SIMULATION STUDY ON THE PERFORMANCE OF VERTICAL AXIS WIND TURBINE

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ABSTRACT

Nowadays, people start to think the Drag type of vertical axis wind turbine (VAWT) as a potential and reliable wind machine in the future. It advantageous of simpler and significantly cheap to build and maintain than conventional Horizontal axis wind turbine (HAWT) attract the world attention. However, such rotor is suffering from poor efficiency problems. The present study will consider the design improvement of Savonius rotor, which is the basic geometry of drag machine, as a critical step to increase the efficiency of output power. Investigation is conducted to study the effect of geometrical configuration on the performance of the rotor in terms of coefficient of torque, coefficient of power and power output. There are three different types of modification; number of blades variable, shielding method and combination of both configuration. Computerized Fluid Dynamics (CFD) simulation is conducted to analyze the flow characteristic of all the rotor types. The continuity and Reynolds Averaged Navier-Stokes (RANS) equations and realizable k-ε epsilon turbulence model are numerically solved by commercial software Ansys-Fluent 14.0. Simulation computed the pressure and velocity field of the flow and the force acting on the rotor blades. The resultant force, pressure and torque coefficient obtained will be used to calculate power coefficient and power output. The results obtained by transient and steady method for the conventional two bladed Savonius rotor are in agreement with those obtained experimentally by other authors and this indicates that the method can be successfully used for such analysis. The modified 3 and 4 bladed rotors with hybrid shielding method give the highest maximum power coefficient which 0.37 at TSR 0.5.

ABSTRAK

Pada ketika ini, dunia mula menyedari kehadiran turbin angin paksi menegak jenis seretan sebagai mesin angin yang sangat berpotensi di masa akan datang. Kelebihannya yang mempunyai bentuk yang mudah dan sangat murah untuk dibina dan diselenggara berbanding turbin angin paksi mendatar yang konvensional menarik perhatian dunia. Walaubagaimanapun, pemutar sebegini mengalami masalah kecekapan. Kajian didalam tesis ini akan dijalankan untuk menambah baik rekabentuk pemutar jenis 'Savonius', dimana ia adalah geometri jenis seretan yang paling asas, sebagai langkah penting untuk meningkatkan kecekapan kuasa keluaran. Penyelidikan dijalanakan untuk mengkaji kesan perubahan geometri terhadap prestasi pemutar dari segi pekali torque, pekali kuasa dan kuasa keluaran.Terdapat tiga jenis penambahbaikan iaitu penambahan bilangan bilah, kaedah perisai, dan kombinasi kedua-duanya. Simulasi komputeran dinamik bendalir (CFD) dijalankan untuk menganalisis sifat aliran pada setiap jenis pemutar yang dikaji. Persamaan kesinambungan, Reynolds Averaged Navier-Stokes (RANS) dan gelora k-ε epsilon realisasi diselesaikan dengan perisian Ansys-Fluent 14.0. Simulasi ini mengira tekanan, halaju dan daya yang bertindak keatas bilah pemutar. Paduan daya, tekanan dan pekali tork yang diperolehi akan digunakan untuk mengira pekali kuasa dan kuasa keluaran. Keputusan yang diperolehi dengan kaedah 'pengaruh masa' dan kaedah 'mantap' untuk pemutar Savonius dua bilah yang konvensional menghampiri keputusan yang diperolehi dengan kaedah eksperimen yang telah dijalankan oleh penulis terdahulu dan ia menunjukkan bahawa kaedah yang dijalankan adalah sesuai digunakan untuk analisis seperti ini. Penambahbaikan dengan pemutar 3 dan 4 bilah yang beroperasi dengan kaedah perisai gabungan memberikan pekali kuasa maksimum yang paling tinggi iaitu 0.37 pada TSR 0.5.

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LIST OF SYMBOLS AND ABBREVIATION

Symbol

A	-	Area
A_s	-	Swept Area
D	-	Diameter
Cp	-	Coefficient of Power
Cm	-	Coefficient of Torque
T	-	Torque
C	-	Chord
d_{pe}	-	End-plate Diameter
d_r	-	Rotor Diameter
H	-	Height
m	-	Mass
V	-	Average wind velocity
P	-	Pressure
F	-	Body Force
e	-	Internal Energy
Q	-	Heat source term
t	-	Time
s	-	Overlap Distance
Rs	-	Overlap Ratio
X_1	-	Distance of upper obstacle shield from blade tip
X_2	-	Distance of lower obstacle shield from blade tip
Y_1	-	Distance between upper obstacle tips to the center of the rotor
Y_2	-	Distance between upper and lower obstacle tip.
R, r	-	Rotor radius
∇q	-	Heat Loss by conduction

Acronym

TSR - Tip speed Ratio

RPM - Revolution per minute

Re - Reynold number

SAR - Stage aspect Ratio

KE - Kinetik Energy

Greek letter (Lowercase)

λ - Tip Speed Ratio (TSR)

ω - Angular Velocity

β - Upper angle of curtain/ Lower angle of obstacle shield

α - Lower angle of curtain/ Twist angle

θ - Degree angle of Rotor

ρ - Fluid Density

τ - Stress Tensor

η - Aerodynamics Efficiency

Greek letter (Uppercase)

Φ - Dissipation Rate

Ψ - Blade arc angle

Subscript

CFD - Computerized Fluid Dynamics

RANS - Reynolds Average Navier-tokes

HAWT- Horizontal Axis Wind Turbine

VAWT- Vertical Axis Wind Turbine

MRF - Multiple Reference Frame

SIMPLE - Semi Implicit Method for Pressure Link Equation

CHAPTER 1

INTRODUCTION

1.1 Introduction

Wind has become an important source of alternative energy for the world since the late of 20th century. By the early 1990's, wind energy industries started to grow rapidly and attracted worldwide interest to develop the technology. The depletion of fossil fuel also becomes the main factor to why the wind starts to get high attention. In the middle of 1990's wind energy conversion systems were drastically developed due to the transformation from small sized to megawatt-sized wind power machines, consolidation of wind technology manufacture and the development of off-shore wind power generation systems. In the 21st century, this trend of development continued, and European countries become the main manufacturers by the support of government policies. The policies highlighted the issues of the development of sustainable energy supplies and reducing the pollutant of emissions [10].

At the start of the re-occurrence wind energy usage, the cost to produce energy from wind power method was far higher compared to fossil fuel. A lot of research, development and testing were carried out to enhance the development of new technology. Wind turbine is the perfect matter to describe of how does modern wind technology look like and how it operates to generate huge amount of mega-watt power. The important issue here is to provide regulation of how the turbines interconnect with electrical networks.

A wind turbine is a device that converts kinetic energy from the wind into mechanical energy. Then, the mechanical energy is used to produce electricity and to

drive machinery for grinding or pumping water. The result of over a millennium of windmill development and modern engineering, today's wind turbines are manufactured in a wide range of vertical and horizontal axis types. Vertical and horizontal axes describe the way of how the turbines interconnect with electrical networks.

