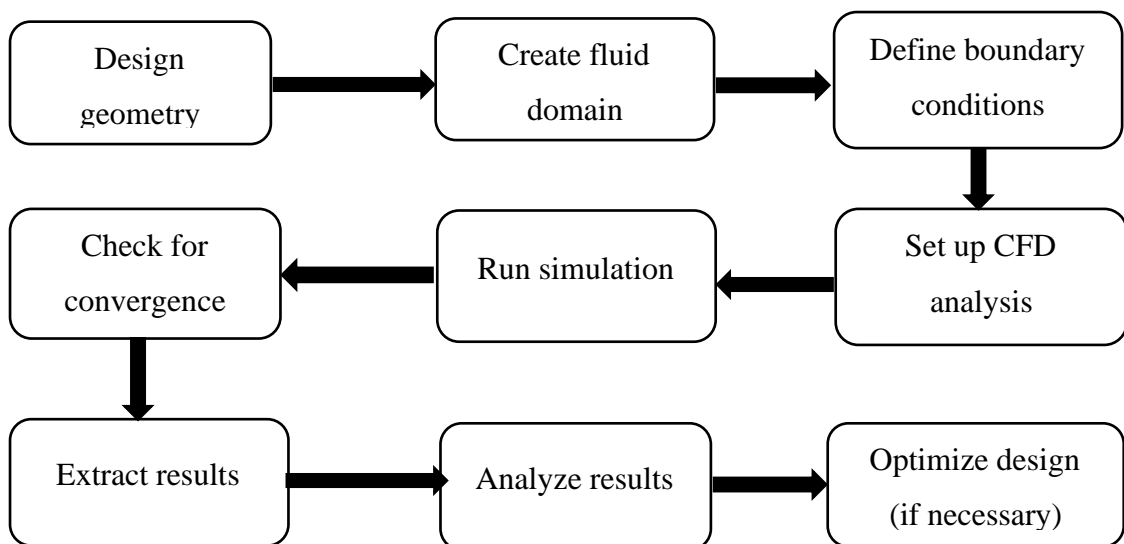


Figure 3.4: Step-by-step procedure of the CFD analysis

### 3.3.5 Fabrication

The fabrication of the wind turbine will be done in the following manner:

#### Fabrication of the Savonius Blades

The Savonius Blade would be constructed using aluminium sheet. A certain level of tolerance would be allowed during the fabrication process.

#### Assembly

The designed model of the Savonius vertical axis wind turbine will be achieved by assembling all of the parts together.

### 3.3.6 Site Selection

The experimental setup and data collection will be done on wind tunnel at aerospace laboratory of Pulchowk Campus, Kathmandu .

### **3.3.7 Testing and Analysis**

Following the assembly phase, a test setup will be prepared, and the Savonius turbine will be tested by varying the speed of the wind between certain low velocity range. During this process, the RPM of the shaft will be measured, the wind velocity will be recorded and the voltage generated at corresponding time at the selected site.

### **3.3.8 Reporting**

Several charts and graphs would be made using the data from the tests and Excel. After these charts and graphs were analyzed, a decision would be reached, and reporting would be completed.

## **3.4 Experimental Setup**

This section focuses on the testing and experimental setup of the Savonius turbine, including the measuring instruments used to measure various parameters.

### **3.4.1 Measuring Instruments**

The following is a list of the instruments used to measure variables like wind speed and RPM:

- i. Tachometer
- ii. Anemometer

### **3.4.2 Measuring Process**

The experiment was carried out on the following process. The step-wise process includes:

- i. Data collection
- ii. Wind speed measurement
- iii. Rotational speed measurement

## CHAPTER FOUR : RESULT AND DISCUSSION

The process of fabrication of turbine blade for experimental setup is ongoing so, final result is on the process. The Savonius wind turbine, which was originally designed using SOLIDWORKS 17, is undergoing fabrication and assembly according to the design specifications. After completion, the final model will be prepared for experimental verification.

### 4.1 Theoretical Analysis

During theoretical rotational speed, torque, wind power, turbine power and efficiency were calculated using formula and equations mention on Chapter Two. Power coefficient of Savonius Rotor ( $C_{ps}$ ) was considered as 0.262 [14].

Table 4.1: Theoretical Data

S.N.	Wind Velocity, $v$ (m/s)	Wind Power, $P_w$ (W)	Turbine Power, $P$ (W)	Theoretical Rotational Speed, $N$ (RPM)	Theoretical Torque, $T$ (Nm)	Theoretical Angular speed ( $\omega$ )
1	2.3	1.577	0.413	78.480	0.050	8.214
2	3.1	3.861	1.012	105.778	0.091	11.071
3	4.1	8.933	2.340	139.900	0.160	14.643
4	4.6	12.615	3.305	156.961	0.201	16.429
5	5.8	25.287	6.625	197.907	0.320	20.714
6	6.3	32.407	8.491	214.968	0.377	22.500

The following chart in Figure 4.1 illustrates that wind power increases significantly with wind velocity, showing a sharp exponential growth. In contrast, turbine power also increases with wind velocity but at a slower, more linear rate. This highlights the potential for generating higher wind power at higher wind speeds, though the actual power harnessed by the turbine is comparatively lower due to efficiency and mechanical limitations

