



Faculty of Engineering

The Efficient Wind Turbines Design for Low Wind Speed Air

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The Efficient Wind Turbines Design for Low Wind Speed Air

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DEDICATION

Specially dedicated to

My beloved Family and Friends

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ABSTRACT

The fossil fuels produce carbon dioxide and carbon monoxide during the incomplete combustion, which lead to environment pollution. A few types of environmentally friendly wind turbine is proposed for operation under low wind speed. These types of wind turbines are suitable to the wind speed of this country, Malaysia. Numerical simulation is implemented, comparison between conventional and new design model related to flow condition. Prototypes have been manufactured, experimental tested, and compared. The first study of this thesis refers to a novel lantern wind turbine designed and compared to a darrieus vertical-axis wind turbines (VAWTs). Both wind turbines is VAWTs design. The second study refers to waterwheel wind turbine compared to a modern horizontal-axis wind turbine (HAWT), both of the wind turbines is a HAWT designed. The lantern wind turbine has wide range of improvement since it is a new design in development process, the angle of attack of the lantern wind turbine can be increases to provide more pressure difference on the blade and some of the rotor available has very high torque, rotor of 1V and 3V should be tested. The results are shown in the form of power coefficient vs tip speed ratio for wind velocities between 3 m/sec to 6 m/sec. The experimental result of the lantern wind turbine shows no rotation when it is compared to Darrieus VAWTs. The modern HAWT model gives the maximum power coefficient of 0.27 at a wind speed of 5 m/s and tip speed ratio of 0.6 which is higher than the waterwheel wind turbine model. The modern HAWT model gives the maximum power coefficient of 0.32 at a wind speed of 3.5 m/s and tip speed ratio of 1.4. The modern HAWT has the optimum torque of 0.01N and 540 RPM. The water waterwheel wind turbine has the optimum torque of 0.01N and 900 RPM. The water wheel wind turbine shows a wide range of improvement at lower speed, which is suitable for rural area in Malaysia.

Keywords: flow condition, C_p , TSR, velocity, RPM, torque

Reka Bentuk Turbin Angin Cekap untuk Kelajuan Angin Rendah

ABSTRAK

Beberapa jenis turbin angin mesra alam dicadangkan untuk beroperasi di bawah kawasan pengedaran kelajuan angin yang rendah. Jenis turbin angin ini sesuai dengan kelajuan angin negara ini, Malaysia. Simulasi berangka dilaksanakan, perbandingan antara model reka bentuk konvensional dan baru yang berkaitan dengan keadaan aliran. Prototaip beberapa reka bentuk telah dihasilkan, uji cuba eksperimen, dan dibandingkan. Kajian pertama tesis ini merujuk kepada turbin angin tanglung baru yang direka dan dibandingkan dengan turbin angin paksi angin darat (VAWTs). Kedua-dua turbin angin adalah reka bentuk VAWTs. Kajian kedua merujuk kepada turbin angin kincir angin berbanding dengan turbin angin paksi (HAWT) yang moden, kedua-dua turbin angin adalah direka bentuk HAWT. Turbin angin tanglung mempunyai pelbagai penambahbaikan kerana ia merupakan reka bentuk baharu dalam proses pembangunan, sudut serangan turbin angin tanglung dapat meningkat untuk memberikan lebih banyak tekanan pada bilah dan beberapa rotor yang dapat digunakan memiliki tork yang sangat tinggi, pemutar 1V dan 3V perlu diuji. Hasilnya ditunjukkan dalam bentuk nisbah kelajuan pukulan berbanding dengan ujung kuasa untuk halaju angin antara 3 m/s hingga 6 m/s. Hasil eksperimen dari turbin angin tanglung tidak menunjukkan putaran bila dibandingkan dengan Darrieus VAWTs. Model HAWT moden memberi pekali kuasa maksimum 0.27 pada kelajuan angin 5 m/s dan nisbah kelajuan tip 0.6 yang lebih tinggi daripada model turbin roda angin. Model HAWT moden memberikan pekali kuasa maksimum 0.32 pada kelajuan angin 3.5 m/s dengan nisbah kelajuan tip 1.4. HAWT moden mempunyai tork optimum dari 0.01N dan 540 RPM. Turbin roda angin mempunyai tork optimum 0.01N dan 900 RPM.

Kata kunci: syarat mengalir, C_p , TSR, halaju, RPM, tork

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LIST OF ABBREVIATIONS

Symbol	Name
P	Power (W)
F	Force vector (N)
λ	Tip speed ratio
v	Wind speed (m/s)
ω	Blade revolution per minutes (rad/s)
L	Length of the wind turbine blade (m)
r	Distance from the center of radius
C _p	Power coefficient
HAWT	Horizontal axis wind turbine
VAWTs	Vertical axis wind turbines
RPM	Revolution per minutes
CFD	Computational fluid dynamics
TSR	Tip speed ratio
Re	Reynolds number

CHAPTER 1

INTRODUCTION/ LITERATURE REVIEW

1.1 Background of research

The wind turbine is a type of renewable energy device that generates electricity. As wind blows the forces that acted on the blades of the wind turbine causes the rotor to rotate produces electricity. Production of electricity reduces the use of natural gas (hydrocarbon fossil fuels) that produces typically carbon dioxide and carbon monoxide during the incomplete combustion in order to generate electricity (Demirbas, 2004). The wind turbine system is capable of producing 5-8GWh of energy annually, which is equal to 1 ton per day of burning coal to produce electricity. The UK's has the objective to increase the renewable source of energy by 14% by 2020. The country has a total renewable energy of 64.4 TWh in 2014 (Musgrove et al., 2010). Therefore, this study is conducted to increase the source if renewable energy. There are two types of wind turbine, the horizontal wind turbine refers to the shaft, which is horizontal to the ground, is known as horizontal axis wind turbine (HAWT), and vertical wind turbine refers to the shaft, which is parallel to the ground, which is known as Vertical-axis wind turbines (VAWTs) (Jamieson, 2011.).

This thesis has two studies; first study refers to a novel lantern wind turbine design compared to a Darrieus wind turbine the conventional design, both of the design is a vertical design. The second study refers to waterwheel wind turbine compared to modern HAWT both of the design is a horizontal design. The results from comparison the study showed that lantern wind turbine has wide range of improvement and waterwheel wind turbine has high performance at low wind speed distribution area.

1.1.1 VAWTs wind turbines

Cycloturbine is one of the VAWTs wind turbines, which uses an aerodynamic shape blade to produce mechanical orientation the pitch of the blades to achieve maximum efficiency. The Darrieus VAWTs design has the ability to start up and rotate in low wind velocity with high efficiency (Tjiu et al., 2015).

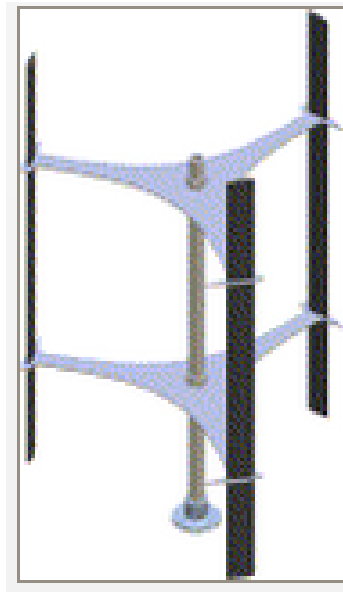


Figure 1: Darrieus VAWTs market designs (Castelli, 2011)

Muller et al. (2009) shown that the Sistan type windmill that produce the drag force energy converted it for building integration. It proven that thier design increases the theoretical efficiency to about 48% or 61%, the experimental research has proven that the wind turbine generates the efficiency which is higher than 40%. Our new design lantern wind turbine belong to one of the VAWTs designed, which is not available in the market, inspired by the shape of the Chinese lantern. The design uses multiple aerodynamic shape blades to produce rotation of the blade. This design allows the torque generated by the wind energy to remain constant over wide angle that allow this system to generatas maximum torque as possible in order to produce more power.

1.1.2 HAWT

Modern HAWT large wind turbine uses a servomotor with a gearbox that turns a low rotation into a higher rotation to power up the electrical generator. (Drewry & Georgiou, 2007). Modern HAWT is often found in wind farms; it generates high renewable energy source and currently used out by many countries (Moroni et al., 2016). However, the conventional wind turbines are huge and consume a lot of space. It requires space to maintain, when these wind turbines are installed. The diameter of a wind turbine can be larger than 124 m with a total height of 200 m (Dutton et al., 2010). The interested readers should refer to Digraskar (2010) regarding CFD simulations on horizontal axis wind turbine. Multiple cases of modern HAWT have exploded recently due to high rotating speed. On the January 29, 2016 Enviro-news showed that wind turbine exploded and caught a fire due to wind turbine excessive speed (Urry, 2016). Dailymail UK news on 6 Jan 2012 also reported that a wind turbine rotating at high speed exploded (Luke & Rob, 2011).

1.2 Problem Statement

The huge and big conventional wind turbine in the wind farm has taken up lots of spaces and a distance is required to place another wind turbine. The development of wind power plant which taken up a lot of space have a direct impact towards citizen such as noise pollution and road accessibility (Hand et al., 2009). A wind power plant project is usually time consuming therefore it requires the cleaning of lands for development in the particular area, which has the possibility of significant degradation and effects on quality of the ecosystem (Arnett, 2013). There are multiple cases of wind turbine explosions due to high speeds, such as an incident where a wind turbine caught a fire due to mechanical failure (Emerson, 2016). Wind turbine accident statistics in Figure 2 shows the yearly increase of the number of wind turbine related

accidents. The expected growth in the installation of wind turbines, also bring the expectation of an increase in the number of accidents of wind turbines.

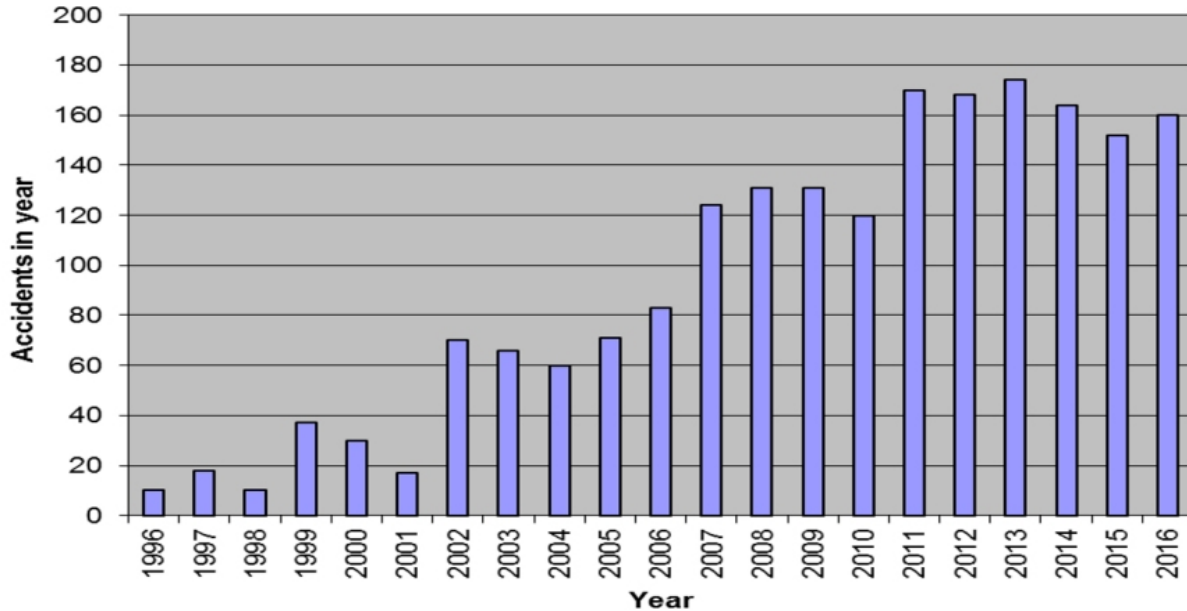


Figure 2: Wind Turbine Accident (Caithness Windfarm Information, 2016)

The high rotating geared of wind turbines that are continuously distressed by numerous gearboxes. The bearings failure within the gearbox is the most significant problem associated with the turbines which lead to explosion and fire. Once a fire is ignited in a wind turbine, the situation rapidly escalates because the high wind favoured by turbine locations enhances the supply of oxygen that lead to fire and explosion.

1.3 Objective

- i. A novel design for lantern wind turbine studied through numerical simulations
- ii. Study of novel design for lantern wind turbine regarding the wind turbine C_p vs TSR, velocity vs RPM , RPM vs torque at low wind speed to reduce mechanical failure and gear distress. Data for C_p , TSR, and torque is obtained.
- iii. novel design waterwheel wind turbine is studied through numerical simulations

- iv. Study of novel design waterwheel wind turbine regarding the wind turbine C_p vs TSR, velocity vs RPM, RPM vs torque at low wind speed to reduce mechanical failure and gear distress. Data for C_p , TSR, and torque is obtained.
- v. reduce the large wind turbine to a smaller wind turbine to reduce land consumptions from their installations

1.4 Aerodynamic consideration

Most of the blade design in this thesis used the basic theory of aerodynamics. Aerodynamics is the interaction between the motion of air and the airfoil design with a curved surface on the top and a flat surface at the bottom. When a laminar flow of air passes through an airfoil, with an angle of attack, the speed above the airfoil is higher which produces lower pressure. The airfoil has a lower speed below it; these differences produce high pressure, which leads to lifting where the airfoil is lifted perpendicular to the direction of the wind flow. The first study in this thesis is about lantern wind turbine compared to a darrieus VAWTs, while the second study is regarding water wheel wind turbine compared to a modern HAWT. All of the studies are designed with aerodynamic consideration.

1.4.1 Tip Speed Ratio

The Tip Speed Ratio (TSR) λ refers to the angular velocity of the rotating turbine and the flow velocity with the formula as shown below:

$$\lambda = \frac{r\omega}{v} \quad (1.1)$$

Where, ω is the angular velocity of the turbine, r is the radius of the turbine and v is the flow velocity. The operating Tip Speed Ratio is chosen for the wind turbine to work at. The flow velocity depends on the mechanical generator that converts the mechanical energy of the

spinning wind turbine into electrical energy (Bhutta et al., 2012; Abdulrahim et al., 2015). Therefore, the operating of Tip Speed Ratio vs C_p is plotted at where a constant Reynolds number is usually obtained (Ragheb & Ragheb, 2011). Furthermore, the optimum Tip Speed ratio which will give the highest efficiency can be identified.

