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Transport

College of Engineering and Technology

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New designs of VAWT and comparing with its traditional type

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Abstract

Renewable energy has been utilized by humans ever since the dawn of the civilization in a try to take advantage of nature's resources to make life better. The many forms of renewable energy come mainly from the sun the heats the planet, subsequently moves the air to make winds that moves the seas the rivers creating all forms of six main renewable energy resources.

Wind energy is a form of renewable that is available everywhere on the planet and can be harnessed in many ways and currently contributes in a huge percentage of overall renewable energy production worldwide. Our aim is manufacture one of wind energy's harnessing equipment and try to modify it for better performance and try to eliminate drawbacks that exists in traditional equipment through various experiments.

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Nomenclature

Cm Torque coefficient [–]

Cms Static torque coefficient [–]

Cp power coefficient [–]

Ct Torque coefficient

Cw Drag coefficient

D rotor diameter [m]

R Turbine radius [m]

r is the pulley radius

A swept area [m2]

e Blade overlap distance [m]

H rotor height [m]

L blade length [m]

M Turbine torque [N m]

P Turbine power output [N m/s]

U Wind speed [m/s]

β Obstacle angle [◦]

γ Deflector angle [◦]

λ Tip Speed ratio [–]

θ Turbine rotation angle [◦]

ρ Air density [kg/m3]

ω Turbine angular velocity [1/s]

U wind velocity [m/s]

Vtb blade velocity at its tip

Fr resisting wind force to rotation

Fw wind force [N]

Pw wind power [W]

Chapter One

1. INTRODUCTION

1.1 DEFNTION OF WIND HARVESTING:

Wind harvesting is the process in which the wind is used to generate mechanical power or electricity. Wind turbines convert the kinetic energy in the wind into mechanical power. This mechanical power can be used for specific tasks (such as grinding grain or pumping water), or can be converted into electricity by a generator. [1]

1.2 THEORY OF OPERATION:

Wind turbines work on a simple principle: instead of using electricity to make wind—like a fan—wind turbines use wind to make electricity. Wind turns the propeller-like blades of a turbine around a rotor, which spins a generator, which creates electricity. When wind flows across the blade, the air pressure on one side of the blade decreases. The difference in air pressure across the two sides of the blade creates both lift and drag. The force of the lift is stronger than the drag and this causes the rotor to spin. The rotor connects to the generator, either directly (if it's a direct drive turbine) or through a shaft and a series of gears (a gearbox) that speed up the rotation and allow for a physically smaller generator. This translation of aerodynamic force to rotation of a generator creates electricity. [2]

1.3 HISTORY OF WIND POWER:

People have been using wind energy for thousands of years, People used wind energy to propel boats along the Nile River as early as 5,000 BC. By 200 BC, simple wind-powered water pumps were used in China, and windmills with woven-reed blades were grinding grain in Persia and the Middle East. New ways to use wind energy eventually spread around the world. By the 11th century, people in the Middle East were using wind pumps and windmills extensively for food production. Merchants and the Crusaders brought wind technology to Europe. The Dutch developed large windpumps to drain lakes and marshes in the Rhine River Delta. Immigrants from Europe eventually took wind energy technology to the Western Hemisphere. American colonists used windmills to grind grain, to pump water, and to cut wood at sawmills. Homesteaders and ranchers installed thousands of wind pumps as they settled the western United States. In 1888 The first known US wind turbine created for electricity production is built by inventor Charles Brush to provide electricity for his mansion in Ohio. In the late 1800s and early 1900s, small wind-electric generators (wind turbines) were also widely used. The number of wind pumps and wind turbines declined as rural electrification programs in the 1930s extended power lines to most farms and ranches across the country. However, some ranches still use wind pumps to supply water for livestock. Small wind turbines are becoming more common again, mainly to supply electricity in remote and rural areas. [3]

Figure 1-1: Traditional Dutch windmill.

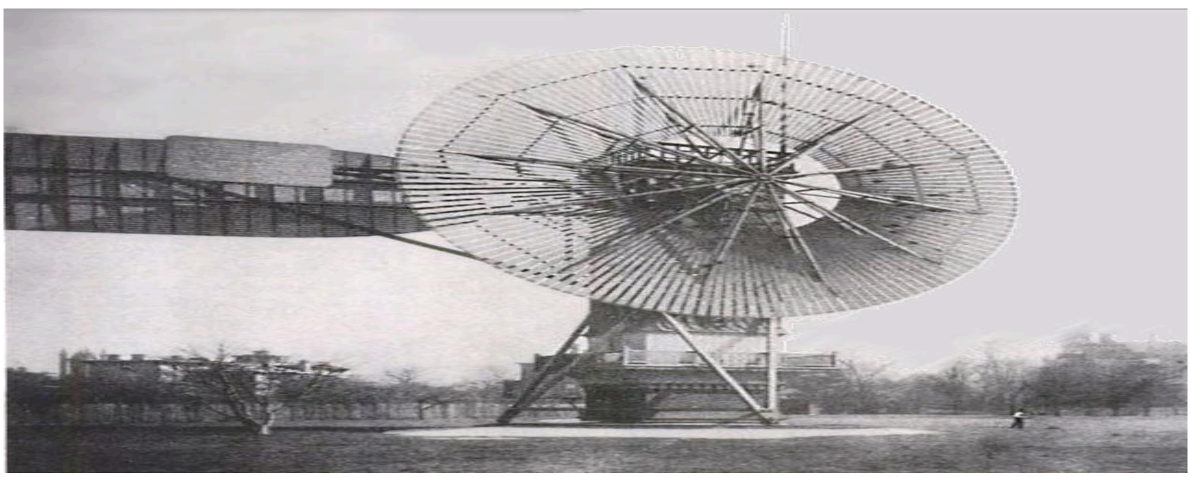


Figure 1-2: The first known US wind turbine created for electricity generation.

1.4 HORZIONTAL AXIS VS VERTICAL AXIS WIND TURBINES:

Wind turbines can be classified according to axis of orientation (the rotating axis of the wind turbine) into two groups: A) **Horizontal** B) **Vertical**

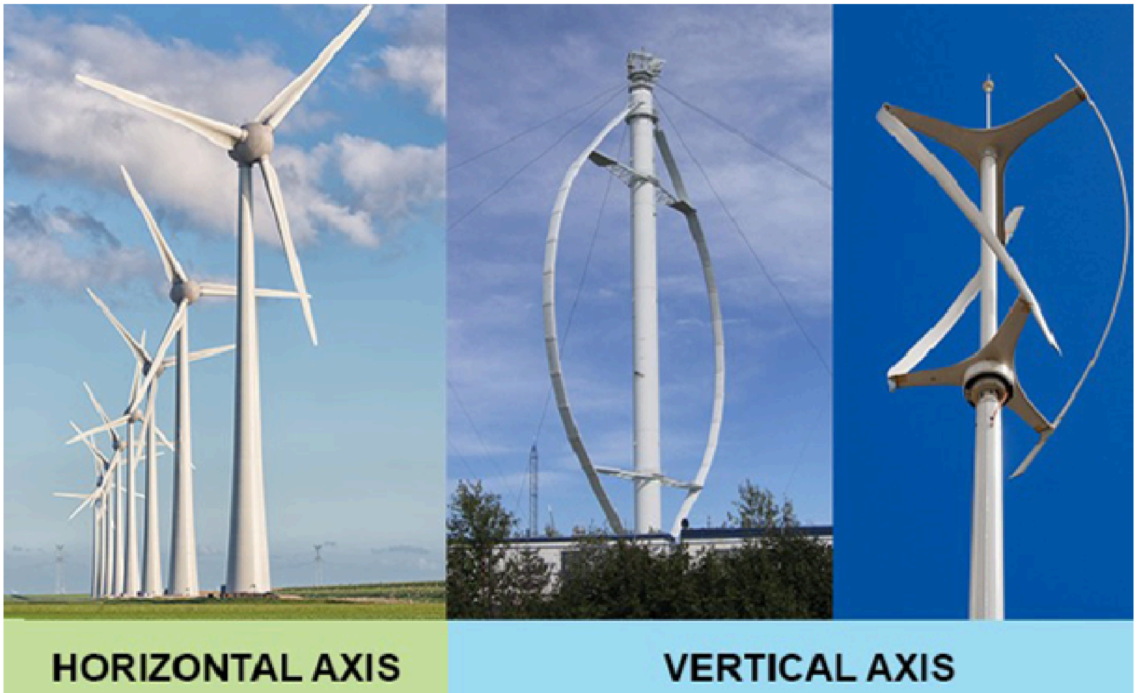


Figure1-3: Horizontal versus vertical axis wind turbines.

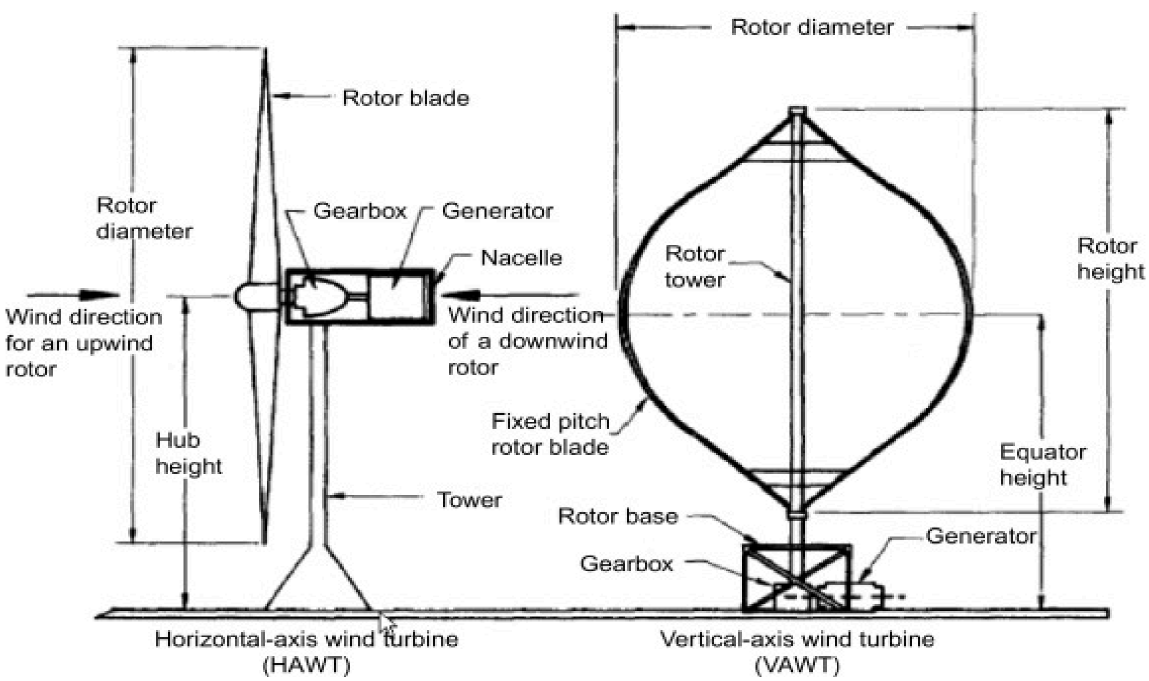


Figure 1-4: Typical diagram of HAWTs and VAWTs.

1.4.1 Horizontal Axis Wind Turbine:

1-Introduction:

Horizontal axis wind turbines utilize wind energy through blades directed on a horizontal axis parallel to the ground. HAWT faces wind perpendicularly so that wind turbine blades turn following an aerodynamic lift. [4]
HAWTs utilize aerodynamic blades (i.e. airfoils) fitted to a rotor, which can be positioned either upwind or downwind. HAWTs are typically either two- or three-bladed and operate at high blade tip speeds. Machines with upwind rotors require a yaw, or tail vane, to help them orient into the wind while downwind rotors have blades that are coned allowing the turbine to orient on its own. One drawback identified with downwind rotors, however, is that they have been known to ‘walk’ around when trying to line up with winds during low speed conditions, diminishing low wind speed energy production. [5]

Figure 1-5: An offshore wind farm with three bladed horizontal axis wind turbines.

2- Working principle:

Modern HAWTs use the aerodynamic lift force to turn each rotor blade, in a manner similar to the way an airplane flies. The lift force generally works as follows. When exposed to winds, air flows around both the upper and lower portions of a blade. As a result of the blade's curvature, however, air passes over the top of the blade more quickly (owing to a longer fetch length) than the lower portion, producing a low-pressure area on the topside. The pressure difference created between the top and bottom sides of the blade produces a force in the direction of the top of the blade. As shown in **Fig. 1-6**, the lift force acts perpendicular to the 'relative wind' acting on the wind turbine blade. The force of the lift is actually stronger than the force of the wind against the blade, or the drag, which acts in parallel with the airflows. This allows turbine blades to turn at speeds greater than could be achieved relying on drag forces alone. Although some wind turbines also use the drag force to produce energy, most HAWTs are designed to minimize drag while maximizing lift. [5]

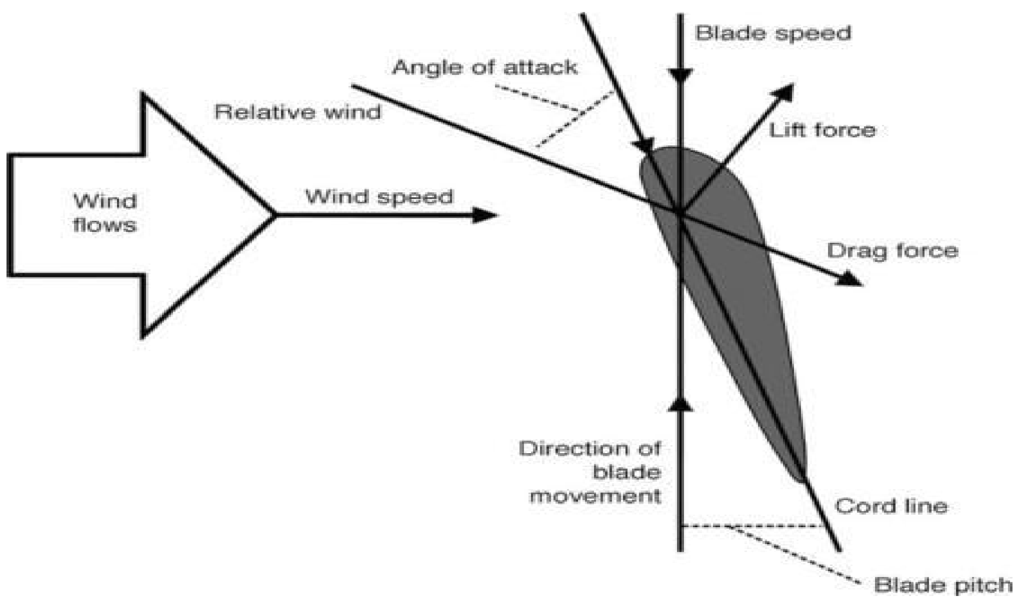


Figure 1-6: Illustration of the lift and drag forces acting on an airfoil blade.