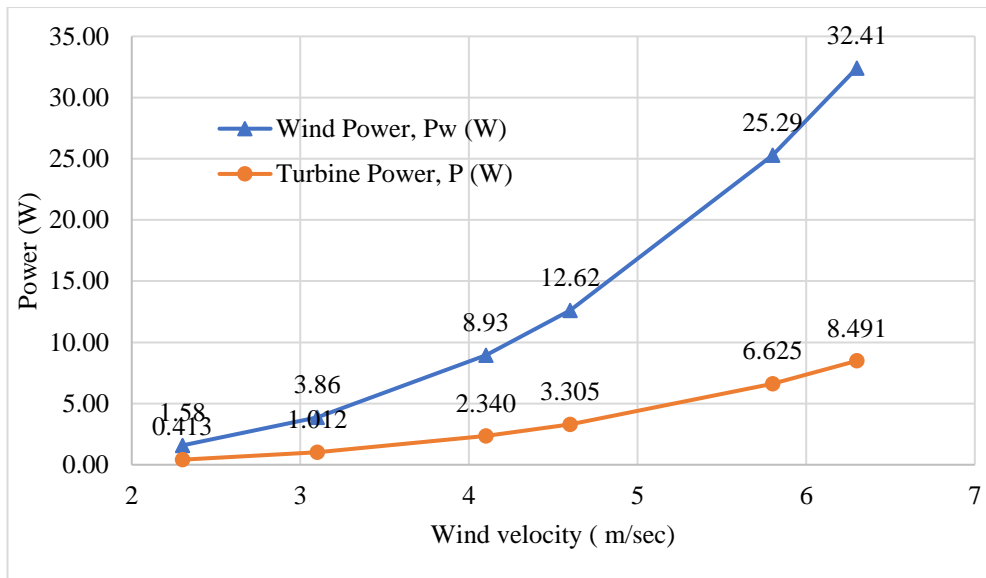


Figure 4.1: Wind Power vs Turbine Power

## 4.2 Result via CFD Analysis

The aim of the analysis was to study the velocity and pressure distributions of the Savonius turbine blades at different wind velocities. The wind velocities considered for the analysis were in range of 2 m/s to 7 m/s. The analysis was conducted using the SOLIDWORKS 17 Flow Simulation module, which utilizes the finite element method (FEM) to solve fluid flow equations.

After the analysis was completed, contours were generated for the velocity and pressure distributions of the turbine blades. Contours are graphical representations of data that show how values change across a two-dimensional surface. The velocity contours showed the magnitude and direction of the fluid flow around the turbine blades. The pressure contours showed the distribution of pressure across the surface of the blades.

### 4.2.1 Wind Velocity of 2.3 m/s

#### i. Velocity Distribution

At an inlet wind velocity of 2.3m/s, the Savonius blades exhibited a maximum velocity of 4.18 m/s and a minimum velocity of 0 m/s, as illustrated in the Figure 4.2.

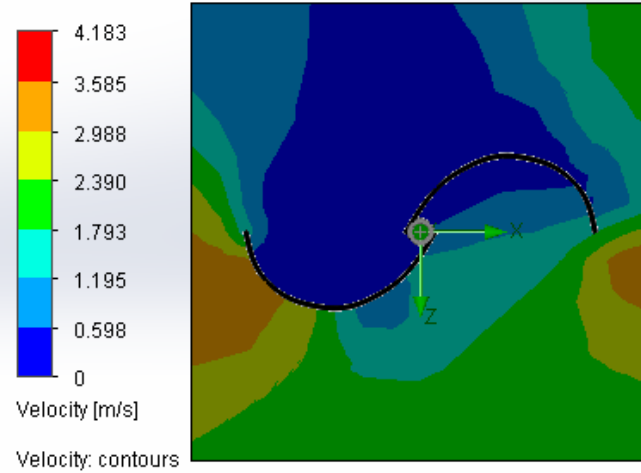


Figure 4.2: Velocity Contour at 2.3m/s

## ii. Pressure Distribution

At a consistent wind velocity of 2.3 m/s, the Savonius blades were observed to experience a maximum pressure of 101337.05 Pa and a minimum pressure of 101320.97 Pa, as depicted in the Figure 4.3.

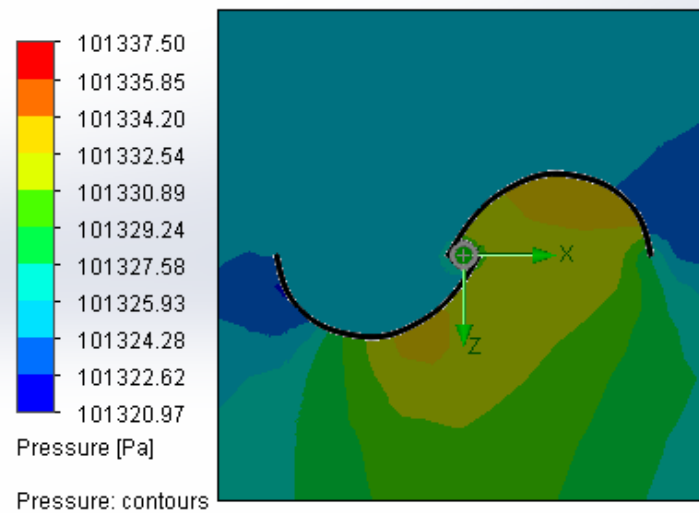


Figure 4.3 : Pressure Contour at 2.3m/s

## 4.2.2 Wind Velocity of 3.1 m/s

### i. Velocity Distribution

At an inlet wind velocity of 3.1m/s, the Savonius blades exhibited a maximum velocity of 5.38 m/s and a minimum velocity of 0 m/s, as illustrated in the Figure 4.4.