1.4.2 Power coefficient

The power coefficient (C_p) is a dimensionless parameter that expresses the amount of power that the turbine is able to be extracted from the flow of the wind in our study. Thus, the C_p is the ratio of the actual power extracted from the flow to the power available from it (Howell et al., 2010; Zanforlin & Letizia, 2015). The power generated by the kinetic energy of a free flowing stream is given by the following equation.

$$P_a = \frac{Sv^3}{2} \quad (1.2)$$

Where, S is the cross-sectional area and v is the flow velocity. The power extracted from the turbine is defined as,

$$W = \frac{1}{2} I \omega^2 t \quad (1.3)$$

Where, I is the moment of inertia (kg.m^2), ω is the angular velocity (rad/s) and t refers to time.

The equations 1.3 and 1.5 are combined in order to get an expression for the power coefficient,

$$C_p = \frac{W}{P_a} = \frac{\frac{1}{2} I \omega^2}{\frac{\rho S v^3}{2}} \quad (1.4)$$

The chart C_p vs TSR plot is obtained to identify the TSR of the wind turbine. If the rotor of the wind turbine is extracting more power from the free stream; the value of this C_p would be 1 in an ideal case (Gupta et al., 2006).

1.4.3 CFD study of a VAWTs and HAWT using a two-way fluid structure interaction

The Reynolds number is defined as the ratio of inertial forces to viscous forces, which specify the importance of these two types of forces at a specific flow conditions. It is used to determine dynamic similarity between two different study of fluid flow, as well as to characterize different flow rules within an identical fluid, such as laminar or turbulent flow (Sezer, 2006). Laminar flow is influence by viscous forces; therefore, it takes place at low Reynolds numbers. It is characterized as smooth, where the fluid flow is at a constant motion. Turbulent flow is influenced by inertial forces; therefore, it takes place at high Reynolds numbers that produce chaotic vortices, eddies and other flow instabilities (Langtry et al., 2006).

$$Re = \frac{\text{inertial forces}}{\text{viscous forces}} = \frac{\rho v L}{\mu} \quad (1.5)$$

ρ is the density of the fluid. u is the mean velocity of the object relative to the fluid, μ is the dynamic viscosity of the fluid. As it will be seen later on, our scenario deals with laminar flow. The figure C_p vs. TSR plot has been obtained from the study, and it is shown in Chapter 4.

1.4.4 Buckingham II represent a dimensionless product

In this research, the turbine is a scaled down model compared to a large prototype. Therefore, it can be easily handled in the laboratory and is at low cost to be manufactured as compared to a large prototype. Therefore, the Buckingham Pi Theorem, a set of dimensionless numbers was derived to compare the performance of VAWTs and HAWT (Qasim et al., n.d.). The dimensional analysis is used to compare the different size of turbines in terms of their performance. The comparison is done between different size of wind turbines in terms of C_p , TSR, and Re . There are 6 parameters (6 Π) which are related to the power of wind turbines.

$$P_t = f(u, \rho, D, \mu, \omega) \quad (1.7)$$

There are six Π subtracted by three which is equal to 3 Π , the dimensionless group of variables as a function of the other dimensionless group (Cengel, 2007). The repeating variables are ρ , D and ω . The three dimensionless Π terms of Buckingham Π theorem is shown in eq 1.8-1.10.

$$\Pi_1 = Cp = \frac{W}{\rho a} = \frac{\mu}{\rho D^5 \omega^3} \quad (1.8)$$

$$\Pi_2 = \lambda = \frac{r\omega}{v} = \frac{D\omega}{v} \quad (1.9)$$

$$\Pi_3 = \frac{\rho D^2 \omega}{W} = Re \quad (1.10)$$

Π_1 refers to the power coefficient, Π_2 refers to the tip-speed ratio and Π_3 refers to the Reynolds number. The relationship of the dimensionless group is shown in eq 1.11-1.12

$$\Pi_3 = f(\Pi_1, \Pi_2) \quad (1.11)$$

$$\Pi_3 = \frac{\rho D^2 \omega}{W} = f(\lambda, Cp) \quad (1.12)$$

The efficiency of which a rotor can extract power from the wind depends on the dynamic matching between the rotor and the wind stream. Hence, the performance of a wind rotor is usually characterized by the variations in its power coefficient with the tip speed ratio. As both of these parameters are dimensionless, the CP vs TSR curve represents the rotor performance, irrespective of the rotor size and site parameters at constant Re . Calculation of $\Pi_3 = Re$ is shown in Section 3.4.

1.5 Betz's law

The rotor of the wind turbine can only convert about 60% of mechanical energy from a 100% of Wind turbine generates electricity through a rotor with kinetic energy (Manyonge et al., 2012). The Betz limits show that utility-scale wind turbines can be achieved at a peak of 60%

to 70%. According to Betz's law, when air flow through a specific area, it slows down due to loss of energy to extraction from the wind turbine then air would spread out to a larger area.

1.6 SOLIDWORKS® numerical basis of CFD

SOLIDWORKS® allows the mesh refinement by splitting each cube into the eight geometrically similar cuboids. The example of meshing refinement at the section where there is bending at the surface of a solid as shown in Figure 3.

According to Lam and Bremhorst (1981), laminar and turbulent flows are homogeneous fluids. The flow in SOLIDWORKS® Flow Simulation can be set as laminar and turbulent flows (Sobachkin & Dumnov, 2014). This study is done with laminar flows under low velocity and low Reynolds number. It is proven that $k-\varepsilon$ turbulence model is efficient for low Reynolds number (El Kasmi, 2008). Therefore, this thesis uses the modified $k-\varepsilon$ turbulence model. During the study, multiple sources where this laminar model can be found in (Chien, 1982; Richards et al., 1993; Sobachkin & Dumnov, 2014; Suzuki, 2016), where the same simulation has been carried out using $k-\varepsilon$ turbulence model and a comparison of the results is presented.

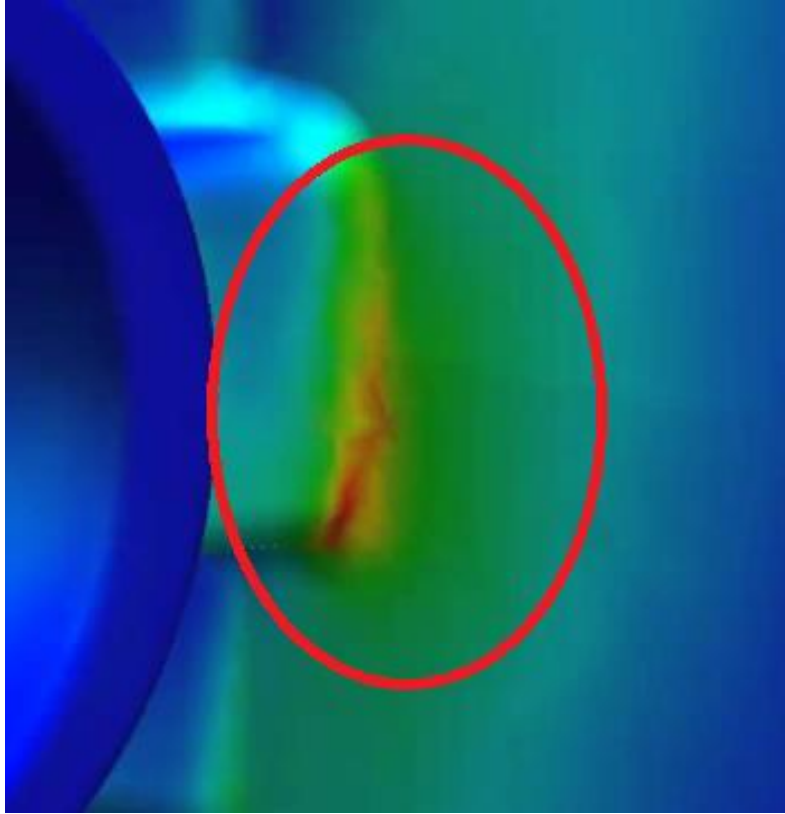


Figure 3: SOLIDWORKS[®] meshing refinement example (Sobachkin et al., 2014)

CHAPTER 2

MATERIALS AND METHODS

2.1 Low wind speed

It was found in this research that Malaysia has low wind speeds, where, the mean monthly wind speed is only 6.22mph (2.78m/s) with a 2m height above ground and Sung reported that the height of 32 m above the ground has a mean monthly speed of 3m/s (Sung, 2013)

Table 1: Wind speed for Kuching, Sarawak, Malaysia in December 2016

Date	Time	0000	0600	1200	1800	Mean speed
4 DEC 2016	Speed(mph)	2	6	10	4	5.5
5 DEC 2016		2	5	8	5	5
6 DEC 2016		3	4	13	5	4.8
7 DEC 2016		2	4	7	4	4.25
8DEC 2016		5	8	13	8	8.5
9 DEC 2016		3	7	14	9	8.25
10 DEC 2016		4	5	12	8	7.25
					Average	6.22

Low wind speed is used in numerical simulation and experimental study. Since it is at low speed, the wind speed in this thesis is measured with a speed anemometer. There is very little power that can be extracted from low wind speed. HAWT would have difficulties in extracting at a certain angle since it does not extract from every part of the rotation. However, experiment has proven that VAWTs extract less energy, required more drag force and weight is added to the blade which made it just a little less efficient than HAWT at low wind speed. Therefore, it can be concluded that VAWTs wind turbine is not suitable for Malaysia's climate.

2.2 Blade Design Method

All wind turbines are designed with three blades except waterwheel. The two-blade design wind turbine has higher efficiency. However, two blade wind turbine noise increases when there is very high rotating speed. The four blades design causes increase in cost and it reduces the performance of the wind turbine when as the weight increases with the number of blade. The higher the number of blades, the lower the power that can be extracted. Therefore, the waterwheel wind turbine design has multiple blades which allow more power to be extracted at low wind speed. The manufacturing cost could be reduced with the simple designed of waterwheel wind turbine. This simple design reduces the time taken for production and all blades is designed with no required twice angle and the blade is not connected directly to the rotor.

2.3 NACA 0020

NACA airfoil with 4-digit NACA 0020 as shown in Figure 4 is designed with the position of the maximum camber 0% of the chord. The maximum camber is 0% of the chord and the thickness is 0.20 or 20% of the chord.

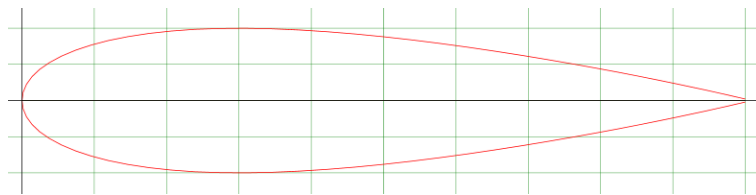


Figure 4: NACA 0020

Initially blade manually drawn without coordinates as shown in Figure 5. There was an obvious difference with the blade design due to lacking of skills in drawing initially

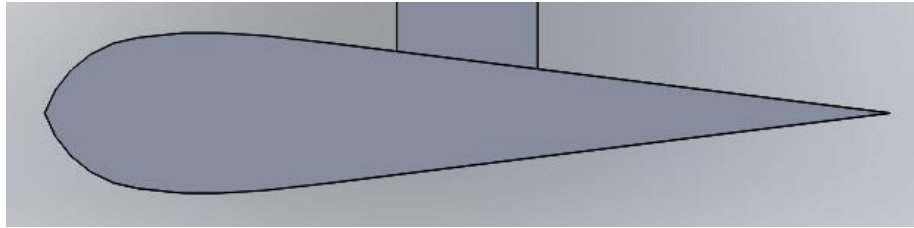


Figure 5: AutoCAD® drawn

Table 2 shows the blade with NACA0020 designed. Lantern wind turbine and darrieus wind turbine design is based on this NACA0020. The darrieus VAWTs wind turbine is a conventional design, which is available in the market.

Table 2: NACA 0020 blade designed wind turbine

Detail	Darrieus VAWTs with NACA0020 blade construction	Lantern wind turbine with NACA0020 as blade which is circularly extruded
NACA0020	A schematic diagram of a Darrieus vertical axis wind turbine (VAWT). It features three curved blades arranged in a Y-shape around a central vertical axis. Three curved arrows indicate the direction of rotation: one at the top pointing right, and two at the bottom pointing left.	A 3D perspective rendering of a lantern-style wind turbine. It has a central horizontal axis with three circular blades attached. The blades are shown in a perspective view, highlighting their circular shape and the overall structure of the turbine.

2.4 NACA2421

The drawing of a modern HAWT is improved. Since, the design is an input of coordinate obtained from NACA four digit generators (Ladson et al., 1996). NACA2421 position of the maximum camber 4% of the chord, maximum camber 2% chord and the thickness is 0.21 or 21% of the chord. Figure 6 shows NACA 2421.

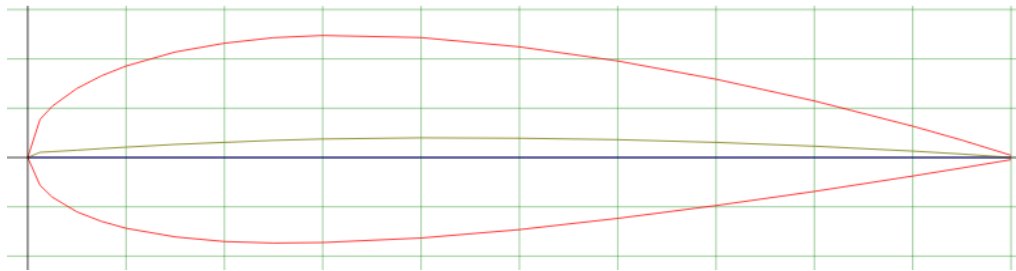


Figure 6: NACA2421 (Ladson et al., 1996)

2.5 AUTOCAD®

AutoCAD® draws precise two dimension (2D) and three dimension (3D) drawings. This study uses both 2D and 3D to design darrieus VAWTs, lantern wind turbine, modern HAWT, and waterwheel wind turbine drawn with AutoCAD® for numerical simulation purpose. First comparisons of results are completed with lantern wind turbine and darrieus VAWTs; both of the designed is constant 60 cm length of the radius. Second study is the comparison between waterwheel wind turbine and modern HAWT under the same radius of 50cm and same volume.

2.5.1 Darrieus VAWTs

The design of darrieus VAWTs vertically extruded from blade design by using AutoCAD® with the input of NACA0020. In the initial study, the angle of attack is set at zero for lantern wind turbine and darrieus VAWTs both VAWTs design. Figure 7 shows the 3D view of the darrieus wind turbine in AutoCAD® drawing and Figure 8 shows the 2D view of darrieus wind turbine.

