COMPUTATIONAL FLUID DYNAMICS (CFD) ANALYSIS OF A MINIATURE WIND TURBINE

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2010

COMPUTATIONAL FLUID DYNAMICS (CFD) ANALYSIS OF A MINIATURE WIND TURBINE

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Thesis submitted in fulfilment of the requirements
for the award of the degree of Bachelor of Mechanical Engineering

Faculty of Mechanical Engineering
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DECEMBER 2010

SUPERVISOR’S DECLARATION

I hereby declare that I have checked this project and in my opinion, this project is adequate in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering.

Signature : ....
Name of Supervisor : IDRIS BIN MAT SAHAT
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Date : 6 December 2011

STUDENT’S DECLARATION

I Muhamad Izzuddin Hilmi Bin Zainal Abidin hereby declare that the work in this project is my own except for quotations and summaries which have been duly acknowledged. The project has not been accepted for any degree and is not concurrently submitted for award of other degree.

Signature : ....
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DEDICATION

Dedicated to my dear parents

Zainal Abidin Bin Johar
And
Siti Aishah Binti Mohd Said

ACKNOWLEDGEMENTS

I am grateful and would like to express my sincere gratitude to my supervisor Mr. Idris Bin Mat Sahat for his germinal ideas, invaluable guidance, continuous encouragement and constant support in making this research possible. He has always impressed me with his outstanding professional conduct, his strong conviction for science, and his belief that a degree program is only a start of a life-long learning experience. I appreciate his consistent support from the first day I applied to graduate program to these concluding moments. I am truly grateful for his progressive vision about my training in science, his tolerance of my naïve mistakes, and his commitment to my future career. I also would like to express very special thanks to my co-supervisor Mr. Devarajan for his suggestions and co-operation throughout the study. I also sincerely thanks for the time spent proofreading and correcting my many mistakes.

My sincere thanks go to all my labmates and members of the staff of the Mechanical Engineering Department, UMP, who helped me in many ways and made my stay at UMP pleasant and unforgettable. Many special thanks go to member engine research group for their excellent co-operation, inspirations and supports during this study.

I acknowledge my sincere indebtedness and gratitude to my parents for their love, dream, sacrifice, patience and understanding that were inevitable throughout my life to make this possible. I cannot find the appropriate words that could properly describe my appreciation for their devotion, support and faith in my ability to attain my goals. Special thanks should be given to my committee members. I would like to acknowledge their comments and suggestions, which was crucial for the successful completion of this study.

ABSTRACT

This study is about the analysis of miniature wind turbine using Computational Fluids Dynamics (CFD). Wind energy is one of the renewable energy resources and the applications of wind turbine have been used in several countries. Basically there are three types of wind turbine that exists. Horizontal Axis Wind Turbine, Vertical Axis Wind Turbine and Offshore Wind Turbine. These three types of wind turbine have their own advantages and disadvantages. Horizontal Wind Turbines is the most popular type of wind turbine in practice nowadays. The miniature wind turbine is more practically used for residential area and has power output in the range of 400 W to 10 kW. Theoretically, in order to produce 10kW of power output, the wind speed must be at least 7 m/s. As for this study, the wind speed is at 4 m/s inaccordance to the Malaysian average wind speed. The maximum size of rotor blade for a miniature wind turbine is 7 m diameter. Analysis has been conducted using Computational Fluid Dynamics (CFD). In this project, the result is achieved by using COSMOFlow Work. In COSMOFlow Work, the value of Torque (Nm) measured is the value of force acting on the miniature rotor blade. A comparison study using Blade Element Momentum (BEM) theory has been conducted to ensure that the value of Torque from CFD and BEM in this project is synchronized. This is to prove that the analysis conducted correlated to the theory of wind turbine is correct and undoubful. As for the conclusion, this project has successfully achieved its targeted objectives.

ABSTRAK

Projek ini adalah mengenai analisa yang telah dilakukan ke atas kincir angin berskala kecil menggunakan *Computational Fluids Dynamics* (CFD). Tenaga angin merupakan salah satu tenaga yang boleh diperbaharui dan aplikasi kincir anign telah diguna pakai di beberapa buah negara. Secara amnya terdapat tiga jenis kincir angin. Kincir Angin Berpaksi Mendatar, Kincir angin Berpaksi Tegak dan Kincir Angin Persisiran Pantai. Ketiga-tiga jenis kincir angin ini mempunyai kelebihan dan kekurangan tersendiri.Kincir Angin Berpaksi Mendatar adalah merupakan kincir angin yang diguna pakai secara meluas masakini. Penggunaan kincir angin berpaksi mendatar berskala kecil adalah lebih sesuai digunakan di kawasan perumahan dan mempunyai kuasa keluaran dalam julat 400 W hingga 10 kW. Secara tiori, kelajuan angin haruslah mencapai sekurang-kurangnya 7 m/s bagi menghasilkan 10kW kuasa keluaran. Projek yang dijalankan menggunakan kelajuan angin pada 4 m/s berpandukan kepada purata kelajuan angin di Malaysia. Saiz maksima garispusat bagi bilah rotor kincir angin berskala kecil adalah berukuran 7 m. Analisa yang dijalankan menggunakan kaedah *Computational Fluid Dynamics* (CFD). Di dalam projek ini, data yang diperolehi diolah menggunakan aplikasi *COSMOFlow Work*. Dengan menggunakan *COSMOFlow Work*, nilai Tork (Nm) yang diukur adalah merupakan nilai daya tujahan ke atas bilah rotor berskala kecil. Satu kajian perbandingan menggunakan *Blade Element Momentum* (BEM) tiori telah dilaksanakan untuk memastikan nilai Tork yang diperolehi menggunakan CFD dan BEM di dalam projek ini adalah selari. Ini telah membuktikan bahawa analisa projek yang telah dijalankan bertepatan dengan tiori kincir angin. Keputusan projek ini didapati benar dan tidak diragui. Secara kesimpulannya, projek ini telah mencapai objektif yang disasarkan.

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LIST OF SYMBOLS

a	Axial induction factor
a'	Angular induction factor
B	Number of blades
c	Aerofoil chord length
C_L	Lift coefficient
C_D	Drag coefficient
C_P	Power coefficient
D	Drag force
F_x	Axial force
F_θ	Tangential force
L	Lift force, angular moment
$\dot{m}$	Massflow
N	Number of blade elements
p	Pressure
P	Power
Q	Tip loss correction factor
r	Radius and radial direction
R	Blade tip radius
T	Torque
V	Absolute velocity
W	Relative velocity
x	Axial coordinate
β	Relatives flow angle onto blades

λ	Tip speed ratio
λ_r	Local Tip speed ratio
ρ	Density
σ'	Local Solidity
θ	Tangential coordinate
Ω	Blade rotational speed
ω	Wake rotational speed
γ	Aerofoil inlet angle

LIST OF ABBREVIATIONS

BEM	Blade Element Momentum Thoery
CFD	Computational Fluid Dynamics
CAD	Computer-aided Drafting

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Malaysia is a country vastly surrounded by South China Sea and The Straits of Melaka. With water body all along the shore, Malaysia has the potential of generating electrical power by means of wind turbine as renewable energy. Wave power and offshore wind power generated by wind turbine has been recognized by the international community as a renewable energy source. Wind speed analysis has been conducted by Malaysia Meteorological Service (MMS) since 1985. The offshore wind energy resources for this region have the highest potential in Peninsular Malaysia with annual vector resultant wind speed of 4 meter per second. (Chiang, Zainal, Aswatha and Seetharamu, 2003)

Wind power is generated by moving air. As the sun heats the land, the air above warms and rises. Cold air then replaces the rising air. This cycle continues and creates the wind. Over the sea, the heat by the sun is slowly cooled by the cold water. Nowadays, lots of resources can be further utilized in lieu with the relevant technologies. One of the alternatives is wind turbine. Large wind turbine technology in Netherland and other country have been used for decade to generate energy. Nevertheless, small wind turbines have big potential to be explored its capability to generate power for household application such as water pump and to generate smaller scale of power supply. (Shafarin, 2008)

1.2 PROBLEM STATEMENT

Wind energy is an alternative source of energy nowadays. By using wind power, it can produce electricity to deliver it to the industrial and residential area. This source of electricity is more efficient and low cost in long period.

When using wind energy, it can reduce the pollution in the country. The source of wind energy is from nature. By using wind energy as a part of power source for a country, it can became a solution on how to reduce pollution that become worst day by day.

Small wind turbine has a very large potential to be build in Malaysia. What is needed in common use of wind turbine are that meet a specification that is flexible enough for general application and be possible to mount almost everywhere and plug-in to the grid. Wind turbines on the market are often larger, mounted on the high towers and need larger area for safety and efficiency. The only way is therefore to specify flexible wind turbines which need a small space, cheap, low risk to install and high efficiency.

1.3 OBJECTIVES OF PROJECT

The main objective of this project is to simulate the designed wind turbine using Computational Fluid Dynamics (CFD) analysis. Another objective in this project is to compare the power produce from Computational Fluid Dynamics (CFD) analysis and calculation using Blade Element Momentum (BEM) theory. In this project, the comparison is focus on one design of wind turbine and the calculation using BEM conclude the three different design of wind turbine. The simulation and calculation are based on the same wind speed applied on the wind turbine.