3- Advantages compared to VAWT:

- Produce higher power because it is installed on the top of a high tower and therefore receives winds of higher velocities than on the ground.[5]
- The blades are more efficient in converting wind speed to a rotational motion because they operate perpendicular to wind direction and can be optimized for maximum power conversion. [5]

4- <u>Disadvantages compared to VAWT:</u>

- High initial construction and installation costs due to the high tower, large blades and heavy gearbox and electric generator that must be placed at the top of the tower. [5]
- Require yaw device to keep the rotor perpendicular to wind. [5]
- Maintenance is more difficult because all moving parts are at the tower top.[5]
- Inappropriate inside cities or narrow spaces. [5]

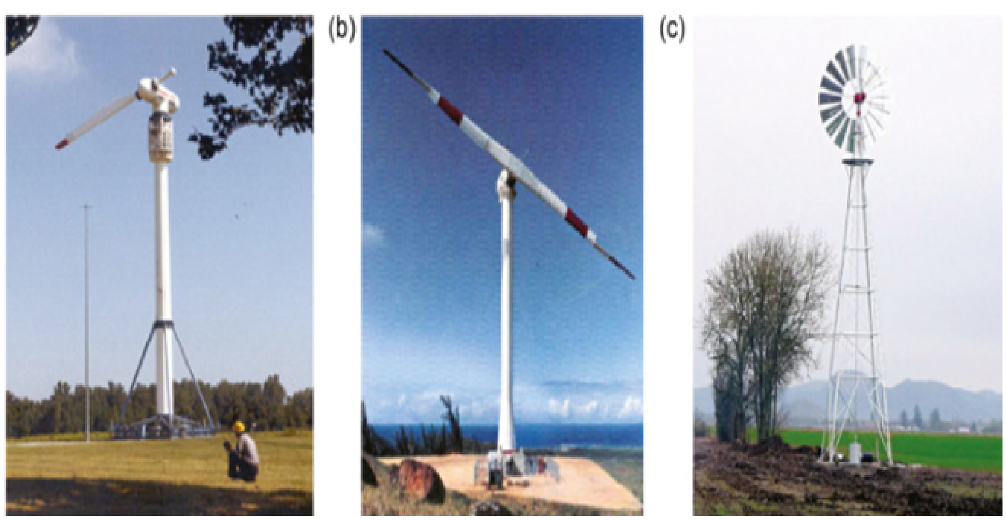
5- <u>Classification and types:</u>

HAWTs can be classified into different groups according to:

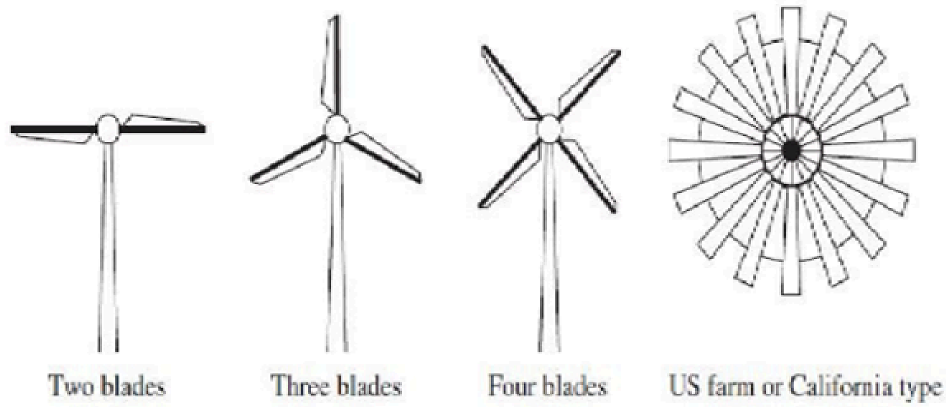
5.1- Number of blades:

The number of rotor blades in a HAWT varies depending on the application for which they are used and wind regimes in which they are expected to work. Based on the number of blades, HAWT rotors can be classified as single bladed, two bladed, three bladed, and multibladed. [5]

(a) (b) (c)



(a) single blade **(b) double blade** **(c) multibladed turbines**



Figures 1-7: Types of HAWTs according to number of blades

A) Single blade rotor:

- **Advantages:**

  The major advantage of a single-bladed rotor is the saving in blade materials, making them comparatively cheaper. It should be noted that the rotor accounts for 20–30% of the cost of a modern wind turbine. Moreover, as the blade area exposed to the flow would be minimum for the single-bladed designs, the drag losses on the blade surface also would be lower. [5]

- **Disadvantages:**

  Single-bladed designs are not very popular due to problems in balancing and visual acceptability. [5]

B) Two blades rotor:

- **Advantages:**

  Two-bladed turbines cost less because they use fewer materials. The removal of one blade makes the rotor lighter, which in turn makes it possible to place the rotor on the downwind side of the tower. Conventional wind turbine rotors face the wind and must resist bending back into the turbine's tower, but downwind rotors can use lighter and even hinged blades that bend away from heavy gusts.

Two-bladed wind turbines are also easier to install. Whereas the three-bladed rotors spinning in today's offshore farms must be assembled on site, two-bladed rotors can be preinstalled on the turbine's machinery onshore; the assembled package fits more conveniently on ships and is light enough to lift onto the tower.[5]

- **Disadvantages:**

  the two-bladed, downwind turbine design has had problems in the past, which have kept it from the market. It's louder, for one thing, in part because the blades spin faster, although this isn't a problem offshore. More importantly, in some wind conditions, the flexible blades can spring back and hit the turbine tower. In fact, this caused the undoing of a major attempt to revive two-blade turbines in 2002.[5]

C) Three blades rotor:

- **Advantages:**

  The loading pattern for these rotors is relatively uniform and they are visually more acceptable. [5]

- **Disadvantages:**

  Difficult to Transport, Install, and Maintain. [5]

D) Multi blades rotor:

- **Advantages:**

  are usually used for specific applications like water pumping. For example, wind-powered water pumping system with piston pumps requires high starting torque to overcome the initial load imposed by the water column on the piston. For such systems, starting torque demand goes up to 3–4 times that of the running torque demand. As the starting torque increases with solidity (the ratio between the actual area of the blades and the swept area of a rotor), rotors with a greater number of blades (high solidity) are preferred for such applications. [5]

- **Disadvantages:**

  However, high-solidity rotors work at low tip speed ratios and hence are not recommended for wind electric generators. Similarly, their efficiency would also be lower as aerodynamic losses increase with solidity.[5]

5.2- Position of rotor:

HAWTs are also classified according to position of the rotor into two groups A) upwind type rotor B) downwind type rotor [5]

A) Upwind type rotor:

An upwind turbine has its rotor fixed in front of the unit, directly facing the incoming wind stream. [5]

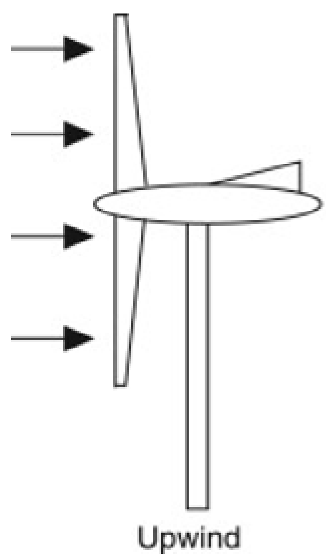


Figure 1-8: upwind HAWT

- **Advantages:**

  The major advantage of upwind rotors is that they do not suffer from the tower shadow effect. [5]

- **Disadvantages:**

However, upwind rotors are to be placed at some distance from the tower and a yaw mechanism is essential to keep the rotor always facing the wind. [5]

B) Downwind type rotor:

In contrast, the downwind turbines have their rotors positioned at the back side, leaving the nacelle to face the wind first. [5]

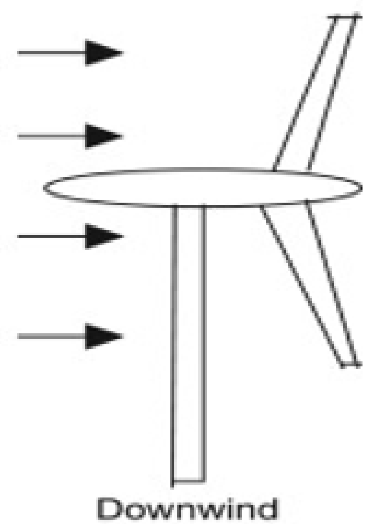


Figure 1-9: downwind HAWT

- **Advantages:**

  downwind machines are more flexible and may not require the yaw mechanism. This makes these designs relatively cheaper. [5]

- **Disadvantages:**

  as the rotors are placed at the leeward side of the tower there may be uneven loading on the blades as they pass through the shadow of the tower. [5]

6- <u>Design and components of HAWT:</u>

HAWTs work predominantly on lift principle. As the wind stream interacts with the rotor blades, lift force is generated as explained in the previous section, causing the rotor to rotate. The rotational speed varies with the design features and the size of the rotor. For a typical MW-sized turbine, this could be as low as 16 rpm. The low-speed main shaft transmits this rotation to the high-speed shaft through the gearbox (there are direct drive turbines also, which do not have a gearbox in the transmission line). The speed is enhanced by the gear trains to match with the higher speed requirement of the generator. The generator then converts the mechanical energy to electrical energy. There are a series of control systems in between for yaw alignment, power regulation, and safety. [5]

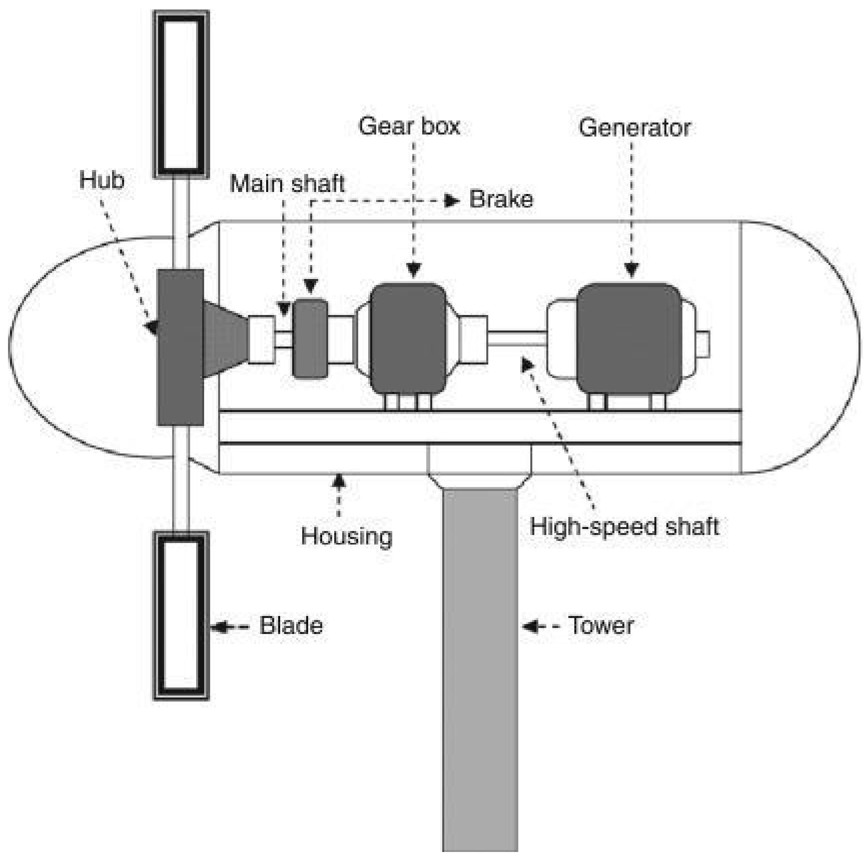


Figure 1-10: Sectional view of a HAWT.

1.4.2 Vertical Axis Wind Turbine:

1- Introduction:

The Vertical Axis Wind Turbine is a type of wind turbine and it is most frequently used for residential purposes to provide a renewable energy source to the home. This turbine includes the rotor shaft and two or three blades where the rotor shaft moves vertically. So, this turbine movement is related to the spinning of coins on the edge. In this turbine, the generator is placed at the bottom of the tower whereas the blades are covered around the shaft. Vertical-axis wind turbines (VAWTs) have an axis of rotation that is vertical, and so, unlike the horizontal wind turbines, they can capture winds from any direction without the need to reposition the rotor when the wind direction changes (without a special yaw mechanism). [6]

2- Working principle:

The vertical axis wind turbine working principle is that, the rotors in the turbine revolve around a vertical shaft by using vertically oriented blades. So they generate electricity by using wind power. The wind operates the rotor which is connected to the generator, so the generator converts the energy from mechanical to electrical. [6]

3- Advantages compared to HAWT:

- Independent on the direction of the wind. [6]
- It is possible to extract power relatively easier. [6]
- Capable of operating at minimal wind speeds. Long curved propellers are designed to be pushed by a small amount of wind. [6]
- Do not have to be placed at a very high place or a tower. Therefore, it is suitable for cities and narrow spaces. [6]
- Require less maintenance cost because all moving parts are near the ground. [6]
- Less expensive during fabrication and installation. [6]

4- Disadvantages compared to HAWT:

- Produce less power and are less efficient than horizontal axis machines.[6]

5- Design and components of VAWT:

The vertical axis wind turbine is composed of the following parts:

A) Rotor blades: the blades in vertical axis turbine can take a variety of shapes. the most common type is Darrieus turbine in which each blade is connected at its two ends to a vertical central shaft via two hubs. This central shaft drives the electric generator. Two or more blades are used in Darrieus turbine. [6]

B) Upper and lower hubs: the blade in Darrieus turbine is connected to the central shaft via two hubs, upper and lower. [6]

C) Central shaft: which is mounted in a vertical direction and drives the electric generator. In large machines the generator is placed at the middle of the central shaft so that the shaft may be of lighter weight and less cost. [6]

D) Power box: which is generally located near the ground at the base of the central shaft. It contains the gear box and the electric generator. [6]

E) Guy wires: Some vertical axis wind turbines require wires or cables to further support the tower and provide more robust design. [6]

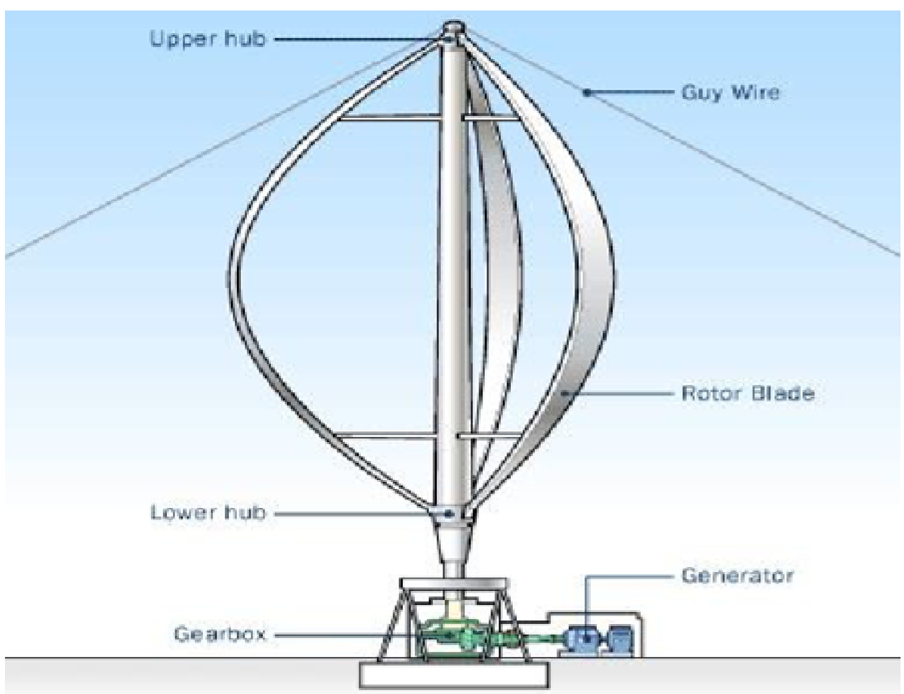


Figure 1-11: Parts of vertical axis wind turbine (Darrieus type).

6- Types of VAWT:

The vertical axis wind turbines are available in two types: A) **Savonius** B) **Darrieus** C) **bladeless wind turbines.** [6]

A) Savonius Wind Turbine:

A.1- Introduction:

Savonius wind turbine includes the blades which are arranged around the vertical shaft within a helix form. One of the most significant features of this turbine is the solid wind-receiving area. These turbines mainly rely on the mechanism of flow resistance to make the rotors active which means, the dynamic force of the wind against the turbine blades thrust the rotor into revolution. Simultaneously, the reverse side of the blades meets an aerodynamic resistance force. This is like when running or cycling, we experience the airflow coming opposite to us. Because of this, these turbines can simply turn fast like the wind speed. [6]

Figure 1-12: Savonius Wind Turbine.

A.2- Theory of operation:

The Savonius wind turbine is a simple vertical axis wind machine invented by Sigurd J. Savonius in 1922. In its original design, it was made with two half-cylindrical blades arranged in an 'S' shape. The convex side of one half-cylinder and the concave side of the other face the wind at the same time as shown in Figure 1-12 As the drag coefficient of the concave surface is more than that of the convex side, in a given wind stream, the drag force experienced by the concave half would be higher than that of the other half . It is this difference in drag force that spins the rotor to develop mechanical power. [7]

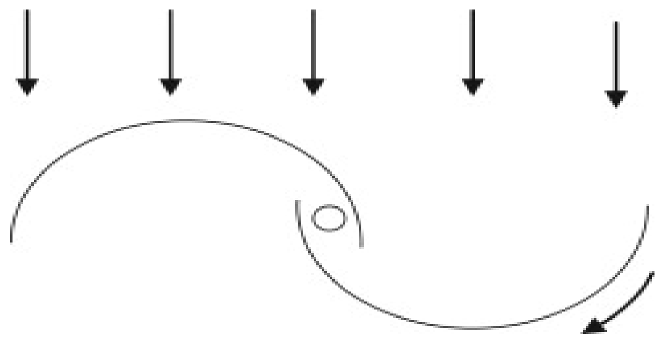


Figure 1-13: Operational principle of a Savonius rotor.

A.3 Components:

1- Turbine Blades:

Turbine blades are selected such that most of the air wetting blade surface should create drag so enough torque should be produced to drive the alternator. [9]

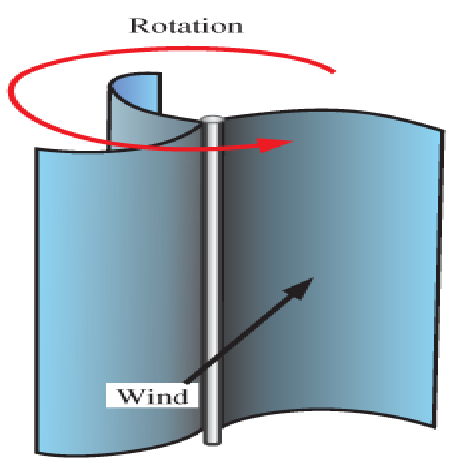


Figure 1-14: Savonius Vertical-Axis Wind Turbine blades.