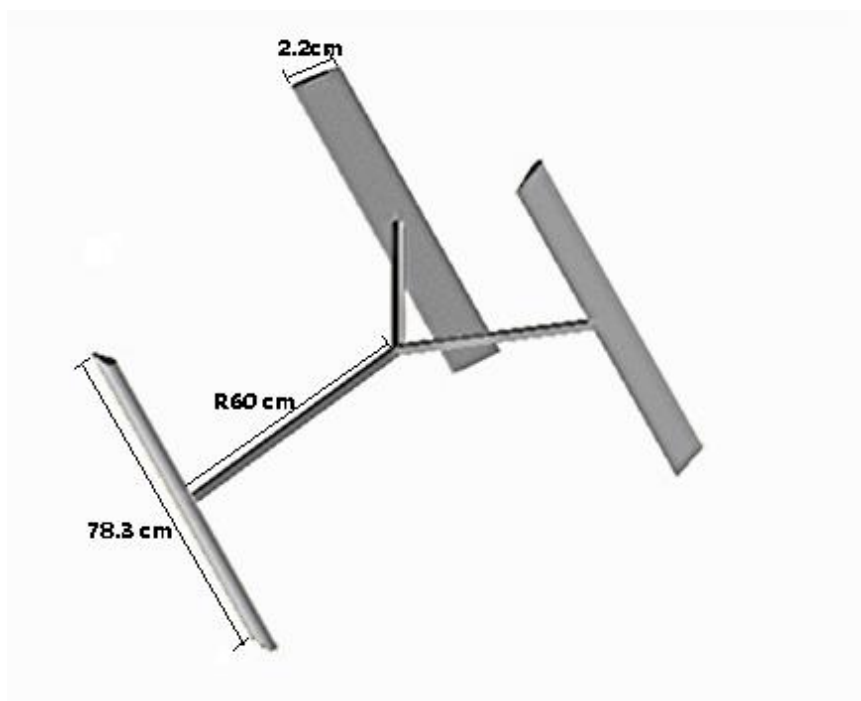


Figure 7: 3D view of darrieus wind turbine

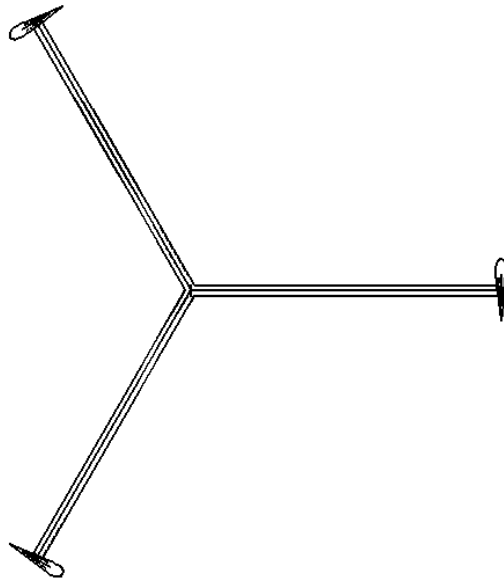


Figure 8: Top view of darrieus wind turbine

2.5.2 Lantern wind turbine

The concept of this lantern wind turbine is obtained from the airplane's nacelles during the travelling flight as shown in Figure 9 (Ibrahim et al., 2015).



Figure 9: Airplane's nacelle

The name given for this wind turbine is lantern wind turbine. This is because the design is similar to the Chinese lantern as shown in Figure 10. The initial study for this lantern wind turbine's angle of attack is zero.



Figure 10: Chinese lantern (Bancroft, 2014)

The lantern wind turbine is a novel designed wind turbine that has multiple blades instead of one blade. The multiple blades of wind turbine have an aerodynamic shape to produce mechanical rotation that maximizes efficiency. The blades comparatively generate more torque for the condition of low wind speed. This blade of lantern wind turbine is extruded circularly from NACA0020 and the process is done in AutoCAD®. Conventional wind turbine is designed with a straightly extruded blade. The difference between lantern wind turbines and the conventional wind turbine are the circular blades. Figure 11 and Figure 12 show the sliced AA view for NACA0020 in 2D. Figure 13 shows the blade of lantern wind

turbine, which is circularly extruded during the drawing process of NACA0020 in the 3D view AA view is the center of the blade.

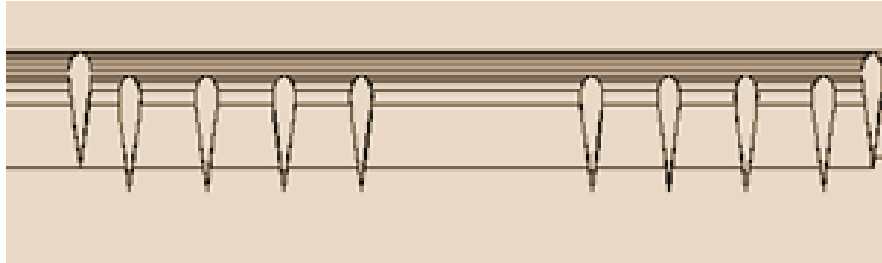


Figure 11: Top slice view of lantern wind turbine blades in AutoCAD®



Figure 12 : Top view of lantern wind turbine blades without slice



Figure 13: Newly designed lantern wind turbine

2.5.3 Waterwheel design

Figure 14 shows the American windmill turbine that is similar to our second new design waterwheel wind turbine. The main problem with American wind turbine is that the design has a very heavy weight and a large amount of metal used for the blade formation, which reduces the efficiency of the wind turbine. The new prototype designed with ABS, known for its light weight. Future actual model would be designed with light material such as aluminum.



Figure 14: American windmill (Manuel, 2006)

Figure 15 shows a bicycle wheel wind turbine, which has the ability to run at very low wind speed. However, there is a small distance from the axis of rotation (Manuel, 2006). The new design waterwheel wind turbine was improved by connecting the blade directly to the axis of the rotation.



Figure 15: bicycle wheel wind turbine (Manuel, 2006)

Water wheel wind turbine is inspired by the common water wheel that is available in the markets. The design is much simpler with no aerodynamic design. As shown in Figure 16. The design of the blade was completed with a basic straight horizontal tip, which acts as the blade. Figure 17 shows the array of the blades, which is done by using AutoCAD®. As shown in Figure 18, the circular ring of the waterwheel wind turbine acts as a holder of the blade.

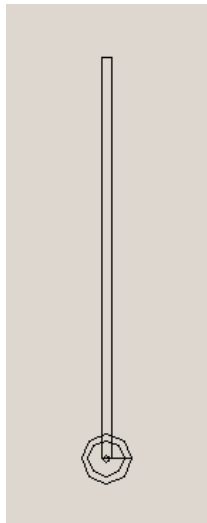


Figure 16: Straight extrude

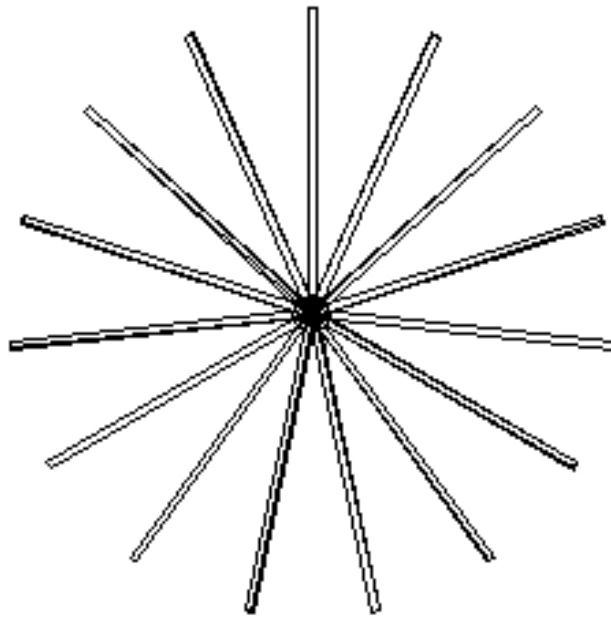


Figure 17: Array of the blade

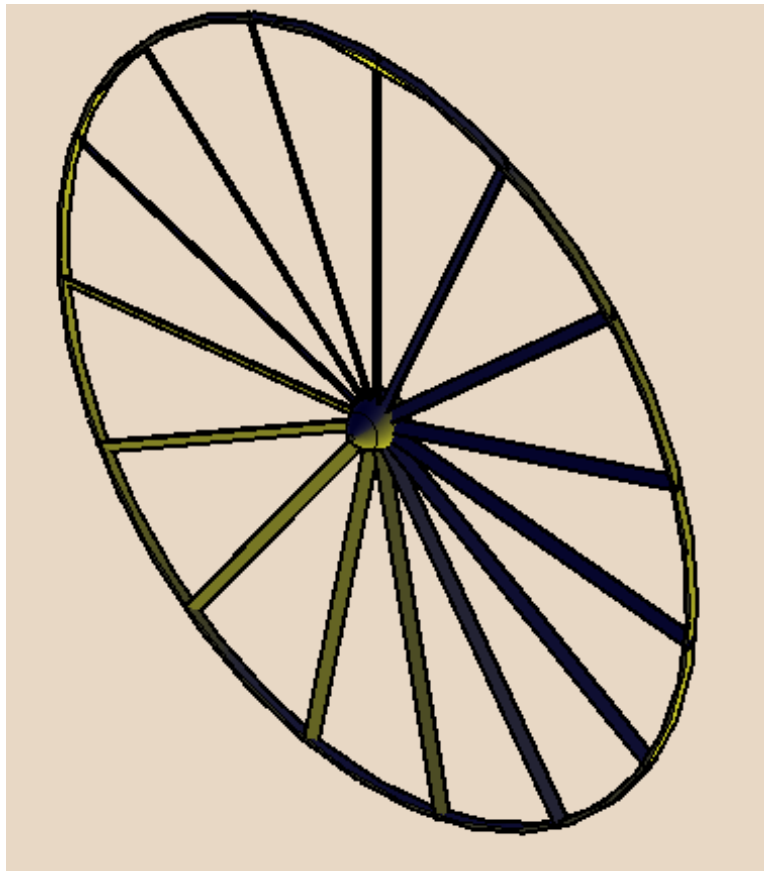


Figure 18: Waterwheel wind turbine

Figure 17 and Figure 18 shows a simple design with multiple blades, which allows more wind to be captured and extracted as power, at a relatively lower wind speed. Figure 19 shows the angles of blade with respect to the low wind speed used for calculation. The calculation of pitch angle and angle of attack is shown in the following equations below.

$$V = r\omega \quad (2.1)$$

$$\text{Relative velocity} = (0.5)(169 \times 2\pi/60) = 8.8 \text{ m/s}$$

$$\text{Velocity wind} = 6 \text{ m/s}$$

$$\text{Pitch Angle} = 34^\circ$$

$$\text{Angle of attack} = 0^\circ$$

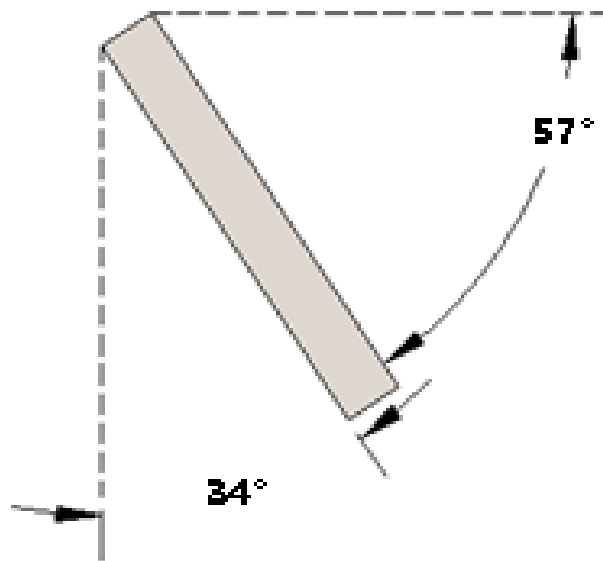


Figure 19: Angle of the blade

The blade is designed in a simple way so that manufacturing cost could be lowered.

2.5.4 Modern HAWT

Modern HAWT is the conventional market product, which can be seen in a typical wind farm. Our design is drawn based on the market product modern HAWT. The calculation is done with a low wind speed for pitch angle and angle of attack, as shown below.

$$\text{Relative velocity} = (0.5)(169 \times 2\pi/60) = 8.8 \text{ m/s}$$

$$\text{Velocity wind} = 6 \text{ m/s}$$

$$\text{Pitch Angle} = 34^\circ$$

$$\text{Angle of attack} = 0^\circ$$

$$\text{Twice angle} = 0^\circ$$

Figure 20 shows the 3D view of the design. Drawing process is finished in AUTOCAD® with the circle line extruded to the bigger drawing of NACA2421 line as shown in Figure 21. The drawing step is extruded from numbering of one to two as indicated in the figure. Then, the drawing of bigger NACA2421 is extruded to the smaller blade from numbering of two to three as shown in the same figure. Figure 22 and Figure 23 show the process of modern HAWT extruded into 3D designs by using AUTOCAD®.

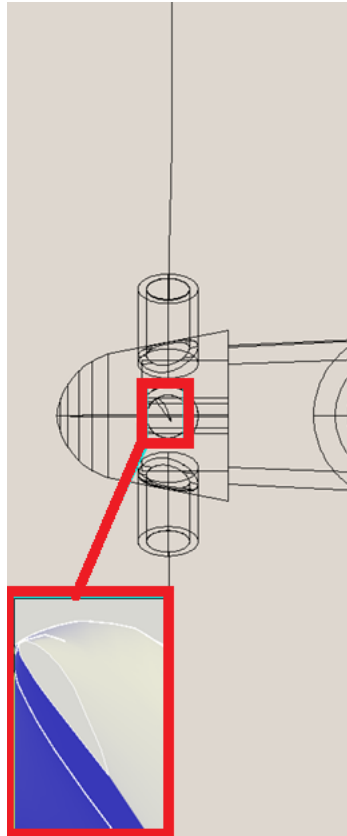


Figure 20: Angle of the blade of modern HAWT

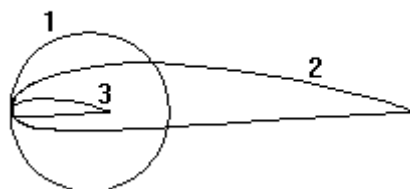


Figure 21: Numbering steps of modern HAWT blade design



Figure 22: Extrusions of first blade



Figure 23: Extrusions of second blade

2.6 Three Dimensional Modelling

This study shows a prototype scaled down model design for this research. All models are printed using the UP 3D printer during the modeling process. There are some printing failures due to uneven heat distributed by the printer during the printing process. Figure 24 shows an example of an uneven heat distributed, which led to material distortion. This is due to the design flaw because the tip is too far from the heated platform.