1.4 SCOPES OF PROJECT

The scopes of this project are:

i. Estimate the dimension of wind turbine
ii. Design a miniature wind turbine using Computer Aided Design (CAD)
iii. Analyze the performance of wind turbine using Computational Fluid Dynamics (CFD)

CHAPTER 2

LITERATURE REVIEW

2.1 WIND TURBINE HISTORY

By the 14th century, Dutch windmills were in use to drain areas of the Rhine River delta. In Denmark by 1900, there were about 2500 windmills for mechanical loads such as pumps and mills, producing an estimated combined peak power of about 30 MW. The first known electricity generating windmill operated, was a battery charging machine installed in 1887 by James Blyth in Scotland. The first windmill for electricity production in the United States was built in Cleveland, Ohio by Charles F Brush in 1888, and in 1908 there were 72 wind-driven electric generators from 5 kW to 25 kW. The largest machines were on 24 m (79 ft) towers with four-bladed 23 m (75 ft) diameter rotors. Around the time of World War I, American windmill makers were producing 100,000 farm windmills each year, mostly for water-pumping. By the 1930s, windmills for electricity were common on farms, mostly in the United States where distribution systems had not yet been installed. In this period, high-tensile steel was cheap, and windmills were placed atop prefabricated open steel lattice towers. (Chiang, Zainal, Aswatha and Seetharamu, 2003)

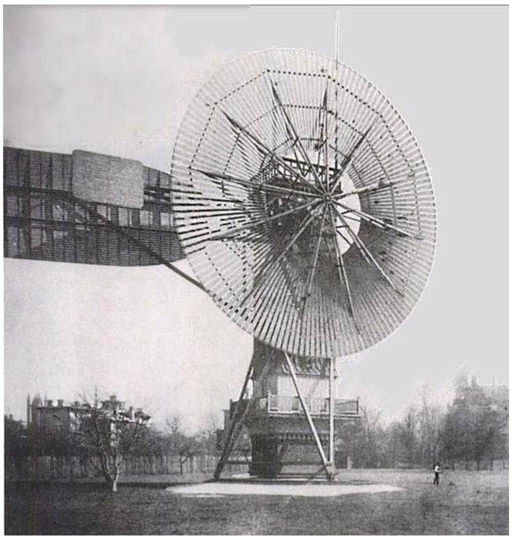


Figure 2.1: The First Automatically Operated Wind Turbine

(Source: Sofian,2006)

A forerunner of modern horizontal-axis wind generators was in service at Yalta, USSR in 1931. This was a 100 kW generator on a 30 m (100 ft) tower, connected to the local 6.3 kV distribution system. It was reported to have an annual capacity factor of 32 per cent, not much different from current wind machines. In the fall of 1941, the first megawatt-class wind turbine was synchronized to a utility grid in Vermont. The Smith-Putnam wind turbine only ran for 1100 hours. Due to war time material shortages the unit was not repaired. (RCAS,2004)

The first utility grid-connected wind turbine operated in the UK was built by John Brown & Company in 1954 in the Orkney Islands. It had an 18 meter diameter, three-bladed rotor and a rated output of 100 kW. (RCAS, 2004)

2.2 HORIZONTAL AXIS WIND TURBINE

There are many types of wind turbines. They can be separated into two general types based on the axis about which the turbine rotates. Turbines that rotate around a horizontal axis are most common.(Sofian, 2006)

All existing HAWTs (or Horizontal Axis Wind Turbine) have the main rotor shaft and generator at the top of a tower, and be pointed to the direction of the wind. Most of the wind turbine has gearbox. The use of the gearbox is to turns the slow rotation of the blades into a quicker rotation that is more suitable for generating electricity. (Shafarin, 2008)

Since a tower produces turbulence behind it, the turbine is usually pointed upwind of the tower. Turbine blades are made stiff to prevent the blades from being pushed into the tower by high winds. Additionally, the blades are placed a considerable distance in front of the tower and are sometimes tilted up a small amount. (Shafarin 2008)

Figure 2.2: Horizontal Axis Wind Turbine

(Source: Shafarin,2008)

2.2.1 Modern Wind Turbines

Turbines used in wind farms for commercial production of electric power are usually consist of three blades and pointed into the wind by computer controlled motors. These have high tip speeds of over 320 km/h (200 miles per hour), high efficiency, and low torque ripple, which contribute to good reliability. The blades are usually colored light gray to blend in with the clouds and range in length from 20 to 40 meters (65 to 130 ft) or more. The tubular steel towers range from 60 to 90 meters (200 to 300 feet) tall. The blades rotate at 10-22 revolutions per minute. At 22 rotations per minute the tip speed exceeds 300 ft per second. A gear box is commonly used to step up the speed of the generator, although designs may also use direct drive of an annular generator.

Some models operate at constant speed, but more energy can be collected by variable-speed turbines which use a solid-state power converter to interface to the transmission system. All turbines are equipped with shut-down features to avoid damage at high wind speeds.

Small wind turbine can be rigid connected for residential generation or can be used in off grid applications such as water pumping or battery charging. Small wind turbines are typically installed as a single unit or in small numbers. The smallest turbines are normally produces less then 1kW power. Turbines with power ratings between 1kW to 20kW are normally used for small business, residential power and government facilities.

2.2.2 Parts of Wind Turbine

Wind turbines come in many sizes and configurations and are built from wide range of materials. In simple terms, a wind turbine consists of a rotor that has wing shaped blades attached to a hub; a nacelle that houses a drive train consisting of a gearbox, connecting shafts, support bearings, the generator, plus other machinery; a tower; and ground mounted electrical equipment. (Priceton)

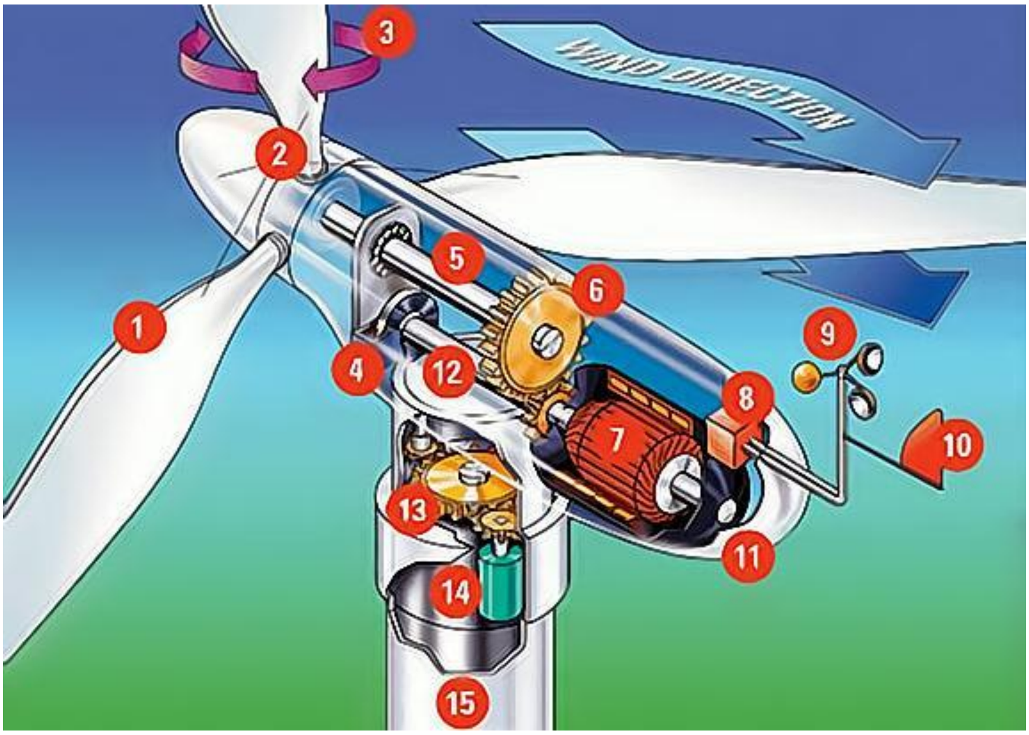


Figure 2.3: Parts of Wind Turbine

(Source: Princeton)

1. Blades:

   Most turbines have either two or three blades. As the wind flow through the blade, it’s rotate. Blades come in various sizes over the years. In the early 1980s, a typical blade was likely to be 33 feet (10 meters) long, and such a wind turbine could generate about 45 megawatt-hours per year. By 1990 the typical blade measured 89 feet (27 meters) and could produce 550 kilowatt-hours per year. In the early twenty-first century blades as long as 233 feet (71 meters) can generate 5,600 megawatt-hours per year.

2. Rotor:

   The rotor is the hub around which the blades are connected. The rotor is the main component, because it converts the wind’s kinetic energy into torque, or turning power.

3. Pitch:

   The pitched are used to control the rotor speed and keep the rotor from turning as the wind flow through it. The controls of the rotor are used to produce electricity.

4. Brake:

   Disc brakes are used to stop the rotor if there are emergencies. It can be applied mechanically, electrically, or hydraulically.

5. Low-speed shaft:

   The rotor turns the low-speed shaft at about 30 to 60 rotations per minute.

6. Gear box:

   Gears connect the low-speed shaft to the high-speed shaft and increase the rotational speeds from about 30 to 60 rotations per minute (rpm) to about 1000 to 1800 rpm to produce electricity. The gear box is a costly part of the wind turbine. Nowadays engineers are exploring "direct-drive" generators that operate at lower rotational speeds and don't need gear boxes.

7. Generator:

   In the wind turbine, the generator produces 60-cycle AC electricity.

8. Controller:

   The controller starts up the machine at wind speeds of about 12 to 25 kilometer per hour (km/h) and shuts off the machine at about 88 km/h. Turbines do not operate at wind speeds above about 88 km/h because the wind turbine might be damaged at high wind speed.

9. Anemometer:

   The used of anemometer is to measures the wind speed and transmits wind speed data to the controller. The controller will starts up the wind turbine.

10. Wind vane:

    Wind vane is to measures the wind direction and communicates with the yaw drive.

11. Nacelle**:**

    In the nacelle, it consists the gearbox, the yaw mechanism, and the electric generator.

12. High-speed shaft:

    The high speed shaft is to drives the generator and yet produces electricity.

13. Yaw drive:

    The yaw mechanism automatically senses the direction of the wind and rotates the rotor to keep it facing into the direction of the wind.

14. Yaw motor:

    Powers the yaw drive.

15. Towers:

    Towers are made from tubular steel, concrete or steel lattice. Because wind speed increases with height, taller towers enable turbines to capture more energy and generate more electricity

2.2.3 Wind Turbine Technology Overview

Wind generation equipment is categorized into three general classifications: (Global Energy Concept, 2005)

1. Utility-Scale

   In Utility scale, it needs a wind turbine that can produce a electricity about 900 kW to 2 MW per turbine. The wind turbine are typically installed in large areas but can also be installed in small quantities on distribution lines or known as distributed generation. Utility scale development is the most common form of wind energy development in the U.S.