2- Shaft:

Shaft is a rotating element of machine which is used to transmit power from one point to another. [9]

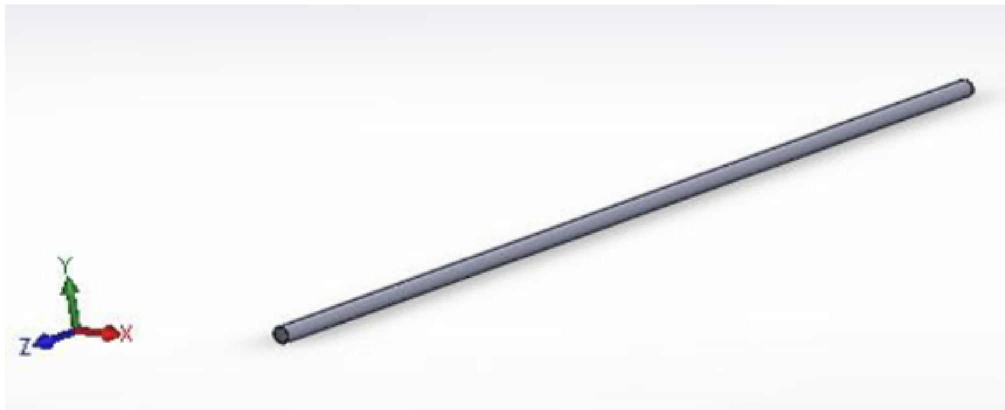


Figure 1-15: Savonius Vertical-Axis Wind Turbine shaft.

3- Bearing:

A bearing is a device used to support the shaft and permit constrained relative motion between two parts, typically rotation or linear movement. [9]

4- Gears:

Two gears are used or torque transformation. The driver gear [70 teeth] is attached to the rotor shaft while the driven gear [19teeth] is connected to the generator shaft (as shown in Fig.4). In order to achieve 150 rpm, we adopt the gear ratio of 1:3. [9]

Figure 1-16: Savonius Vertical-Axis Wind Turbine gears.

A.4- <u>Performance:</u>

A.4.1- coefficient of power:

The performance of Savonius wind turbine can be expressed in the form of coefficient of power Cp and torque coefficient Cm in comparison with the tip speed ratio (TSR). TSR is a ratio between the speed of tip blade and wind speed through the blade obtained by:

$$\lambda = \frac{V_{rotor}}{V} = \frac{\omega R}{V}$$

$$P_A = Kinetic \text{ energy } \times \text{mass flow rate} = \frac{1}{2}V^2 \times \rho SV$$

$$P_T = T\omega(watt)$$

$$C_p = \frac{P_T}{P_A} = \frac{P_T}{\frac{1}{2}\rho SV^3}$$

$$C_m = \frac{T}{T_W} = \frac{4T}{\rho SV^2}$$

Conventional Savonius rotor is a rotor with the geometrical parameters a and e are respectively equal to 0 and D/6.This rotor has been largely studied. The values of Cp and Cm are experimentally determined as a function of the velocity coefficient λ. [10]

A.4.2- Power and rotational speed:

According to Betz's law, the maximum power that is possible to extract from a theoretical ideal rotor is $P_{\max} = \frac{16}{27}\frac{1}{2}\rho \cdot h \cdot d \cdot v^3$, where ρ is the density of air, h and d are the height and diameter of the rotor and v is the wind speed. However, in practice the extractable power is about half that (one can argue that only one half of the rotor — the scoop co-moving with the wind — works at each instant of time) and depends also on the efficiency of the given rotor. Thus, for the theoretical ideal rotor, one gets

$P_{\max} \approx 0.18\,\mathrm{kg\,m^{-3}} \cdot h \cdot d \cdot v^3$, but the average maximum efficiency **C**p of the Savonius wind turbine is around 20% (**C**p=0.2), making the real extractable power of the typical Savonius

$$P_{\max} \approx 0.12\,\mathrm{kg\,m^{-3}} \cdot h \cdot d \cdot v^3 .$$

The angular frequency of a rotor is given by $\omega = \frac{\lambda \cdot v}{r}$, where r is the radius and λ is a dimensionless factor called the tip-speed ratio. λ is a characteristic of each specific windmill, and for a Savonius rotor λ is typically around unity.

For example, an oil-barrel sized Savonius rotor with *h*=1 m and *r*=0.5 m under a wind of *v*=10 m/s, will generate a maximum power of 120 W and a maximum angular speed of 20 rad/s (190 revolutions per minute). [9]

A.4.3- Parameters that affect the performance of Savonius wind turbine:

1- Effect of blades number:

The number of blades have an important impact in the rotor's performance. U.K. Saha and S. Thotla conclude that the optimum number of blades is two for the Savonius rotor whether it is single, two or three stage, M.Hadi Ali also conclude that the two blades Savonius wind turbine is more efficient, it has higher power coefficient under the same test condition than that of three blades Savonius wind turbine.[9]

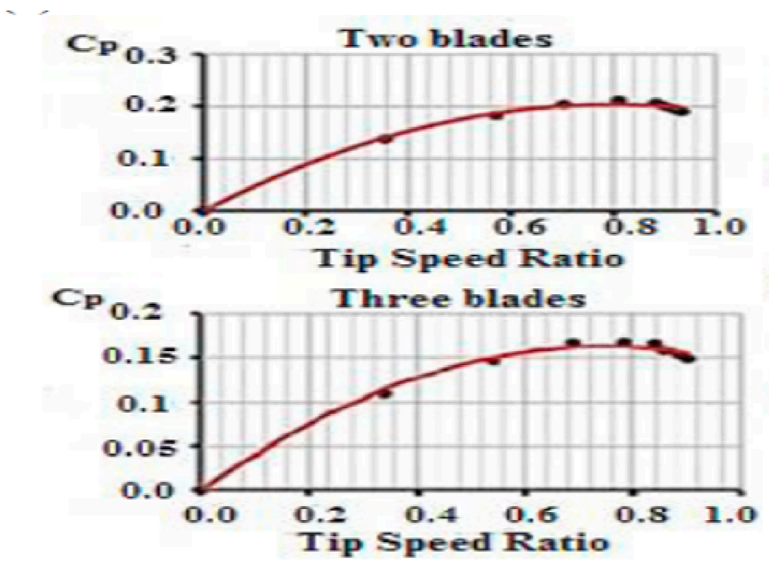


Figure 1-17: The Cp variation with the TSR for two & three blades.

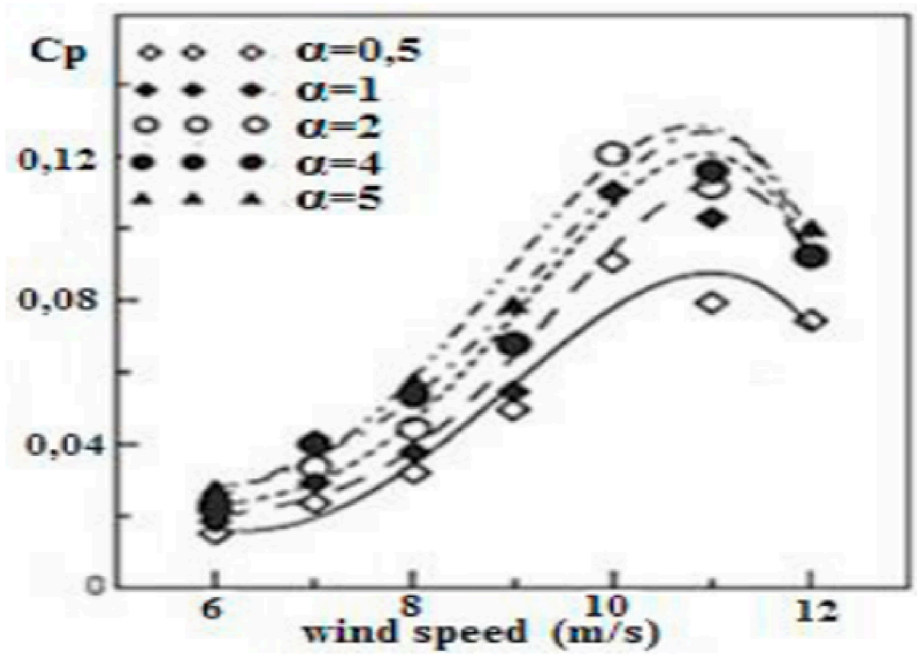


Figure1-18: Variation of Cp with wind speed for different aspect ratios.

2- Effect of Aspect Ratio:

The aerodynamic performance of the Savonius rotor depends strongly on the aspect ratio (AR). N.H. Mahmoud tested different configurations for aspect ratios (noted α) of 0.5, 1, 2,4,5 by keeping other parameters constant, the results show that the power coefficient increases with the rise in aspect ratio, Lately, studies with various designs of changed Savonius rotor having low ARs have been reported out. According to Kamoji. The rotor with an aspect ratio of 0.7 is having a maximum Cp equal to 0.21. Modi also conclude that an AR of 0.77 leads to a maximum Cp of 0.24 However, several studies on Savonius new rotors use AR near to 1, generally the use of ARs within the range of 1.5–2.0 set good results on the performance of the Savonius rotor. [9]

3- Effect of Overlap ratio:

The overlap ratio is a major parameter that influences the structure of the flow inside the rotor and consequently its aerodynamic performances, the influence of the overlap ratio has been widely investigated, however there is not an accord among the outcomes acquired in previous studies. According to

Blackwell [16] the optimal value of overlap ratio is in the range of 0.1 to 0.15. J.Menet indicate that the primary overlap ratio must be between 0.15 and 0.3 and the optimal value equal to 0.242.Akwa [18] has also done a detailed investigation on the effect of overlap ratio and indicate that the configuration of Savonius rotor that shows the best performance is the one where the overlap ratio equal to 0.15, which gives an averaged power coefficient equal to 0.3161 for the TSR of 1.25.[9]

4- Effect of Number of stages:

Number of stages mean one or more stages of an S-Rotor in a single design. This means that the wind currents will have more area to sweep through and better torque uniformity around 360 degrees. This eliminates the dead zones left by rotor's blades that are not rotating. Note that the stages of an S-Rotor are shifted at a specific phase shift angle.

Its debated that that a Double staged S-Rotor may produce the best power coefficient as compared to a single or three staged S-Rotor. This explains the hypothesis that as the stages of an S-Rotor are increased it means if one of the stages of S-Rotor is rotating it must carry the inertia of the other stages since they are not producing any torque.

In conclusion a **single staged rotor gave a power coefficient of 0.18**, a **two-staged rotor gave a power coefficient of 0.29**, while the **three-staged demonstrated a Cp of only 0.23**. [11]

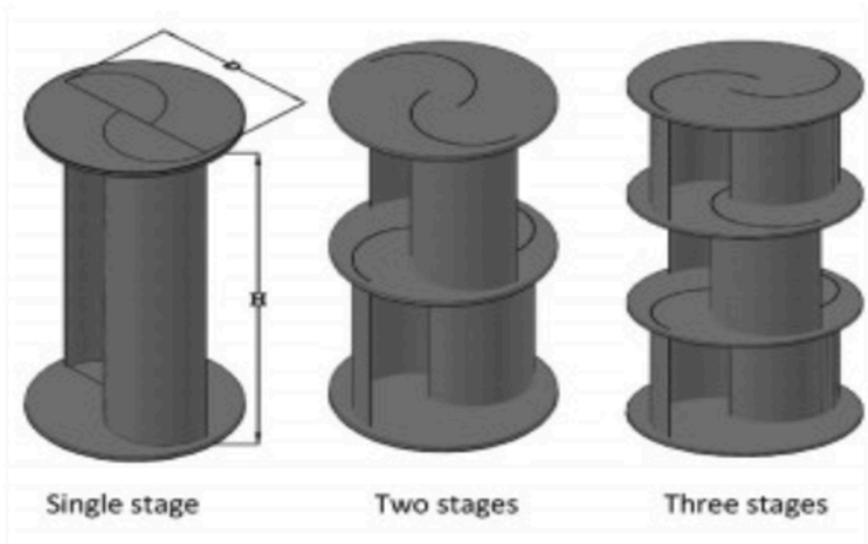


Figure 1-19: Single and Multistage S-rotors.

5- Blade shapes:

Although S-Rotors are generally similar S-shaped rotors, there have been few attempts to modify the blade shape in order to increase its aerodynamic property in order to increase the Cp.

Muscoloa and Molfinob (2014) simulated five different S-type VAWTs, including a simple S-Roto. In the four wind rotors, two were new models and two were proposed by Kyozuka (2008). The rotor named Bronzinus, performed the best and produced the highest power coefficient. But if the tip speed was crossed Cp of the wind rotor proposed by Menet (2004) was found to be superior.[11]

A.5- <u>Applications:</u>

Savonius turbines are used whenever cost or reliability is much more important than efficiency, Design is simplified because, unlike with horizontal axis wind turbines (HAWTs), no pointing mechanism is required to allow for shifting wind direction and the turbine is self-starting. for these reasons it is used in:

1- Most anemometers (as efficiency is irrelevant to the application of measuring wind speed).

2- Much larger Savonius turbines have been used to generate electric power on deep-water buoys, which need small amounts of power and get very little maintenance.
3- Savonius and other vertical-axis machines are suited to pumping water and other high torque, low rpm applications, and are not usually connected to electric power grids.
4- the Flettner ventilator, which is commonly seen on the roofs of vans and buses and is used as a cooling device. This rotor was developed for ventilation by the German aircraft engineer Anton Flettner in the 1920s. It uses the Savonius wind turbine to drive an extractor fan. The vents are still manufactured in the UK by Flettner Ventilator Limited.
5- n Europe, small Savonius wind turbines can sometimes be seen used as "animated" advertising signs in which the rotational movement helps to draw attention to the item advertised. They sometimes feature a simple two-frame animation. [12]

B) Darrieus Wind Turbine:

B.1 <u>Introduction:</u>

An alternate name of Darrieus Wind Turbine is an Eggbeater turbine. This kind of turbine was invented in the year 1931 by Georges Darrieus. A Darrieus machine is a low torque and high-speed device used to generate AC (alternating current). Generally, Darrieus requires physical push so some exterior power source is used to start rotating because the initial torque is extremely low. This machine consists of two blades that are vertically oriented and rotating around a perpendicular shaft. [13]

B.2- <u>Features:</u>

The features of the Darrieus wind turbine include the following:

- These turbines are eggbeater shaped which includes high efficiency, but they are not consistent.
- In order to utilize this turbine, you should have an exterior power source to start them. [13]

B.3- <u>Advantages:</u>

(1) The rotor shaft is vertical. Therefore, it is possible to place the load, like a generator or a centrifugal pump at ground level. As the generator housing is not rotating, the cable to the load is not twisted and no brushes are required for large twisting angles.

(2) The rotor can take wind from every direction.

(3) The visual acceptation for placing of the windmill on a building might be larger than for an horizontal axis windmill.

(4) Easily integrates into buildings.

(5) Ease of maintenance.

(6) Reduced construction and transport costs.

(7) Don’t need to be pointed into the wind. [14]

B.4- <u>Disadvantages:</u>

(1) Difficult start unlike the Savonius wind turbine.

(2) Low efficiency.

(3) The blades often spin back into the wind, and that causes drag.

(4) They operate at a physically lower level where there is more turbulent wind.