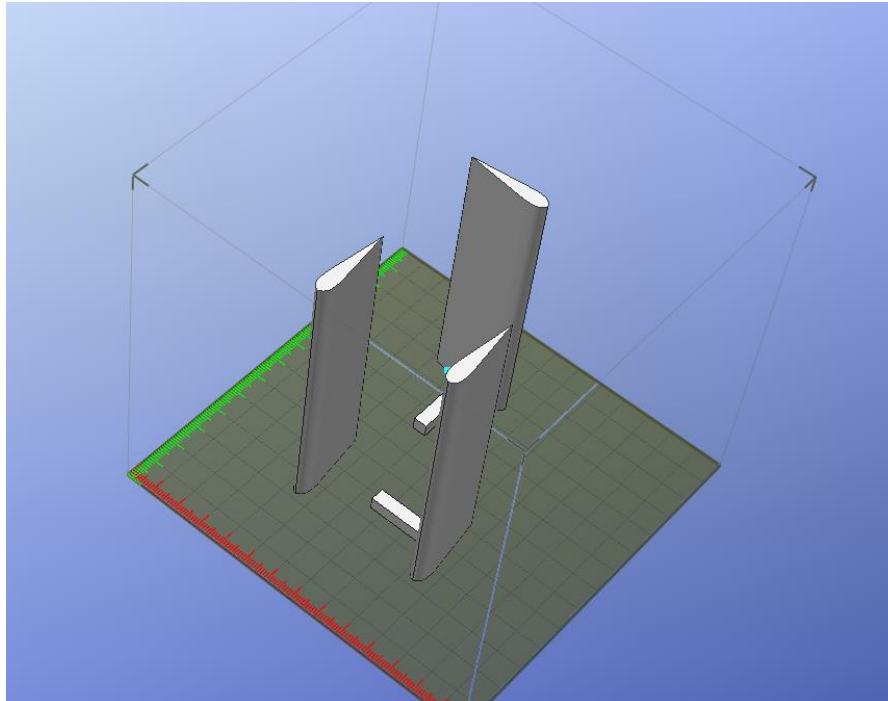


Figure 24: Printing arrangement

Initial printing of 3D model were distorted. Figure 25 shows a distorted darrieus wind turbine model and Figure 26 shows a distorted model due to the shaking of the platform when an external force applied carelessly.

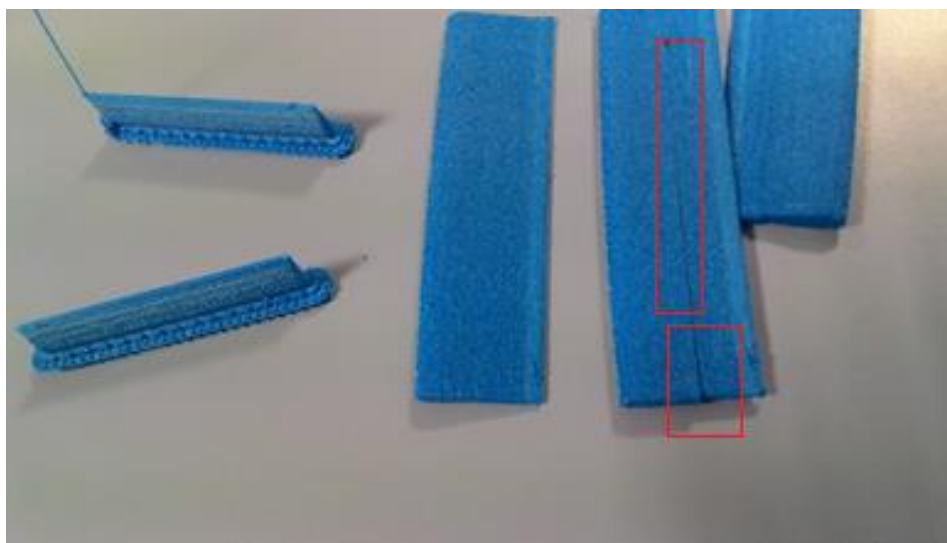


Figure 25: Example of distorted model during printing



Figure 26: Distorted model with shaking of platform

Figure 27 shows a lantern wind turbine printed with an uneven surface.

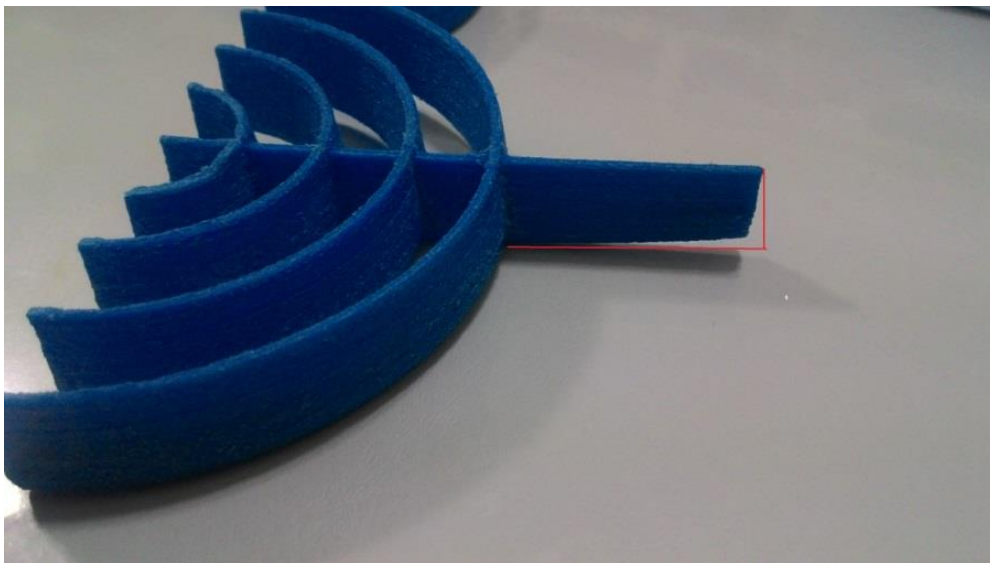


Figure 27: Uneven surfaces of printed lantern wind turbine

Figure 28 show an example of printed material without the surface finishing which was stopped during the printing process.



Figure 28: Designed failed to be printed.

The experience gained through printing has improved after multiple attempts of products are printed. Various tools are used for surface finishing as shown in Figure 29.



Figure 29: Tools used for surface cleaning

Latest update of Up 3D model printing software allows the distortion of material to be reduced by increasing the size of the printed platform. Figure 30 shows the printing model that is closely packed together; which allows the heat to be distributed more effectively from each model and it increases the heat preservation between the models.

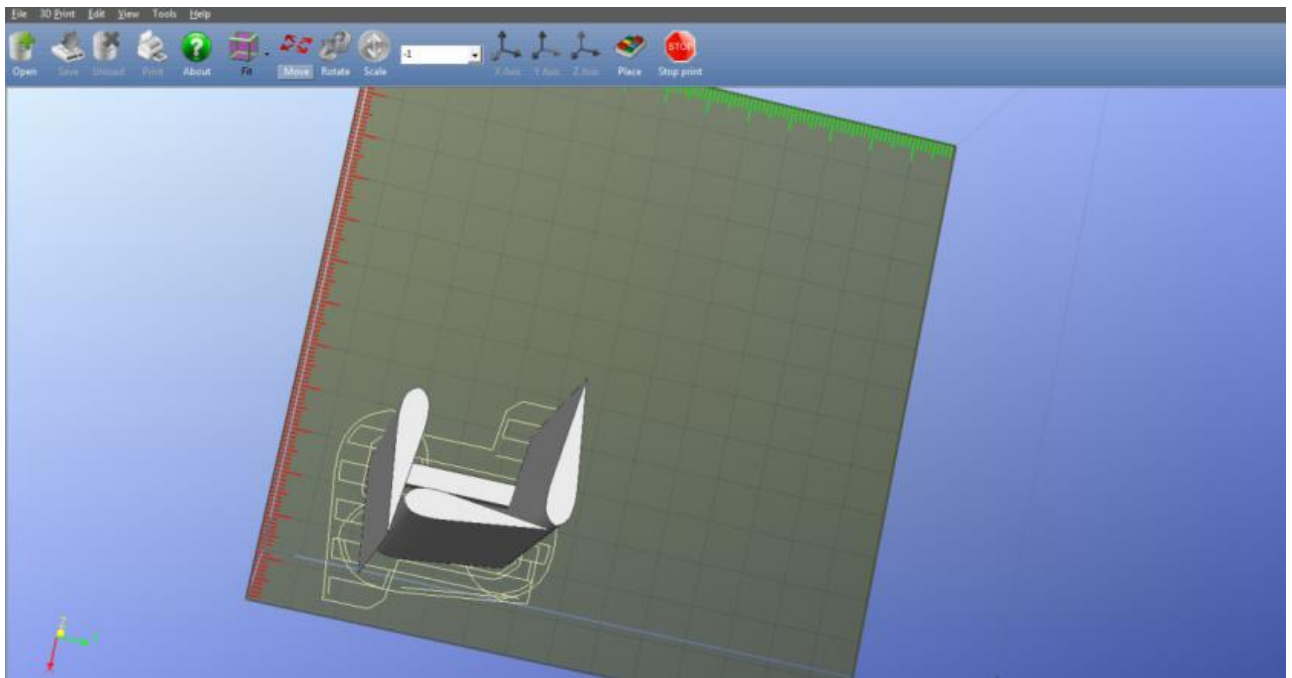


Figure 30: Group arrangement for better heat preservation

Figure 31 is the designed lantern wind turbine, which may look simple; however the printing process took at least 45 minutes to 1 hour 30 minutes for each model. Figure 32 shows the total printing models, which took 20 hours for all the parts that created a lantern wind turbine. Other designs such as modern HAWT, darrieus VAWTs and water wheel wind turbine also took about 20 printing hours each.

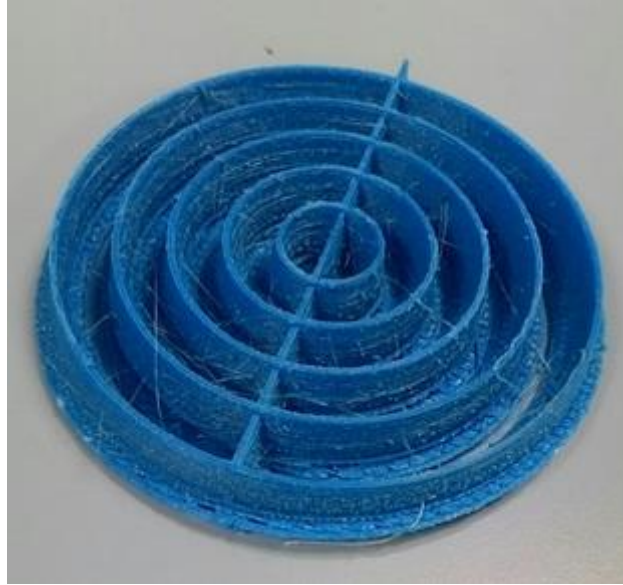


Figure 31: Printed lantern wind turbine with printed support before surface finishing



Figure 32: Printed lantern wind turbine after surface finishing

Figures 33 to Figures 35 show printed waterwheel wind turbine, darrieus VAWTs and modern HAWT. The blade and pole which is printed is combined together after printing using super glue. The model is printed for experimental purposes.



Figure 33: Printed darrieus VAWTs



Figure 34: Printed waterwheel wind turbine



Figure 35: Printed Modern HAWT

There are two types of motor used. First study uses a motor from a computer exhaust fan as rotor and the second study uses a small motor from a mini car. Figure 37 shows the motors extracted from the computer exhaust fans. Dynamic of rotor discuss about the parameter best characterizes blade flexibility, and how does this parameter vary as a function of rotor size. There is variety of rotor blades having large differences in mass, size, stiffness, and rotational speed. Therefore, 1v and 5v rotor is selected which is suitable for small scale wind turbine.



Figure 36: Motor from the computer is removed and use as a rotor for darrieus VAWTs and lantern wind turbine experimental modeling

2.7 SOLIDWORKS® parameter and setting for flow simulation

A computational fluid dynamics (CFD) is a tool that is suitable for analysis of wind turbine power. Hence, SOLIDWORKS® is selected for simulation purposes. Using this software the torque, pressure, and velocity flow condition of the wind turbine and pressure on the rotor can be predicted (Strickland et al., 1979). SOLIDWORKS® are used for flow simulation. Flow simulation uses Cartesian meshes for model in meshing processes. These mesh generation process is simple, faster and robust, which minimizes local truncation errors. The data shown below are the input data that are placed for the study of numerical simulation. Velocity is set at 5, 6, 7, 8 and 9 (m/s) as low wind speed distribution area for air. Rotating wind turbine is set as constant rotation of 2 (rad/s). Table 3 and 4 show the parameters and settings set for numerical simulations.

Table 3: Parameters for analysis settings

Detail	Setting
Analysis types	External flow
Fluid flow	Air
Flow type	Laminar and turbulent

Table 4: Boundary conditions

Environmental condition	101325Pa
Velocity flow x-axis	0 m/s
Velocity flow y-axis	5-9 m/s
Velocity flow z-axis	0 m/s

There are two types of low simulation solver solving mode, which are serial mode and parallel mode. Parallel mode uses two or more computers running in parallel. The mode that is used for this study is serial mode. Figure 37 shows the rotating region of the wind turbine, which is selected as boundary condition.