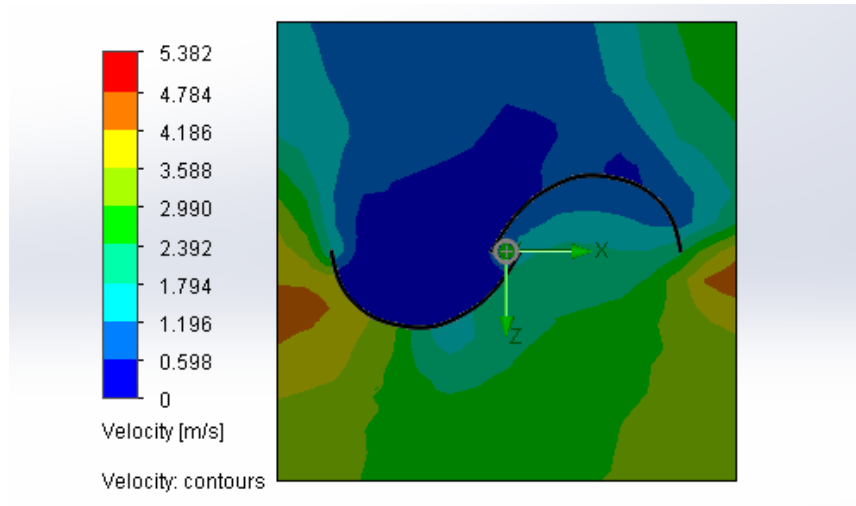


Figure 4.4: Velocity Contour at 3.1m/s

### ii. Pressure Distribution

At a consistent wind velocity of 3.1 m/s, the Savonius blades were observed to experience a maximum pressure of 101349.64 Pa and a minimum pressure of 101313.35 Pa, as depicted in the Figure 4.5.

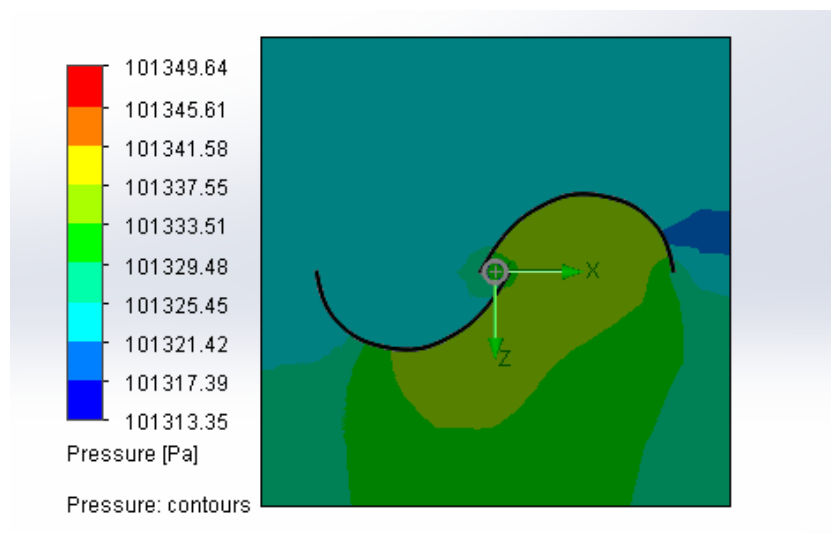


Figure 4.5: Pressure Contour at 3.1 m/s

## 4.2.1 Wind Velocity of 4.1 m/s

### i. Velocity Distribution

At an inlet wind velocity of 4.1m/s, the Savonius blades exhibited a maximum velocity of 7.14 m/s and a minimum velocity of 0 m/s, as illustrated in the Figure 4.6.

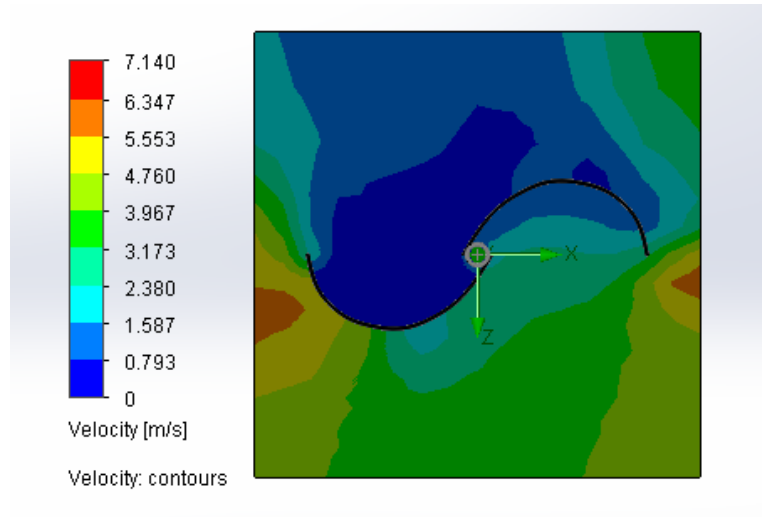


Figure 4.6: Velocity Contour at 4.1 m/s

### ii. Pressure Distribution

At a consistent wind velocity of 4.1 m/s, the Savonius blades were observed to experience a maximum pressure of 101368.09 Pa and a minimum pressure of 101305.17 Pa, as depicted in the Figure 4.7.