2. Industrial-Scale

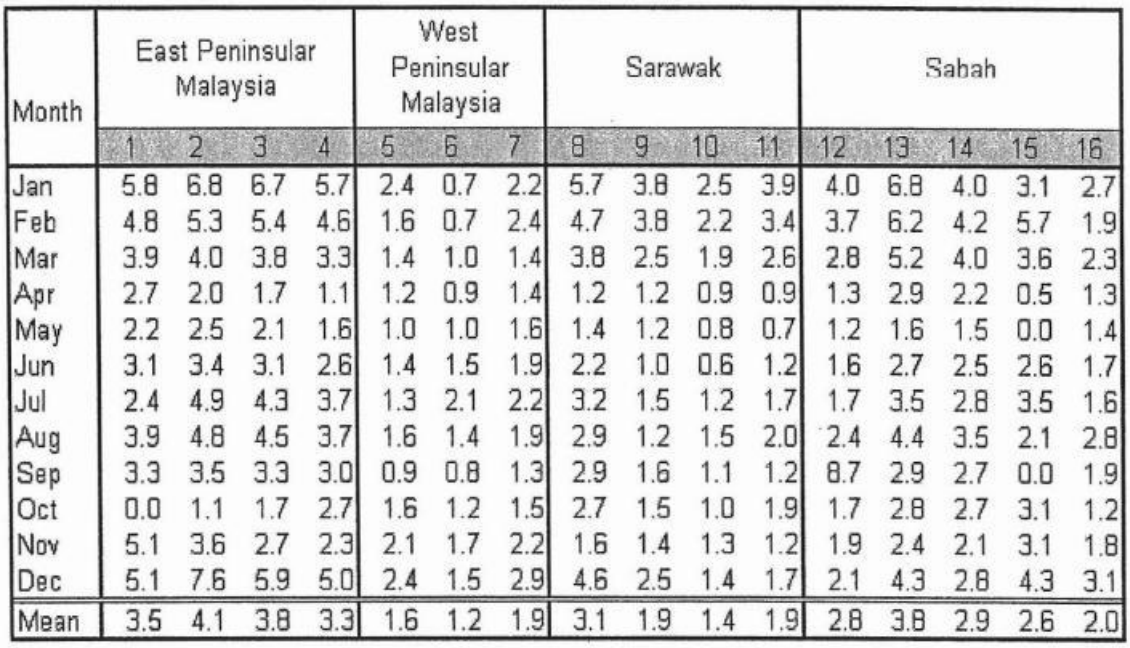
   In Industrial scale, it needs a wind turbine that can produce a electricity about 50 kW to 250 kW. For this type of wind turbine, it is often in conjunction with diesel generation or load-side generation to reduce consumption of higher cost grid power and possibly to even reducing peak loads.

3. Residential-Scale

   In Residential scale, it needs a wind turbine that can produce a electricity about 400 watts to 50 kW For this type of wind turbine, it is intended for remote power, battery charging, or net metering type generation. The small turbines can be used in conjunction with solar photovoltaic, batteries, and inverters to provide constant power at remote locations.

2.3 AVERAGE WIND SPEED IN MALAYSIA

The mean wind speed over the sea surface around the sea surrounding Malaysia is generally below 5 m/s. Wind speed above 5 m/s is during the northeast monsoon season and for the rest of the year, the wind speed is low. Table 2.1 shows the average of wind speed in Malaysia from January to December. (Chiang, Zainal, Aswatha and Seetharamu, 2003)



Month	East Peninsular Malaysia				West Peninsular Malaysia			Sarawak				Sabah				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Jan	5.8	6.8	6.7	5.7	2.4	0.7	2.2	5.7	3.8	2.5	3.9	4.0	6.8	4.0	3.1	2.7
Feb	4.8	5.3	5.4	4.6	1.6	0.7	2.4	4.7	3.8	2.2	3.4	3.7	6.2	4.2	5.7	1.9
Mar	3.9	4.0	3.8	3.3	1.4	1.0	1.4	3.8	2.5	1.9	2.6	2.8	5.2	4.0	3.6	2.3
Apr	2.7	2.0	1.7	1.1	1.2	0.9	1.4	1.2	1.2	0.9	0.9	1.3	2.9	2.2	0.5	1.3
May	2.2	2.5	2.1	1.6	1.0	1.0	1.6	1.4	1.2	0.8	0.7	1.2	1.6	1.5	0.0	1.4
Jun	3.1	3.4	3.1	2.6	1.4	1.5	1.9	2.2	1.0	0.6	1.2	1.6	2.7	2.5	2.6	1.7
Jul	2.4	4.9	4.3	3.7	1.3	2.1	2.2	3.2	1.5	1.2	1.7	1.7	3.5	2.8	3.5	1.6
Aug	3.9	4.8	4.5	3.7	1.6	1.4	1.9	2.9	1.2	1.5	2.0	2.4	4.4	3.5	2.1	2.8
Sep	3.3	3.5	3.3	3.0	0.9	0.8	1.3	2.9	1.6	1.1	1.2	8.7	2.9	2.7	0.0	1.9
Oct	0.0	1.1	1.7	2.7	1.6	1.2	1.5	2.7	1.5	1.0	1.9	1.7	2.8	2.7	3.1	1.2
Nov	5.1	3.6	2.7	2.3	2.1	1.7	2.2	1.6	1.4	1.3	1.2	1.9	2.4	2.1	3.1	1.8
Dec	5.1	7.6	5.9	5.0	2.4	1.5	2.9	4.6	2.5	1.4	1.7	2.1	4.3	2.8	4.3	3.1
Mean	3.5	4.1	3.8	3.3	1.6	1.2	1.9	3.1	1.9	1.4	1.9	2.8	3.8	2.9	2.6	2.0

Table 2.1: Average wind speed in Malaysia [8]

(Source: Chiang, Zainal, Aswatha and Seetharamu, 2003)

2.4 BLADE ELEMENT AND MOMENTUM THEORY

Blade Element Momentum Theory equates two methods of examining how a wind turbine operates. The first method is to use a momentum balance on a rotating annular stream tube passing through a turbine. The second is to examine the forces generated by the aerofoil lift and drag coefficients at various sections along the blade. (Grant Ingram, 2005)

2.4.1 Momentum Theory

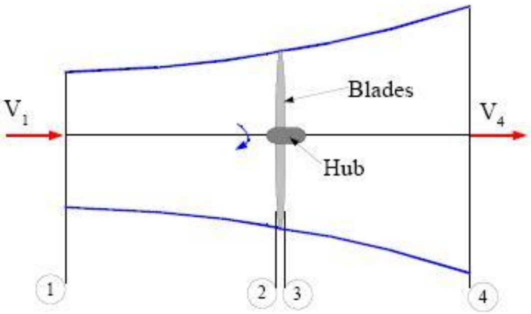


Figure 2.4: Axial Stream Tube Around A Wind Turbine
(Source: Grant Ingram, 2005)

Consider the stream tube around a wind turbine shown in figure 2.4. Assume $p_1 = p_4$ and that$V_2 = V_3$. We can assume between 1 and 2 and between 3 and 4 the flow is frictionless so we can apply Bernoulli's equation. After some algebra:

$$p_2 - p_3 = \frac{1}{2}\rho(V_1^2 - V_4^2) \tag{2.1}$$

Noting that force is pressure times area we find that:

$$dF_x = \frac{1}{2}\rho(V_1^2 - V_4^2)dA \tag{2.2}$$

Define a the axial induction factor as:

$$a = \frac{V_1 - V_2}{V_1} \tag{2.3}$$

$$a = (1 + \frac{4cos^2\beta}{\sigma' C_L \sin\beta})^{-1} \tag{2.4}$$

$$V_4 = V_1\,(1 - 2a) \tag{2.5}$$

Substituting:

$$dF_x = \frac{1}{2}\rho V_1^2[4a(1-a)]2\pi r dr \tag{2.6}$$

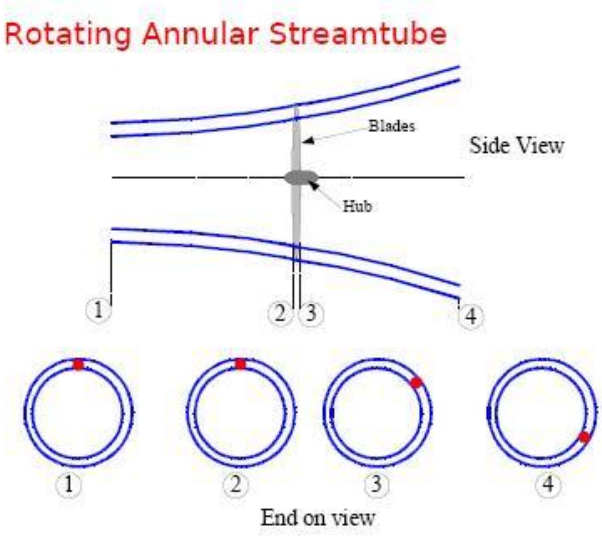


Figure 2.5: Rotating annular stream tube

(Source: Grant Ingram, 2005)

For the rotating annular element:

$$dT = \rho 2\pi r dr V_2 \omega r^2 = \rho V_2 \omega r^2 2\pi r dr \tag{2.7}$$

Define angular induction factor a' :

$$a' = \frac{\omega}{2\Omega} \tag{2.8}$$

$$a' = \frac{1-3a}{4a-1} \tag{2.9}$$

2.4.2 Blade Element Theory

Blade element theory relies on two key assumptions:

- There are no aerodynamic interaction between different blade elements
- The forces on blade elements are solely determined by the lift and drag coefficients

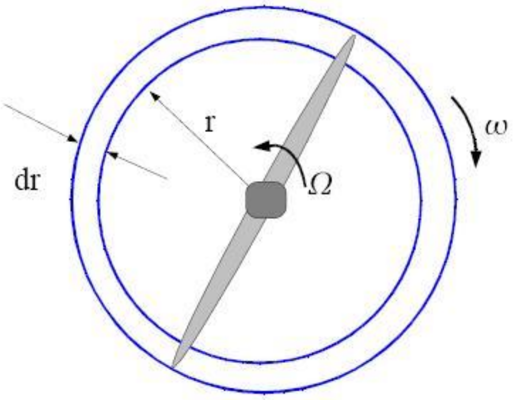


Figure 2.6: Rotating Annular Stream tube

(Source: Grant Ingram, 2005)

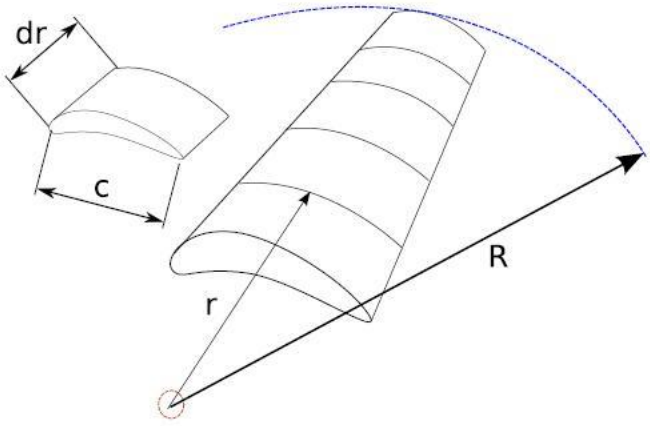


Figure 2.7: The Blade Element Model

(Source: Grant Ingram, 2005)

Consider a blade divided up into N element as shown in figure 2.7. Each of the blade elements will experience a slightly different flow as they have different rotational speed (Ωr), a different chord angle (c) and a different twist angle (γ). Blade element theory involves dividing up the blade into a sufficient number of elements and calculating the flow at each one. (Grant Ingram, 2005)