(5) They have a low starting torque and may need energy to begin turning**.** [15]

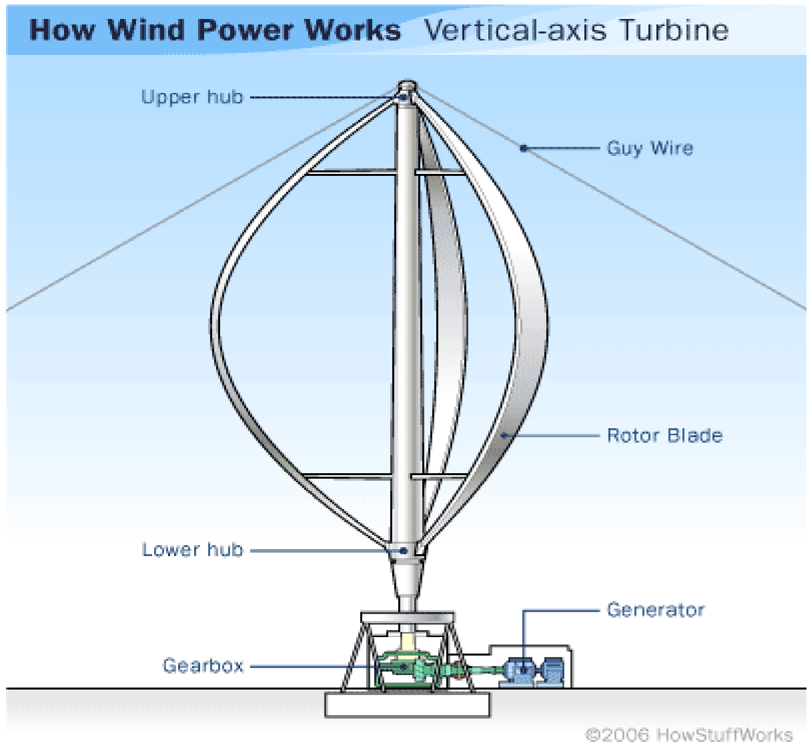


Figure1-20: Darrieus Wind Turbine components

B.5- **<u>Rotor's performance characteristics under turbulent wind:</u>**

the force interaction between fluid flow and a rotating H-type Darrieus vertical axis wind turbine. The main goal of this study is to determine the wind rotor's performance characteristics under turbulent wind: torque M = f (n), normal force FN = f (n), output power P = f (n) and the aerodynamic characteristics CM = f (λ), CN = f (λ), CP = f (λ). The flow passing through the turbine has a complex structure due to the rotation of the rotor. The constantly changing angular position of the turbine's blades is leading to a variation in the blades angle of attack. This angle can vary from positive to negative values in just a single turbine revolution. The constant fluctuations of the angle of attack are the main factor which leads to the unsteady nature of the flow passing through the turbine. At low tip-speed ratios, the phenomena deep dynamic stall occurs which leads to intensive eddy generation. When the turbine is operating at higher tip-speed ratio the flow is mainly attached to the blades and the effect of the dynamic stall over the turbine performance is from weak to none. The Darrius turbine performance characteristics are obtained through a numerical investigation carried out for several tip-speed ratios. The used CFD technique is based upon the URANS approach for solving the Navier-Stokes equations in combination with the turbulence model k – ω SST. Also, a numerical sensitive study concerning some of the simulation parameters is carried out. [16]

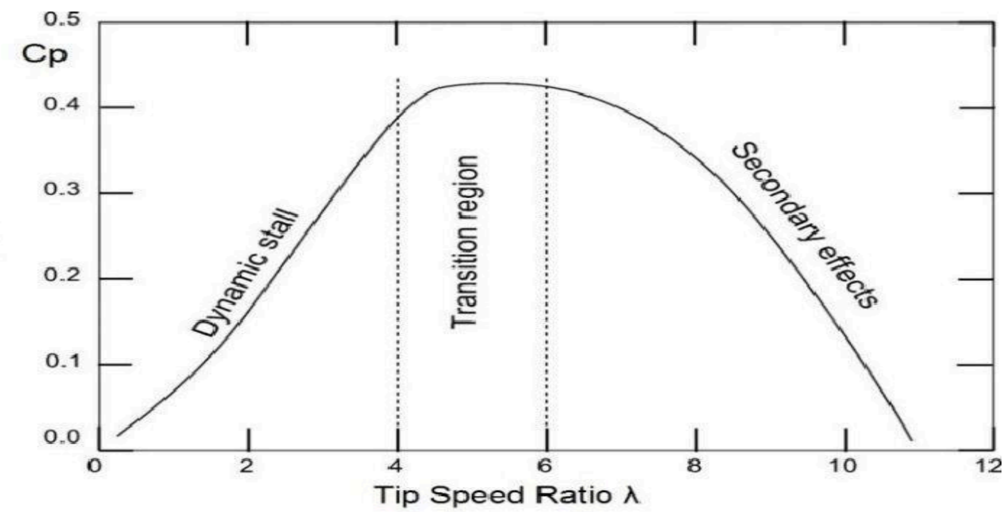


Figure 1-21: Darrieus turbine power coefficient curve.

CHAPTER TWO

THEORETICAL MODELLING

Chapter Two

theoretical modeling

2.1 SAVONIOUS TURBINE:

2.1.1 Overlap Relation:

The overlap relation is a dimensionless parameter that relates the perpendicular distance between the cross and the center of rotation with the chord line length which is given by:

$$\textbf{Overlap Relation = Rs = e/d} \quad \frac{\omega .\ r}{V}$$

2.1.2 Aspect Ratio:

The aspect ratio is a dimensionless parameter which involves the height of the rotor H and the diameter of the circle that is formed when rotating the tips of the blades called diameter of the rotor dr. The equation that relates the height of the rotor H with the diameter of the rotor dr, is given by:

$$\textbf{Rotor Aspect Ratio=}\ \alpha\ \alpha\ \textbf{= H/L}$$

2.1.3 Swept Area:

The swept area of a rotor is generally defined as the projected area that is formed during the rotation of the blades. In the case of a Savonius-type rotor, the projected area corresponds to the area of a rectangle. Thus, the calculation of the swept area by the Savonius rotor will be given by:

$$\mathbf{A = H*D}$$

2.1.4 Torque and Mechanical Power:

The mechanical power for Savonius rotor is equal to the product of mechanical torque on the rotating shaft and rotational speed. Thus, the calculation of the mechanical power by the Savonius rotor will be given by:

$$F = (m-s) * g$$

$$T = F*r$$

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

$$P = T* w$$

where T is the mechanical torque (Nm), ω is the angular speed (rad/s), Pm is mechanical power (W), n is the shaft rotational speed (rpm), r is the pulley radius (m), F is The force acting on the rotor shaft (N), m is the mass loaded on the pan (kg), s is the spring balance reading in kg and g is the gravitational acceleration.

2.1.5 Wind Torque, Force and power:

$$Tw = 1/2*density * A * D * v^2$$

$$Fw = Cw (1/2* \rho * A * v^2)$$

Where Cw is the drag coefficient value, “drag coefficient” Cw is an indication of the aerodynamic qualities of an object.

$$Pw = 1/2* \rho * A * U^3 * D/2$$

2.1.6 Torque and power coefficients:

$$Ct = T/Tw = T / (1/2*density * A * D * v^2)$$

$$Cp = P/Pw = T*\omega / (1/2*density * A * D * v^2)$$

2.1.7 Tip Speed Ratio:

$$TSR: \lambda = Vtb / U = Vrotor / 60\ Vwind = \omega .\ R / 60\ Vwind$$

ω=angular velocity, R represents radius revolving part of the turbine, U = Undisturbed wind speed.

Maximum tip speed ratio that Savonius can reach is 1.

2.1.8 Relation Between TSR and Coefficients of Power and Torque:

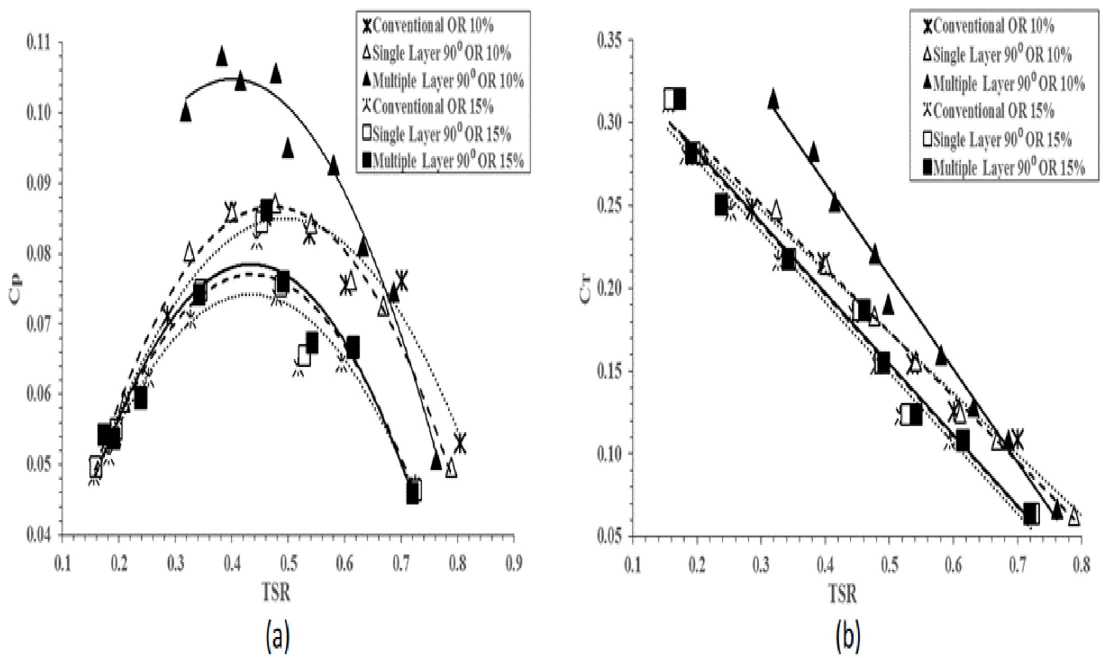


Figure: 2-1 (a) Cp of all rotor configuration with TSR variation on V = 7.27 m/s, (b) CT of all rotor configuration with TSR variation on V = 7.27 m/s.

2.1.9 Relation Between Actual Power and Wind Speed:

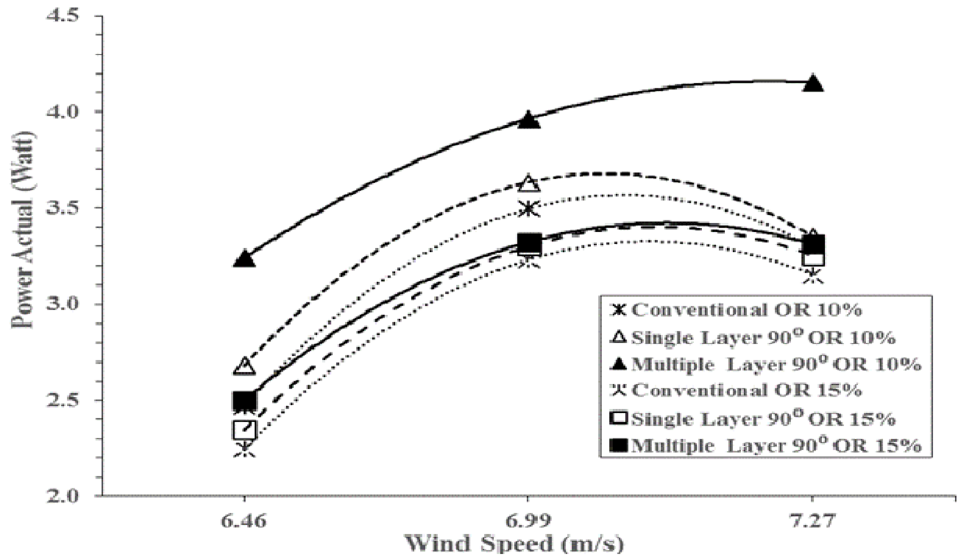


Figure 2-2: Turbine actual power on various wind speed for basic and modified Savonius turbine configuration.

2.2 DARRIEUS TURBINE:

2.2.1 Swept Area:

$$A = H*D$$

2.2.2 Torque and Mechanical Power:

$$F = (m-s) * g$$

$$T = F*r$$

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

$$P = T* w$$

2.2.3 Pressure coefficient:

$$Pc = p - p\infty / (1/2 * \rho * V\infty)$$

2.2.4 Wind Torque, Force and power:

$$Tw = 1/2*density * A * D * v^2$$

$$Fw = Cw (1/2* \rho * A * v^2)$$

Where Cw is the drag coefficient value, "drag coefficient" Cw is an indication of the aerodynamic qualities of an object.

$$Pw = 1/2* \rho * A * V\infty^3 * D/2$$

2.2.5 Moment, Torque and power coefficients:

$$Cm = T/ (1/2 * \rho * V\infty^2 *A * R)$$

$$Ct = T/Tw = T / (1/2*density * A * D * v^2)$$

$$Cp = P/Pw = T*\omega / (1/2*density * A * D * v^2)$$

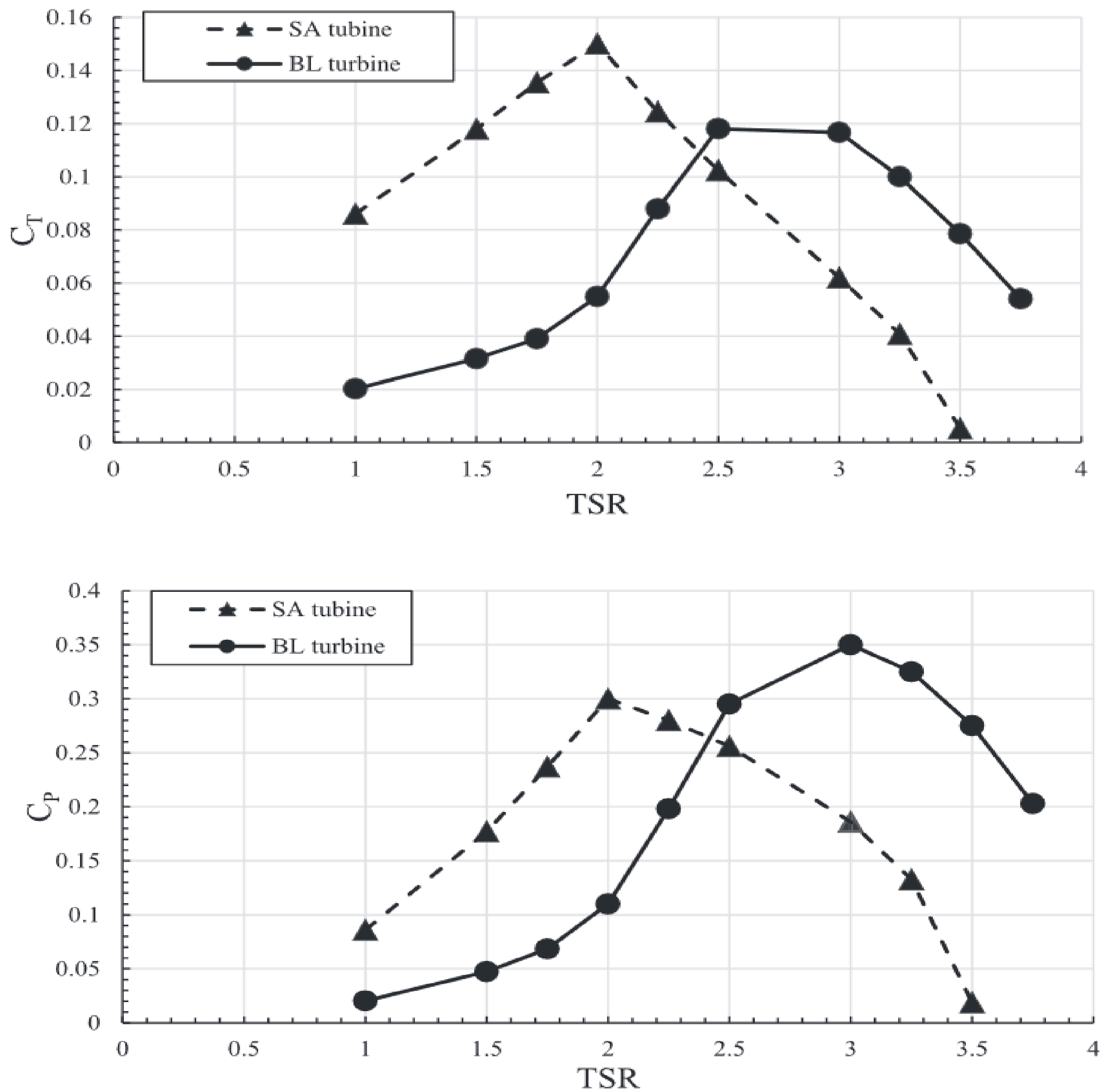
2.2.6 Tip Speed Ratio (TSR):

$$\lambda = \omega * R / V\infty$$

2.2.7 Angle OF Attack (AoA):

$$AOA = tan^{-1}(sin\theta/(\lambda + cos\theta)$$

2.3.8 Relation Between TSR and Coefficients of Power and Torque:



Figures 2-3: Relation Between TSR and Coefficients of Power and Torque.