Horizontal axis wind turbine (HAWT) is widely used nowadays across the region of around the world and already proven its high efficiency in generating power from the wind. However the existence of Vertical wind axis (VAWT) becomes new phenomenon in wind technology development. The advantages of VAWT which not own by HAWT give high interest to researcher to perform more study on this type of wind turbine. VAWT have the advantages of simple construction, cheaper to build and maintain and also able to catch wind from any direction without re-orientation.

In Malaysia, the interest in wind turbine had emerged since past few years. Few designs were developed by worldwide but still don't give an expected result. An important reason could be that wind velocity in Malaysia, apart from coastal region, is relatively low and varies with seasons. (Christopher 2010). This low velocity and seasonal wind requires high cost of exploitation of wind energy. So, it becomes huge challenge to design appropriate wind turbine which can be used in small scale especially in rural area. VAWT gives promising solution to this particular problem since it is low cost and simple construction rather than HAWT which requires high tech company with advanced technology to set it up.

There are two types of VAWT which are the lift type and the drag type. Lift type has low torque but high speed of rotation that makes it applicable to produce high electricity power. Drag type has high torque but low rotational speed makes it applicable for pumping water purpose. Low torque or lift type gives huge disadvantage where it requires external power source to initiate the rotation. It is quite impossible to deal with this problem since further improvement seems not possible with this kind of design. But for the drag type, since it already own the advantages of the high torque, the weakness of its low rotation can still undergo an improvement. This is because; it looks possible to do modification since it only needs to rotate faster. Therefore, in this paper, our interest is for the drag type. A few designs of drag type will be analyzed to determine the performance of generating electricity.

1.2 Background study

Advanced in VAWT lift type analysis made it suitable as an alternative mean to HAWT in producing high electricity power. The aerodynamic effects on VAWT are mostly known since the design is approaching the airfoil geometry. Drag type is still very poorly understood since the application is only restricted for pumping purpose which is not very popular in industry. Analysis of performance for several designs of drag type was already performed by previous researchers. But there is still no particular study in comparing all those designs and determine the best among them.

Most of the previous studies use the simulation CFD method to analyze the characteristic of flow which then will be validated with experimental method. CFD is known as a powerful tool in applying finite element volume method to characterize external flow problems. CFD methods are based on numerically solving the Reynolds Averaged Navier-Stokes (RANS) equations with an accompanying *turbulence model* [24]. Jianhui Zhang said in his study Numerical Modeling of Vertical Axis Wind Turbine (VAWT), with finite difference volume, the turbine is represented as an actuator disk and flow field is described either by Navier-Stokes or Eular equation, and the modified k-epsilon model for shear flow under gravitational influence has been chosen for the closure of time-averaged turbulent flow.

Previous studies also have proven that, by the CFD method, power coefficient (Cp) and tip speed ratio (TSR) can be determined from result of rotational force and torque. The curve of Cp versus TSR is very important in determining the efficiency of VAWT. Ivan Dobreva and Fawaz Massouha mentioned in their studies that values of Cp are between TSR 0.6 and 1.05. Aerodynamic analysis is also important in determining the drag force and drag coefficient of the VAWT where the maximum power of the drag based wind turbine can be determined with the knowing of these values.

Since this study is aiming to choose the best geometry of drag type VAWT, critical evaluation and observation need to be done before choosing the various types of these VAWT to perform analysis on them. There are a few types which become our interest to study on such as, savonius, multi bladed and twisted VAWT. VAWT Shield or casing with different angles of inlet will become new features of

modification to optimize the angle of attack. This paper will also study the aerodynamic effect of the rotor radius to height ratio variation.

1.3 Problem statement

Drag base VAWT due to its low running speed have low efficiency which the value of the corresponding power coefficient Cp (which can be identified with the efficiency) reaches only 50% of the one of the best fast running horizontal axis wind turbines (this is essentially due to the low aerodynamics performances of such rotors, based on the difference between the drag forces on the paddles). (Menet, 2004). Menet et al conclude that this particular phenomenon made the savonius rotors have high productivity but low technicality as a wind machines device. It is maybe why savonius is often used for water pumping instead of electricity generation purpose.

Due to this matter where drag type is known of it low technicality characteristic, blade geometry and configuration become crucial in determining the performance on wind capturing to improve the power generation. Several geometry efficiency developments have been conducted in previous study. Some modification have been made on the shape of conventional savonius such as adjusting overlap ratio and aspect ratio (Sargolzaei and Kianifar (2007), Saha (2008)), use other type of drag based VAWT such as Helical shape and multi blade shape (Kamoji (2008), Saha (2005)) and add an external feature to improve wind capturing ability (Altan (2008)).

All of these studies have been conducted successfully and each of them claims a good result of their design in improving the efficiency of the drag base VAWT performance. But yet, among all those geometry shape, there is still no particular study that discuss briefly which geometry is the best among them. So it is essential to do the performance comparison and for that reason, this study will conduct an analysis of VAWT by treating the various type of drag-base geometry as a variable. High torque performance also an important issue to be analyzes since lift type do not have self-start ability. Several study were conducted on drag type to make it available for the electricity generating purpose.

1.4 Objective

The objectives of this study are:

i). to investigate the wind effect on vertical axis wind turbine performance in generating electricity.

ii). to investigate the effect of multi bladed wind turbine by means of varying the number of blades from 2 to 5 rotor bucket.

iii). to investigate the effect of shield/casing to the wind turbine speed by determining the optimal inlet angle of the shield as the wind flow past through the turbine blade.

iv). to determine optimum type of vertical axis turbine blade that lead to the highest performance in generating electrical power.

1.5 Scope of study

The scopes are:

i). the types of the vertical wind turbines involve in this study are the modern savonius, multi-bladed and twisted blade. Additional modification features for the installation is the shield or casing to cover-up the wind turbine.

ii). the variables of concerned are:

a) The blade geometry of drag types which is the modern savonius type, semicircular and multi blade.
b) the angle inlet variation for Shield/casing, (20^{o} to 90^{o}),
c) The dimension of the wind turbine constant for all type (height, 0.2m and rotor diameter, 0.2m).
d) Wind speed is set from 20 km/hr to 120km/hr.

The optimal relationships to be determined are on the basis of tip speed ratio, power coefficient, and torque coefficient and power measurement from the turning blade due to the wind impact.

1.6 Importance of study

It is important to study the behavior of VAWT for drag types that have the potential to become good wind machines in delivering power. Since this type of VAWT has the high torque characteristic where it gives the ability to produce continues power, but the low rotational speed makes it hard to produce high density power.

So with this present study, it will help manufacturer to determine which geometry can increase the rotational speed of the drag type and as a result can also make this type of VAWT suitable for electricity generation.