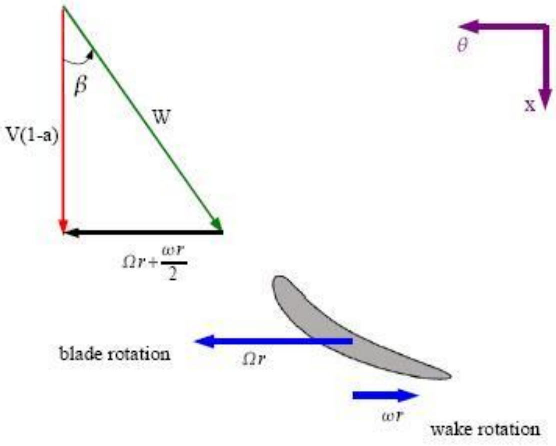


Figure 2.8: Flow onto the turbine blade

(Source: Grant Ingram, 2005)

Lift and drag coefficient data are available for a variety of aerofoil from wind tunnel data. Since most wind tunnels testing is done with the aerofoil stationary we need to relate the flow over the moving aerofoil to that of the stationary test. To do this we use the relative velocity over the aerofoil. (Grant Ingram, 2005)

The flow around the blades starts at station 2 in Figures 2.5 and 2.4 and ends at station 3. At inlet to the blade the flow is not rotating, at exit from the blade row the flow rotates at rotational speedω. That is over the blade due to wake rotation has been introduced. The average rotational flow over the blade due to wake rotation is $\omega/2$. The blade is rotating with speed Ω. The average tangential velocity that the blade experiences is therefore $\Omega r + \frac{\omega r}{2} \omega r$. (Grant Ingram, 2005)

From Figure 2.7 we can note that:

$$\Omega r + \frac{\omega r}{2} = \Omega r(1 + a') \tag{2.10}$$

$V_2 = V_1(1 - a)$ so:

$$tan\beta = \frac{\Omega r(1 + a')}{V(1 - a)} \tag{2.11}$$

The local tip ratio is defined as:

$$\lambda_r = \frac{\Omega r}{V} \tag{2.12}$$

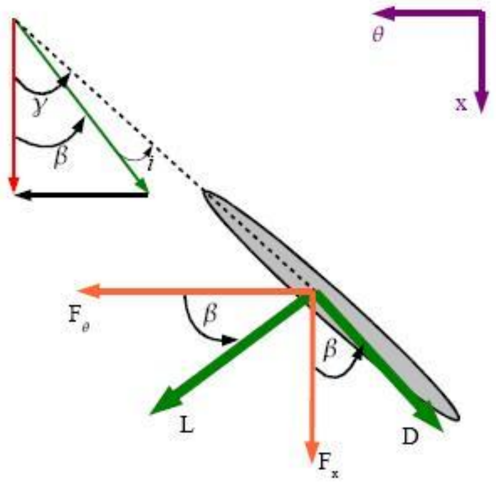


Figure 2.9: Forces on the turbine blade

(Source: Grant Ingram, 2005)

So the expression for tan β can be further simplified:

$$\beta = 90° - \frac{2}{3} tan^{-1}\left(\frac{1}{\lambda_r}\right) \tag{2.13}$$

From Figure 2.7:

$$W = \frac{V(1-a)}{\cos\beta} \tag{2.14}$$

The forces on blade element are shown in Figure 2.9. For each blade element:

$$dF_\theta = dLcos\beta - dDsin\beta \tag{2.15}$$

$$dF_x = dLsin\beta + dDcos\beta \tag{2.16}$$

$$dL = C_L \frac{1}{2} \rho W^2 cdr \tag{2.17}$$

$$dD = C_D \frac{1}{2} \rho W^2 cdr \tag{2.18}$$

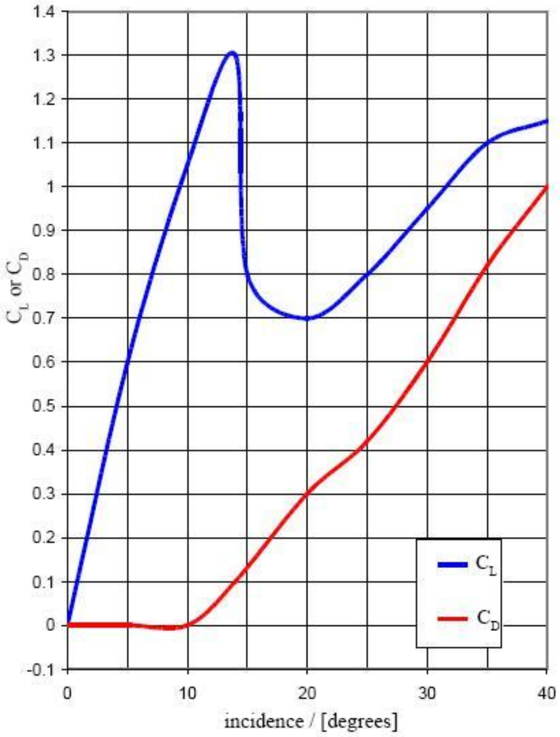


Figure 2.10: Lift and Drag Coefficients for a NACA 0012 Aerofoil

(Source: Grant Ingram, 2005)

Lift and Drag coefficients foe NACA 0012 aerofoil are shown in Figure 2.10 this graph shows that for low values of incidence the aerofoil successfully produces a large amount of lift with little drag. If there are B blades: (Grant Ingram, 2005)

$$dF_x = B\frac{1}{2}\rho W^2(C_L sin\beta + C_D sin\beta)crdr \tag{2.19}$$

$$dF_\theta = B\frac{1}{2}\rho W^2(C_L cos\beta - C_D sin\beta)cdr \tag{2.20}$$

The torque on an element dT is simply the tangential force multiplied by the radius:

$$dT = B\frac{1}{2}\rho W^2(C_L cos\beta - C_D sin\beta)crdr \tag{2.21}$$

By noting that β and W in terms of induction factors:

$$dF_x = \sigma^{'}\pi\rho\frac{V^2(1-a)^2}{cos^2\beta}C_L sin\beta + C_D cos\beta)rdr \tag{2.22}$$

$$dT = \sigma^{'}\pi\rho\frac{V^2(1-a)^2}{cos^2\beta}(C_L cos\beta - C_D sin\beta)r^2dr \tag{2.23}$$

Where σ´ is called the local solidity

$$\sigma^{;} = \frac{Bc}{2\pi r} \tag{2.24}$$

2.4.3 Tip Loss Correction

At the tip of the turbine blade losses are introduced in a similar manner to those found in wind tip vorticies on turbine blades. This correction factor Q varies from 0 to 1. (Grant Ingram, 2005)

$$Q = \frac{2}{\pi}cos^{-1}\left[\exp\left\{-\left(\frac{\frac{B}{2}\left[1-\frac{r}{R}\right]}{\frac{r}{R}cos\beta}\right)\right\}\right] \tag{2.25}$$

The result of cos^{-1} must be in radian. The tip loss correction then applied to equation

$$dF_x = Q\rho V_1^2[4a(1-a)]\pi rdr \tag{2.26}$$

$$dT = Q4a^{'}(1-a)\rho V\Omega r^3\pi dr \tag{2.27}$$

2.4.4 Power Output

The contribution to the total power from each annulus is:

$$dP = \Omega dT \tag{2.28}$$

The total power of the rotor is:

$$P = \int_{r_h}^{R} dPdr = \int_{r_h}^{R} \Omega dTdr \tag{2.29}$$

Where r_h is the hub radius. The power coefficient is:

$$C_P = \frac{P}{P_{wind}} = \frac{\int_{r_h}^{R} \Omega dT}{\frac{1}{2}\rho\pi R^2 V^3} \tag{2.30}$$

$$C_P = \frac{8}{\lambda^2}\int_{\lambda_h}^{\lambda} Q\lambda_r^3 a^{'}(1-a)\left[1-\frac{C_D}{C_L}tan\beta\right]d\lambda_r \tag{2.31}$$

2.5 COMPUTATIONAL FLUID DYNAMICS (CFD)

Computational Fluid Dynamics (CFD) is the analysis of system involving fluid flow, heat transfer and associated phenomenon by means of computer based simulation. The example of the problem that could be analyzed using CFD is the aerodynamics of aircraft and vehicle. (John F. Wendt, 2008)

From 1960s the aerospace industry has integrated CFD technique into the design, R&D and manufacture of aircraft and jet engines. Nowadays, the CFD has been widely applied to predict drag force, under – bonnet air flows and in car environment by motor vehicle manufacturer and also used to design of internal combustion engines, combustion chambers of gas turbine and furnaces. (Song, Keane, Eres, Pound and Cox)

There are the advantages of using the CFD compared to experimental testing. By using CFD, ones can produce extremely large volume of results at virtually no added expenses and it is very cheap to perform parametric studies and also for instance to optimize the equipment performance. In contrast, conducting the experimental testing will involve a variable cost in terms of facility hire and time consumption for data collection and model development. (Sufian, 2006)

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

For methodology in Computational Fluid Dynamic analysis of a miniature wind turbine, we noticed that there are several parameters in order to complete the research criteria. The parameters show the step by step procedure and also including a flow chart as a guide. The parameters are:

- Literature study
- Wind Turbine system
- Design of Wind turbine
- CFD analysis

3.2 FLOW CHART

A flow chart is needed to make sure the objective of the project is complete successfully. The flow chart for overall project shows in Figure 3.1 has been created due to planning from the beginning to the end.