CHAPTER THREE

EXPERIMENTAL METHOD

Chapter three

EXPERIMENTAL METHOD

3. Savonious Turbine:

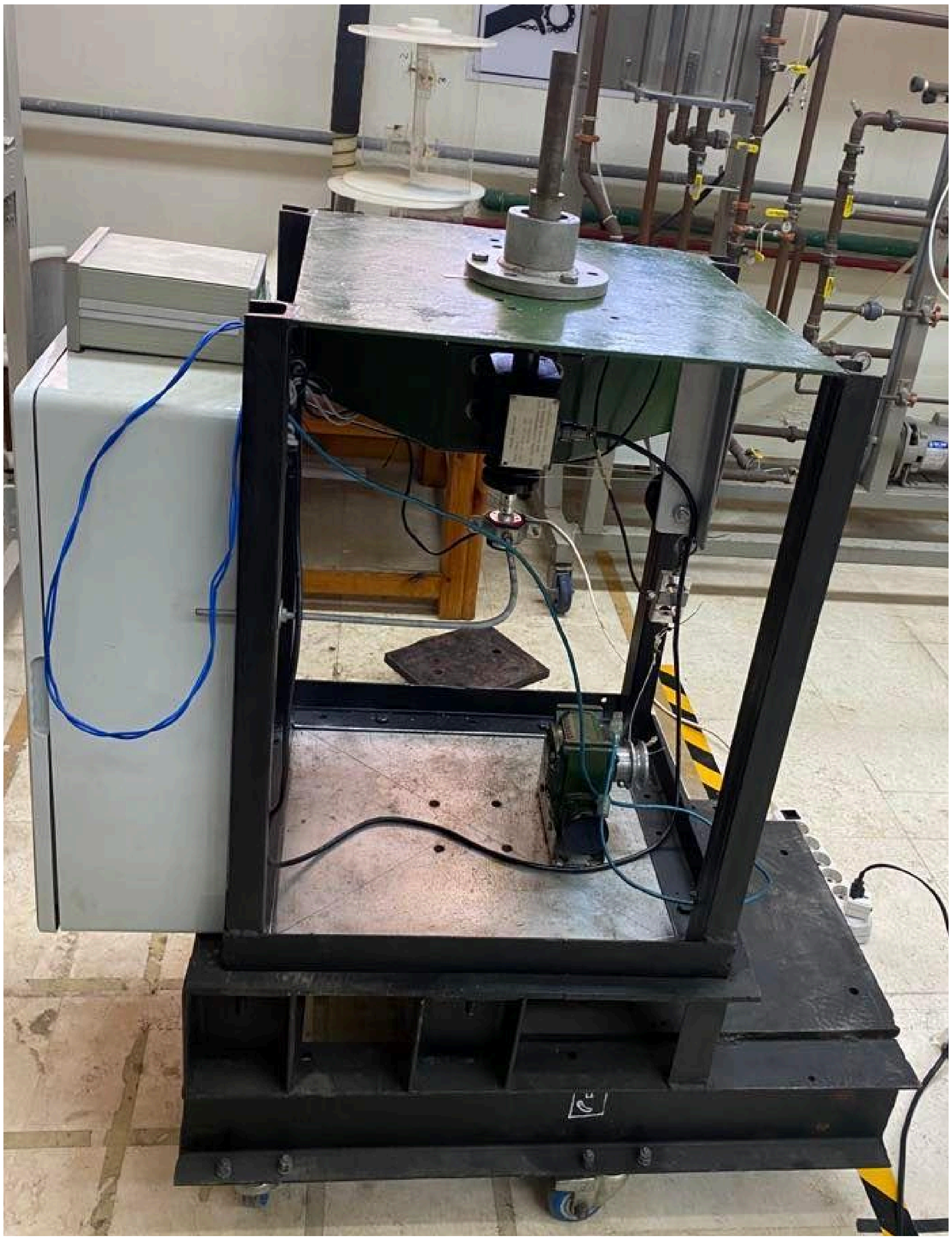


Figure 3-1: Savinous turbine

Figure 3-2: Savinous turbine with traditional blade

Figure 3-3: control board of Savinous turbine

3.1 Savonious Turbine Components:

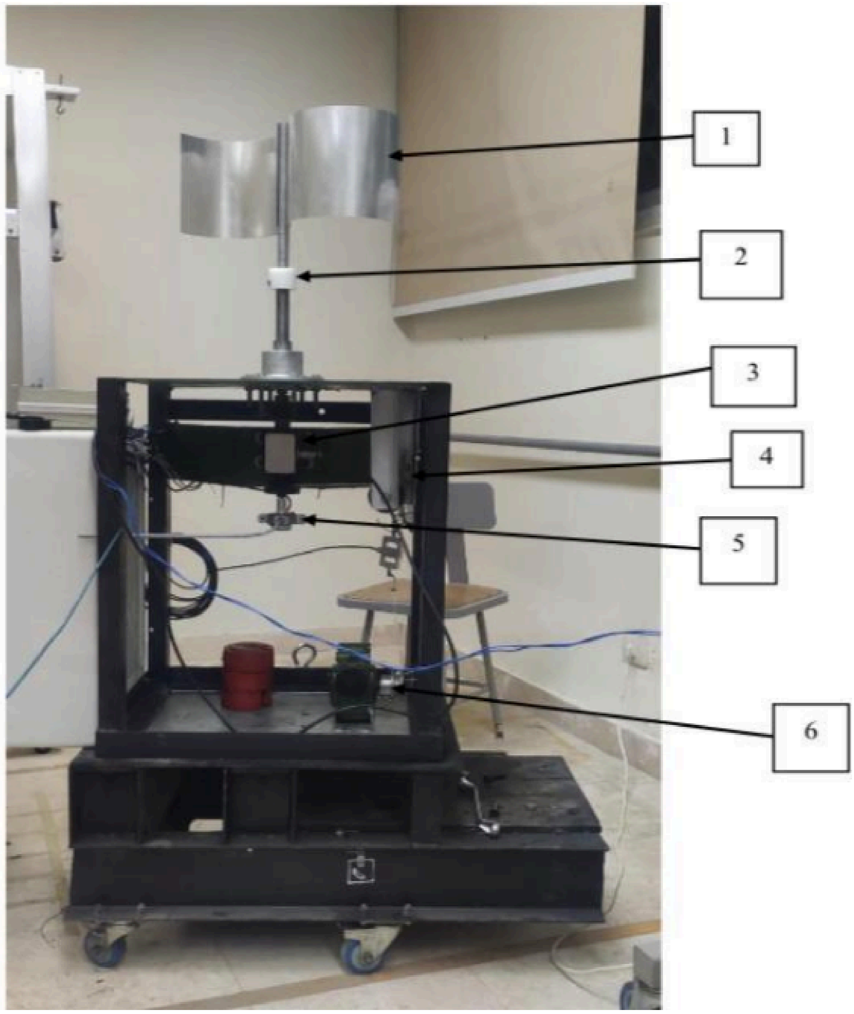


Figure 3-4:savinous turbine components

1- Blades

2- Artylon Coupling

3- Dynamic torque sensor

4- Load cell

5- Speed Sensor

6- Worm gear configuration

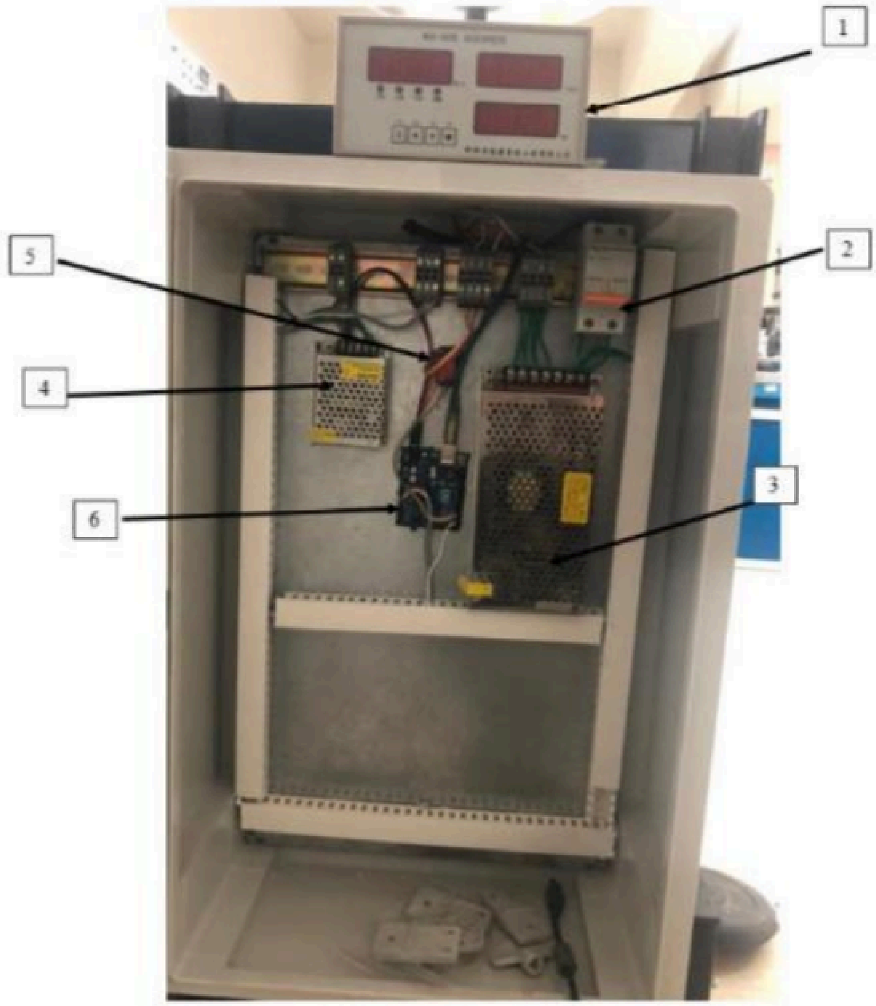


Figure 3-5: Components of control box of Savinous turbine

1- Display set of torque sensor

2- Circuit breaker

3- 24V power supply

4- Amplifier

5- 12V power supply

6- Arduino board

3.2 Savonious Turbine Blade Types:

A) Traditional Blade

Figure 3-6: traditional Savinous blade

B) One Gate Blade

Figure 3-7: one gate Savinous blade

C) Two Gates Blade

Figure 3-8: two gate Savinous blade

C) Four Gates Blade

Figure 3-9: four gate Savinous blade

D) Modified Artylon Blade

3-10 Figure 3-10: modified Artylon Savinous blade

3.3 Experiment 1:

Measuring Static torque, RPM, Power produced by Savonius rotor for different angular position at various wind speed:

Experiment was carried out to evaluate the static torque, RPM, power produced by traditional and modified Savonius blades for different angular position at every 30° Of the rotor angle at various value of wind speed.

Test Procedure:

1- Adjust the rotor blades to be at the specified position 0,30,60,90,120,150 and 180.

2- Rotate the worm to increase the forces F1 and F2and then loading the rotor of the turbine, loading the break drum measuring system until the force f4 reach a value about 5 Kg.

3- Start the wind tunnel and adjust the speed of the fan to obtain the required value of the air velocity at downstream from the wind tunnel exit section.

4- Use the pitot static tube which attached to the inclined manometer to measure the velocity of the free air stream up stream of the rotor position.

5- Make a fine turning for the fan speed to get the desired value of the free air velocity.

6- Release the loading of the brake down system by ready the worm gradually in the c.c.w direction till the rotor start to move.

7- Make a fine turning for the motion of the worm to obtain the condition for static torque.

8- Record the value of F1 (load cell) and F2 (weight balance).

9- Determine the value of static torque using the relation (4) as:

$$Ts = (F1 - F2)*g*(Dpulley-Dwire)/2*(1/1000)$$

10- Determine the value of rpm of rotor

11- Calculate the power by multiplying torque by RPM

Repeat the experiment from different angular position at various wind speeds. Coefficient of static torque is obtained is for rotor angles ranging from 0 to 360 in step of 30.

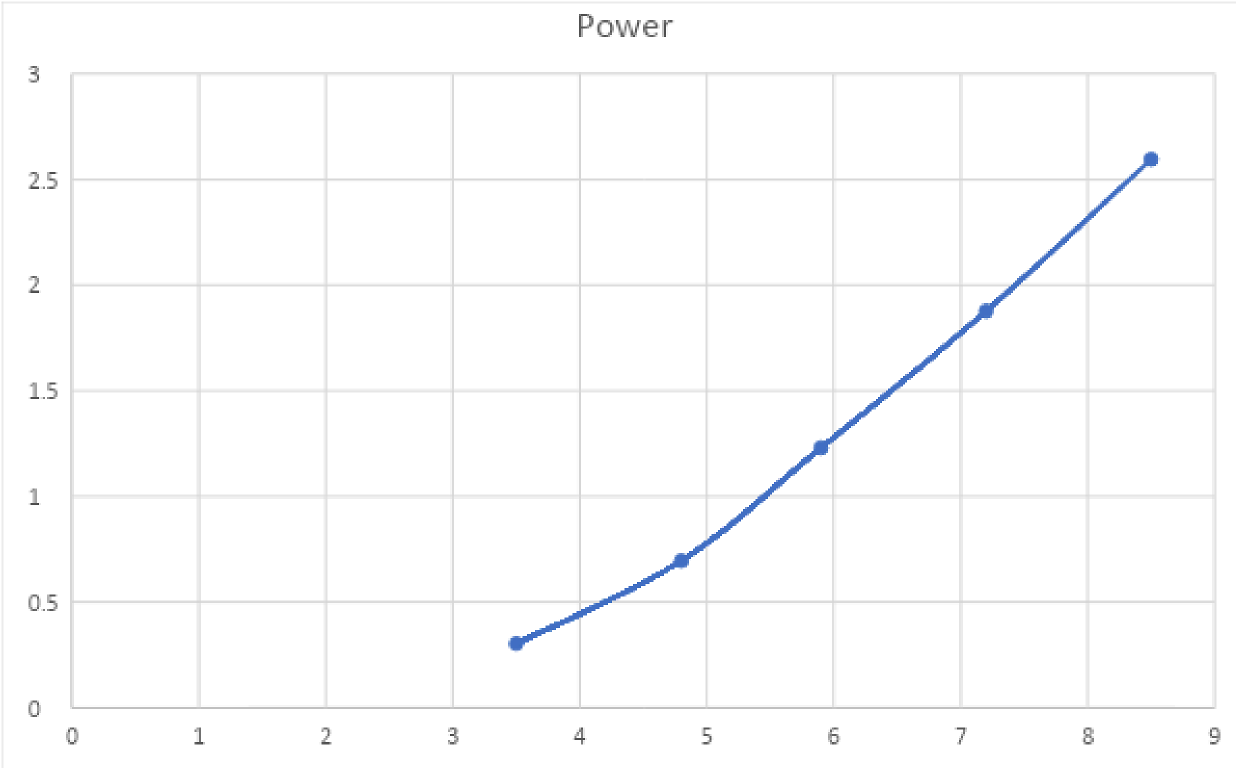
3.4 Experiment 1 Results and Discussion:

3.4.1 Traditional Design Results:

A) Power:

Tunnel RPM	**Air velocity (m/s)**	T (N.m)	W (rpm)	W (rad/s)	Power (w)
1500	3.5	0.0753	38.5	4.031	0.303
1800	4.8	0.1023	65	6.806	0.696
2100	5.9	0.13506	87	9.11	1.23
2400	7.2	0.17351	103.5	10.838	1.877
2700	8.5	0.1927	121	11.517	2.219

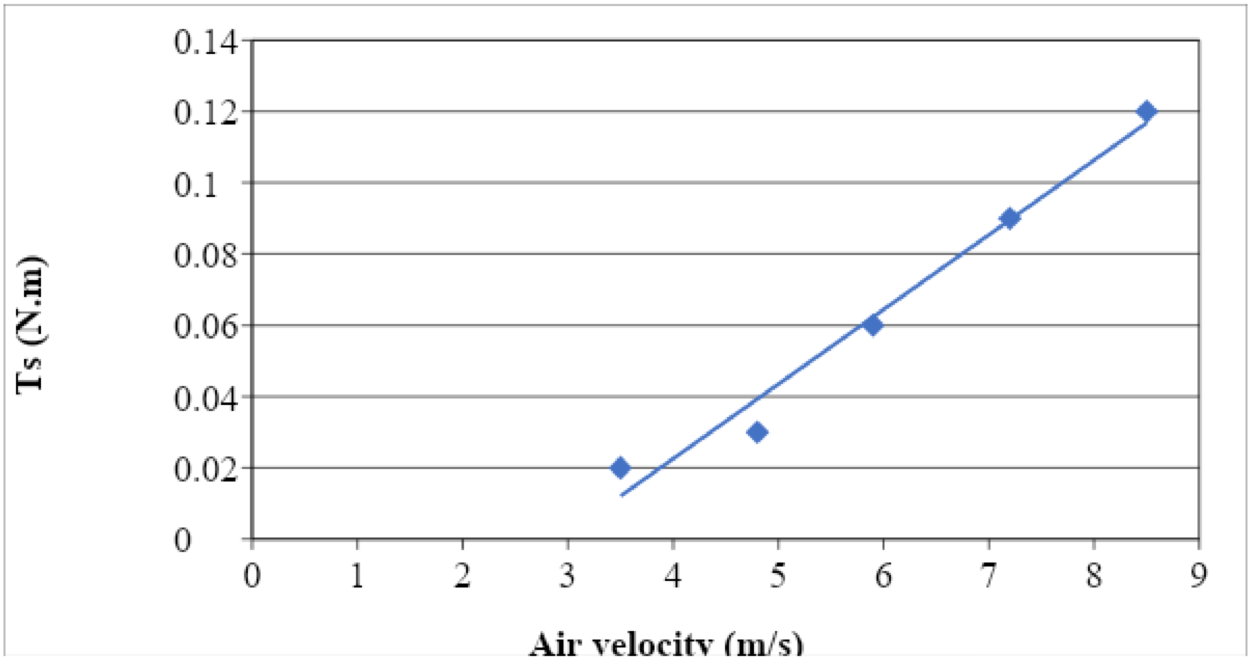
Table 1: air velocity and power of Traditional Design blade