The method that will be applied in this study is the simulation method that will not only help to determine the optimum value of VAWT efficiency but also reduce the production cost by means of modeling simulation at the very first stage. Any modification at this stage does not cost anything. But if modification is performing

on the manufacturing process stage to provide desirable geometry outcomes, the cost will far beyond the expectation.

So this guide of simulation study will give a very good practice in the design and manufacturing industries and of course is a good step of advancement in the development of Vertical axis wind turbine field.

1.7 Expected Outcome.

Analysis with CFD simulation is expected to give reasonable result that will lead to better precision. Data collected from the simulation also can give information efficiency for different type of VAWT. This information will then be converted into measureable data and comparing process will be conducted to determine the optimum geometry of the VAWT.

Analysis on additional features and modification like installing casing and controlling the height to radius ratio of rotor is expected to increase the efficiency of the VAWT performance in terms of rotational speed, power and torque generation.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Wind energy as renewable energy sources is growing faster nowadays. In the future of renewable energy derives from wind turbine is expected to play an important role as a tool in generating electrical power. The turbines can be divided into two types that are Horizontal axis Wind turbine (HAWT) and Vertical axis wind turbine (VAWT). The different between these two types is based on the axis position. HAWT are already commonly used with an abundance of manufacturer. VAWT is still very new to be implemented as commercial usage. VAWT also still been studied by various researchers using modern analysis technique. Unlike VAWT, HAWT is not omni-directional. As the wind direction change, HAWT must also change direction to enable continues functioning. There are several techniques to orienting the HAWT to the direction of Wind. One of the popular methods is yaw system.

Zhi Wu (2011) said that Current all modern big wind turbines use active yaw system, which, according to senor signal, adjust wind turbines to the windward position by electric or hydraulic device. Active yaw is a control electric (hydraulic) way, which is flexibility and controllability, yaw stably and accurately to avoid frequent rotation, reduce the mechanism wear. As the daily electric consumption of user increasing, the market need of kw-class or even 10 kw wind turbines is also on the rise. Power of wind turbines increases, structure becomes complex, components' weight and load increase, the moment of inertia also increases.

Biegel, (2011) said in his study, the wind field from which they generate power is also the source of large fatigue load on the turbine, which creates the structural wear and tear, increasing maintenance costs and decreasing the operational lifetime of the turbine. To reduce fatigue load of HAWT, critical design on blade pitching must undergo critical controlling. Ajedegba, (2008) said that the rotor speed and power output need to control by pitching the rotor blades along the longitudinal axis. They need a mechanical or electronic blade pitch control mechanism to control pitch angle.

From the above previous study, it is prove that HAWT are expensive to build and maintain because of it complex construction. The existence of VAWT gives new approach in wind turbine technology. The advantages of VAWT are they can catch wind from any direction and thus eliminating the need to re-orienting towards the wind. As a result, VAWT promising new hope for simple construction and design, reduce cost to build and maintenance, aid installation, and eliminates the problem imposed by gyroscopic forces on the rotor of a conventional machine, as a turbine track the wind. The vertical axis of rotation also permits mounting the generator and drivetrain at ground level. VAWT is attracting a growing interest over the worldwide. It's modular and scalable size, among other advantages over conventional HAWT is attracting researchers and developers to improve the performance of VAWT.

2.2 VAWT's Background

Vawt is originally invented from Persia. The windmill was used as a source of mechanical power in tenth century natives, who live in eastern Persia, utilized the windmill as vertical axis and drag type of windmill as shown in figure 2.1. The basic mechanism of the vertical axis windmills in far ahead eras, such as placing the sail above the millstone, is elevating the driver to a more open exposure, which improved output by exposing the rotor to the higher wind speeds, and using reeds instead of cloth to provide the working surface. [10]

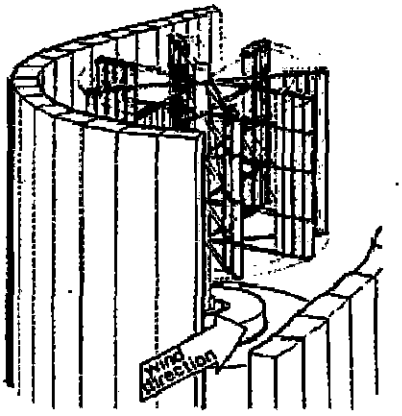

Figure 2.1: Persian windmill [10]

A transition from windmill that supply mechanical power, to wind turbine generating electrical power was occur towards the end of nineteenth century. The basic used of wind for electricity generation which different to mechanical power, lead to successful commercial development of small wind generators, further research and experiment with large turbines.[10]

There are two types of VAWT that commercialized today in the wind energy market that are Darrieus lift type and Savonius drag type. The next section will discuss briefly about these two turbines.

2.2.1 Darrieus lift base

French aeronautical engineer Georges Jean Marie Darrieus patented in 1931 a "Turbine having its shaft transverse to the flow of the current", and his previous patent (1927) covered practically any possible arrangement using vertical airfoils. Actually this kind of turbines has becomes a starting point for further studies on VAWT to improve efficiency [1].

Darrieus VAWT is significantly shown the phenomenon of lift. This lift type consist two types of turbines, "eggbeater-type and "H-type". The lift phenomenon was created by the airfoil shape of the turbines blades. When these kind of blades shape cut through the air with an angle of attack to the wind, pressure differential will occur. The resulting pressure differentials will cause a force called lift, which drives the blade to move forward. In order to drives the turbine, the net torque caused by lift forces must be greater than net torque caused by drag forces.

2.2.2 Darrieus Use and operation

The swept area on a Darrieus turbine is A= 2/3 x D^2, a narrow range of tip speed ratios around 6 and power coefficient C_p just above 0.3 as in figure 2.2.

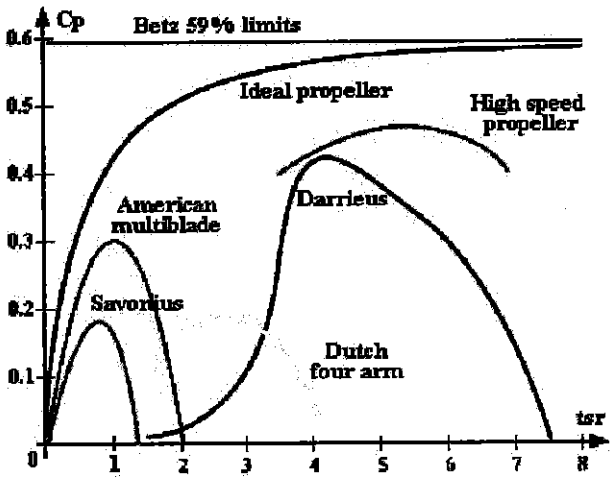

Figure 2.2: Cp-λ diagram for different type of wind turbines [2]

Each blade seems to have maximum lift (torque) only twice per revolution, resulting a huge torque and power sinusoidal output that is not present in HAWTs. The long VAWT blades cause many natural frequency of vibration occur which must be avoided during operation. [1] Clear visualization on how force act on a turbine is shown in figure 2.3.