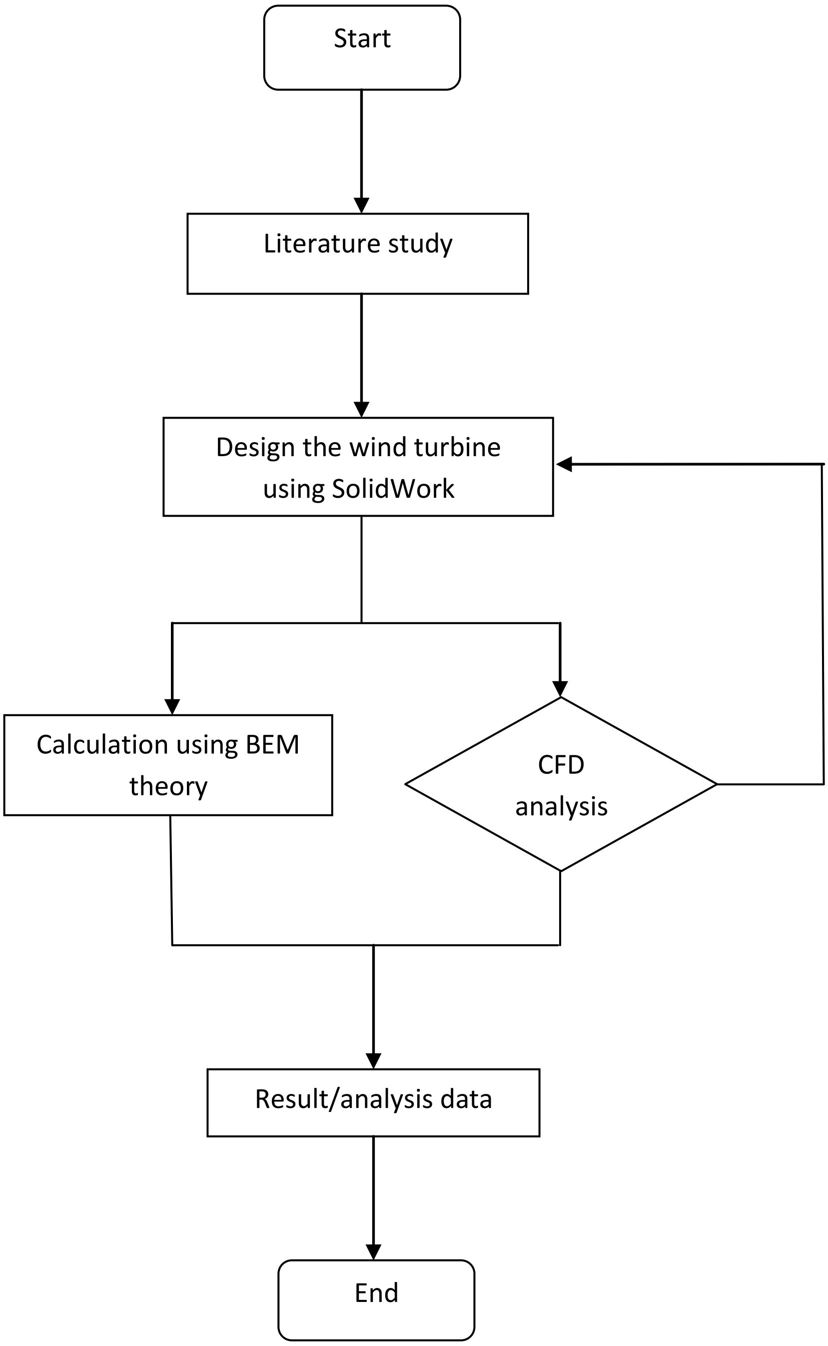


Figure 3.1: Flow Chart

3.2.1 Literature review

The important of literature review is to guide, referring planning of this project. The information such as Blade Element Momentum Theory, the wind turbine and the usage of CFD analysis have been used in this project.

All the information are come from:

- Journal
- Article
- Experience engineer
- Books
- Renewable Energy Resources

1.2.2 CAD drawing

The data for CAD drawing are collected from the literature review of small wind turbine. The collections of data dimension are important to make sure it can be simulate using CFD analysis to get the exact value of pressure and torque. The dimension is shown below.

- Tower (height; 7.1m diameter:0.2m)
- Nacelle (length: 0.95m diameter: 0.3m)
- Blade (length: 3.6m diameter: 0.2m width: 0.5m)

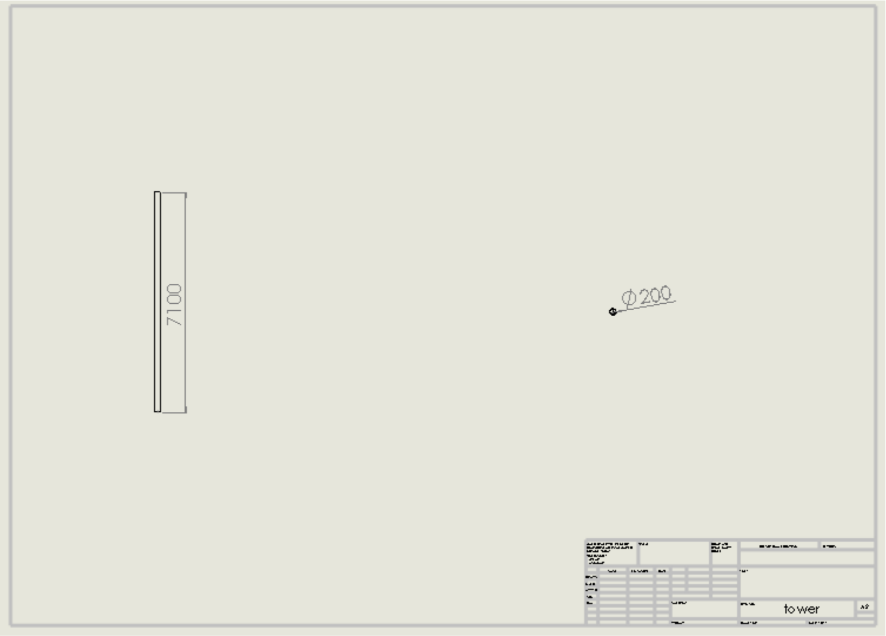


Figure 3.2: The dimension of wind turbine tower using CAD

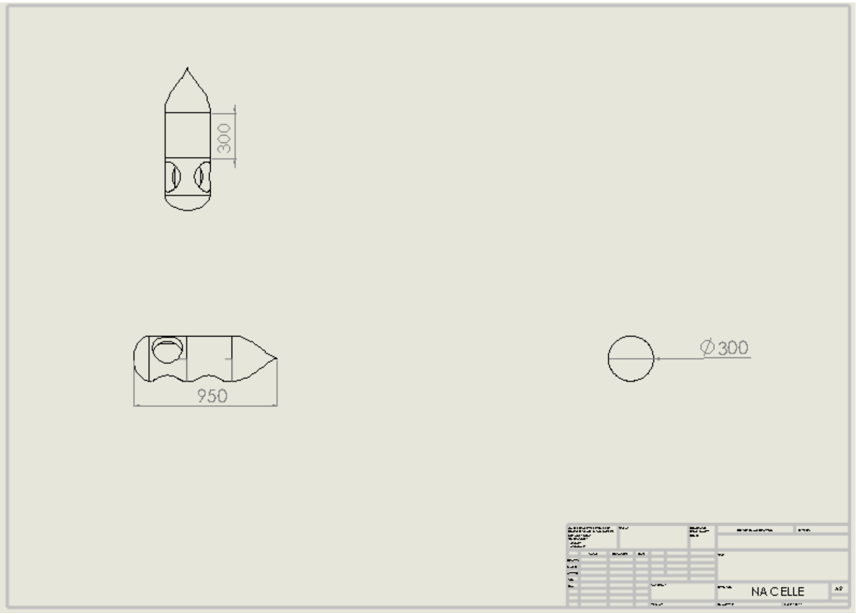


Figure 3.3: The dimension of wind turbine nacelle using CAD

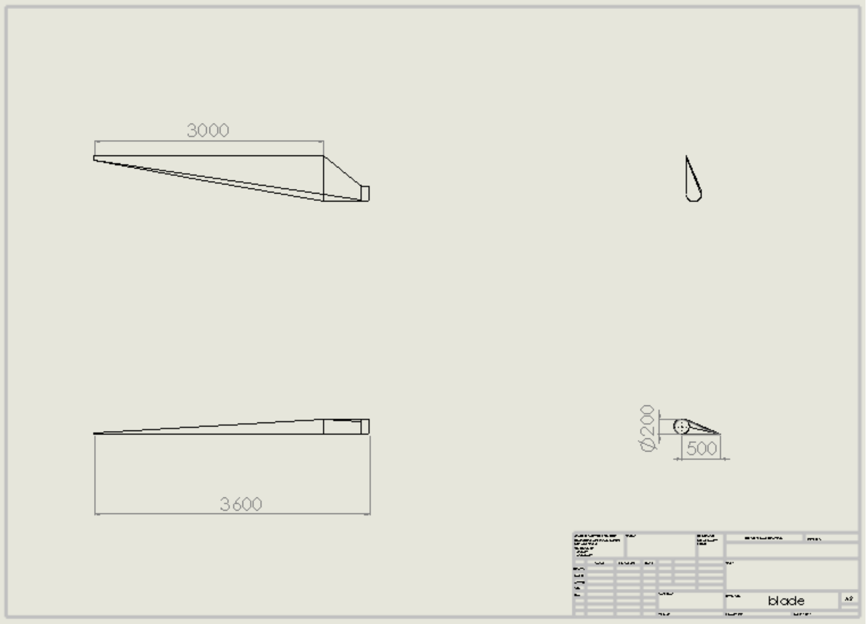


Figure 3.4: The dimension of wind turbine blades using CAD

3.2.3 SolidWork modeling

After drawing a model of wind turbine using CAD, the model then transfered to SolidWork modeling in 3D forms.