B) Static Torque:

Air velocity (m/s)	Ts (N.m)
3.5	0.02
4.8	0.03
5.9	0.04
7.2	0.06
8.5	0.08

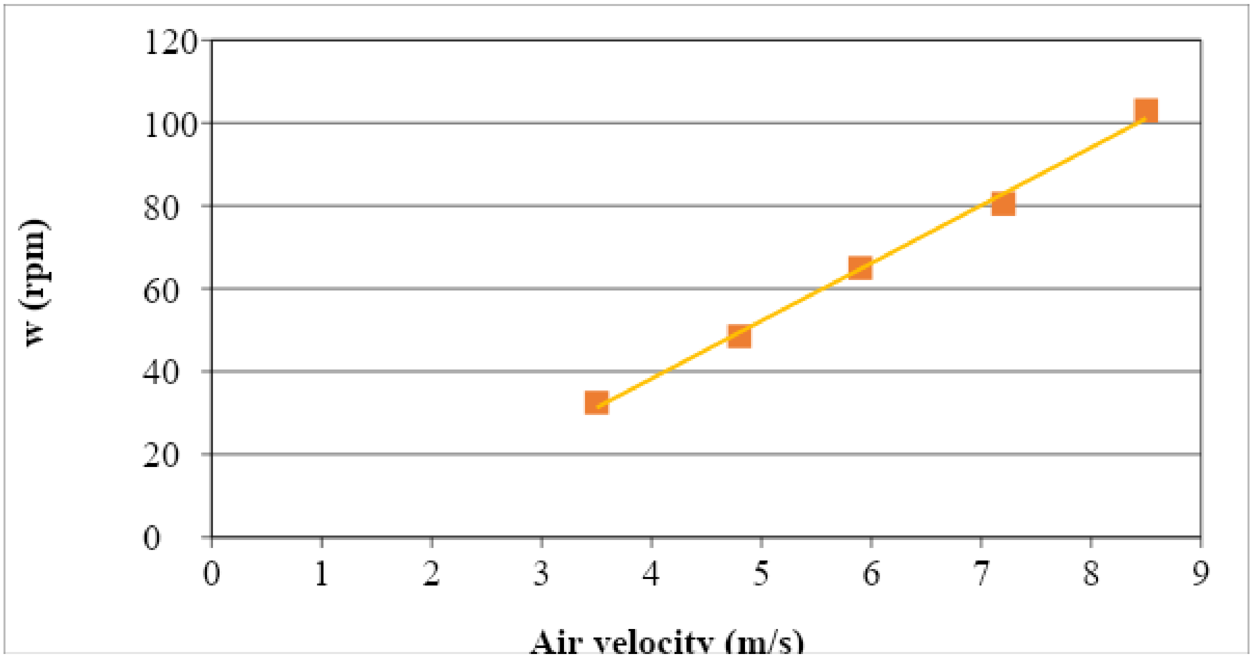
Table-2: air velocity and static torque of Traditional Design blade.



C) Zero Torque:

Air velocity (m/s)	W (rpm)
3.5	32.5
4.8	48.5
5.9	65
7.2	80.5
8.5	103

Table-3: air velocity and turbine RPM of Traditional Design blade

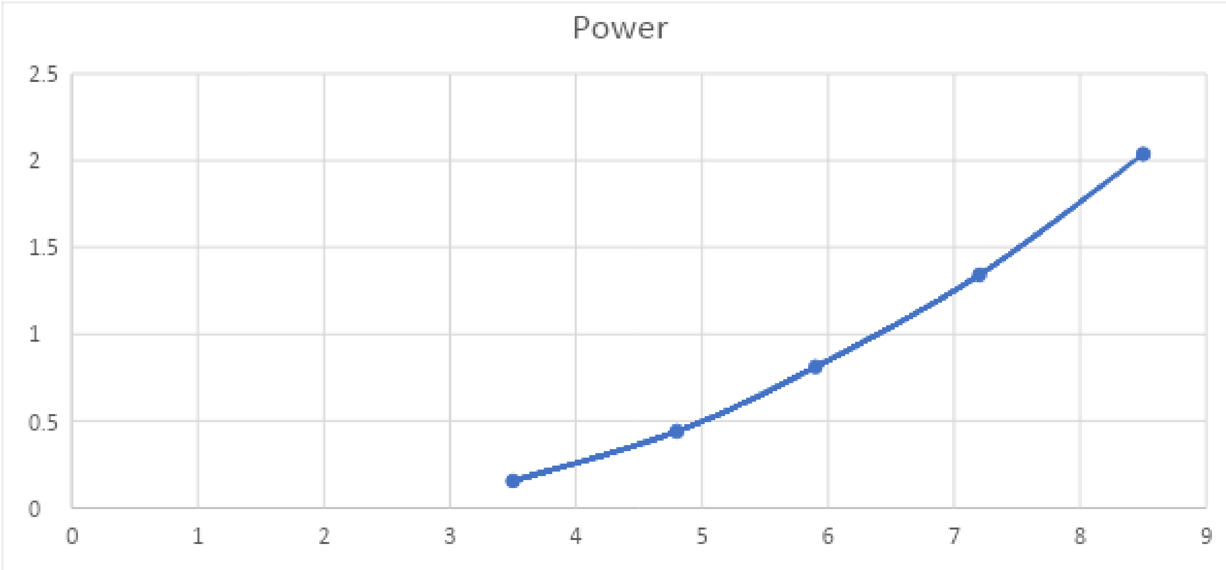


3.4.2 One gate Design Results:

A) Power:

Tunnel RPM	Air velocity (m/s)	T (N.m)	W (rpm)	W (rad/s)	Power (w)
1500	3.5	0.004566	32.5	3.403	0.0155
1800	4.8	0.008241	51	5.348	0.044
2100	5.9	0.011314	68.5	7.173	0.0811
2400	7.2	0.014819	86.5	9.058	0.1342
2700	8.5	0.017932	108.5	11.362	0.2037

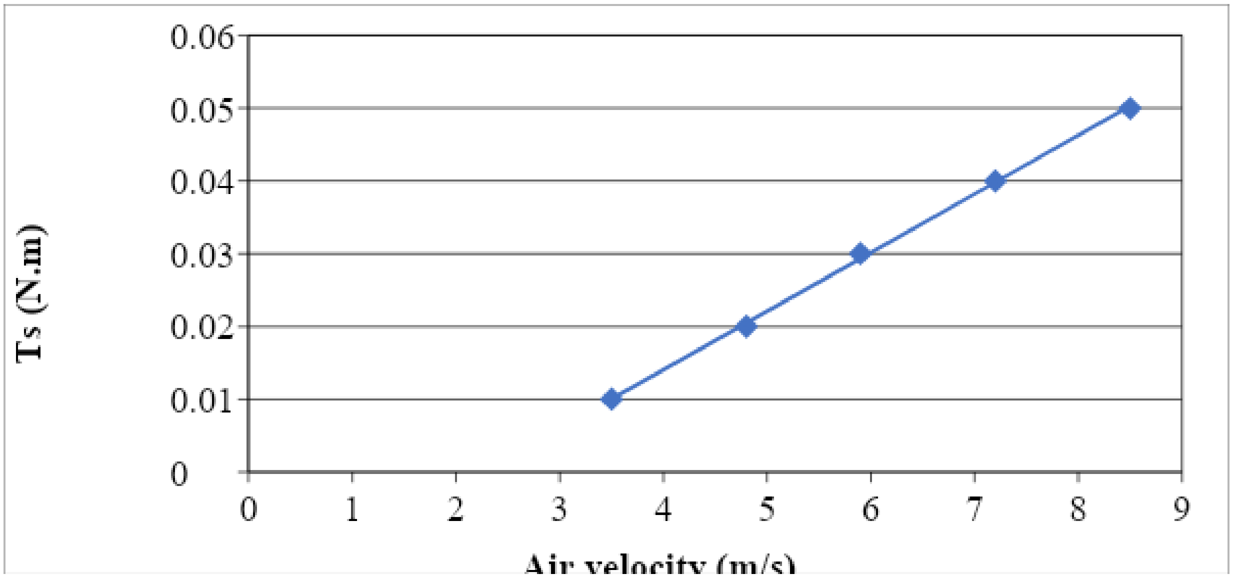
Table 4: air velocity and power of one gate Design blade



B) Static Torque:

Air velocity (m/s)	Ts (N.m)
3.5	0.01
4.8	0.02
5.9	0.03
7.2	0.04
8.5	0.05

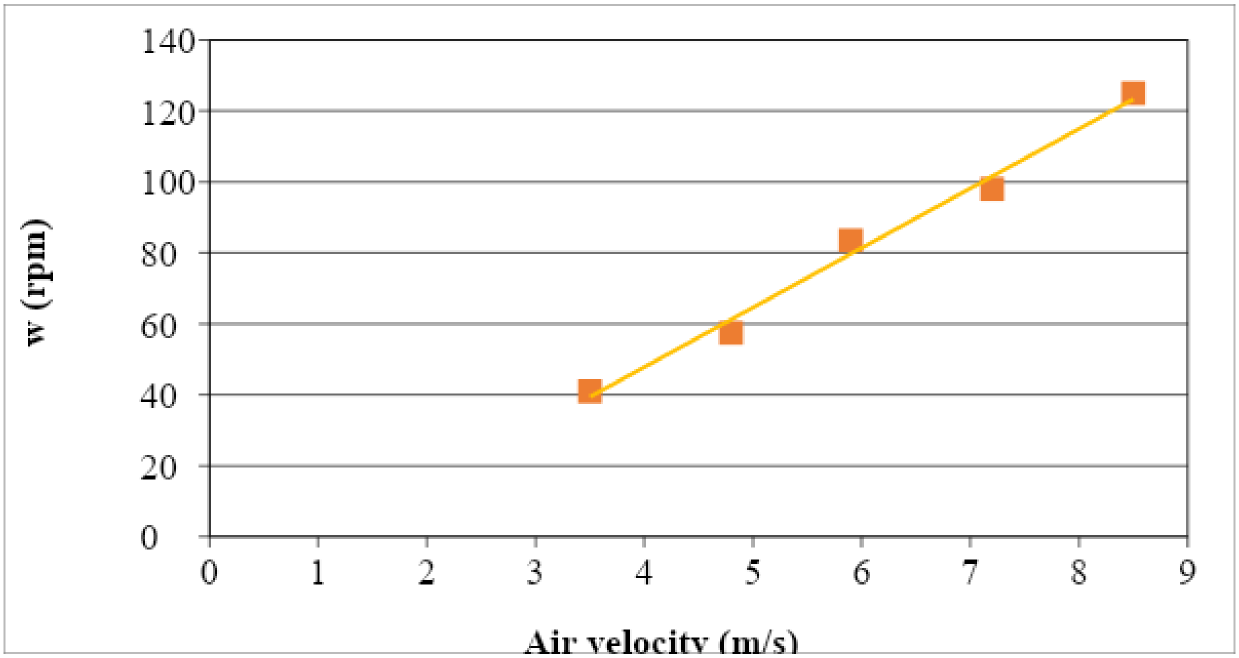
Table 5: air velocity and static torque of one gate Design blade



C) Zero Torque:

Air velocity (m/s)	W (rpm)
3.5	33.5
4.8	47.5
5.9	72
7.2	94
8.5	116.5

Table 6: air velocity and turbine RPM of one gate Design blade

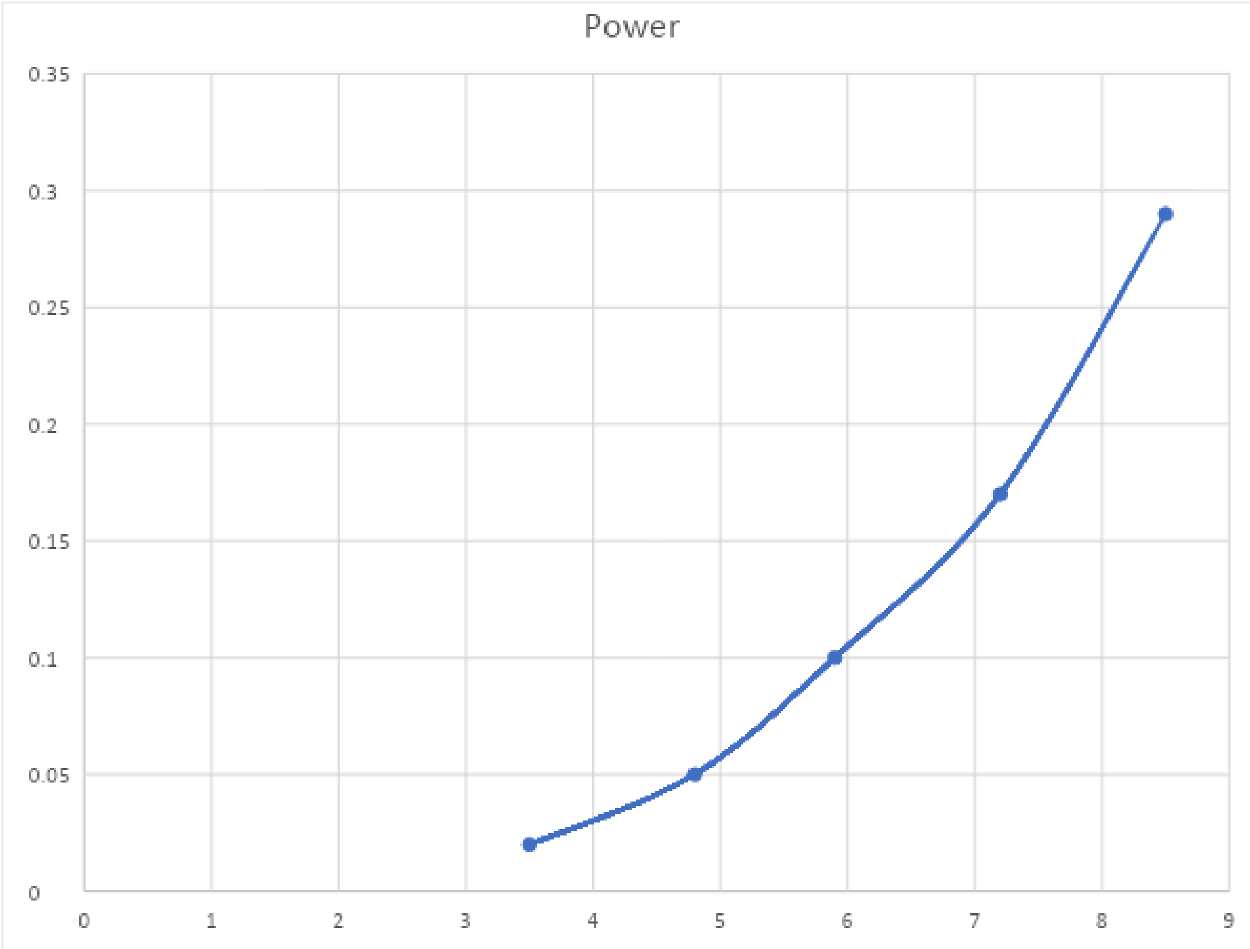


<u>**3.4.3** Two gate Design Results:</u>

A) Power:

Tunnel RPM	**Air velocity (m/s)**	T (N.m)	W (rpm)	W (rad/s)	Power (w)
1500	3.5	0.006113	36.5	3.822	0.02
1800	4.8	0.00971	52	5.445	0.05
2100	5.9	0.01365	74.5	7.801	0.1
2400	7.2	0.01827	93	9.738	0.17
2700	8.5	0.02392	117.5	12.304	0.29