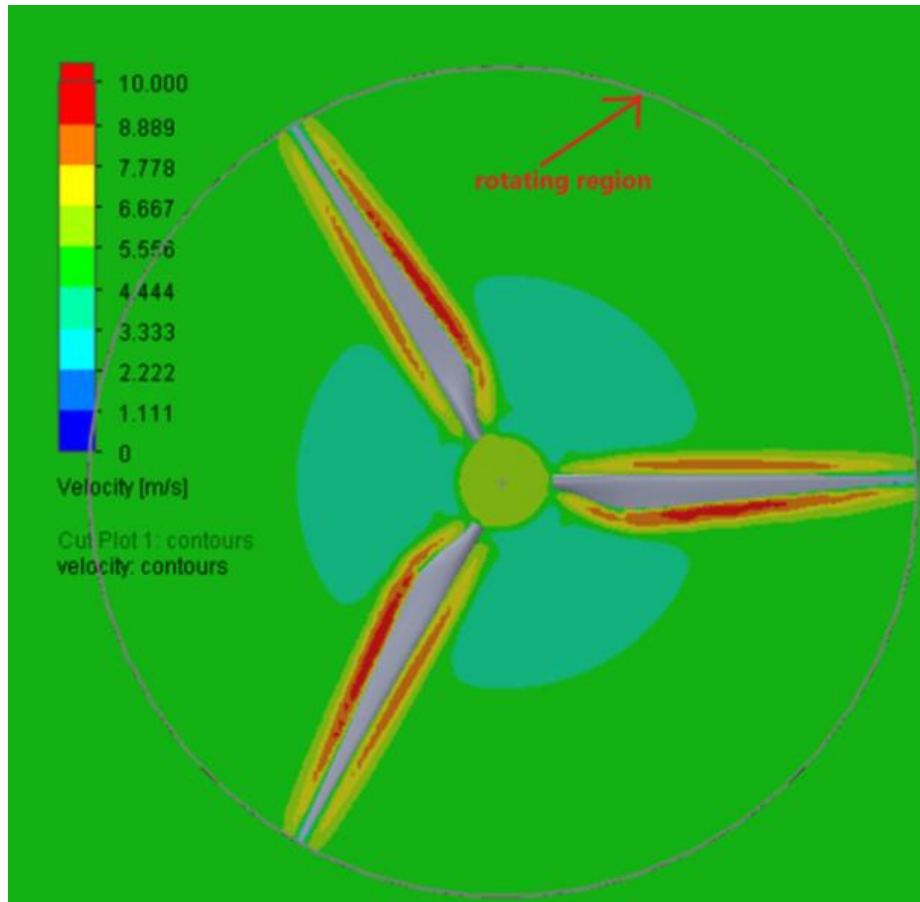


Figure 37: Boundary condition of rotating region

2.7.1 The results generated by SOLIDWORKS®

In order to reach a converged state, the minimum numbers of iteration of CFD numerical analysis fluid flow has to be increased. Figure 38 shows that most of the result generated is converged after 200-300 iterations. In this case, all results are converged when it reaches 300 iterations; however, the iteration was increased to 1000 to obtain results that are more accurate. Higher iteration might consume more than a week for a computer with specification of 16 GB RAM. Table 5 shows that the result of a velocity which is converged at 250 iterations.

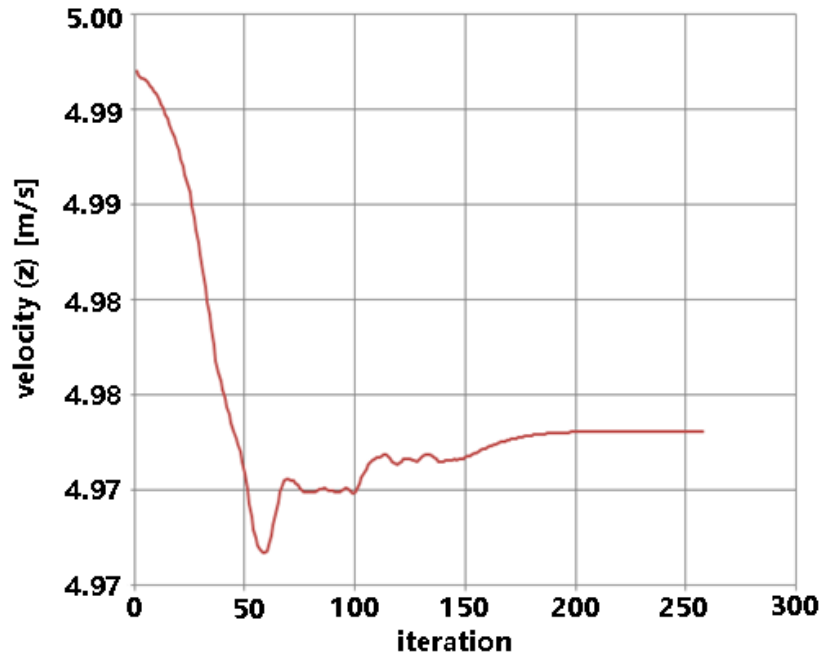


Figure 38: Result of velocity converged

Table 5 shows the goal that is set to run in SOLIDWORKS® solver. The goal name such as pressure, force, normal force, velocity, torque, and others are shown in the table. As shown in the table all the goals are converged with a 100% progress.

Table 5: All results converged for all wind turbines

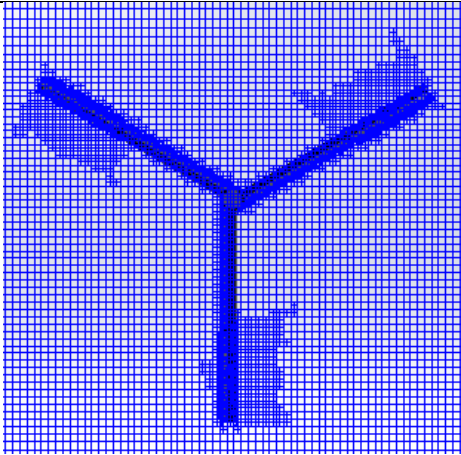
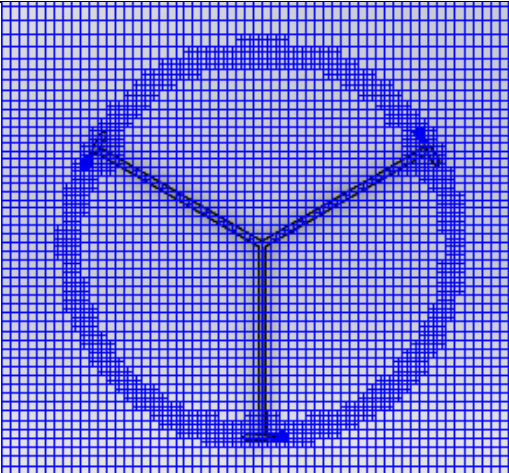
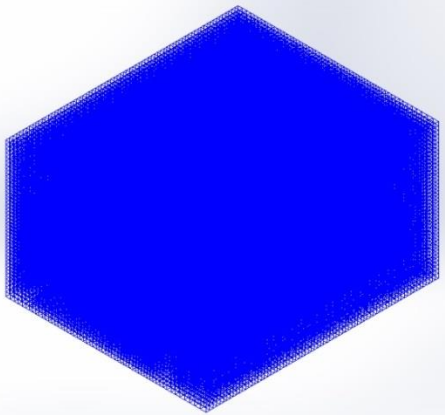
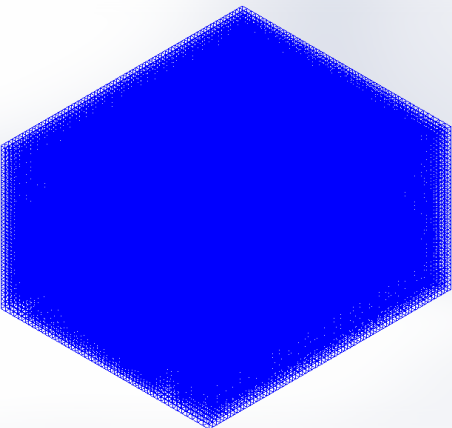
Goal Name	Unit	Value	Progress [%]	Use In Convergence
SG Min Total Pressure 1	[Pa]	101295	100	Yes
SG Av Total Pressure 1	[Pa]	101350	100	Yes
SG Max Total Pressure	[Pa]	101660	100	Yes
SG Min Velocity 1	[m/s]	0.081408985	100	Yes
SG Av Velocity 1	[m/s]	0.542453762	100	Yes
SG Max Velocity 1	[m/s]	0.999752264	100	Yes
SG Normal Force 1	[N]	0.533367024	100	Yes
SG Normal Force (Y) 1	[N]	0.334031182	100	Yes
SG Normal Force (Z) 1	[N]	0.122092066	100	Yes
SG Force 1	[N]	0.641060797	100	Yes
SG Force (X) 1	[N]	0.534813697	100	Yes
SG Force (Y) 1	[N]	0.332010403	100	Yes

2.7.2 Meshing generation

The mesh generation has a direct impact towards the results. The time taken for CFD simulation to take place depends on meshing sizes. Different meshing sizes, such as course and fine also influence the results generated from CFD solution. The grid generation through meshing is a preprocessing step before the solver takes place. The average time taken for the result solving is three to six hours a day for each set of result. In this study, meshing is done with SOLIDWORKS® flow simulation, which generates square meshing for rotational of wind turbines. This is a moving mesh where the rotating region is fully enclosing the wind turbine. Furthermore, the rotating region is extended passed the tips of the wind turbine blades that allow mesh refinements. The first study done with the level of meshing set as the maximum of eight (fine mesh). The minimum wall thickness and minimum gap size for meshing is set as 0.033m. Table 6 shows the meshing generated by SOLIDWORKS®. The 3D meshing view is not obvious due to the small grid generated in the meshing region. SOLIDWORKS® uses Cartesian meshes for lantern wind turbine and darrieus VAWTs.

For the second study, the level for initial mesh is set as seven, to reduce the time consumed for simulation. Manual specification of the minimum gap size and the minimum wall thickness is set as 0.01m. Similarly, SOLIDWORKS® uses Cartesian meshes for waterwheel wind turbine and modern HAWT, as shown in Table 7.

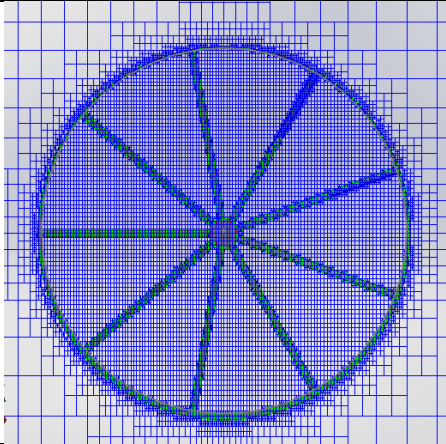
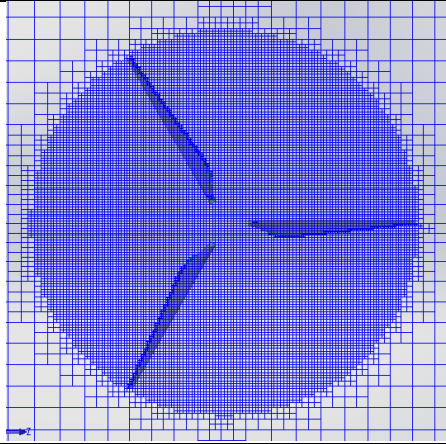
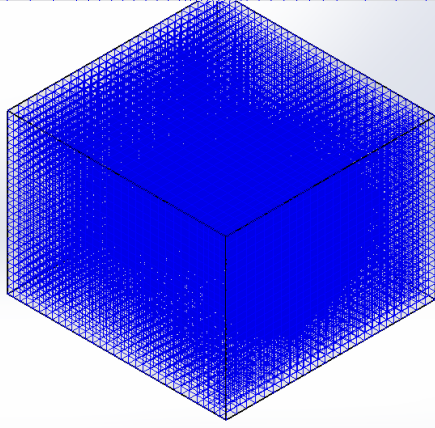
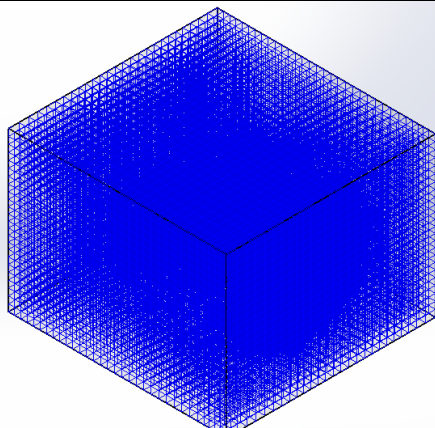
Table 6: Meshing view for lantern wind turbine and darrieus VAWTs

Detail	Lantern wind turbine	Darrieus VAWTs
Meshing top view		
Meshing 3d view		

2.7.3 Study finishing condition

As shown in Table 8, the finishing condition is set to reduce the time consumed for simulation. Most of the result in this study has converged in the range between 300-400 iterations. Therefore, maximum iteration is set at 1000.

Table 7: Meshing view for waterwheel wind turbine and modern HAWT

Detail	Waterwheel wind turbine	Modern HAWT
Meshing top view		
Meshing 3d view		

2.8 Experiment material

Various types of instruments are used in this research. Figure 39 shows the speed anemometer used for wind measurements. Figure 40 shows the digital tachometer used to measure the rotation of the wind turbine through reflection sticker, which is placed on the wind turbine. This device measures the rotation per minutes of a rotating object. Figures 39 to 44 shows all the materials and instruments used for the experiments.

Table 8: Parameter and setting

Parameter	Value
Finish condition	All satisfied
Maximum iteration	1000
Goal convergence (Goal's criteria) Min velocity x-axis Max velocity x-axis Average velocity x-axis Min velocity y-axis Max velocity y-axis Average velocity y-axis Min velocity z-axis Max velocity z-axis Average velocity z-axis Normal force x Normal force y Normal force z Force x Force y Force z Frictional force x Frictional force y Frictional force z Torque x Torque y Torque z	Auto



Figure 39: Anemometer



Figure 40: Digital tachometer

The rotation of the industrial fan used for the blower is turbulent flow; therefore, paper rolls are used as honeycomb in the tunnel to produce laminar and homogenous flow.



Figure 41: Honeycomb

Figure 42 shows a rotating modern HAWT design, which is placed at a constant distance from the fan and laminar compartment.

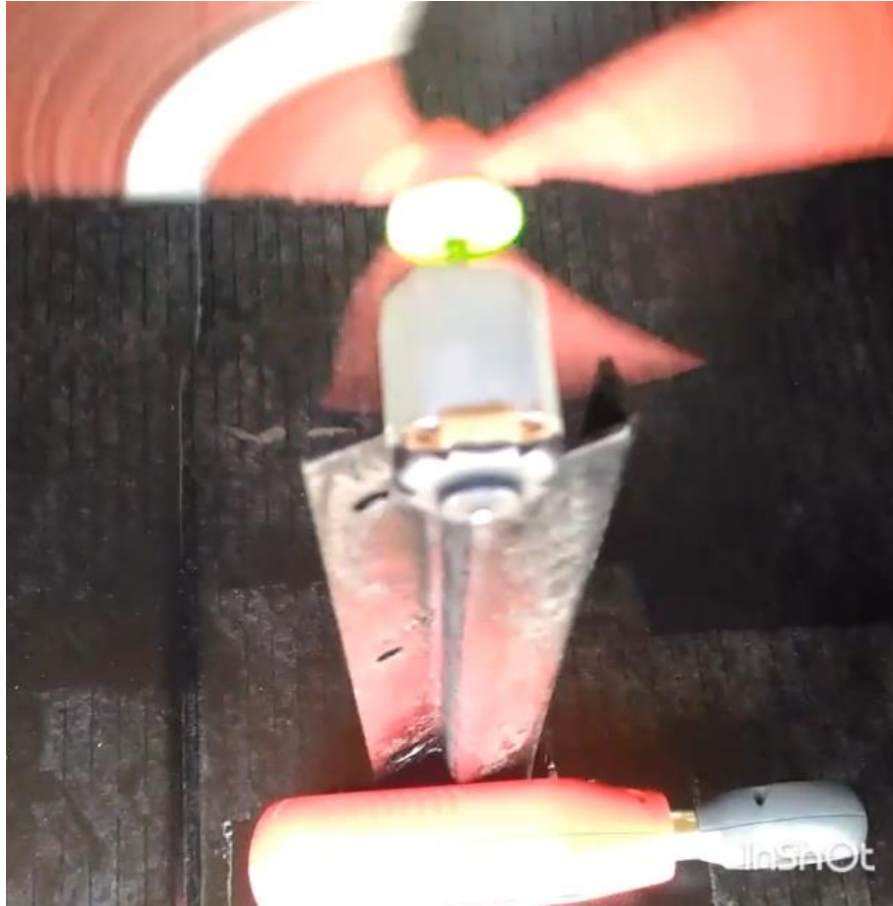


Figure 42: Wind turbine is placed on a metal plate with a constant distance from the fan and the laminar compartment

Figure 43 shows the fan, which is located behind the laminar compartment. Figure 44, shows the variable resistor, which is used to control the wind speed.