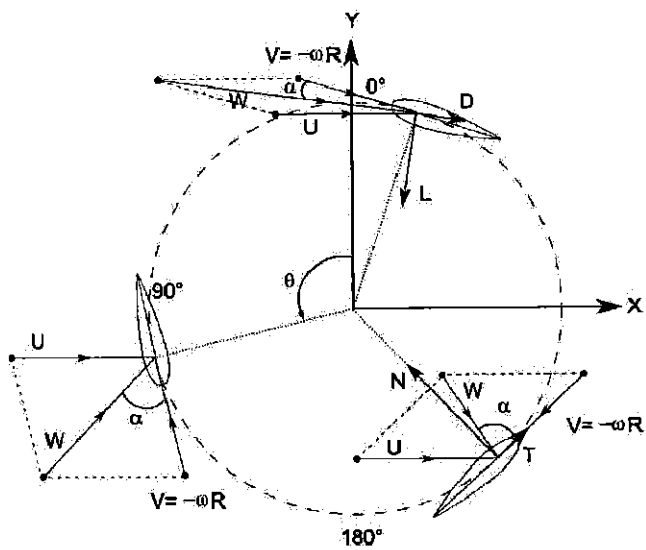

Figure 2.3: Forces that act on the turbines [2]

One problem with lift type is that the angle of attack changes as the turbine spins, so each blade generates it maximum torque at two points on its cycle front and back of the turbine). This leads to a sinusoidal power cycle that complicates design.

Another problem of VAWT is because the majority of the mass of the rotating mechanism is at the periphery rather than at the hub, as it is with a propeller. This leads to very high centrifugal stresses on the mechanism, which supposed to be stronger and heavier to withstand them. The most common shape is the one similar to an egg-bitter that can avoid in part this problem, having most of the rotating mass not far from the axis. Usually I have 2 or 3 blades, but some studies during the 80's demonstrate that the 2 bladed configurations have higher efficiency. [1]

2.2.3 Savonius Drag base

Savonius wind turbines were invented by the Finnish engineer Sigurd J. Savonius in 1992, but Johann Ernst Elias Bessler (born 1680) was the first to attempt to build a horizontal windmill of the Savonius type in the town of Furstenburg in Germany in 1745. Nowadays they are not usually connected to electric power grids. [1]

2.2.4 Savonius Use and operation

The Savonius is a drag-type VAWT, so it cannot rotate faster than the wind speed. This means that the tip speed ratio is equal to 1 or smaller. The efficiency also very low compared to t=other types, so it usually use for pumping water or grinding grain. Savonius wind machines have a low cut-in speed and can operate in wind as low as 5 mph. This makes the machine suitable for electricity generation in low-power applications such as individual domestic installations. This machine is particularly suited to locations of variable wind direction. A swiss company markets a 6kW version of the savonius machine. The peak efficiency of this form of turbine is about 30% and the tip-speed ratio is low.

The disadvantages of the savonius design is it high-solidity factor. Also the machine is heavy if metal vanes are used. Because of the nature of the construction, the vane or sail area cannot be modified, so that the machine may need to be tied stationary in high winds. [1,11].

2.3 Modern Savonius Turbines development analysis tools.

As we know from the previous section, the lift based VAWT have very low self-starting torque and it was a major disadvantages in wind machine requirement. A as result, the average torque of Lift base at low tip speed ratio is almost zero or sometimes negative. As a counter action for this problem, starting motors or engines are required to initiate the VAWT rotation. [9,11]. The other problem with this VAWT is their small effective operation range. Although the maximum power coefficient of the darrieus VAWT is close to the magnitude of conventional turbine which is HAWT, the effective TSR operation range is too narrow for electric power generators [9]. This disadvantage reduces the net amount of electricity generation. Therefore, the savonius becomes new study matter and interest due to their high starting torque among other reasons.

Development in other related areas of wind technology have been adapted to the drag based wind turbine, which will help improve its presence in the global wind market. Some related fields that have contributed to a new generation of wind turbines include material science, aerodynamic, analytical methods, experiment and testing.

Our Focus is on the aerodynamic performance since this study is very significant to analyze power generation behavior due to aerodynamics characteristic.

Yao (2012) in his study mention that the study way for the vertical axis wind turbine's aerodynamic performance can be classifies as analytical solution, wind tunnel experiment, wind field experiment and numerical simulation. He said that pipe flow model method and eddy method is an approach to predict the performance of the vertical axis wind turbine in analytical solution. This method is all can be used to calculate the overall performance of the vertical axis wind turbine as resistance, force moment, power and so on. But when the tip speed ratio is much higher or lower, the solution may not be convergence. The analysis result of wind tunnel experiment and wind field experiment are reliable, but are limited by the experimental and technical conditions, have high cost and long cycle. With the development of the computational and CFD technology, CFD is becoming an important part of the aerodynamic performance analysis for wind turbine.

2.3.1 Computational Fluid Dynamic approaches (CFD).

CFD is the method that uses numerical approximation to the equation that governs fluid motion. The steps require to analyze fluid problem in CFD are as follow. First, the mathematical equations are written to describe fluid flow. These are usually a set of partial differential equations. These equations will then discretize to produce a numerical analogue of the equations. The domain is then divided into small grids or elements. Finally, the initial conditions and the boundary conditions of the specific problem are used to solve these equations. The solution method can be direct or iterative. In addition, certain control parameters are used to control the convergence. [12]

2.3.2 Drag VAWT analysis by CFD software tools.

Since 1970, several fluid dynamics prediction models have been formulated for vertical axis turbines such as the Darrieus turbines [4]. Previous authors have performed CFD computations of wind turbines with a variety of methods. CFD simulation can be performed either in 3D or 2D computation. The general steps to perform CFD analysis involve geometry development, meshing, domain and boundary definition and finally execute the simulation. Different researcher use different type of software and different way to defining their model of simulation.

McTavish (2011) use steady two-dimensional simulations and rotating three dimensional simulations and he choose commercial software CFdesign 2010 to simulate his model. He performed three-dimensional simulations using a single rotor stage. A schematic of the computational domain, including a cylinder which represents the rotating portion of the domain, is presented in figure 2.4. He also set all of the rotor walls had a no-slip boundary condition, the inlet had a uniform velocity of 6m/s, the outlet had a zero gauge static pressure boundary condition and the remaining four outer boundaries had a free slip condition.