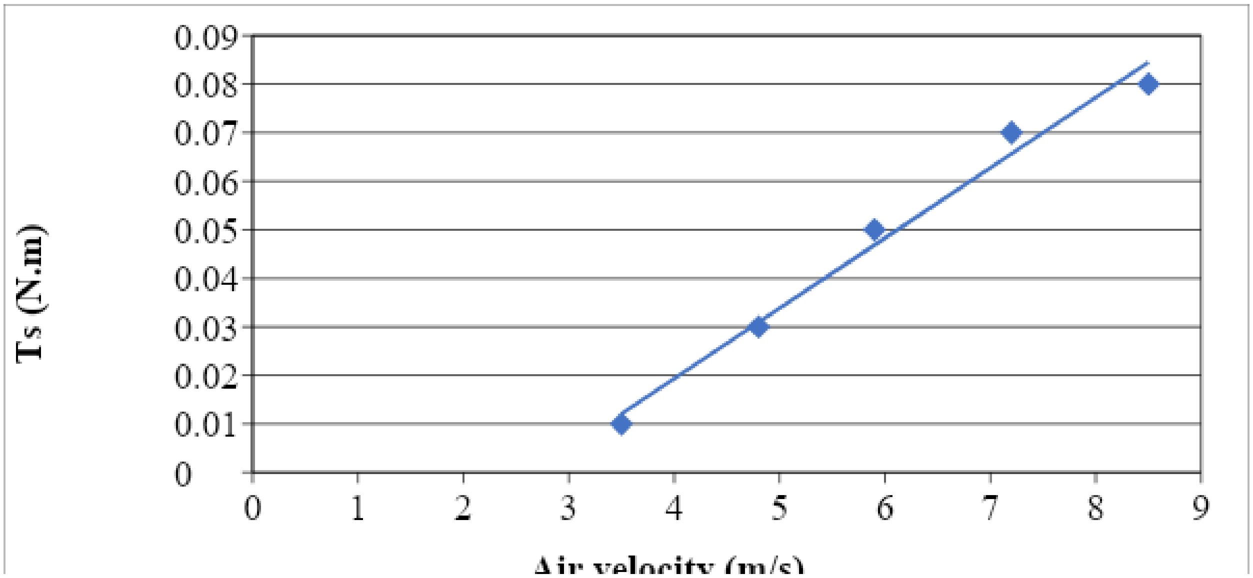
Table 7: air velocity and power of two gate Design blade



B) Static Torque:

Air velocity (m/s)	Ts (N.m)
3.5	0.01
4.8	0.03
5.9	0.05
7.2	0.07
8.5	0.08

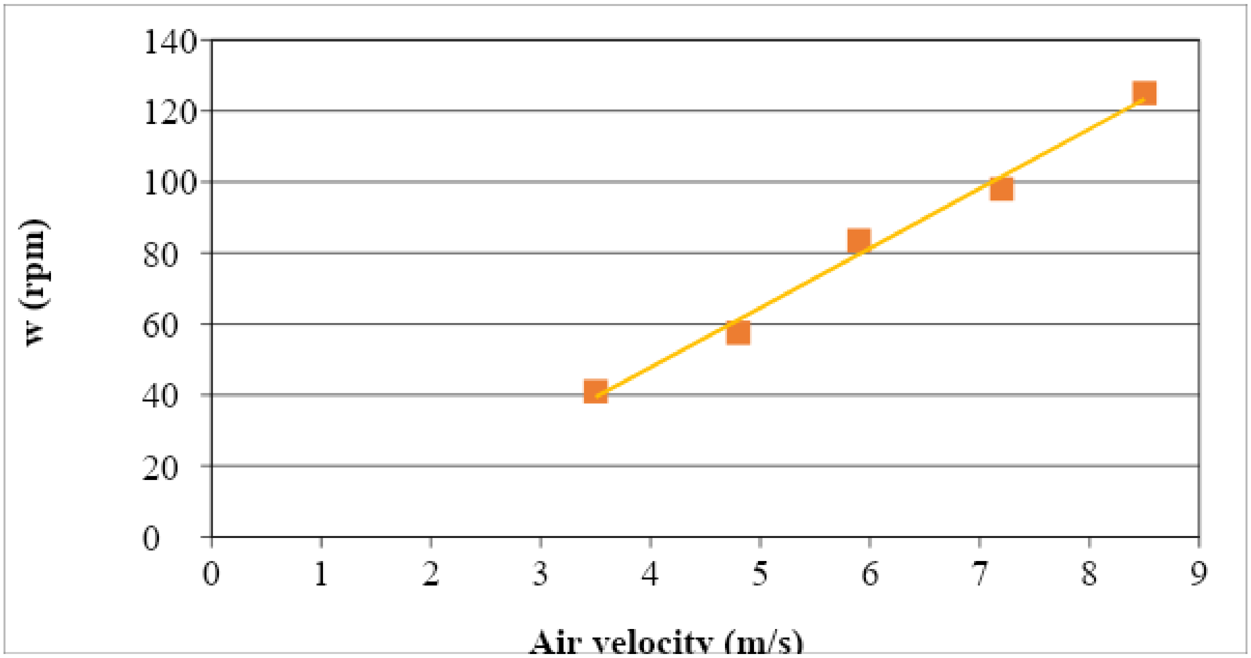
Table 8: air velocity and static torque of two gate Design blade



C) Zero Torque:

Air velocity (m/s)	**W (rpm)**
3.5	41
4.8	57.5
5.9	83.5
7.2	98
8.5	125

Table 9: air velocity and turbine RPM of two gate Design blade

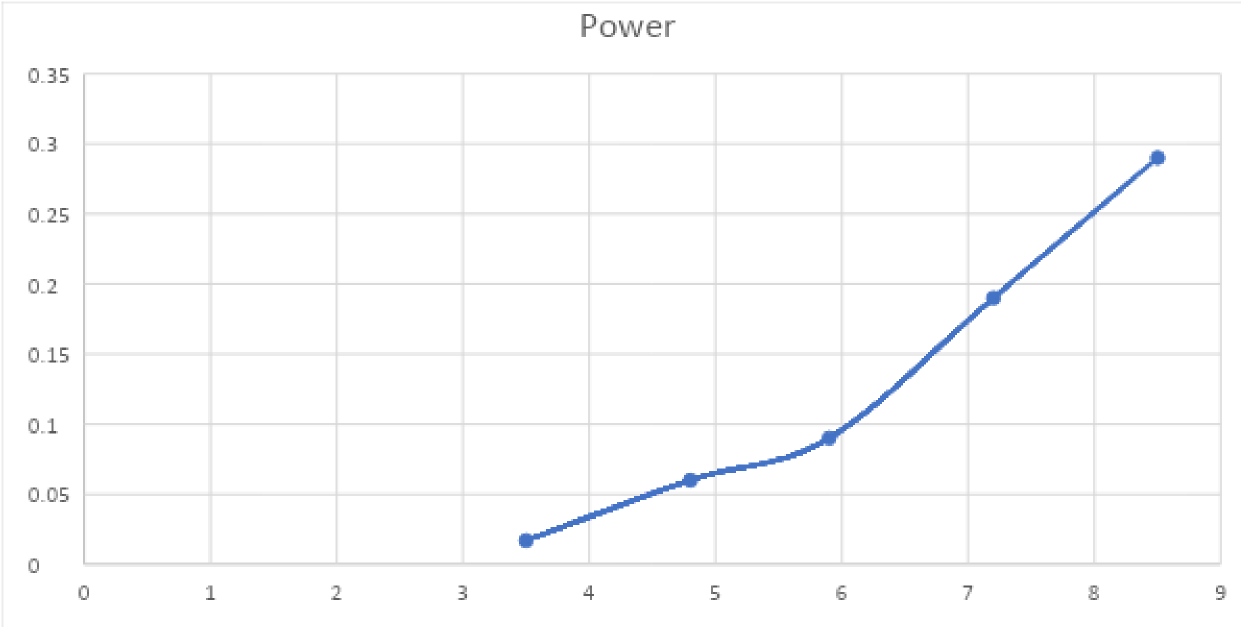


3.4.4 Four gate Design Results:

A) Power:

Tunnel RPM	**Air velocity (m/s)**	T (N.m)	W (rpm)	W (rad/s)	Power (w)
1500	3.5	0.004566	41	4.2935	0.017
1800	4.8	0.008241	61.5	6.44	0.06
2100	5.9	0.011314	87.5	9.1629	0.09
2400	7.2	0.014819	101.5	10.629	0.19
2700	8.5	0.017932	125	13.0899	0.29

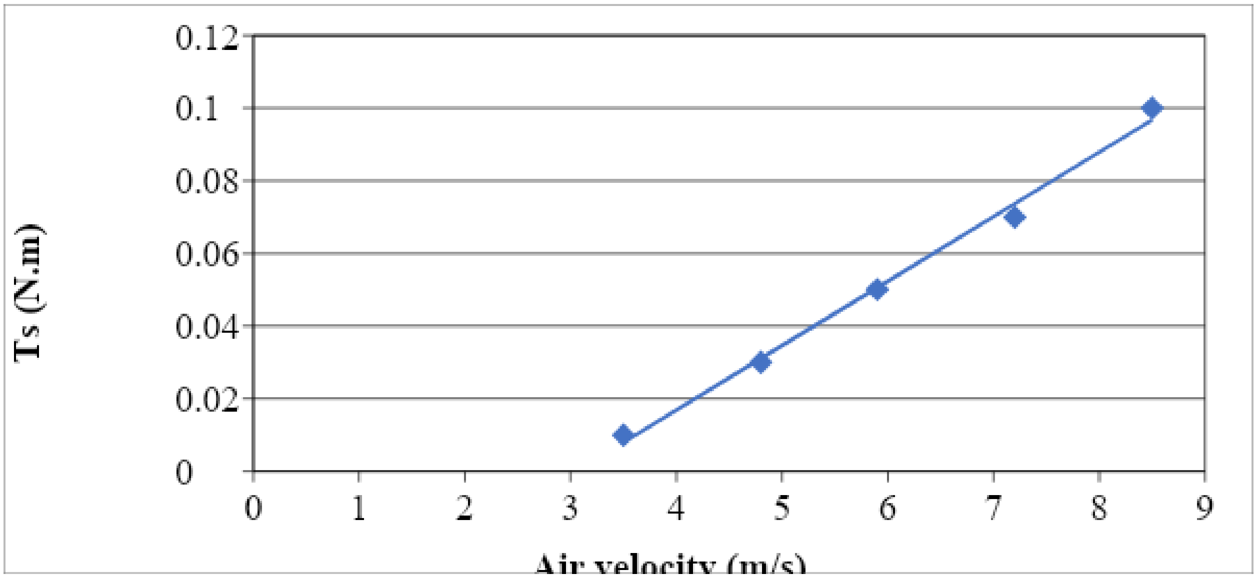
Table 10: air velocity and power of four gate Design blade



B) Static Torque:

Air velocity (m/s)	Ts (N.m)
3.5	0.01
4.8	0.03
5.9	0.05
7.2	0.07
8.5	0.1

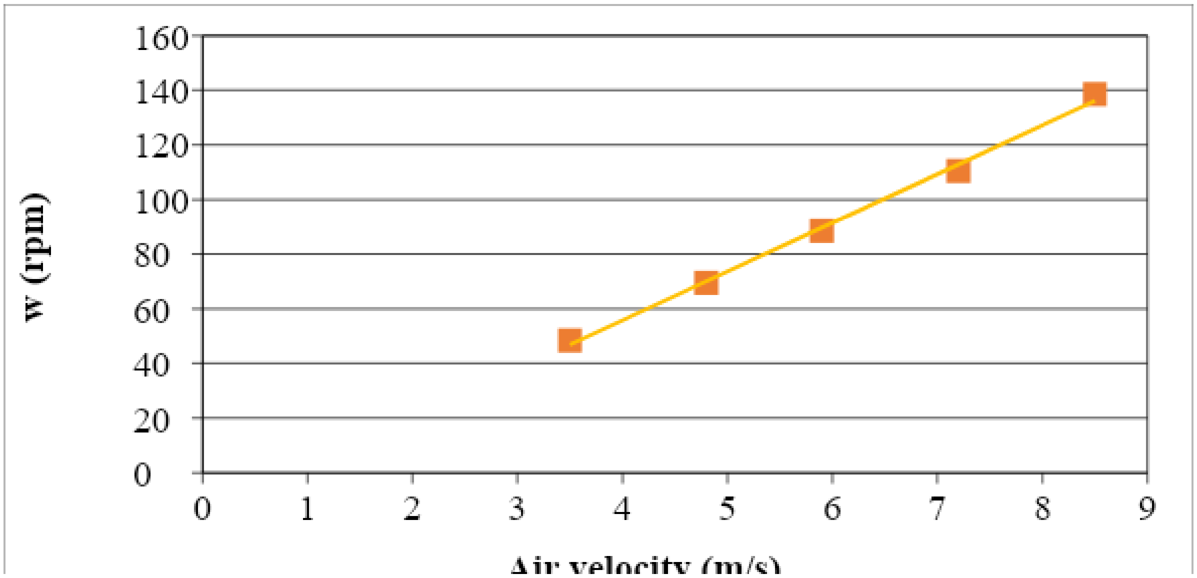
Table 11: air velocity and static torque of four gate Design blade



C) Zero Torque:

Air velocity (m/s)	W (rpm)
3.5	48.5
4.8	69.5
5.9	88.5
7.2	110.5
8.5	138.5

Table 12: air velocity and turbine RPM of four gate Design blade

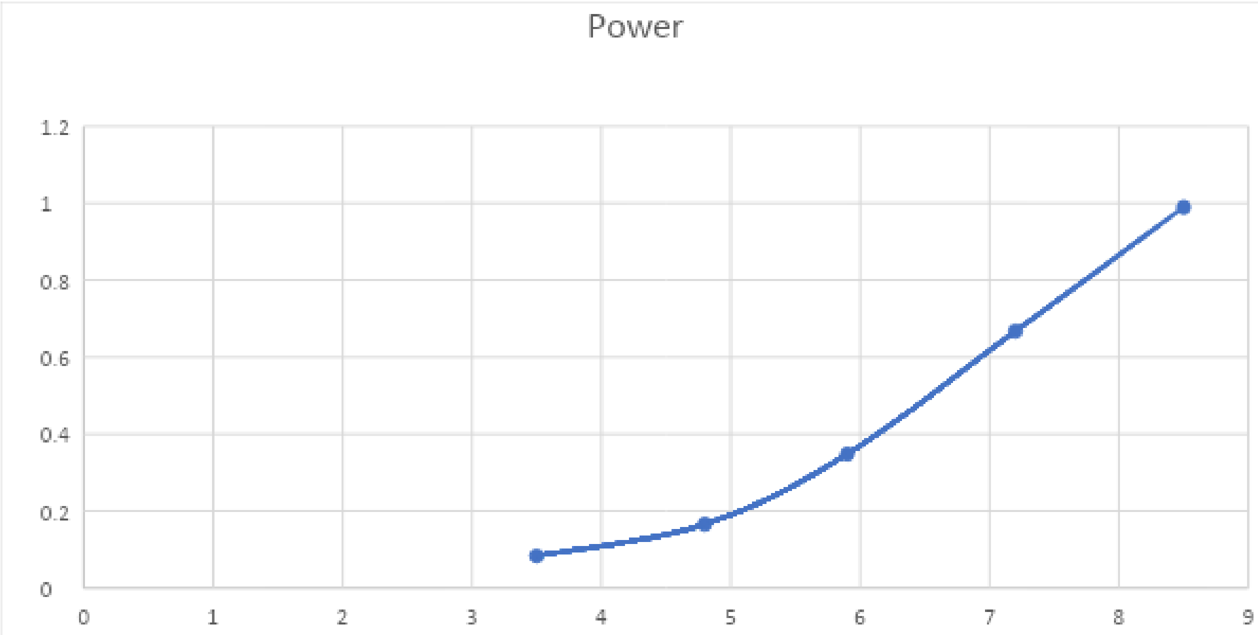


<u>**3.4.5** Modified Artylon Design Results:</u>

A) power:

Tunnel RPM	**Air velocity (m/s)**	T (N.m)	W (rpm)	W (rad/s)	Power (w)
1500	3.5	0.02388	33.5	3.506	0.0837
1800	4.8	0.03268	48.5	5.078	0.1659
2100	5.9	0.04927	67	7.016	0.3482
2400	7.2	0.06969	91.5	9.581	0.6676
2700	8.5	0.08112	116.5	12.199	0.9895