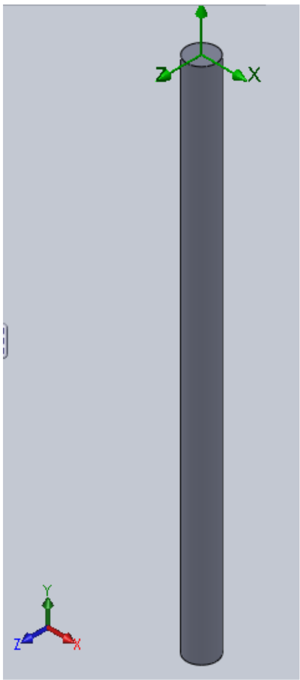


Figure 3.5: SolidWork model of wind turbine tower

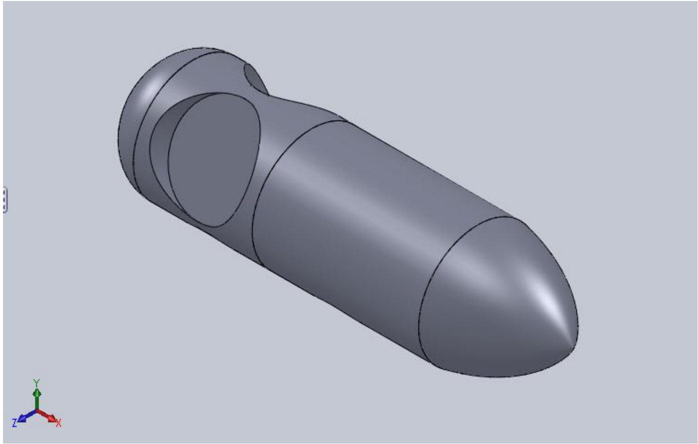


Figure 3.6: SolidWork model of wind turbine nacelle

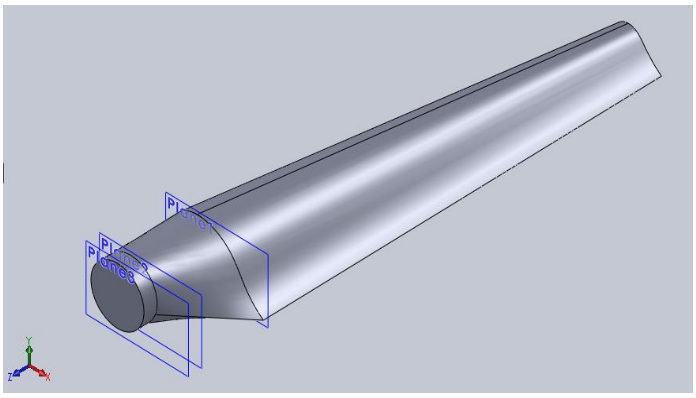


Figure 3.7: SolidWork model of wind turbine blade

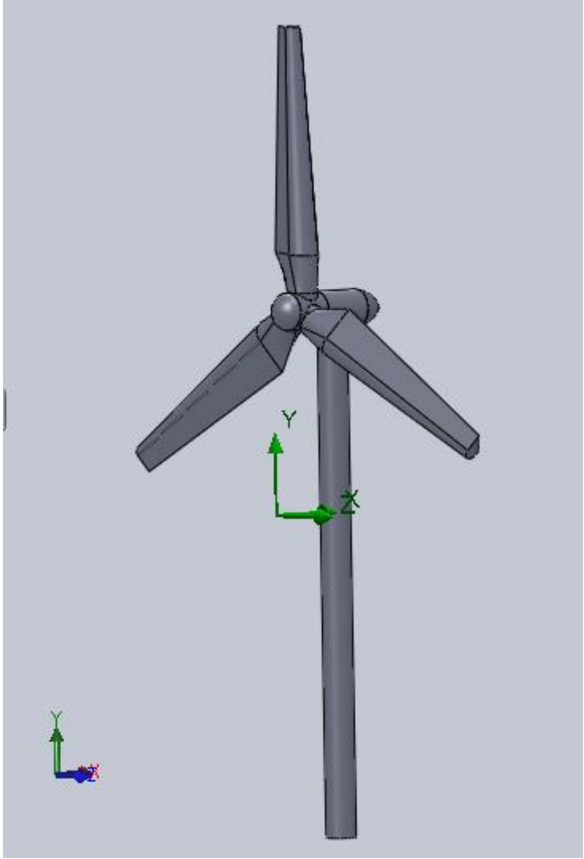


Figure 3.8: SolidWork model of wind turbine

3.3 CFD ANALYSIS

In this project, CFD analysis is the next step after modeling the wind turbine using SolidWork. CFD analysis in this project will be run using the COSMOSFloWorks software. At this stage, the air flow will be set as 4 m/s due to average wind speed in Malaysia. The boundary condition in this project is external flow with adiabatic wall. Figure 3.8 shows the boundary condition of CFD analysis.

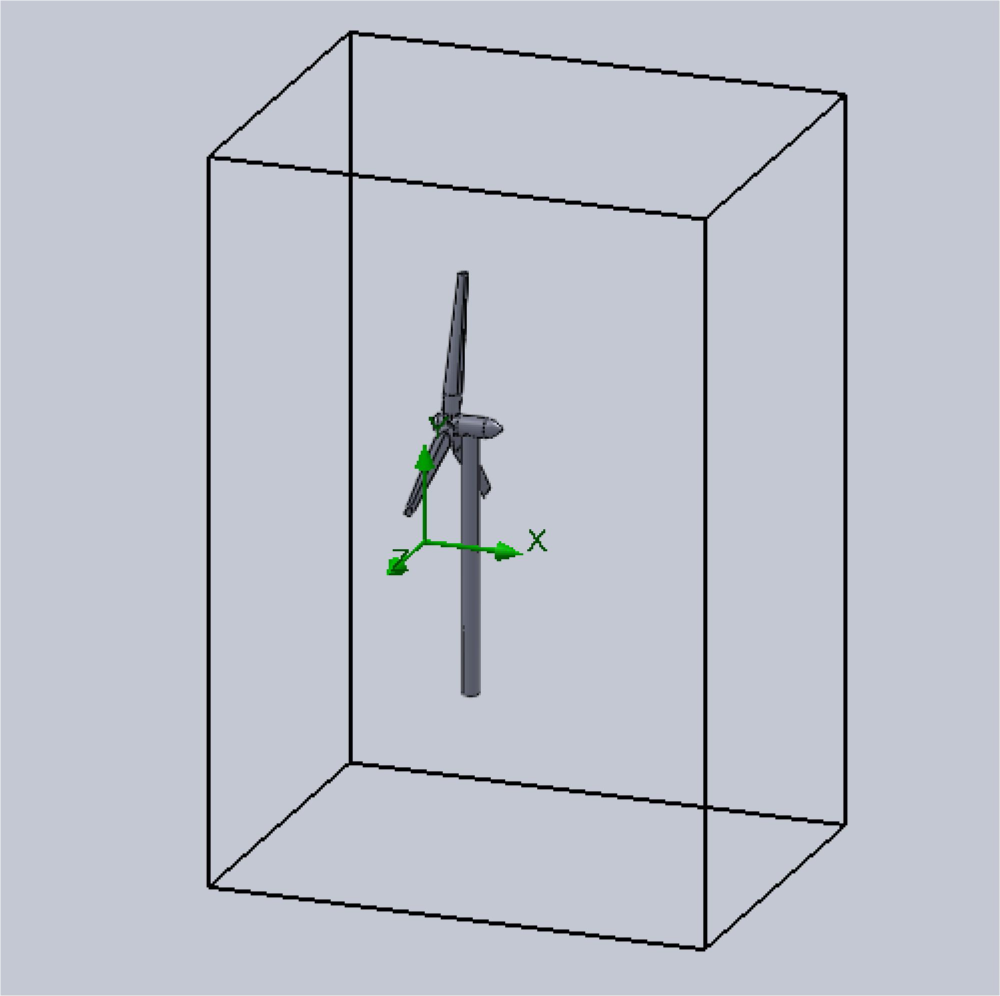


Figure 3.9: Boundary condition of CFD analysis

CHAPTER 4

RESULT AND DISCUSSION

4.1 INTRODUCTION

The purpose of this chapter is to calculate, analyze and discuss the result of the project. The data for calculation and analyzing are taken from the literature review. As mention before, the parameters being search in CFD is Torque and Force acting on a blade.

4.2 DATA ANALYSIS

4.2.1 Blade Element Momentum (BEM) equation

In BEM equation, the main parameters to be used are the wind speed, diameter of the wind turbine, the tip radius of a blade, the aerofoil angle and aerofoil chord length. In this project, the parameters are referring from the literature review.

- Wind speed, $v = 4$ m/s
- Diameter, $D= 7$ m
- tip radius, $r = 2$ m
- Aerofoil inlet angle,$\gamma = 84.9$
- Aerofoil chord length, $c = 0.44$

4.2.2 Calculation of Tip Loss Correction and Torque

To calculate power produced form each wind turbine, the value of tip loss correction, Q and torque, dT has to determine. Various diameter of wind turbine have been used to compare the power produces Value of axial induction factor, a and angular induction factor, a’ have to determine before measuring the torque value for each blade. Table 4.1 below shows the value of each parameter.

Diameter of Wind Turbine	**Radius direction, r**	**Local tip speed ratio, λ_r**	**Axial induction factor, a**	**Angular induction factor, a’**
2 m	0.20 m	0.32	0.2260	0.8994
5 m	1.00 m	1.60	0.2443	0.0676
7 m	2.00 m	3.20	0.2533	0.0180

Table 4.1: Value of parameters of various wind turbine diameter

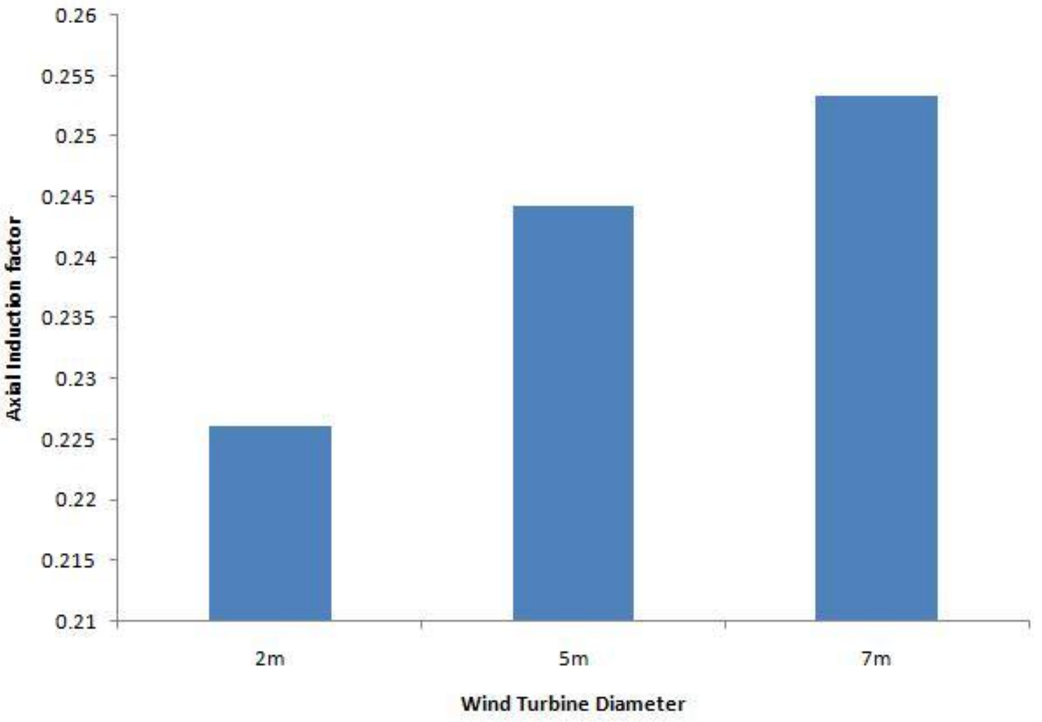


Figure 4.1: Axial Induction Factor, a for 2m, 5m and 7m diameter blade

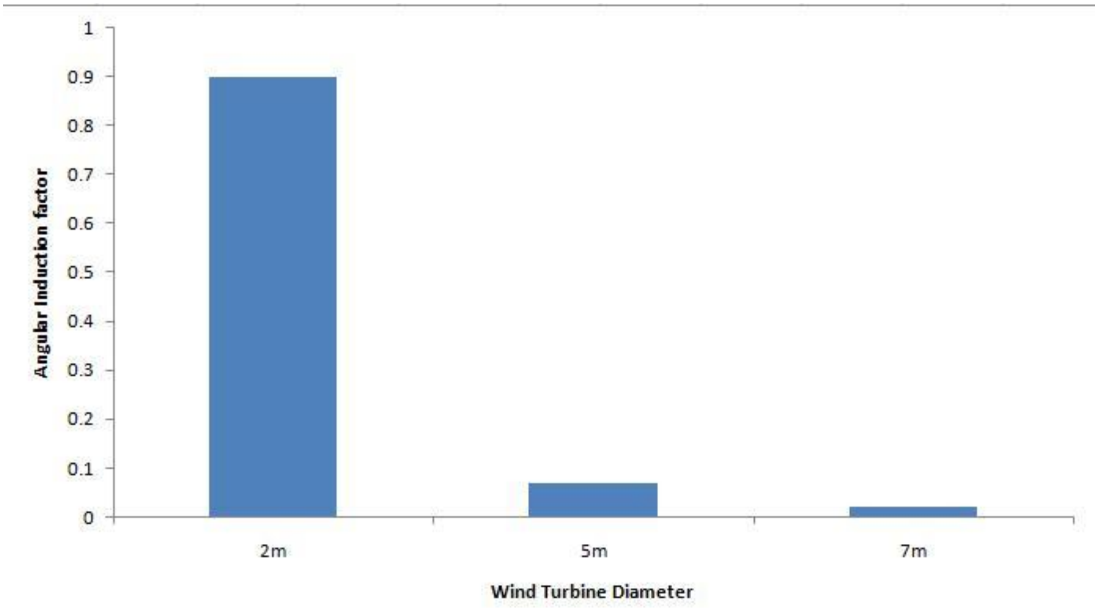


Figure 4.2: Angular Induction Factor, a' for 2m, 5m and 7m diameter blade

4.2.2.1 Sample calculation of Tip Loss Correction

To calculate tip loss correction, Q equation (2.25) was used. From equation (2.25):