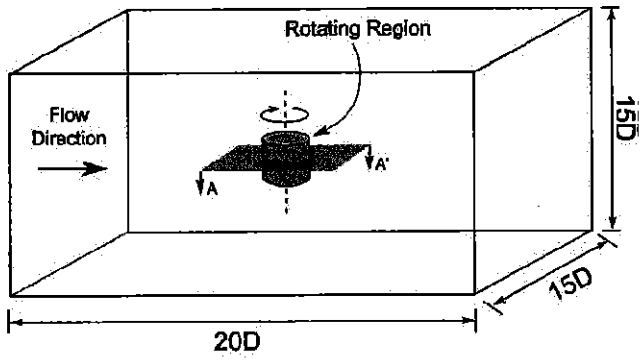

Figure 2.4: Schematic of the computational domain [5]

Dobrev & Massouha (2011) creates meshing or grid using Ansys gambit 2.4.6 software and solves the simulation using Ansys Fluent 12.1 solver. Dobrev et. al used the concept of sliding mesh because the rotor changes its position with respect to upstream wind direction. The grid has two distinct parts: an external stationary, which represents the flow around the turbine and an internal, which rotates in order to represent the rotor blade. Figure 2.5 a and b below show how he visualizes his model.

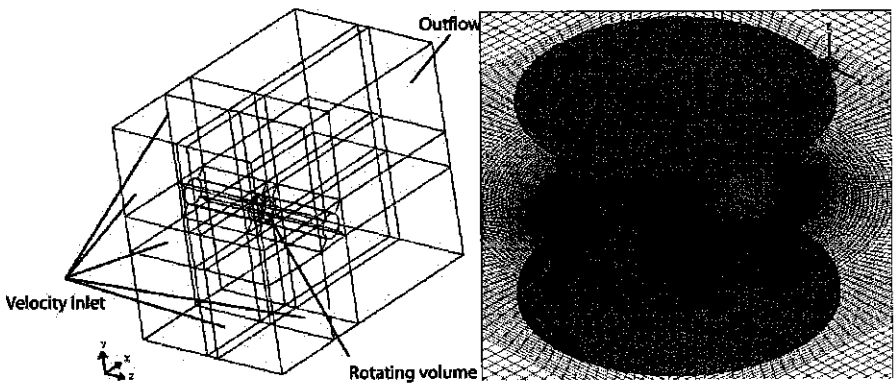

Figure 2.5: (a) three dimensional simulation domains, (b) Moving internal grid [6]

2.4 Development and performance of Savonius VAWT geometry.

Analysis of drag-base type had been perform for various type and many time by previous researcher. Early section from figure 2.1, it prove that slow running vertical axis wind turbine such as savonius in this case produce power at very low wind speed. Power coefficient, Cp also not exceeds 0.3 which means only reach's 50% of the one of the best fast running HAWT. But previous study also proved that modified savonius and other type of drag-based VAWT can affect their efficiency.

Sargolzaei & Kianifar (2007) comparing six prototype of vertical axis turbine as in figure 2.6. J. Sargolzaei et.al adds that a vertical axis turbine especially for drag based rotation speed is low and torque is high. Therefore, this device could be used for local production of electricity. Sargolzaei et.al simulates Rotor's power factor and different angles of blade in proportion to blowing wind in a complete rotation. Figure 2.7 show the comparison of power factor between all the tested rotors.

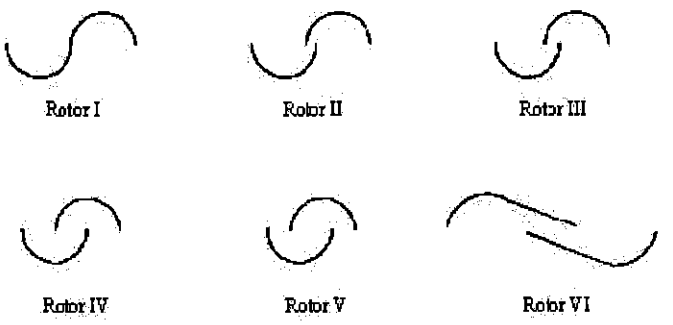

Figure 2.6: Six rotor blade prototype. [7]

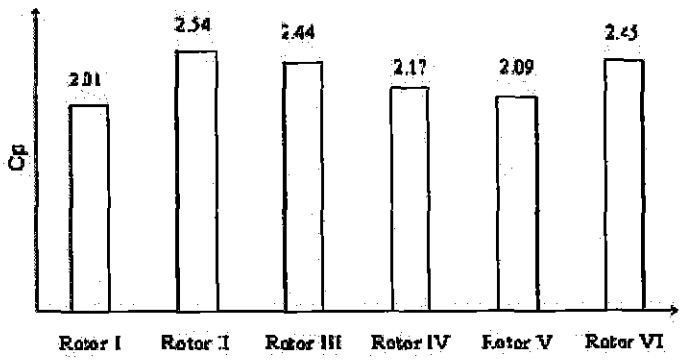

Figure 2.7: Comparison between power factors. [7]

Sargolzaei et.al conclude from the result that curves for rotors "II" to "IV" have greater power factor than other rotors, because of the gap distance, leads to decrease of power factor. So the best blade curve is rotor "II". Other results prove that, increase of wind speed (Reynolds number) leads to serious increase of output power (is related to third exponent of speed).

Graph of power coefficient as figure 2.8 also show that Rotor "II" can increase the Cp up until 0.3 which was quiet high compared to the origin savonius.

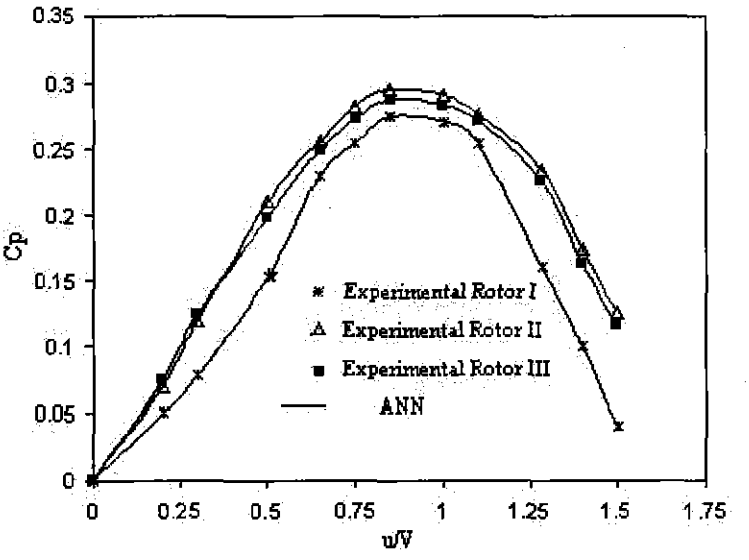

Figure 2.8: Comparison between Power factor rotor"I" to "III". [7]

In this study, Sargolzaei et.al also performed the torque analysis. From the result that gains from the experiment, Chart of torque on different blades in wind speed 12m/s is presented as figure 2.9 below. By comparing different charts, he prove that, although rotor "I" has greatest torque in angles 0° to 60°, in angles greater then 60° there is serious decrease in torque. This decrease continues until angle160°. Totally, for a complete rotation, rotor "II" has the greatest outlet torque. According to figures, increasing wind speed leads to increase of torque. For all examined rotors, maximum amount of torque happens in angle about 60° and minimum amount of torque happens in angle about 120°. Figure 2.10 show the torque of rotor II at different wind speed.