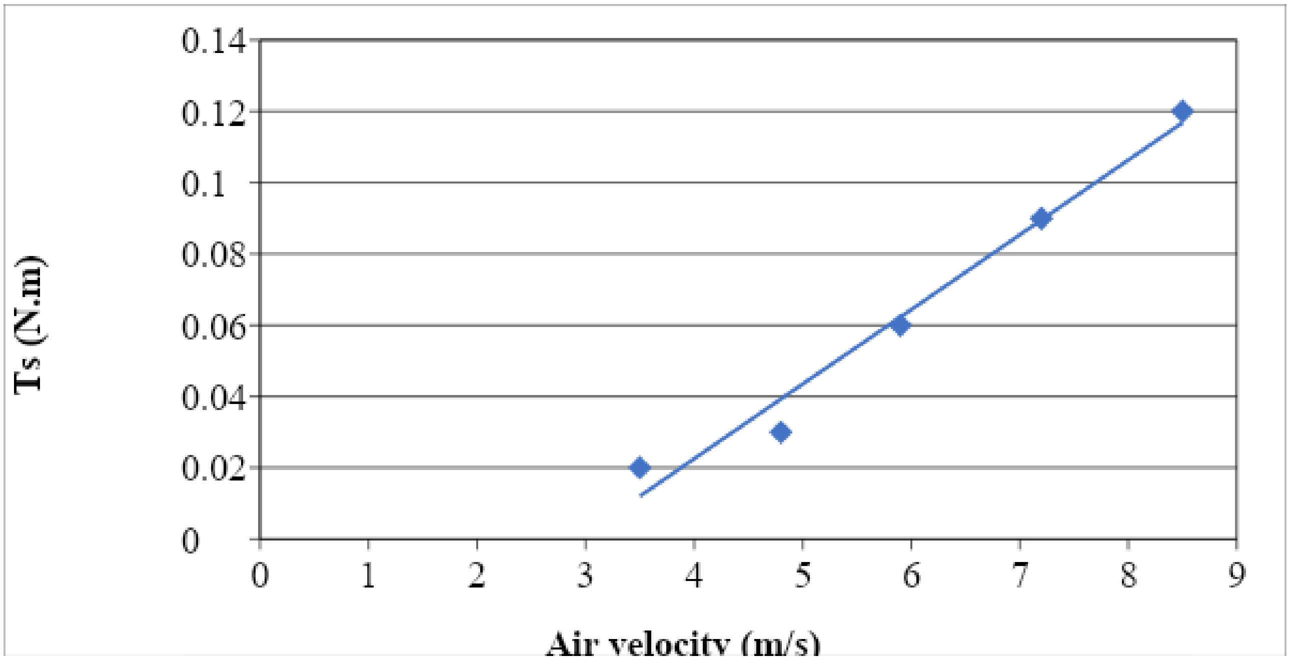
Table 13: air velocity and power of Modified Artylon Design blade



B) Static Torque:

Air velocity (m/s)	Ts (N.m)
3.5	0.02
4.8	0.03
5.9	0.08
7.2	0.09
8.5	0.12

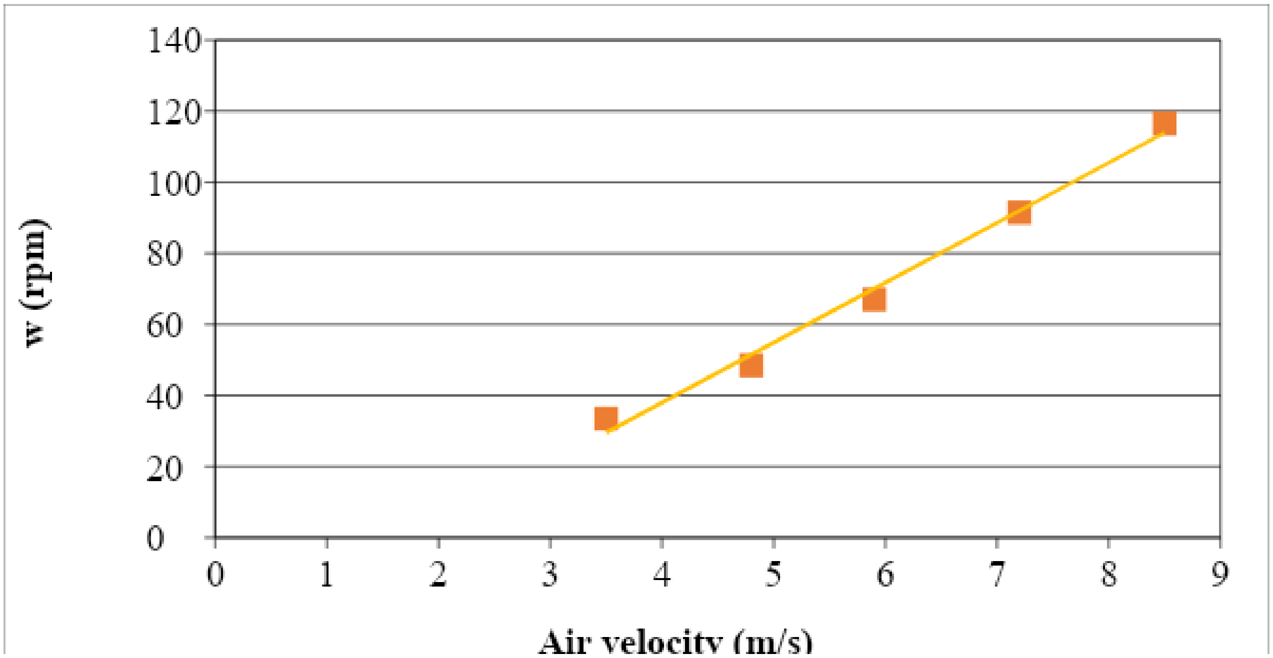
Table 14: air velocity and static torque of Modified Artylon Design blade



C) Zero Torque:

Air velocity (m/s)	W (rpm)
3.5	33.5
4.8	48.5
5.9	67
7.2	91.5
8.5	116.5

Table 15: air velocity and turbine RPM of Modified Artylon Design blade



3.5 Darrieus Turbine:

Figure 4-1: Darrieus turbine in the wind tunnel

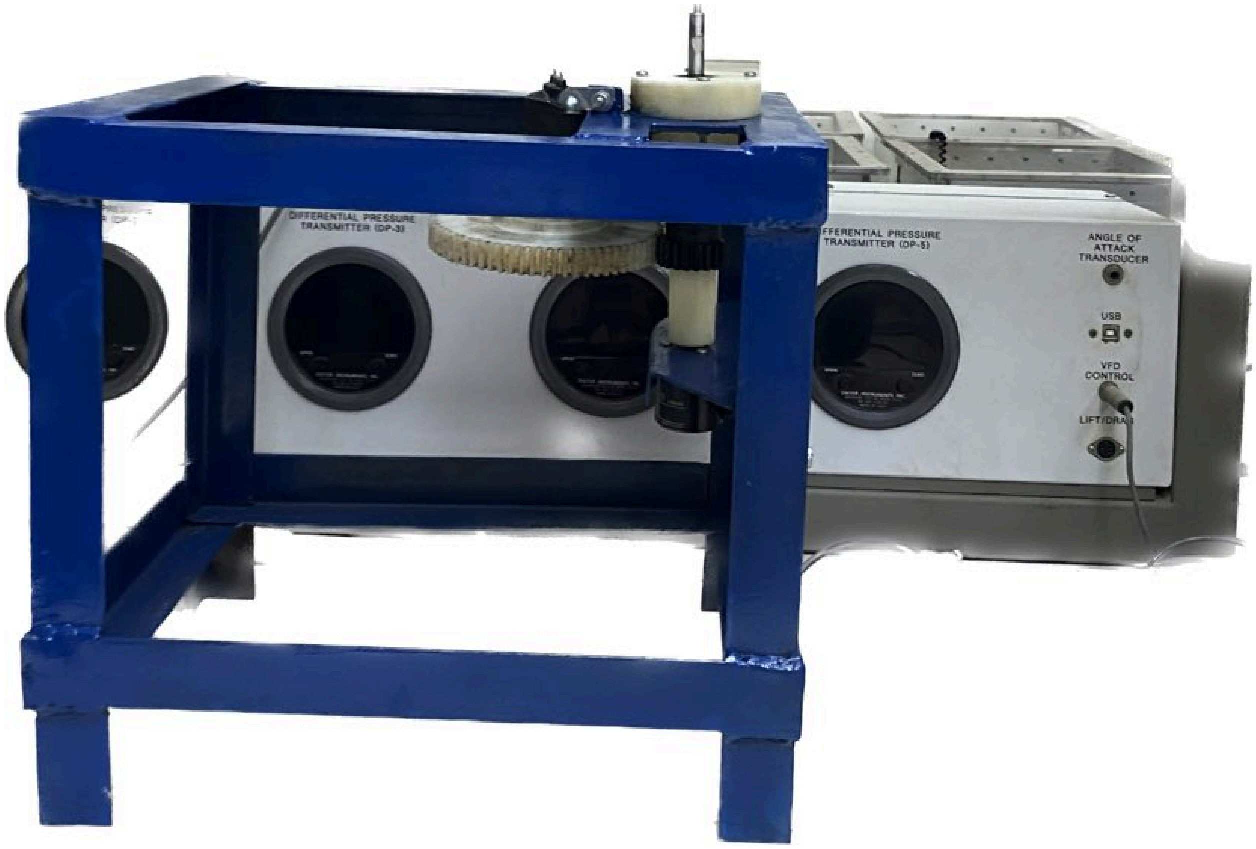


Figure 4-2: Darrieus turbine base

3.5.1 Darrieus turbine components:

A) 3 blades (L=20 W=1.33 cm at 120 degree)

B) 50 cm shaft

C) Two gears

D) Encoder

E) Dynmo 6V

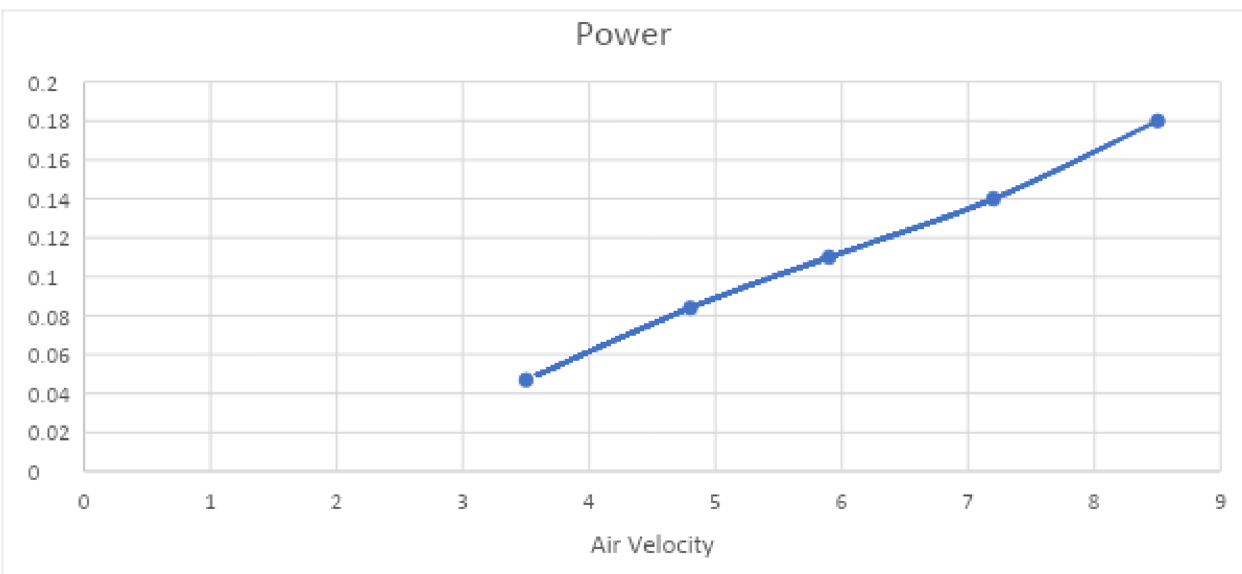
3.5.2 Experiment 2:

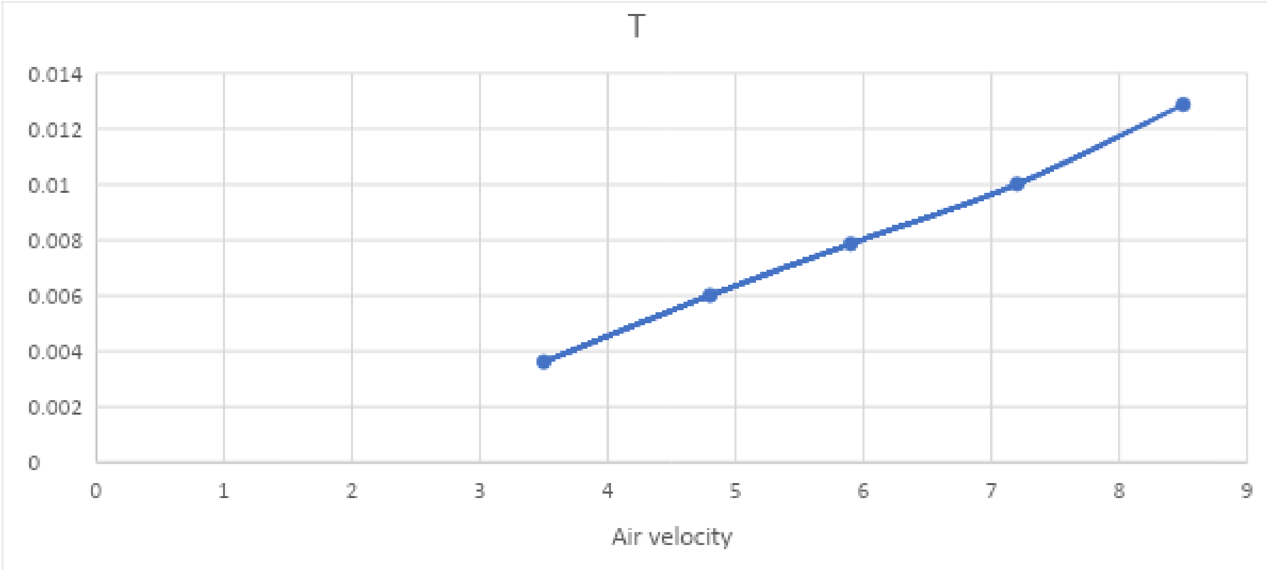
Measuring RPM and torque using measuring software in order to calculate the power generated. then measuring RPM using Tachometer (GM8905) and Voltage, Current from the dynamo using Avometer (15XP-A) at different wind speeds in order to check the results.

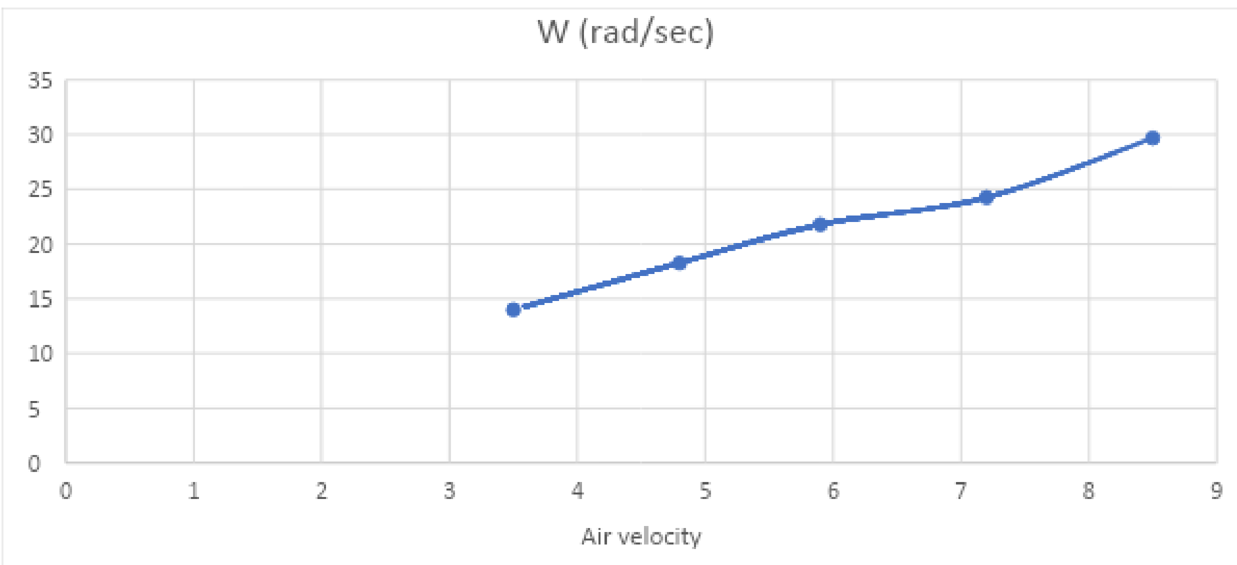
3.5.3 Experiment 2 Results and Discussion:

Tunnel RPM	Air velocity	Turbine RPM	W (rad/sec)	T (N.m)	Power (watt)
1500	3.5	133.5	13.98	0.003619	0.047
1800	4.8	174.5	18.2735	0.006008	0.084
2100	5.9	208	21.781	0.007868	0.11
2400	7.2	231.5	24.242	0.010014	0.14
2700	8.5	283.5	29.688	0.012875	0.18

Table 16: air velocity and power of Darrieus turbine




T
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
0 1 2 3 4 5 6 7 8 9
Air velocity


W (rad/sec)
35
30
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9
Air velocity

CHAPTER FOUR

CONCLUSION

4.1 CONCLUSION:

We followed the same experimental procedure in all cases and it can be concluded that the Savinous turbine produces higher power than Darrieus turbine, although the results of the darrieus turbine and some Savinous blades design (one, two, four gates blades) are nearly similar but the modified Artylon blade design and the traditional design blade produces much higher power. Finally it was concluded that the traditional blade design is the best design producing nearly double the power produced by the modified Artylon blade.

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