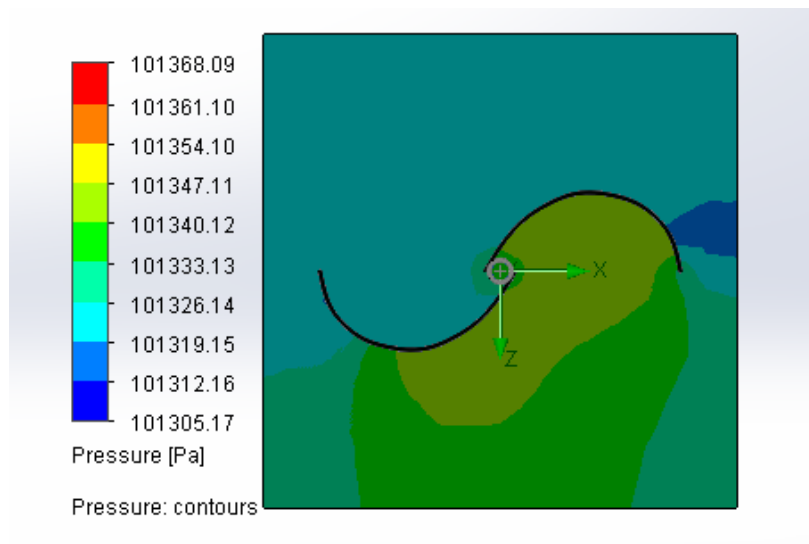


Figure 4.7: Pressure Contour at 4.1m/s

## 4.2.1 Wind Velocity of 4.6 m/s

### i. Velocity Distribution

At an inlet wind velocity of 4.6m/s, the Savonius blades exhibited a maximum velocity of 8.02 m/s and a minimum velocity of 0 m/s, as illustrated in the Figure 4.8.

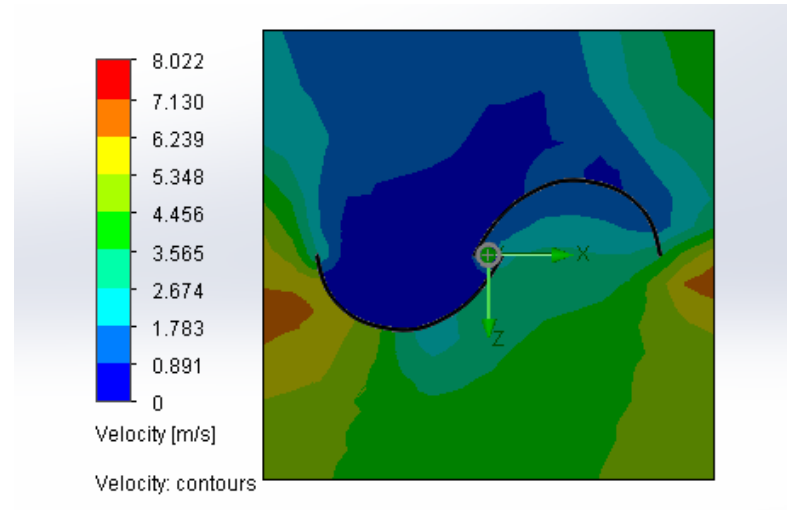


Figure 4.8: Velocity Contour at 4.6 m/s

**ii. Pressure Distribution**

At a consistent wind velocity of 4.6 m/s, the Savonius blades were observed to experience a maximum pressure of 101379.25 Pa and a minimum pressure of 101300.24 Pa, as depicted in the Figure 4.9.

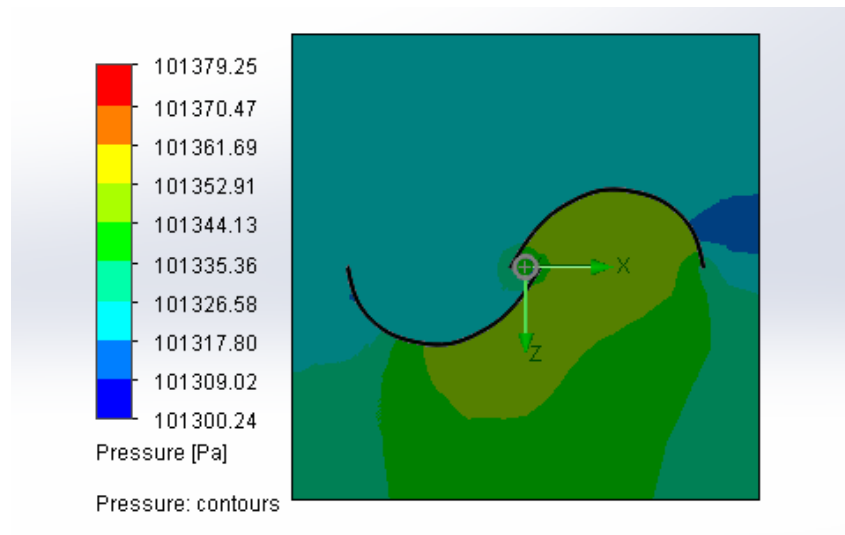


Figure 4.9: Pressure Contour at 4.6 m/s

**4.2.1 Wind Velocity of 5.8 m/s**

**i. Velocity Distribution**

At an inlet wind velocity of 5.8m/s, the Savonius blades exhibited a maximum velocity of 10.12 m/s and a minimum velocity of 0 m/s, as illustrated in the Figure 4.10.