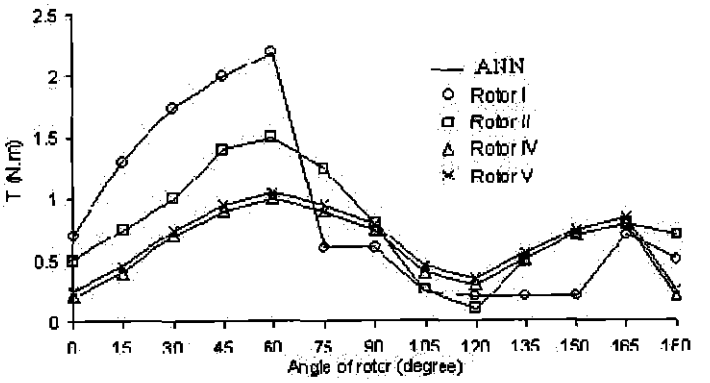

Figure 2.9: Comparison output torque of different rotors in wind speed 12 m/s. [7]

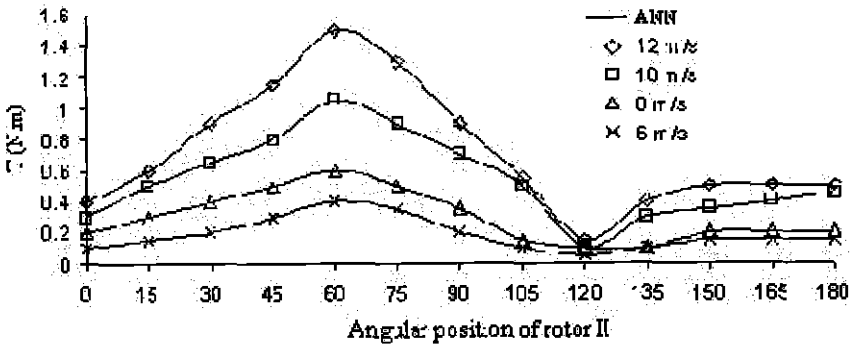

Figure 2.10: Torque vs. angular position of rotor "II" in different wind speeds. [7]

Akwa (2011) performed almost similar studies as Sargolzaei et. al. He improvise the way of previous studies was performed by identifying the exact value of overlap ratio for optimum rotor (which is rotor II) from previous section. He conclude, the configuration that shows the best performance is the one where Rs = 0.15 as in figure 2.11, which gives an averaged power coefficient equals to 0.3161 for the tip speed ratio 1.25.

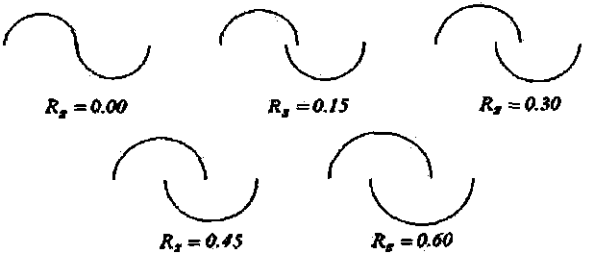

Figure 2.11: Savonius rotor geometry changes. [20]

2.5 Development and performance of Savonius VAWT geometry with additional features.

From the previous study, some modification of savonius does not require any geometrical changing from the original shape. The idea is to add an external accessory to enhance the speed of wind so that it can turn the savonius blade faster. This kind of modification seems to give promising higher efficiency compared with the original shape without any external support.

Altan & Atılgan (2008) introduces a curtain design where it has been arranged to improve the low performance levels of the savonius wind rotors. It was design to prevent the negative torque on the convex blade of the rotor. It has been placed in front of the rotor as shown in figure 2.12, and performance experiments have been carried out when the rotor is with and without curtain.

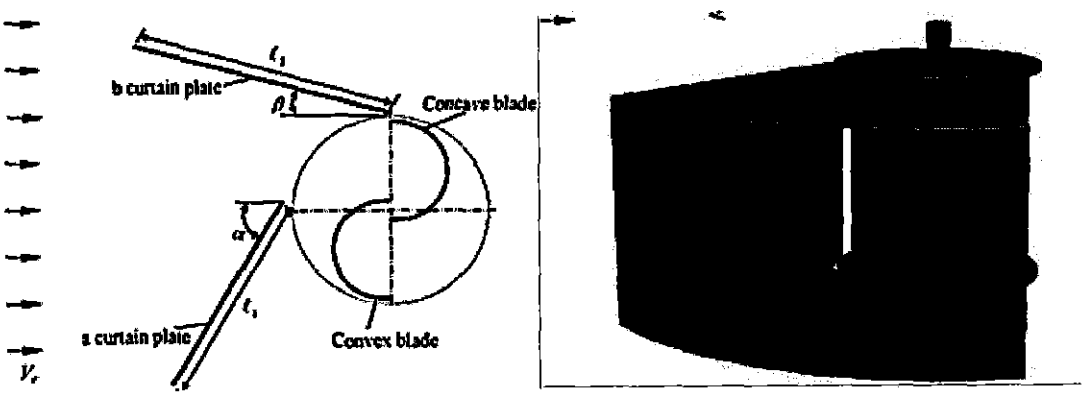

Figure 2.12: Curtain design parameters and design of the curtain arrangement. [14]

Altan et. al serves several types of curtain arrangements which classified as curtain 1, curtain 2 and curtain 3. Curtains was classified due to it long, medium and short dimension. The curtain 1 has the optimum length as shown in figure 2.13 due to high power coefficient gain. The lengths of the curtain 2 and 3 are 75% and 50% of the optimum lengths, respectively.

The best performance has been obtained from curtain 1 at its position $\theta = 60$ for the angles $\beta = 15$ and $\alpha = 45$ from both with experimental measurements and numerical analysis

Altan et. al said most of the fluid guided by the curtain when the rotor's position is $\theta = 90$ escapes from over the convex blade will leads to an negative torque effect. This is the critical reason why it is when the rotor position is $\theta = 90$, the lower torque value is obtained. When the rotor's position is$\theta = 45$, however, more fluid escapes from between the end of the curtain and blade and the value of the applied torque decrease.