2.9 Experimental Methods

The schematic diagram in Figure 45 shows the measurements of initial and final wind velocity results recorded which is numbered as 1 and 2. The layer outside is the casing of the blower which is numbered as 3. The laminar flow compartment is numbered as 4. Number 5 represents the fan and number 6 is the variable controller to control the wind speed. The wind speed is measured with an anemometer while the rotational speed of the wind turbine model is measured with a digital tachometer.

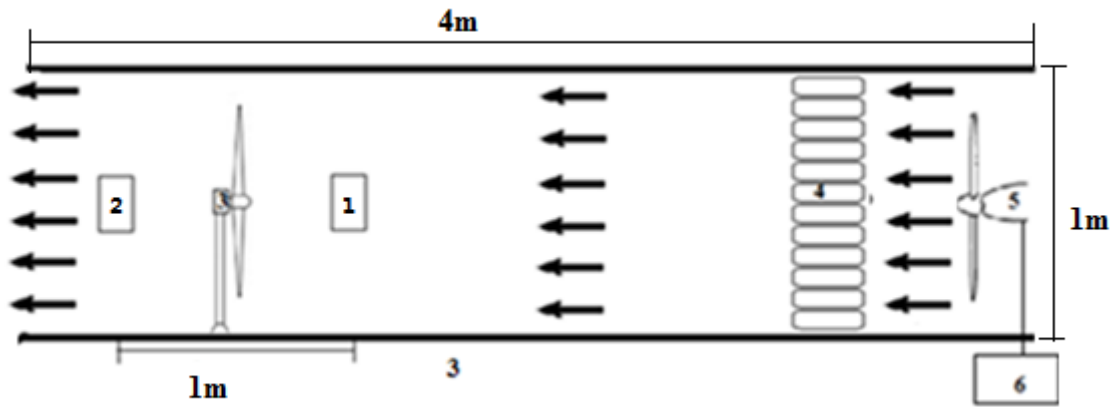


Figure 45: schematic diagram

Figures 46 to 51 shows the photo, which was taken from the video, captured during the experimental process. Figure 47 shows the velocity measured by an anemometer. Figure 49 shows the RPM which is measured when the tachometer placed near the rotating wind turbine.



Figure 46: Waterwheel wind turbine experiment



Figure 47: Speed measurement velocity 4.2 m/s (pictures obtained from experimental video)

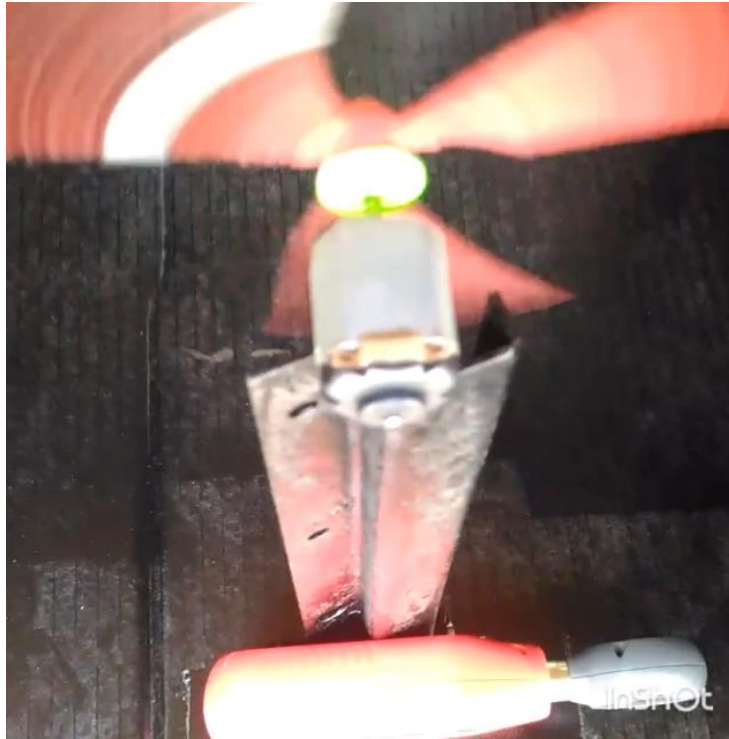


Figure 48: Modern HAWT experiment



Figure 49: Angular velocity recording

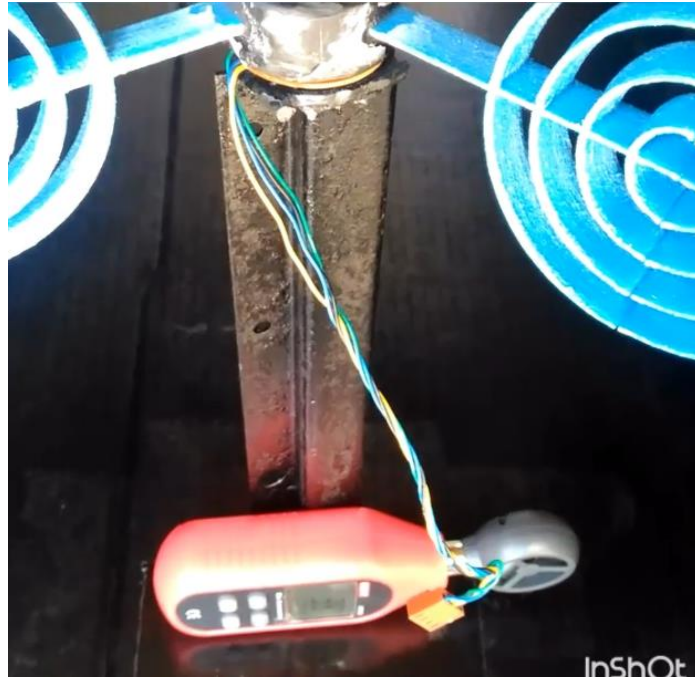


Figure 50: Lantern wind turbine



Figure 51: Darrieus VAWTs experiment, rotor of 1V

CHAPTER 3

RESULTS

3.1 Mass measurement of printed model parts

Table 9 show the mass of models measured with laboratory scale. The mass measured is used for theoretical calculations.

Table 9: Mass measurement

Detail	Waterwheel wind turbine	Darrieus VAWTs 1	Modern HAWT	Lantern wind turbine 1
Image				
Mass	5.08g	3.68g	2.12g	7.97g

3.2 Darrieus VAWTs vs lantern wind turbine, simulation results

The results generated based on the study method as shown in Chapter 2.7. The first study shows the results of darrieus VAWTs compared to lantern wind turbine. Table 10 shows the velocity streamline view of darrieus VAWTs compared to lantern wind turbine under the velocity of 5-9 m/s with a constant 2 rad/s rotational speed.

Table 11 shows contour view of darrieus VAWTs compared to lantern wind turbine under the velocity of 5-9 m/s with a constant 2 rad/s rotational speed. Lantern wind turbine's blade

chord distance is 3.5328 cm. The darrieus VAWTs blade chord distance is 12 cm. The design has the same radius with difference in chord sizes. These values are shown in equation 3.1.

Table 10: Streamline view for darrieus VAWTs compared to lantern wind turbine

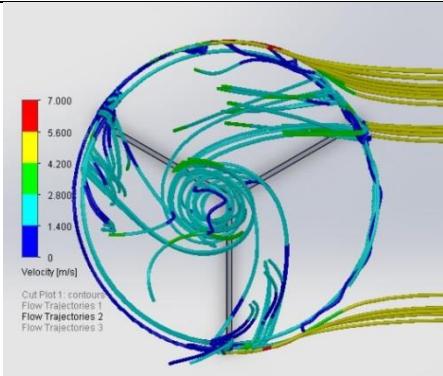
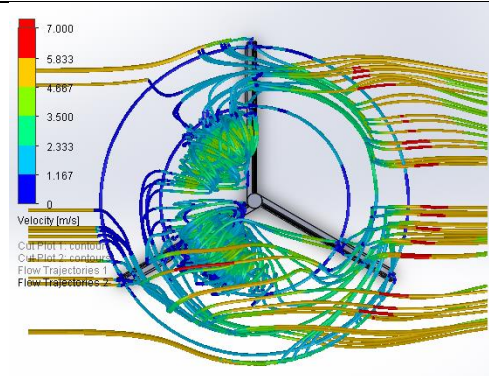
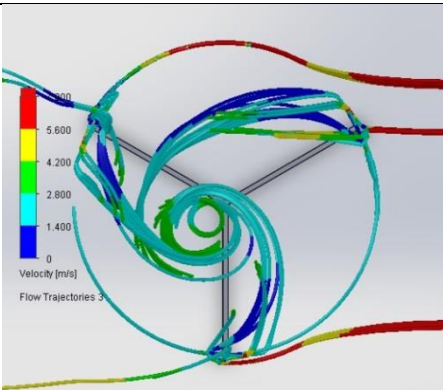
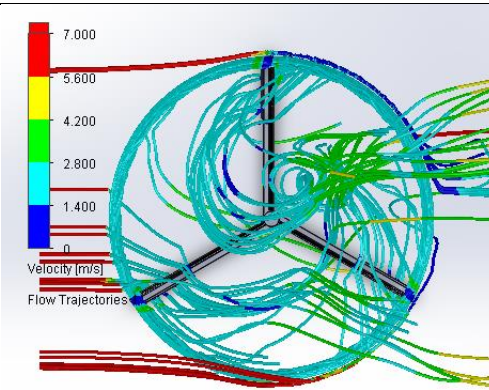
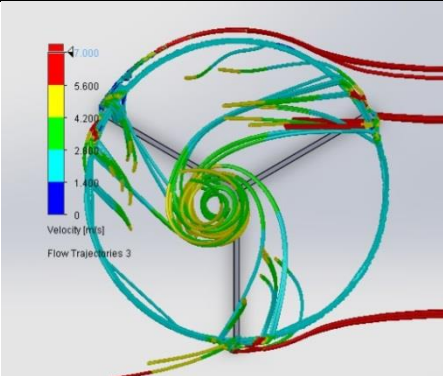
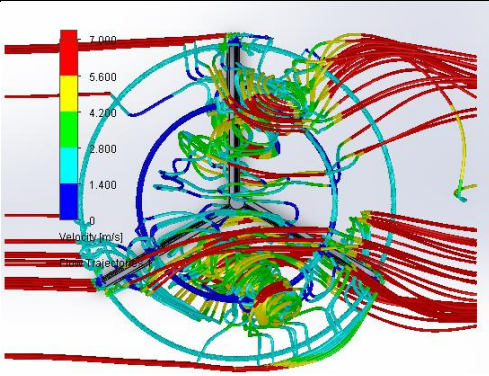
Detail	Darrieus VAWTs	Lantern wind turbine
Velocity of 5m/s		
Velocity of 6m/s		
Velocity of 7m/s		

Table 10 continued

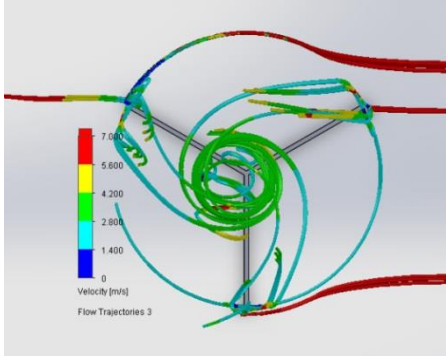
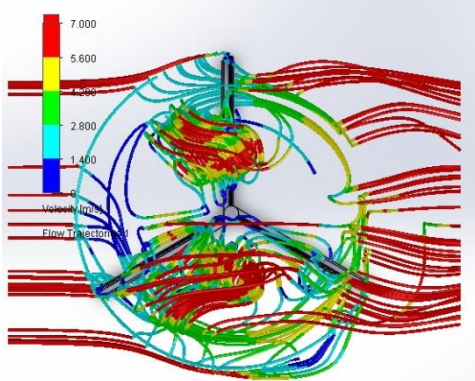
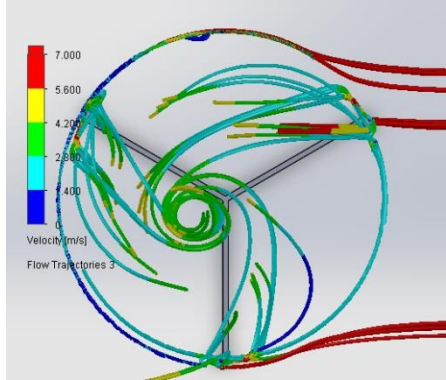
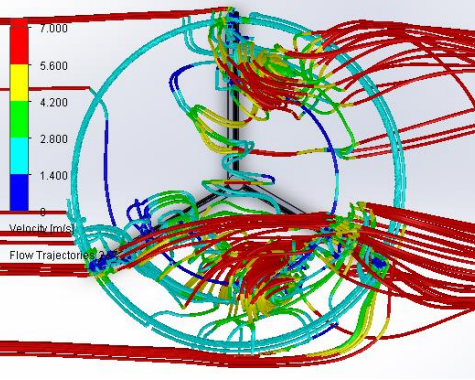
Detail	Darrieus VAWTs	Lantern wind turbine
Velocity of 8m/s		
Velocity of 9m/s		