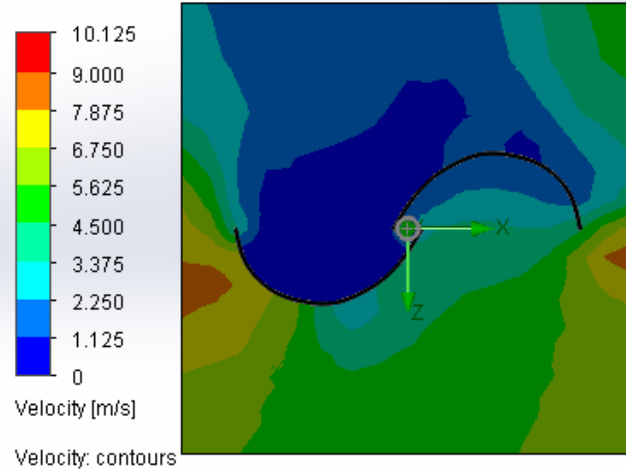


Figure 4.10: Velocity Contour at 5.8 m/s

### ii. Pressure Distribution

At a consistent wind velocity of 5.8 m/s, the Savonius blades were observed to experience a maximum pressure of 101411.46 Pa and a minimum pressure of 101275.86 Pa, as depicted in the Figure 4.11.

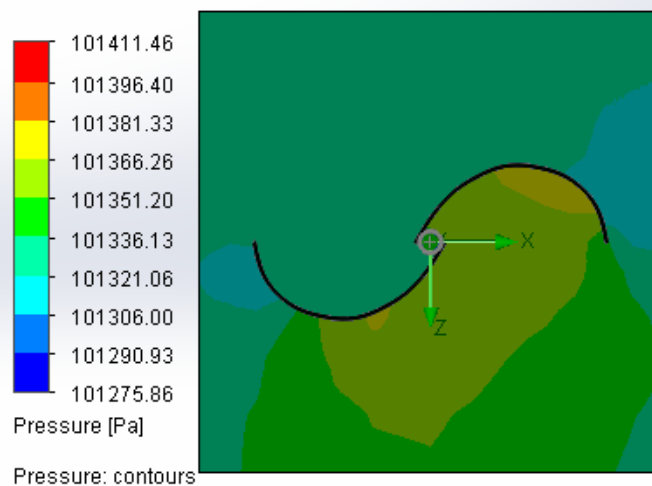


Figure 4.11: Pressure Contour at 5.8 m/s

## 4.2.1 Wind Velocity of 6.3 m/s

### i. Velocity Distribution

At an inlet wind velocity of 6.3m/s, the Savonius blades exhibited a maximum velocity of 11.00 m/s and a minimum velocity of 0 m/s, as illustrated in the Figure 4.12.

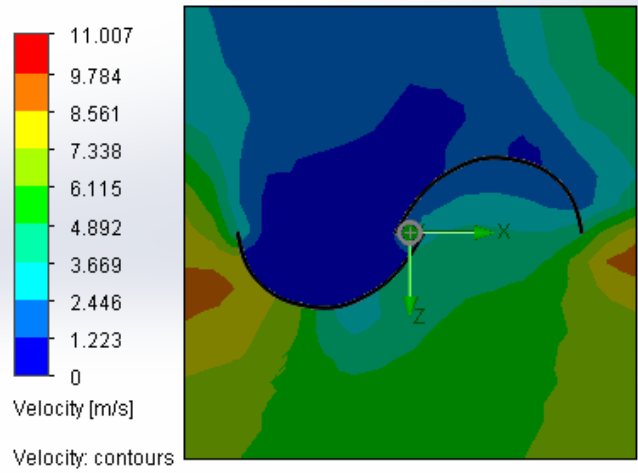
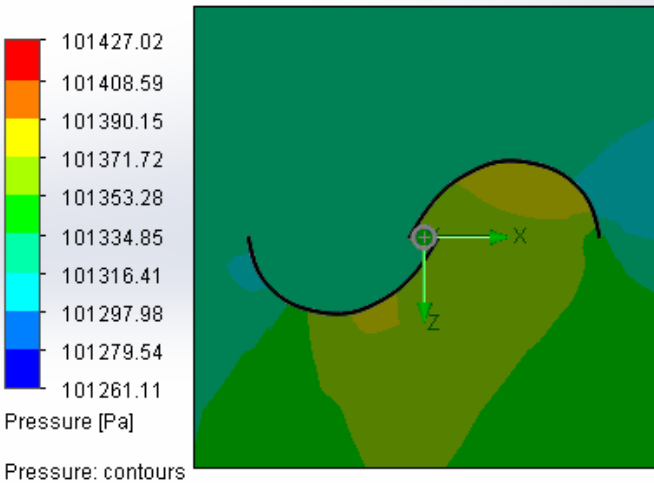


Figure 4.12: Velocity Contour at 6.3 m/s

**ii. Pressure Distribution**

At a consistent wind velocity of 6.3 m/s, the Savonius blades were observed to experience a maximum pressure of 101427.02 Pa and a minimum pressure of 101261.11 Pa, as depicted in the Figure 4.13.



S

Figure 4.13: Pressure Contour at 6.3 m/s

**4.2.2 Goal Analysis**

The goal of the simulation was to find out torque, maximum of velocity of wind across turbine profile, maximum total pressure on profile and torque along vertical direction.