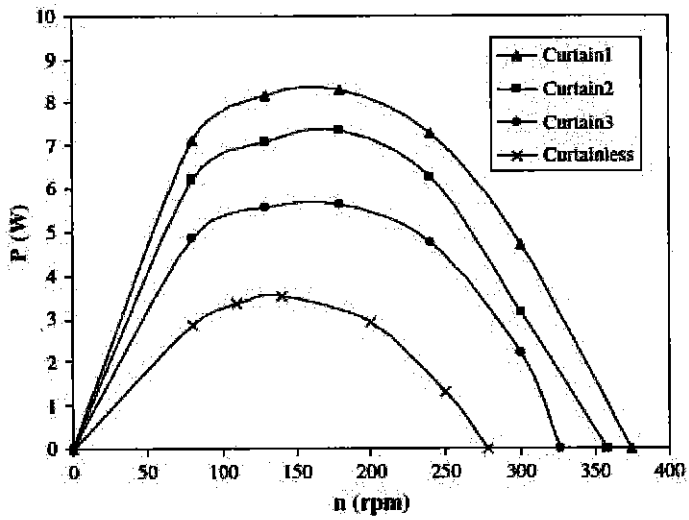

Figure 2.13: Comparison of the power changes with the rotor without curtain and the rotor with different curtain types for a $\alpha = 45$ and $\beta = 15$. [14]

The other researcher idea instead of curtain is obstacle shielding. It seems to have the same concept but different approach and more simple construction. Mohamed, (2010) highlight the present study that considers an improved design in order to increase the output power of a savonius turbine by considering the usage either two or three blades. Mohamed et. al add that to achieve the improved design leads to a better self-starting capability, position of an obstacle shielding as shown in figure 2.14 should be set and determine which could lead to optimizing a better flow orientation toward the advancing blade.

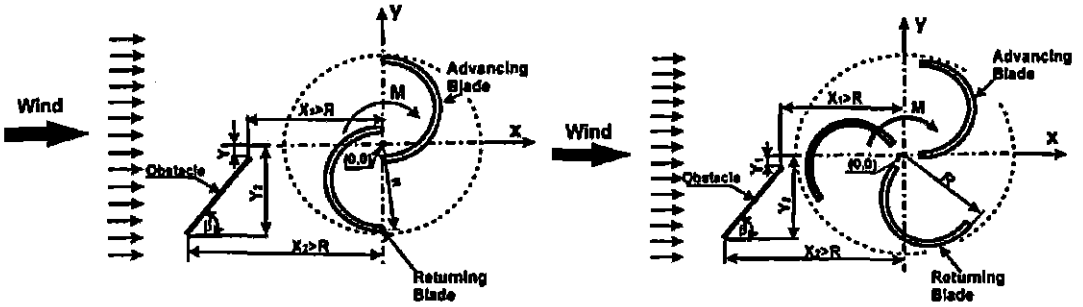

Figure 2.14: Schematic description of the geometry and free optimization parameters X1, Y1, X2 used to modify the position of the shielding obstacle. Top: two-blade Savonius rotor; bottom: three-blade savonius. [15, 16].

From this study, followed result and conclusion are obtained. The overall effect of this obstacle is extremely positive for both designs. Considering the obtained output power coefficient and the cost and complexity of the rotor, the two-blade configuration is clearly better than the three-blade turbine. This optimal configuration leads to a peak power output coefficient of 0.258 at $\lambda = 0.8$, and seems therefore very promising for wind energy generation in urban areas.

Mohamed et. al add another one important modification on his savonius turbine shape as shown in figure 2.15, He said from result obtained, the modified shape leads to an increase of the positive moment of the advancing blade as shown result in figure 2.16. For the overall conclusion, better configuration might be perhaps found by optimizing simultaneously blade shape and size and position of the obstacle plate.

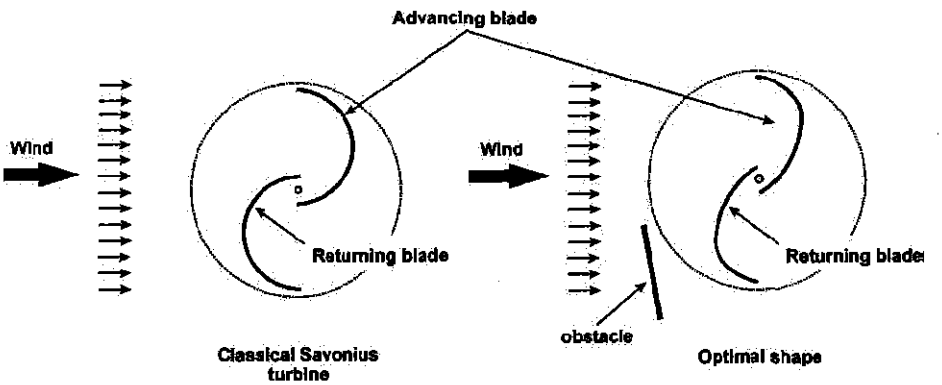

Figure 2.15: Optimum configuration (right) obtained with the optimization procedure compared to the classical Savonius turbine (semi-cylindrical shape:left).[15,16]

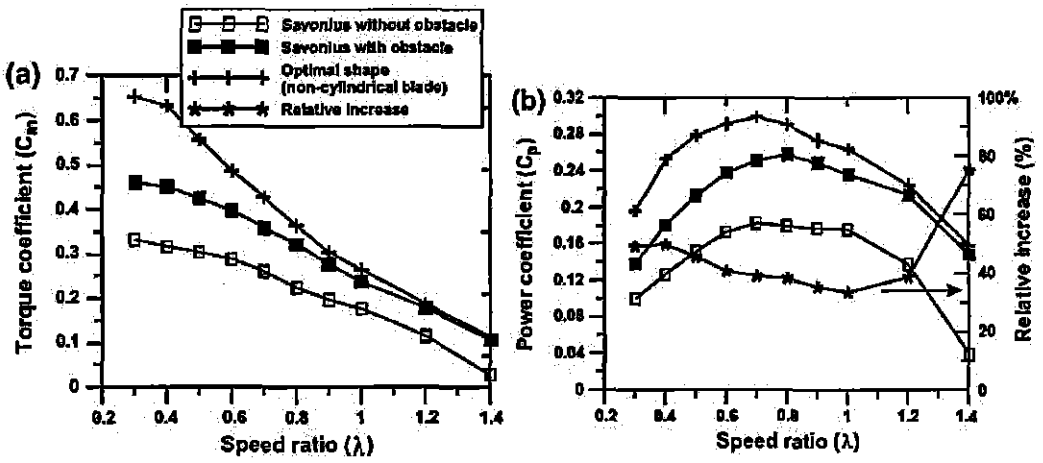

Figure 2.16: Performance of the optimized configuration (black plus) compared to the conventional Savonius with and without obstacle plate (filled an empty squares, respectively) (a) torque coefficient; (b) power coefficient. The corresponding relative increase compared to the standard configuration is shown with stars.[15,16]

Another one interesting design of external features of savonius turbine is guide box tunnel. Irabu & Roy, (2006) investigates to improve and adjust the output power of savonius rotor under various wind power and the method to prevent the rotor from strong wind disaster need to be suggest. So he employed guide-box tunnel (GBT) as drawn in figure 2.17, as an appropriate device to achieve the purpose. The GBT is like a rectangular box as wind passage in which a test rotor is included. The ratio between the inlet and exit of it is variable to adjust the inlet mass flow rate or input power.