For 2m rotor diameter:

$$Q = \frac{2}{\pi} cos^{-1}\left[\exp\left\{-\left(\frac{\frac{B}{2}\left[1-\frac{r}{R}\right]}{\frac{r}{R} cos\beta}\right)\right\}\right]$$

$$Q = \frac{2}{\pi} cos^{-1}\left[\exp\left\{-\left(\frac{\frac{3}{2}\left[1-\frac{0.2}{1}\right]}{\frac{0.2}{1}\cos 81.049}\right)\right\}\right]$$

$$Q = 1$$

For 5m rotor diameter

$$Q = \frac{2}{\pi} cos^{-1} \left[\exp \left\{ - \left(\frac{\frac{B}{2}\left[1 - \frac{r}{R}\right]}{\frac{r}{R} cos\beta} \right) \right\} \right]$$

$$Q = \frac{2}{\pi} cos^{-1} \left[\exp \left\{ - \left(\frac{\frac{3}{2}\left[1 - \frac{1}{2.5}\right]}{\frac{1}{2.5} \cos 81.049} \right) \right\} \right]$$

$$Q = 0.959$$

For 7m rotor diameter

$$Q = \frac{2}{\pi} cos^{-1} \left[\exp \left\{ - \left(\frac{\frac{B}{2}\left[1 - \frac{r}{R}\right]}{\frac{r}{R} cos\beta} \right) \right\} \right]$$

$$Q = \frac{2}{\pi} cos^{-1} \left[\exp \left\{ - \left(\frac{\frac{3}{2}\left[1 - \frac{2}{3.5}\right]}{\frac{2}{3.5} cos 81.049} \right) \right\} \right]$$

$$Q = 0.84$$

Diameter of Wind Turbine (m)	Tip Loss Correction, Q
2m	1
5m	0.959
7m	0.84

Table 4.2: Value of Tip Loss Correction

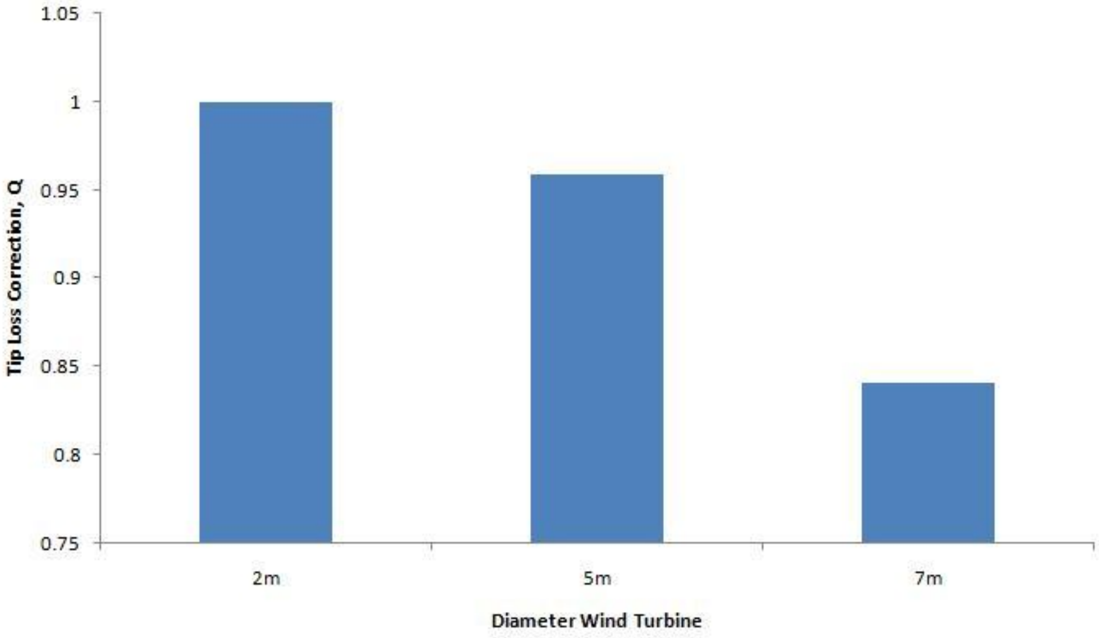


Figure 4.3: Tip Loss Correction for 2m, 5m and 7m diameter blade

4.2.2.2 Sample calculation of Torque

After calculate Tip Loss Correction, Q the value of torque was calculated. To calculate torque for different blade diameter, equation (2.27) was used.

For 2m rotor diameter:

$$dT = Q4a^{'}(1-a)\rho V\Omega r^{3}\pi dr$$

$$dT = (1)4(0.8994)(1-0.2260)(1.23)(4)(6.4)(0.20)^{3}\pi dr$$

$$dT = 2.204\ Nm$$

For 5m rotor diameter:

$$dT = Q4a^{'}(1-a)\rho V\Omega r^{3}\pi dr$$

$$dT = (0.959)4(0.0676)(1-0.2443)(1.23)(4)(6.4)(1)^{3}\pi dr$$

$$dT = 19.385\ Nm$$

For 7m rotor diameter:

$$dT = Q4a'(1-a)\rho V\Omega r^3 \pi dr$$

$$dT = (0.84)4(0.0180)(1-0.2533)(1.23)(4)(6.4)(2)^3\pi dr$$

$$dT = 35.739\ Nm$$

Diameter of Wind Turbine (m)	Torque, dT (Nm)
2m	2.204 Nm
5m	19.385 Nm
7m	35.739 Nm

Table 4.3: Value of Torque for each blade

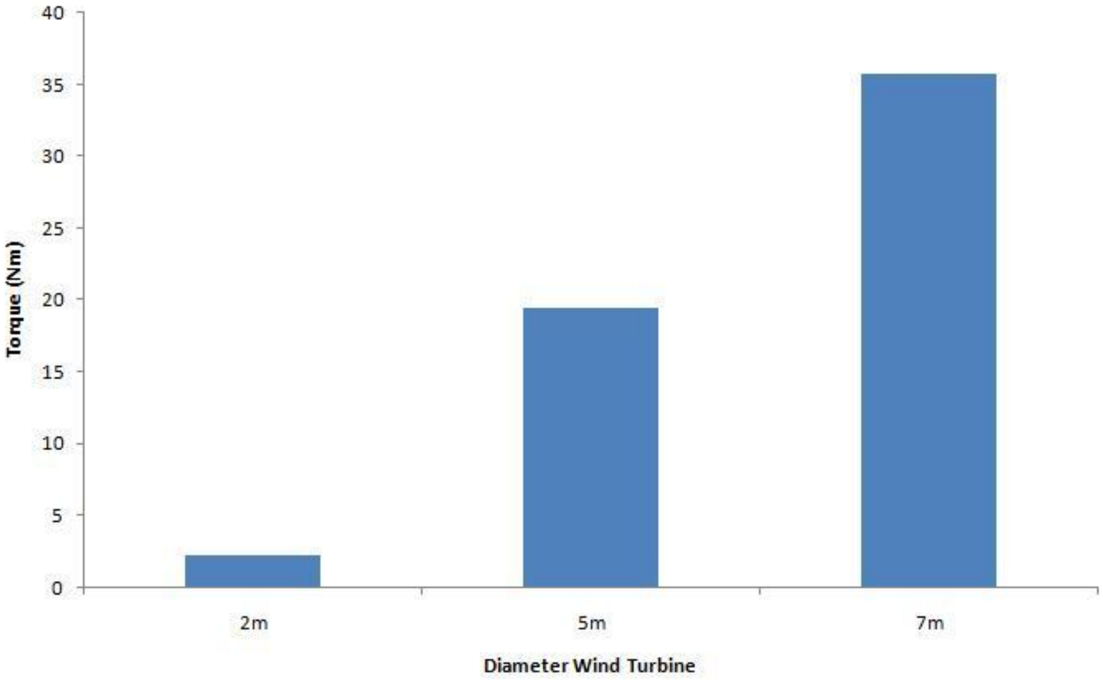


Figure 4.4: Torque (Nm) for 2m, 5m and 7m diameter blade

4.2.3 Calculation of Power

After calculate the value of Torque and Tip Loss Correction, the value of power produce was calculated. Table below shows the value of Torque and Tip Loss Correction for different diameter of wind turbine.

Diameter of Wind Turbine (m)	Tip Loss Correction, Q	Torque, dT (Nm)
2m	1	$2.204\ Nm$
5m	0.959	$19.385\ Nm$
7m	0.84	$35.739\ Nm$

Table 4.4: Value of Tip Loss Correction, Q and Torque, dT (Nm)

4.2.3.1 Sample Calculation of Power

In this calculation, equation (2.28) and (2.29) were used.