Table 4.2: Goal Result Table

S.N.	Wind Velocity, v (m/s)	Simulated Torque, T (Nm)	Maximum Velocity at Profile, (m/s)	Maximum Total Pressure, (Pa)
1	2.3	0.058	4.18	101337.05
2	3.1	0.077	5.38	101349.64
3	4.1	0.136	7.14	101368.09
4	4.6	0.174	8.02	101379.25
5	5.8	0.274	10.12	101411.46
6	6.3	0.323	11.00	101427.02

The chart in Figure 4.14 shows a linear relationship between wind velocity from a wind tunnel and the maximum velocity at a specific profile. As the wind tunnel velocity increases from 2.3 to 6.8 m/s, the maximum velocity at the profile rises from 4.18 to 11 m/s. The data points and the connecting line illustrate that the maximum velocity at the profile increases proportionally with the wind tunnel velocity

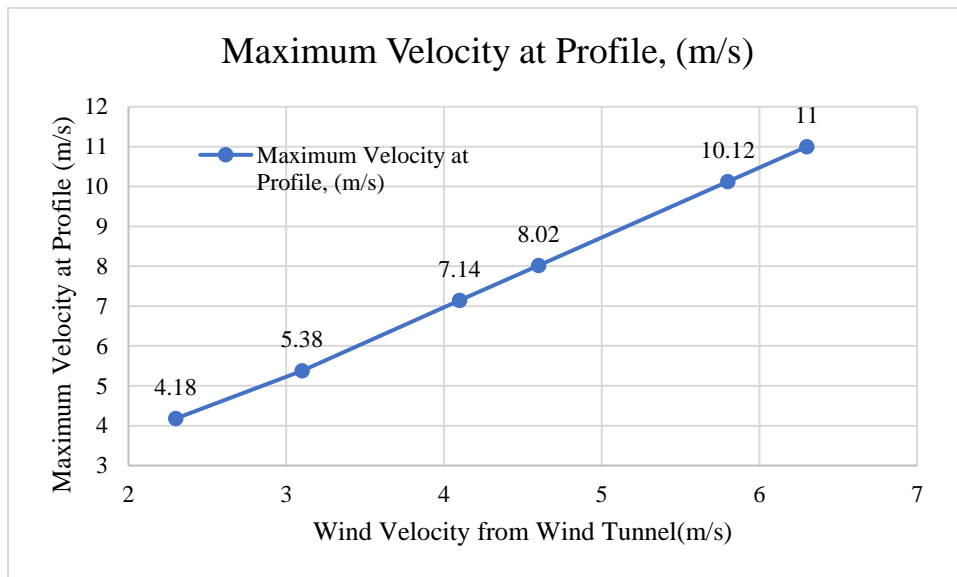


Figure 4.14: Maximum Velocity at Profile vs Wind Tunnel Velocity

The chart in Figure 4.15 exhibits a nearly linear relationship between wind velocity from a wind tunnel and the maximum total pressure at a specific profile.

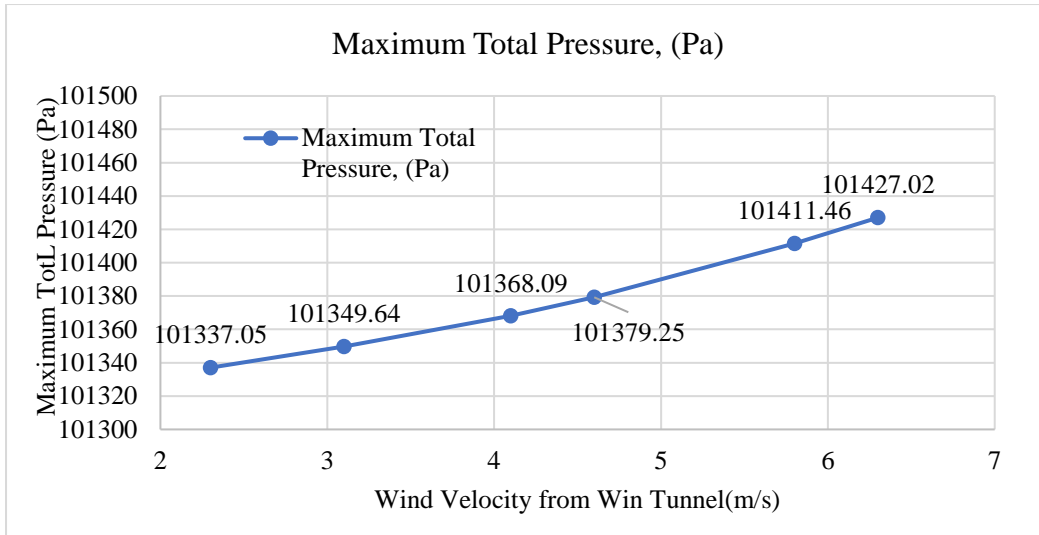


Figure 4.15: Maximum Total Pressure vs Wind Tunnel Velocity

### 4.3 Result via Experimental Analysis

Experiment and testing were performed on wind tunnel at Aerospace laboratory of Pulchowk Campus, Kathmandu, Nepal.

Table 4.3: Experimental Data

S.N.	Wind Velocity, $v$ (m/s)	Wind Power, $P_w$ (W)	Turbine Power, $P$ (W)	Experimental Rotational Speed, $N$ (RPM)	Experimental Torque, $T$ (Nm)	Experimental Angular speed ( $\omega$ )
1	2.3	1.577	0.413	77	0.051	8.059
2	3.1	3.861	1.012	135	0.072	14.130
3	4.1	8.933	2.340	162	0.138	16.956
4	4.6	12.615	3.305	184	0.172	19.259
5	5.8	25.287	6.625	251	0.252	26.271
6	6.3	32.407	8.491	266	0.305	27.841

### 4.3.1 Wind Velocity Vs Angular Speed of Turbine Shaft

The chart shows the relationship between wind velocity (in m/s) and angular speed (in  $\omega$ ) for both theoretical and experimental values. As the wind velocity increases from 2.3 to 6.3 m/s, both the theoretical and experimental angular speeds increase. The experimental angular speed consistently exceeds the theoretical angular speed across all wind velocities. Notably, at 6.3 m/s wind velocity, the experimental angular speed reaches 27.8  $\omega$ , while the theoretical angular speed is 22.5  $\omega$ .