Table 11: Lantern wind turbine and darrieus VAWTs rotation contour view

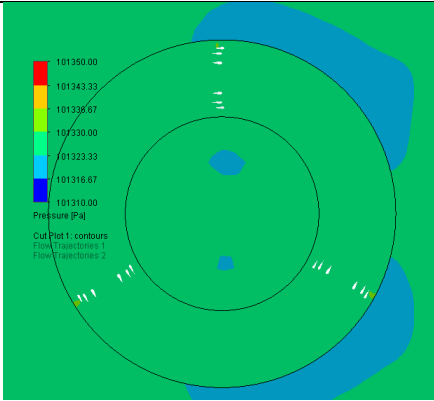
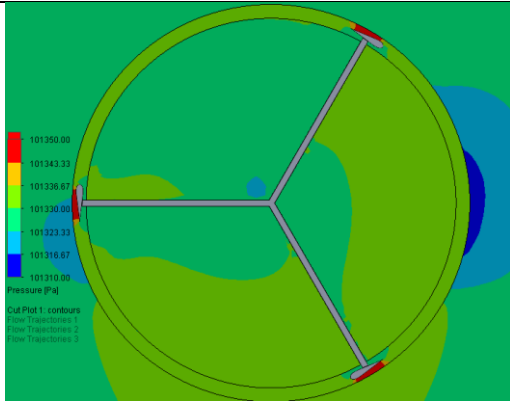
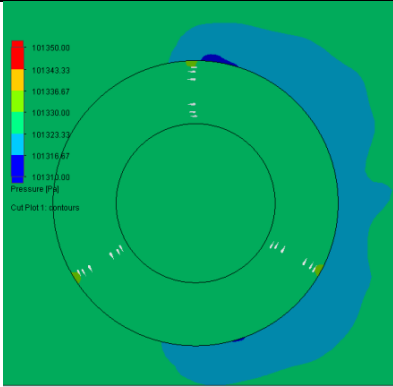
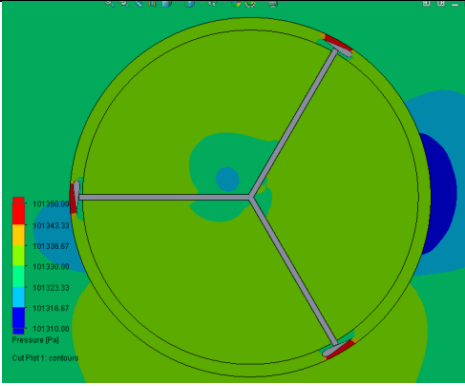
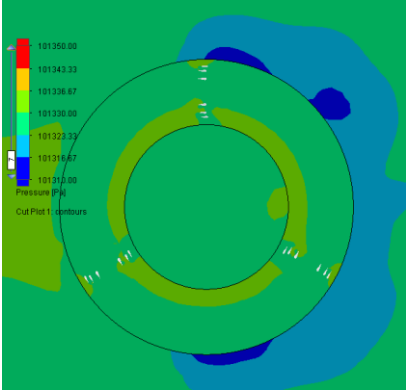
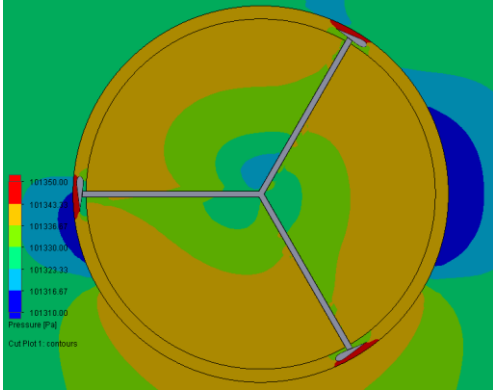
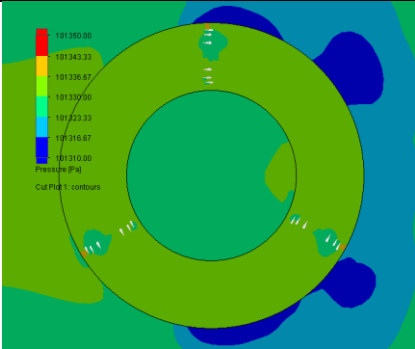
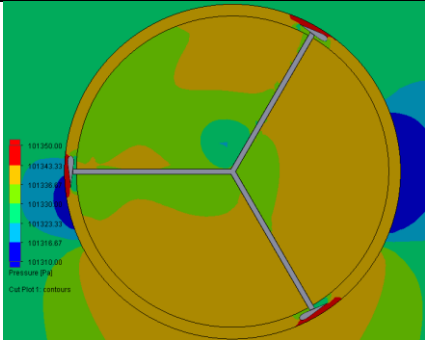
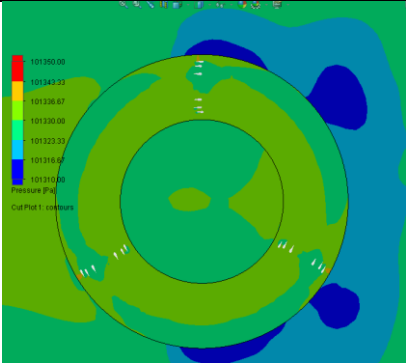
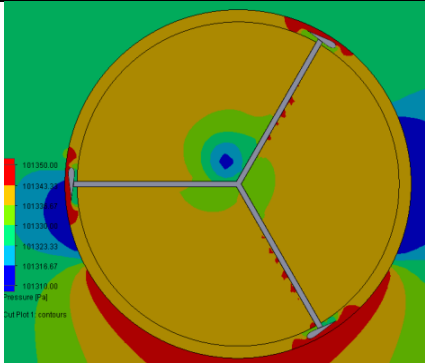
Velocity	Lantern wind turbine	Darrieus VAWTs
5m/s	 $Re = 10689$	 $Re = 36308$

Table 11 continued

Detail	Lantern wind turbine	Darrieus VAWTs
6m/s	 $Re = 12827$	 $Re = 43570$
7m/s	 $Re = 14964$	 $Re = 50832$
8m/s	 $Re = 17102$	 $Re = 58093$
9m/s	 $Re = 19240$	 $Re = 65355$

3.3 Waterwheel wind turbine vs modern, simulation results

The results generated are based on the study method explained in Section 2.7. The second study shows the results of the waterwheel wind turbine vs modern HAWT. Table 12 shows the pressure contour view of the waterwheel and modern HAWT comparison under the velocity of 5-9 m/s. Table 13 shows the velocity distribution of contoured view.

Table 12: Waterwheel wind turbine and modern HAWT pressure contour view

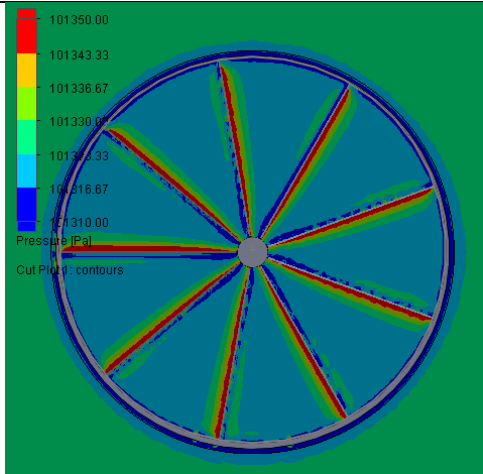
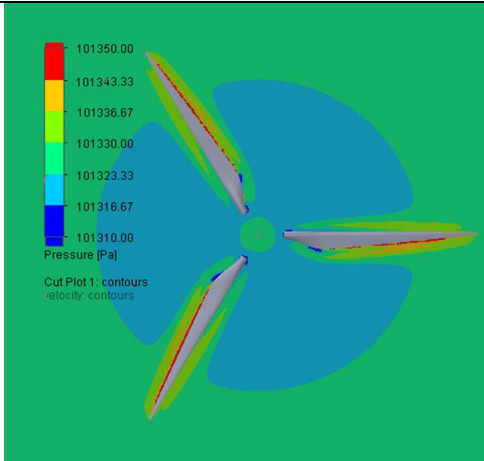
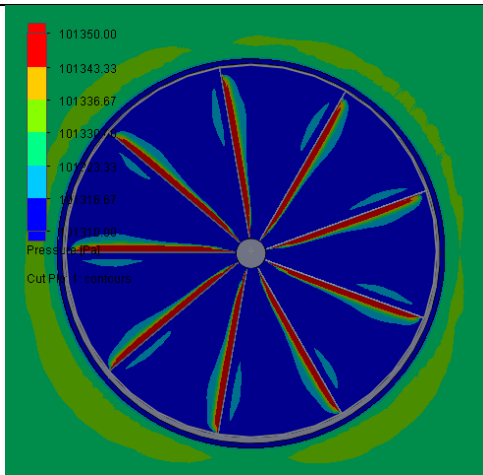
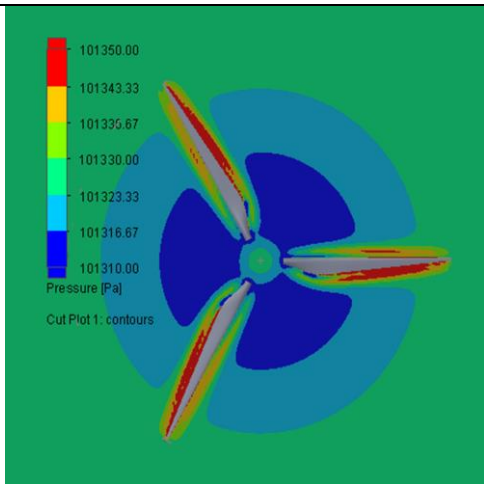
Velocity	Waterwheel wind turbine	Modern HAWT
5	 <i>Re</i> = 5446	 <i>Re</i> = 5446
7	 <i>Re</i> = 7625	 <i>Re</i> = 7625