For 2m rotor diameter:

$$dP = \Omega dT$$

$$dP = (6.4)(2.204)$$

$$dP = 14.106$$

The total power from rotor is:

$$P = \int_{r_h}^{R} dP dr$$

$$P = \int_{0.2}^{1} 14.106\, dr$$

$$P = 11.28\, W$$

For 5m rotor diameter:

$$dP = (6.4)(19.385)$$

$$dP = 124.064$$

The total power from rotor is:

$$P = \int_{1}^{2.5} 124.064\, dr = \ 186.098\, W$$

For 7m rotor diameter:

$$dP = (6.4)(35.739)$$

$$dP = 228.730$$

The total power from rotor is:

$$P = \int_{2}^{3.5} 228.730\, dr = 343.095\, W$$

Diameter of wind Turbine	**Tip loss correction factor, Q**	**Torque, dT**	**Power produce, P**
2 m	1	2.204 Nm	11.28 W
5 m	0.959	19.385 Nm	186.098 W
7 m	0.84	35.739 Nm	343.095 W

Table 4.5: Value of Tip loss correction factor, Torque and Power produce

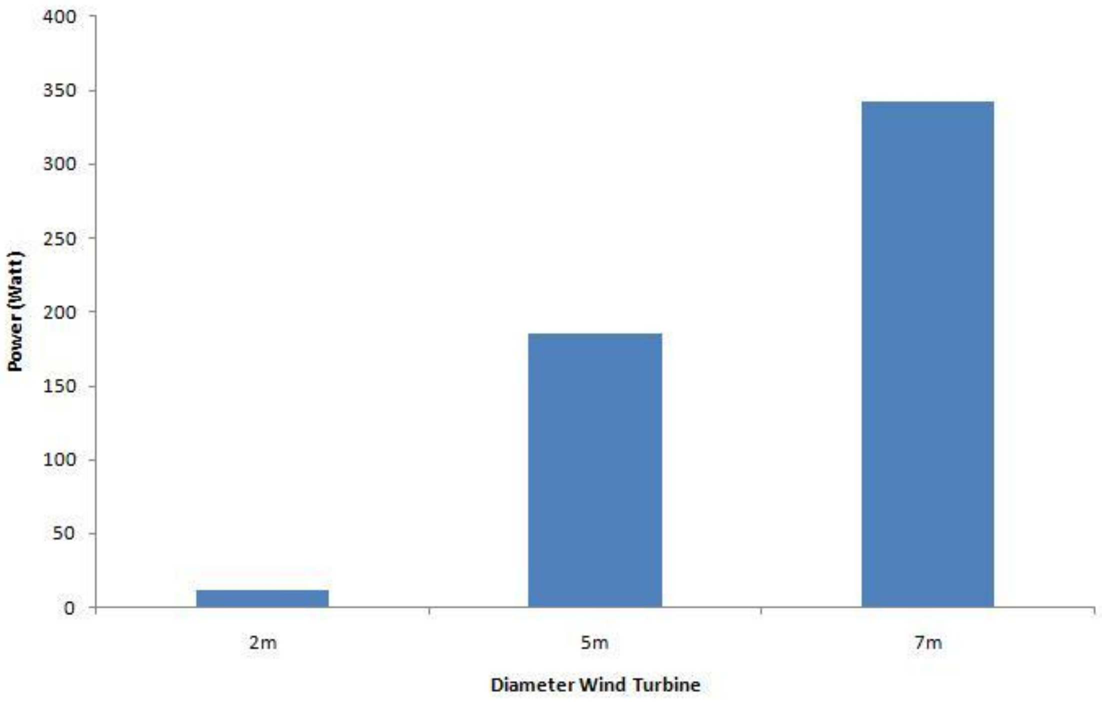


Figure 4.5: Power (Watt) for 2m, 5m and 7m diameter blade

4.3 COMPUTATIONAL FLUID DYNAMICS (CFD) ANALYSIS

After modeling the wind turbine using SolidWork, the model is been analyze using COSMOSFlow Work. In CFD result, it shows the value of torque and force acting on the blade after the wind passes through it. In this analysis, there are several parameter have to consider in CFD analysis using COSMOSFlow Works.

- Fluid Type : Air
- Parameter conditions
  - Pressure : 101325 Pa
  - Temperature : 283 K
- Analysis type : External Flow
- Wall Condition : Adiabatic
- Wind Speed : 4 m/s

The result are shown in Figure 4.6

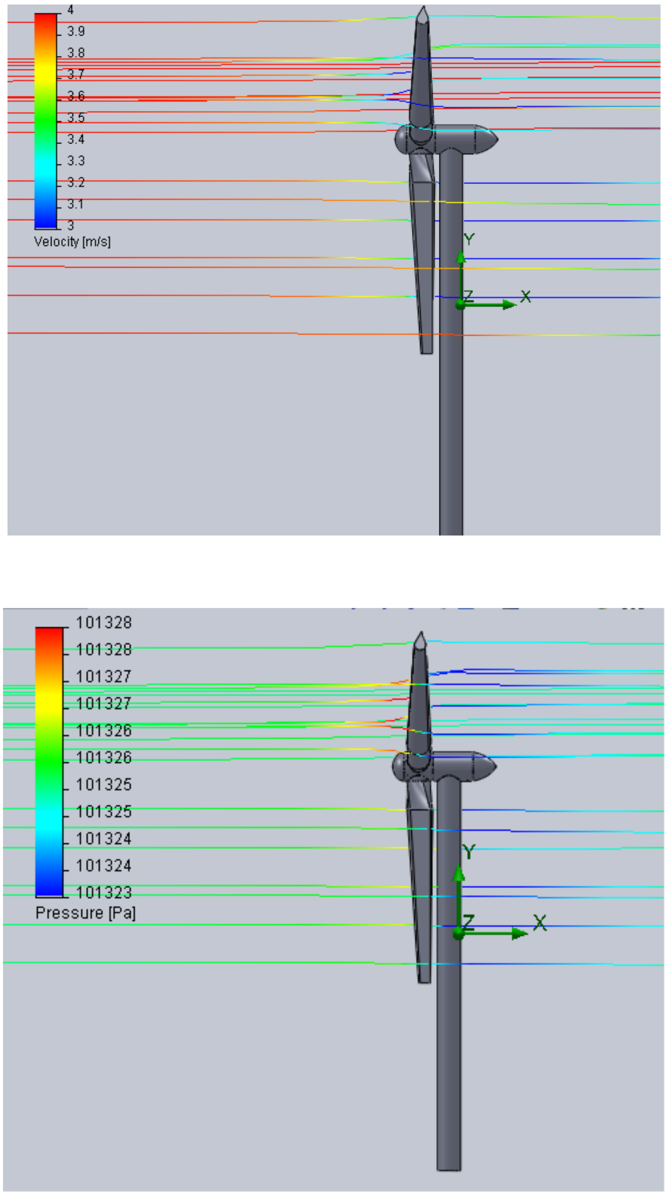


Figure 4.6: Velocity and Pressure – COSMOFlow Work

Goal Name	Unit	Value
GG Y - Component of Forc	[N]	0.252680094
GG Y - Component of Torqu	[N*m]	37.32484494

Table 4.6: The value of force and torque based on CFD analysis

4.3.1 Power calculation using CFD analysis data

In this project objective, one of it is to compare the value of power produce using data from CFD analysis and BEM calculation. From the Table 4.3, we can use the value of torque to measure the power produce by using equation (2.28) and (2.29). In this calculation, the diameter of rotor is 7m.

$$dP = \Omega dT$$

$$dP = (6.4)(37.324)$$

$$dP = 238.874$$

The total power from rotor is:

$$P = \int_{2}^{3.5} 238.874 dr$$

$$P = 358.311\ W$$

4.4 DATA COMPARISION

In this topic, the data from BEM calculation and data from CFD calculation have been taken and use to calculate the power produces. From this, the project has achieved the objective. For the comparison, the data show in table 4.4

	Torque	**Power**
CFD analysis	37.325 Nm	358.311 W
BEM	35.739 Nm	343.095 W

Table 4.7: Value of Torque and Power produce Using CFD and BEM

4.4.1 Power Efficiency

After getting the value of power produce form CFD and BEM theory, the power efficiency was calculated. The value of power efficiency is show in equation below,

$$\eta = \frac{358.311 - 343.095}{358.311}\ (100\%)$$

$$\eta = 4.246\%$$

4.5 DISCUSSION

From the BEM calculation, the Torque for 7m diameter wind turbine is 37.325Nm. From CFD analysis, the Torque produce at blade for 7m diameter wind turbine is 37.739 Nm. From this two value, it shows that both value are approximately same and proved that the simulation is on track. The value of Torque form BEM and CFD analysis than be used to calculate power. Form the calculation, the BEM theory gives 343.095 Watt and CFD analysis gives 358.311 Watt. The different between these two power produce only 4.43%. The actual miniature wind turbine gives a minimum power output around 400 Watt. The different between actual power produce and calculation power produce are due to different wind speed. For actual miniature wind turbine, a minimum wind speed requires is 7 m/s meanwhile in this paper, the wind speed used is 4 m/s due to average wind speed in Malaysia. After getting the power produce from calculation, it shows that Malaysia have a big potential to developed a wind turbine as a source of electricity. Just to be considered that the unstable wind speed in Malaysia and space available to build a large wind turbine.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

As a conclusion for this project, learning process of simulating a miniature wind turbine has been achieved. A 7m diameter rotor blade wind turbine has been simulating using CFD to gain the value of torque and force. After simulation process complete, the value of torque has been used to calculate the power produce.

Beside the simulation using CFD, this project also focus on the calculation. For calculation, BEM equation has been used. In this calculation, various diameter of rotor blade were used, such as 2m, 5m and 7m. By using BEM, the value of torque was determined for each diameter. The power produce form each blade was determined from the value of torque. From this result, it shows that larger rotor diameter will give high number of power produce.

After getting the value of power produce from CFD and BEM, the value was compared. From the comparisons, it shows that the power produces was in the nearest value to each blade. From these result, the objective of the project have been achieved.

5.2 RECOMMENDATION

For recommendation, there are some suggestions on how to improve the flow of this project for better result output. For example, while measuring the power produces from the parameter of wind speed, we can also calculate the wind speed that is required to produces the amount of energy. By doing this, more parameters can produce several result.

Other than that, the choice of software involved is also important. As shown in this project, COSMOSFlow Work is one of the software that can produces CFD analysis. Other software is also available such as Fluent. The benefit of using different software, more accurate result can be obtained in order to correlate the theory and the project undertaken.

Last recommendation to put forward is the continuity of this project in calculating the power produce in the scope of motor or turbine performance. Further study on turbine performance will enhanced the knowledge and new findings in the subject matter.

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APPENDIX A

Project Gantt Chart 1

Activities/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Title project briefing	■															
Verify project objectives and scopes		■	■													
Literature Study	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Study the BEM theory/equation				■	■	■	■	■	■							
Study on CFD analysis					■	■	■	■	■	■	■	■				
Determine the method of methodology							■	■	■	■	■	■	■			
Modeling the Wind Turbine								■	■	■	■	■	■	■		
Submit proposal and draft of chapter 1,2 and 3															■	
Presentation of project																■

APPENDIX B

Project Gantt Chart 2

Activities/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Title project briefing	■															
PSM 2 ideas and planning		■	■													
Literature Study	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Study the BEM theory/equation				■	■	■	■	■	■							
Study on CFD analysis					■	■	■	■	■	■	■	■				
Modeling the Wind Turbine (actual size)								■	■	■						
BEM calculation on different blade diameter										■	■	■				
CFD analysis on 7m diameter Wind Turbine													■	■		
Submit draft PSM														■	■	
Presentation of project																■