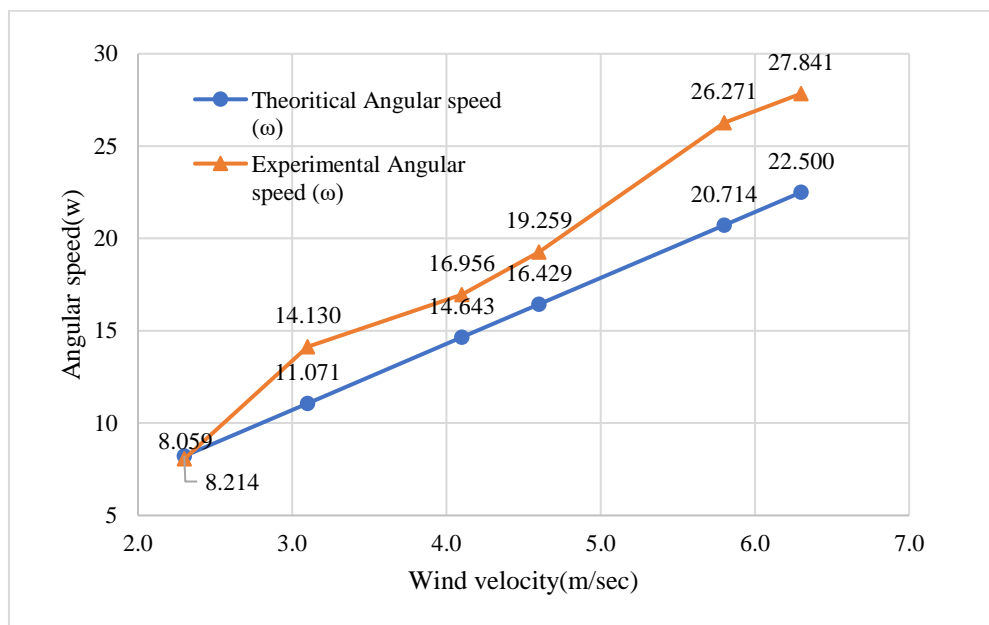


Figure 4.16: Theoretical Angular Speed vs Theoretical Angular Speed

### 4.3.1 Wind Velocity Vs Rotational Speed of Turbine Shaft

The chart illustrates the relationship between wind velocity (in m/s) and rotational speed (in RPM) for both theoretical and experimental values. As wind velocity increases from 2.3 to 6.3 m/s, both theoretical and experimental rotational speeds rise. The experimental rotational speed is consistently higher than the theoretical rotational speed at each wind velocity. At 6.3 m/s, the experimental rotational speed reaches 266 RPM, while the theoretical speed is 214.9 RPM.

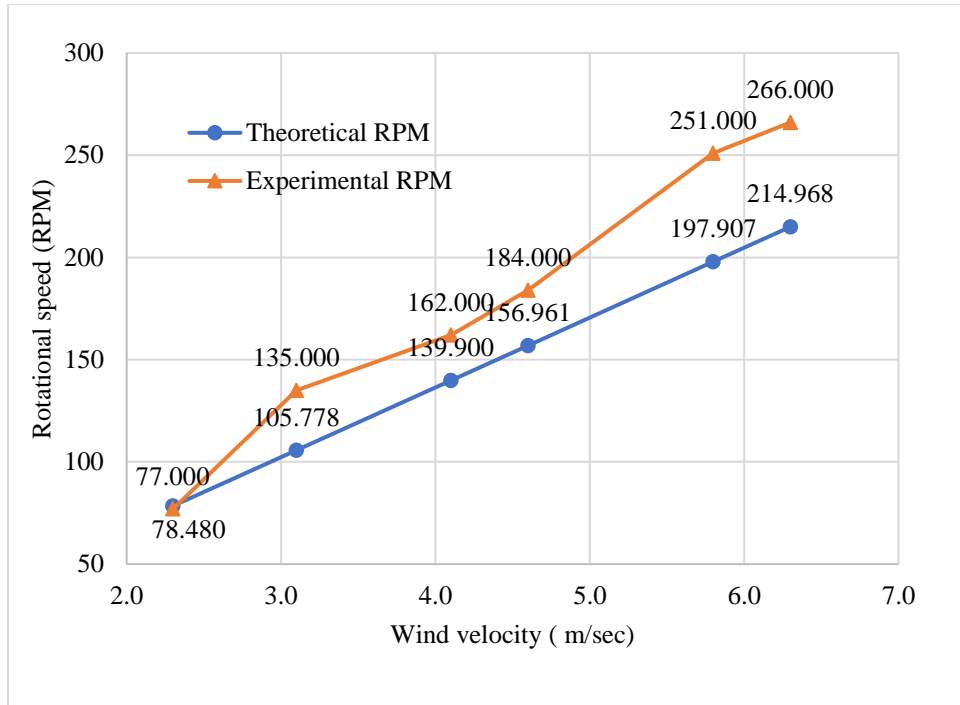


Figure 4.17: Theoretical Rotational Speed vs Experimental Rotational Speed

### 4.3.1 Wind Velocity Vs Torque of Turbine Shaft

The chart displays the relationship between wind velocity (in m/s) and torque (in Nm) for theoretical, experimental, and simulated values. As wind velocity increases from 2.0 to 6.0 m/s, the torque also increases for all three measurements. The theoretical torque is consistently higher than both the experimental and simulated torques, while the experimental torque is generally higher than the simulated torque. At 6.0 m/s wind velocity, the theoretical torque reaches 0.377 Nm, the experimental torque is 0.323 Nm, and the simulated torque is 0.305 Nm.