In this study, Irabu et. al introduce new parameter to measure optimum size of GBT passage that is widths ratio where$\delta = \frac{l}{dt}; l =$ width of GBT, $dt =$ rotor diameter. Using the GBT, as shown in figure 2.18, this study found that the maximum output power coefficient for two blades rotor is about 1.23 times at the largest compared with that without GBT and 1.5 times for three blades rotor of which reasonable width ratio of GBT is 1.4 and area ratio of it is 0.43.

The maximum output power coefficient of the two blades rotor in GBT is approximately 1.08 times as large as that for the three blades rotor configuration in GBT. Therefore, the two blades configuration is better than that of three blades to effectively convert wind power through GBT, except for rotation starting.

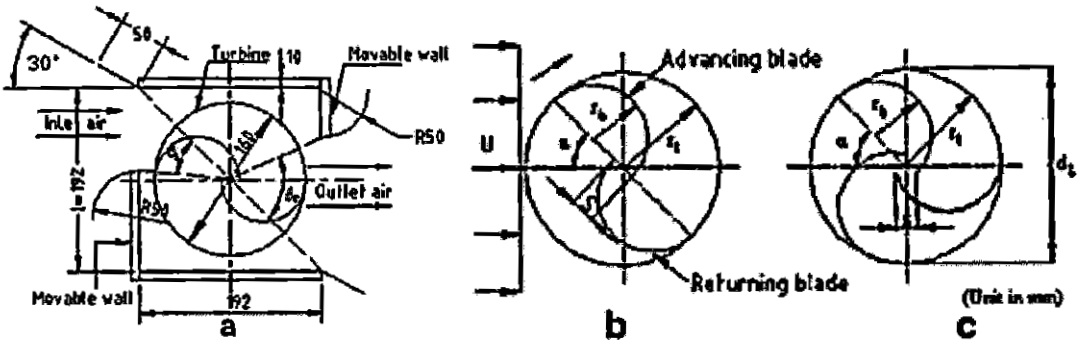

Figure 2.17: Details of test rotors and guide-box tunnel: (a) guide-box tunnel with rotor; (b) two-blade rotor; and (c) three-blade rotor. [17]

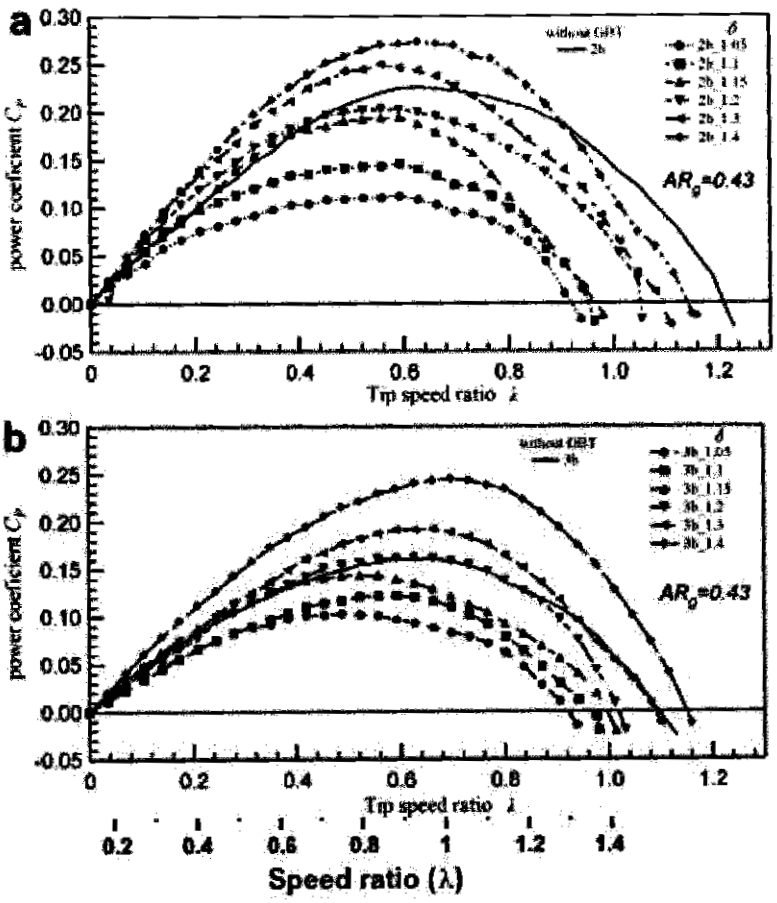

Figure 2.18: Power coefficients vs. tip speed ratio of the rotors with GBT of a fixed ARg: (a) two blades rotor; (b) three blades rotor. [17]

2.6 Development and performance of various types' geometry of drag-based VAWT.

Drag-based VAWT not only restricted in the form of savonius shape only. Nowadays, there are numerous numbers of different types and shape of VAWT in the market. Helical turbine, twisted, hunter turbine, zephyr vane are few example of drag-based VAWT. There is still lack study of performance of all those VAWT until today.

Hassan et. al presents CFD analysis on helical blade savonius (figure 2.19). He said that design twisted rotor will be used in a small seafloor power generation system. Since this research study set the purpose below the sea, which means the fluid flow is water instead of air, so the Power coefficient is low. But the author said the simulation results show better performance of twisted savonius as compared to the other conventional Savonius rotors which in this case the fluid is water. So it's quite possible to predict that performance of twisted savonius might be interesting to study in the air fluid stream condition.

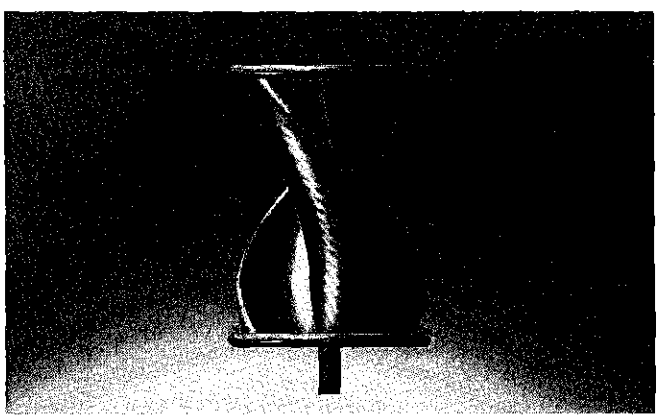

Figure 2.19: Half pitch turn (180°) helical Savonius turbine [8]

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