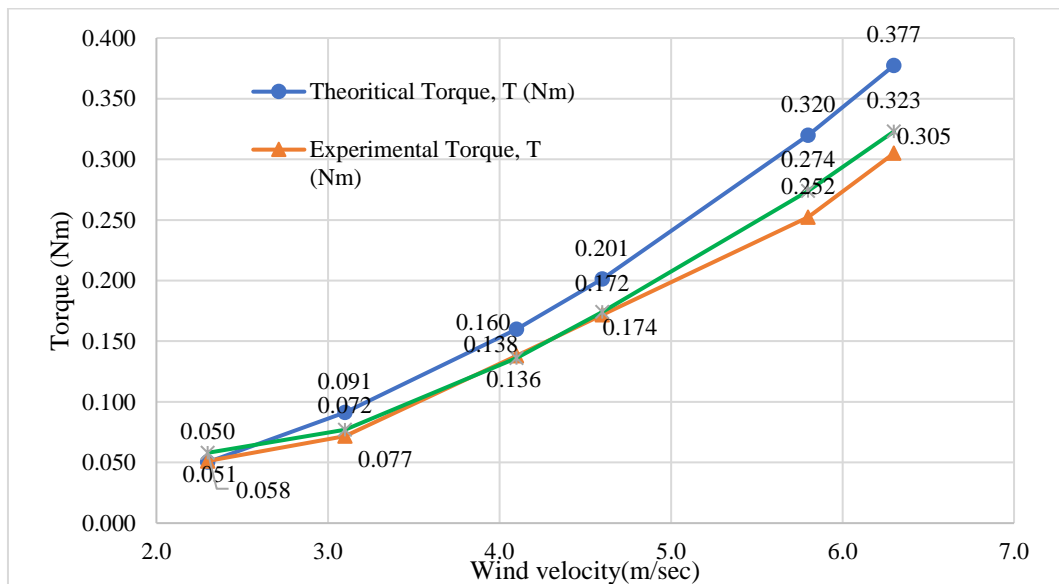


Figure 4.18: Theoretical Torque vs Simulated Torque vs Experimental Torque

## CHAPTER FIVE : CONCLUSION AND RECOMMENDATIONS

### 5.1 Conclusion

The Savonius wind turbine has a simple design and can be easily installed on low wind velocity site to harness the wind energy.

- The model was successfully designed and fabricated with stable structure to hold turbine. Testing of the model was done for the speed range of 2.3 – 6.3 m/s in a wind tunnel.
- The model was simulated in Solidworks software with addition to Flow Simulation Plugin to find the torque output along the rotating axis of turbine
- The maximum and minimum rotational speeds were experimentally determined to be 266 rpm and 77 rpm, respectively, at wind velocities of 6.3 m/s and 2.3 m/s. Theoretical maximum and minimum rotational speeds were also calculated and found to be 214.9 rpm and 78.4 rpm, respectively.
- The minimum and maximum angular velocity were experimentally determined to be  $8.214 \omega$  and  $22.5 \omega$ , respectively, at wind velocities of 2.3 m/s and 6.3 m/s. Theoretical minimum and maximum angular velocity were also calculated and found to be  $8.05 \omega$  and  $27.84 \omega$ , respectively, at wind velocities of 2.3 m/s and 6.3 m/s.
- The minimum and maximum turbine torque were experimentally determined to be 0.051 and 0.305, respectively, at wind velocities of 2.3 m/s and 6.3 m/s. Theoretical minimum and maximum turbine torque were also calculated and found to be 0.05 and 0.377, respectively, at wind velocities of 2.3 m/s and 6.3 m/s. Simulated minimum and maximum turbine torque were also calculated and found to be 0.058 and 0.323, respectively, at wind velocities of 2.3 m/s and 6.3 m/s.
- The mean absolute errors between the experimental and theoretical torque, experimental and simulated torque, experimental and theoretical rotational speed were determined to be 18.85%, 6.35% and 15%.

In conclusion, the project has demonstrated that energy generation using a Savonius wind turbine is a promising technology for generating renewable energy. With further research and development, this technology could become an important component of the renewable energy mix and contribute to reducing greenhouse gas emissions and mitigating climate change.

## **5.2 Recommendations**

The project study has demonstrated that the Savonius wind turbine have great potential in the field of wind energy. However, further research is required to improve their efficiency and reliability. The following recommendations can be made to achieve this goal:

- Experimental study of the model with various altitudes should be done.
- Testing should be done by varying different parameters that affect the turbine's performance, such as aspect ratio, tip speed ratio, blade profile, etc. This will help identify the optimal design parameters that can maximize the turbine's efficiency.
- Proper testing equipment should be used to ensure accurate and reliable data. This includes equipment for measuring blade rotation speed, torque, and power output.
- Testing should be conducted over a wide range of wind speeds to evaluate turbine's reliability and performance under different wind conditions.

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