Table 12 continued

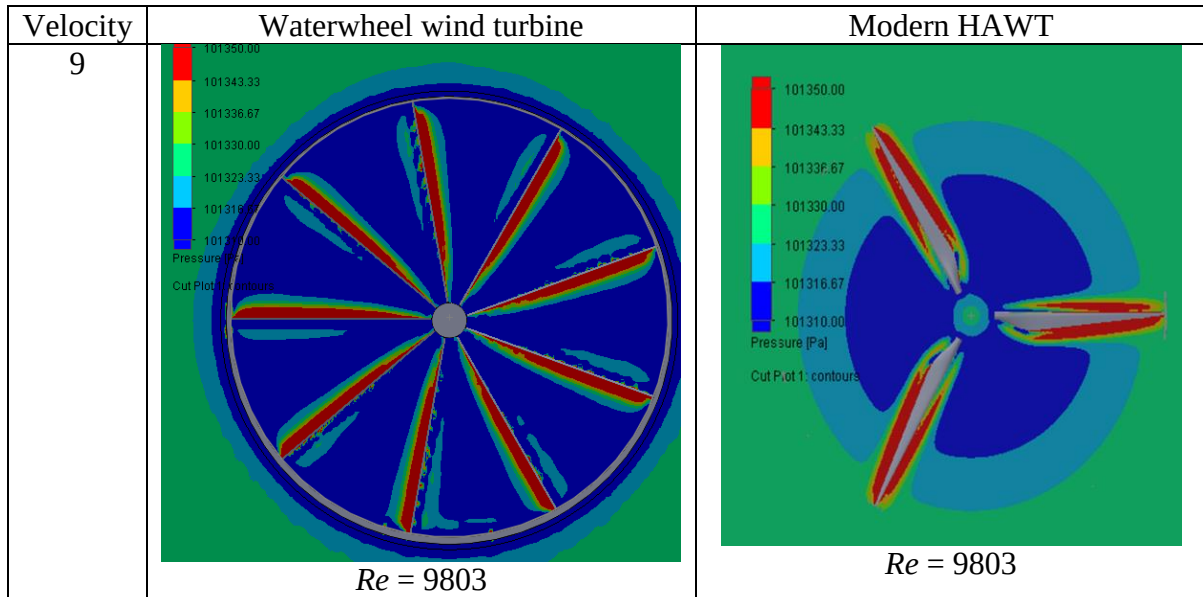


Table 13: Velocity distribution contour view

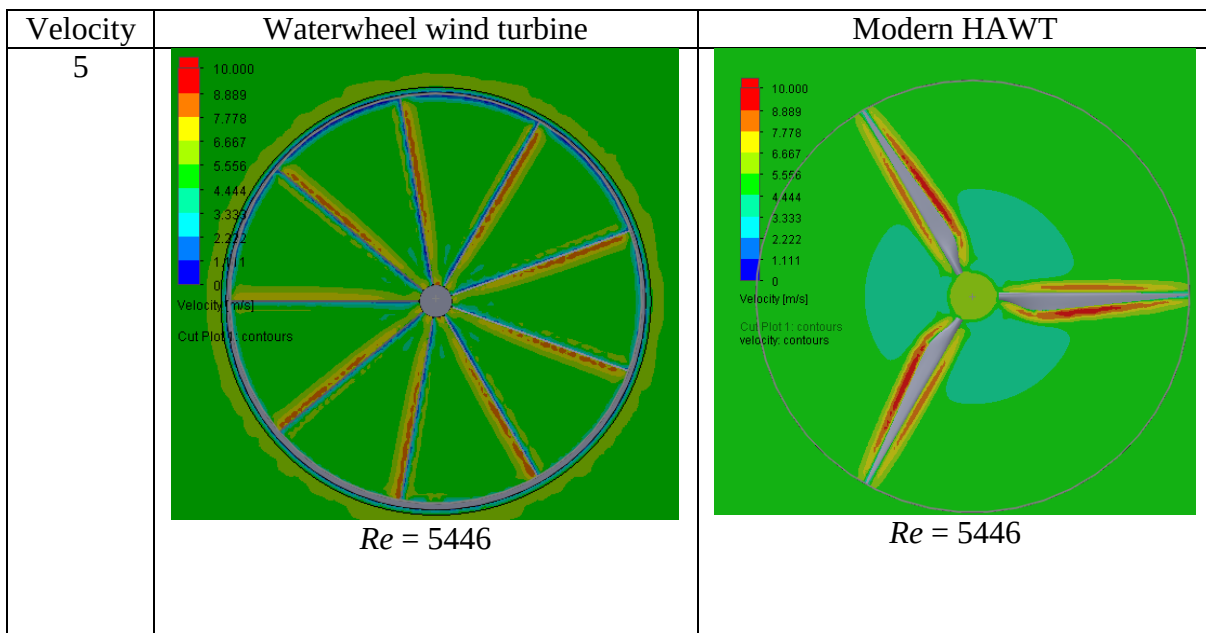
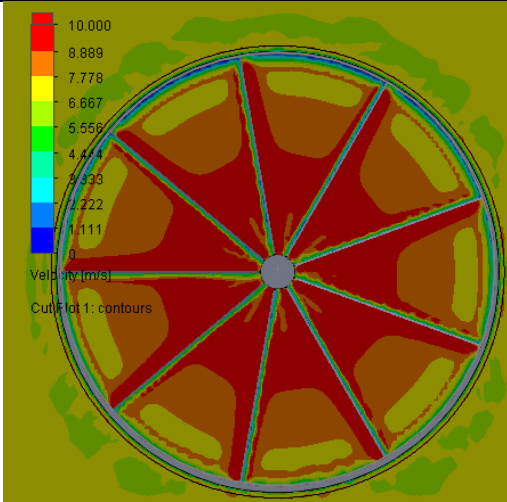
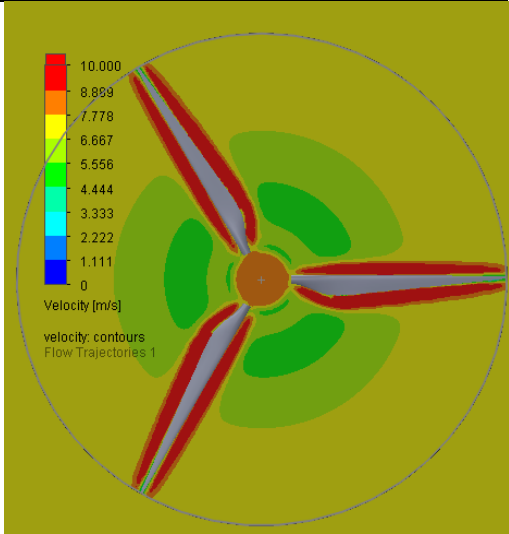
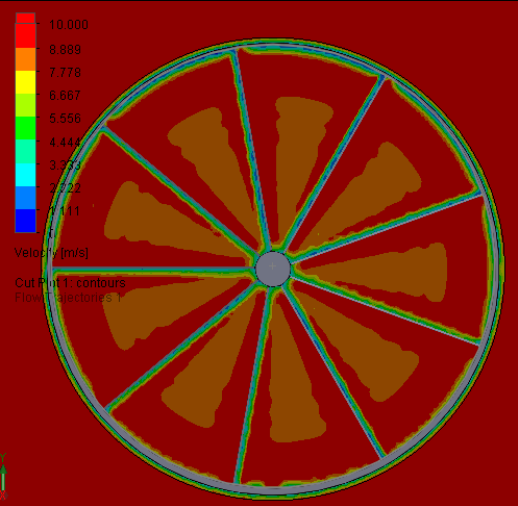
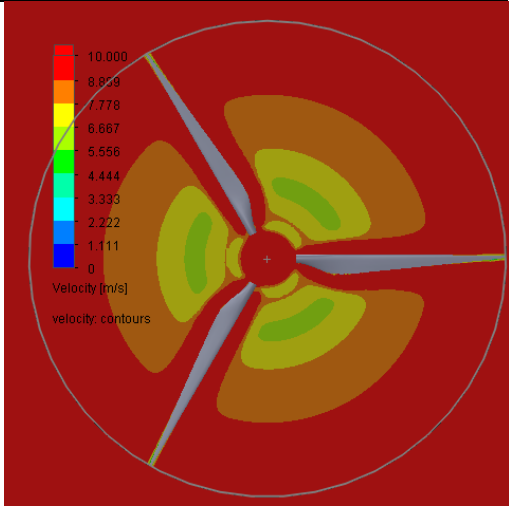


Table 13 continued

Velocity	Waterwheel wind turbine	Modern HAWT
7	 $Re = 7625$	 $Re = 7625$
9	 $Re = 9803$	 $Re = 9803$

3.4 Darrieus VAWTs and lantern wind turbine experimental results

The variable resistor controls the speed of 4.5m /s, 5.0m /s and 5.8m /s of the industrial fan. The laminar compartment turns the turbulent air of the fan to laminar flows. The RPM and wind velocity were recorded. Experiments were repeated with different velocities. Table 14 to Table 32 below show the results recorded from the experiments.

The first study is done to compare darrieus VAWTs and lantern wind turbine. Reynolds number (Re) helps to determine flow patterns of different fluid flow situations. Re number is kept constant for experimental and simulation validation at an instance where velocity is equal for experiment. Table 14 to Table 16 shows the results recorded from darrieus VAWTs. Velocity of wind speeds controlled with the variable resistor and RPM of wind turbine were also recorded.

$$\Pi_3 = Re = \frac{\rho V L}{\mu} = \frac{\rho D^2 \omega}{W} \quad (3.1)$$

$$\text{Density of air } \rho = 1.2 \text{ kg/m}^3$$

$$\text{Small chord } 2.8\text{cm} = 0.028\text{m}$$

$$\mu = 1.983 \times 10^{-5} \text{ N s/m}^2$$

Table 14: Darrieus HAWT, RPM, velocity 4.5m/s

Velocity	4.5m/s											
Re	7624											
Result	1	2	3	4	5	6	7	8	9	10	Total	Average
RPM	815	808	812	811	814	819	826	808	815	821	8142	814.2

Table 15: Darrieus HAWT, RPM, velocity 5m/s

Velocity	5m/s											
Re	8472											
Result	1	2	3	4	5	6	7	8	9	10	Total	Average
RPM	852	840	847	851	853	850	839	844	842	838	8444	844.4

Table 16: Darrieus HAWT, RPM, velocity 5.8m/s

Velocity	5.8m/s											
Re	9827											
Result	1	2	3	4	5	6	7	8	9	10	Total	Average
RPM	887	899	886	899	814	877	886	878	885	875	8798	879.8

Table 17 to Table 19 show the results recorded from the lantern wind turbine. The following calculation is done based on equation 3.1.

$$\text{Density of air } \rho = 1.2 \text{ kg/m}^3$$

$$\text{Small chord } 0.85\text{cm} = 0.0085\text{m}$$

$$\mu = 1.983 \times 10^{-5} \text{ N s/m}^2$$

Table 17: Lantern wind turbine, RPM, velocity 4.5m/s

Velocity	4.5m/s											
Re	2314											
Result	1	2	3	4	5	6	7	8	9	10	Total	Average
RPM	0	0	0	0	0	0	0	0	0	0	0	0

Table 18: Lantern wind turbine, RPM, velocity 5m/s

Velocity	5.0m/s											
Re	2572											
Result	1	2	3	4	5	6	7	8	9	10	Total	Average
RPM	0	0	0	0	0	0	0	0	0	0	0	0

Table 19: Lantern wind turbine, RPM, velocity 5.8 m/s

Velocity	5.8m/s											
Re	2983											
Result	1	2	3	4	5	6	7	8	9	10	Total	Average
RPM	0	0	0	0	0	0	0	0	0	0	0	0

3.5 Waterwheel wind turbine and modern HAWT experimental results

A second study is done by comparing darrieus VAWTs and lantern wind turbine. The Re number helps to determine flow patterns of different fluid flow situations. Re number is kept constant for experimental and simulation purposes at an instance where velocity is equal for

the experiment. Table 20 to Table 25 shows the results recorded for the waterwheel wind turbine. Velocity of wind speeds controlled with the variable resistor and RPM of wind turbine were similarly recorded.

$$R = 0.083m$$

$$Diameter = 0.166m$$

Table 20: Velocity 3 m/s result of waterwheel wind turbine

Velocity	3.0 m/s											
Re	545											
Result	1	2	3	4	5	6	7	8	9	10	Total	Average
RPM	238	229	235	231	231	230	233	237	229	226	2310	231

Table 21: Velocity 3.5 m/s result of waterwheel wind turbine

Velocity	3.5m/s											
Re	635											
Result	1	2	3	4	5	6	7	8	9	10	Total	Average
RPM	322	336	310	325	338	332	329	338	337	333	3300	330

Table 22: Velocity 4 m/s result of waterwheel wind turbine

Velocity	4.0m/s											
Re	726											
Result	1	2	3	4	5	6	7	8	9	10	Total	Average
RPM	387	398	403	389	394	389	385	402	394	401	3942	394.2

Table 23: Velocity 4.5 result of waterwheel wind turbine

Velocity	4.5m/s											
Re	817											
Result	1	2	3	4	5	6	7	8	9	10	Total	Average
RPM	422	418	431	427	423	439	428	429	426	427	4270	427

Table 24: Velocity 5m/s result of waterwheel wind turbine

Velocity	5.0m/s											
<i>Re</i>	908											
Result	1	2	3	4	5	6	7	8	9	10	Total	Average
RPM	439	452	457	446	420	436	449	442	455	450	4446	444.6

Table 25: Velocity 5.8 m/s result of waterwheel wind turbine

Velocity	5.8m/s											
<i>Re</i>	1052											
Result	1	2	3	4	5	6	7	8	9	10	Total	Average
RPM	468	471	457	477	473	475	462	461	454	468	4666	466.6

Table 26 to Table 31 show the results recorded for modern HAWT.

$$R = 0.085m$$

$$\mu = 1.983 \times 10^{-5} \text{ N s/m}^2$$

$$\text{Density of air } \rho = 1.2 \text{ kg/m}^3$$

Table 26: Velocity 3 m/s result of modern HAWT

Velocity	3.0m/s											
<i>Re</i>	545											
Result	1	2	3	4	5	6	7	8	9	10	Total	Average
RPM	0	0	0	0	0	0	0	0	0	0	0	0

Table 27: Velocity 3.5 m/s result of modern HAWT

Velocity	3.5m/s											
<i>Re</i>	635											
Result	1	2	3	4	5	6	7	8	9	10	Total	Average
RPM	0	0	0	0	0	0	0	0	0	0	0	0

Table 28: Velocity 4 m/s result of modern HAWT

Velocity	4.0m/s											
<i>Re</i>	726											
Result	1	2	3	4	5	6	7	8	9	10	Total	Average
RPM	445	448	456	460	459	436	463	446	455	452	4520	452

Table 29: Velocity 4.5 m/s result of modern HAWT

Velocity	4.5m/s											
<i>Re</i>	817											
Result	1	2	3	4	5	6	7	8	9	10	Total	Average
RPM	611	617	607	619	619	618	622	614	615	608	6150	615

Table 30: Velocity 5 m/s result of modern HAWT

Velocity	5.0 m/s											
<i>Re</i>	908											
Result	1	2	3	4	5	6	7	8	9	10	Total	Average
RPM	781	792	779	779	791	789	790	796	783	786	7866	786.6

Table 31: Velocity 5.8 m/s result of modern HAWT

Velocity	5.8m/s											
<i>Re</i>	1052											
Result	1	2	3	4	5	6	7	8	9	10	Total	Average
RPM	873	878	879	889	888	891	889	878	884	893	8842	884.2

3.6 Experimental vs theory calculation results

The calculation done for torque, C_p , output energy as shown in Table 32 and Tables 33 are the result obtained from experimental analysis. The calculations done are based on each of the equations shown below. Velocity and RPM are obtained from experimental analysis. The radius for wind turbine measured and recorded was 0.08m. Re number are maintained for comparison.

Power input for wind turbine is;

$$P_{in} = \frac{1}{2} \rho A V^3 \quad (3.2)$$

where,

P_{in} = power input (J/s)

ρ = density (kg/m³)

A = area (m²)

V = velocity (m/s)

Power output for wind turbine;

$$P_{out} = C_p \times P_{in} \quad (3.3)$$

where,

P_{in} = power in (J/s)

C_p = power coefficient

Kinetic energy of rotating wind turbine;

Assuming that time is one second;

$$KE = \frac{1}{2} I \omega^2 \quad (3.4)$$

where,

I = moment of inertia (kg.m²)

ω = angular velocity (rad/s).

While kinetic energy of power and time;

$$KE = Pt \quad (3.5)$$

The equations for the torque is,

$$\tau = \frac{P}{\omega} \quad (3.7)$$

$$\tau = Fr \quad (3.8)$$

where,

P = power (J/s)

ω = angular velocity (rad/s)

F = force (N)

r = radius (m)

Table 32: Waterwheel wind turbine experimental torque and other values

Re	Velocity, m/s	RPM	Radius, m	TSR	Mass, kg	KE,J
545	3.0	231	0.08	0.669	0.036	0.0725
635	3.5	330	0.08	0.819	0.036	0.148
726	4.0	394	0.08	0.856	0.036	0.211
817	4.5	427	0.08	0.824	0.036	0.247
908	5.0	444	0.08	0.772	0.036	0.268
1052	5.8	466	0.08	0.699	0.036	0.295
Re	Energy in,J	C_p	Energy out, J	Torque, Nm		
545	0.350	0.2068	0.0725	0.0029		
635	0.556	0.2658	0.1480	0.0042		
726	0.831	0.2541	0.2112	0.0051		
817	1.183	0.2094	0.2478	0.0055		
908	1.623	0.1655	0.2686	0.0057		
1052	2.533	0.1167	0.2959	0.0060		

Table 33: Modern HAWT experimental torque and other values

Re	Velocity, m/s	RPM	Radius, m	TSR	Mass, kg	KE,J
545	3.0	0	0.08	0	0.02	0
635	3.5	0	0.08	0	0.02	0
726	4.0	452	0.08	1.005	0.02	0.177
817	4.5	615	0.08	1.216	0.02	0.329
908	5.0	786	0.08	1.400	0.02	0.539
1052	5.8	884	0.08	1.3567	0.02	0.681
Re	Energy in,J	C_p	Energy out, J	Torque, Nm		
545	-	-	-	-		
635	-	-	-	-		
726	0.871	0.20418	0.1779	0.00376		
817	1.241	0.26548	0.3295	0.00511		
908	1.702	0.31661	0.5390	0.00654		
1052	2.657	0.25629	0.6811	0.00735		

Table 34 and Table 35 shows the simulation results for torque of water wheel wind turbine and modern HAWT. Re number are maintained for comparison. Same parameter and setting

that are being set for the wind turbine is previously shown in Table 3 and Table 4 in Chapter 3.

The summary of the visual results presented in Chapter 3 is tabulated in the following tables.

Table 34: Waterwheel wind turbine simulation, torque

Re	Velocity, m/s	RPM	Normal Force, N	R, radius	Torque, Nm
545	0.500	231	0.028	0.5	0.014
635	0.583	330	0.051	0.5	0.026
726	0.667	394	0.072	0.5	0.036
817	0.750	427	0.077	0.5	0.039
908	0.834	444	0.099	0.5	0.050
1052	0.965	466	0.109	0.5	0.055

Table 35: Modern HAWT simulation, torque

Re	Velocity, m/s	RPM	Normal Force, N	r	Torque, Nm
545	0.500	0	0	0.5	0
635	0.583	0	0	0.5	0
726	0.667	452	0.044	0.5	0.022
817	0.750	615	0.082	0.5	0.041
908	0.834	786	0.137	0.5	0.069
1052	0.965	884	0.21	0.5	0.105

CHAPTER 4

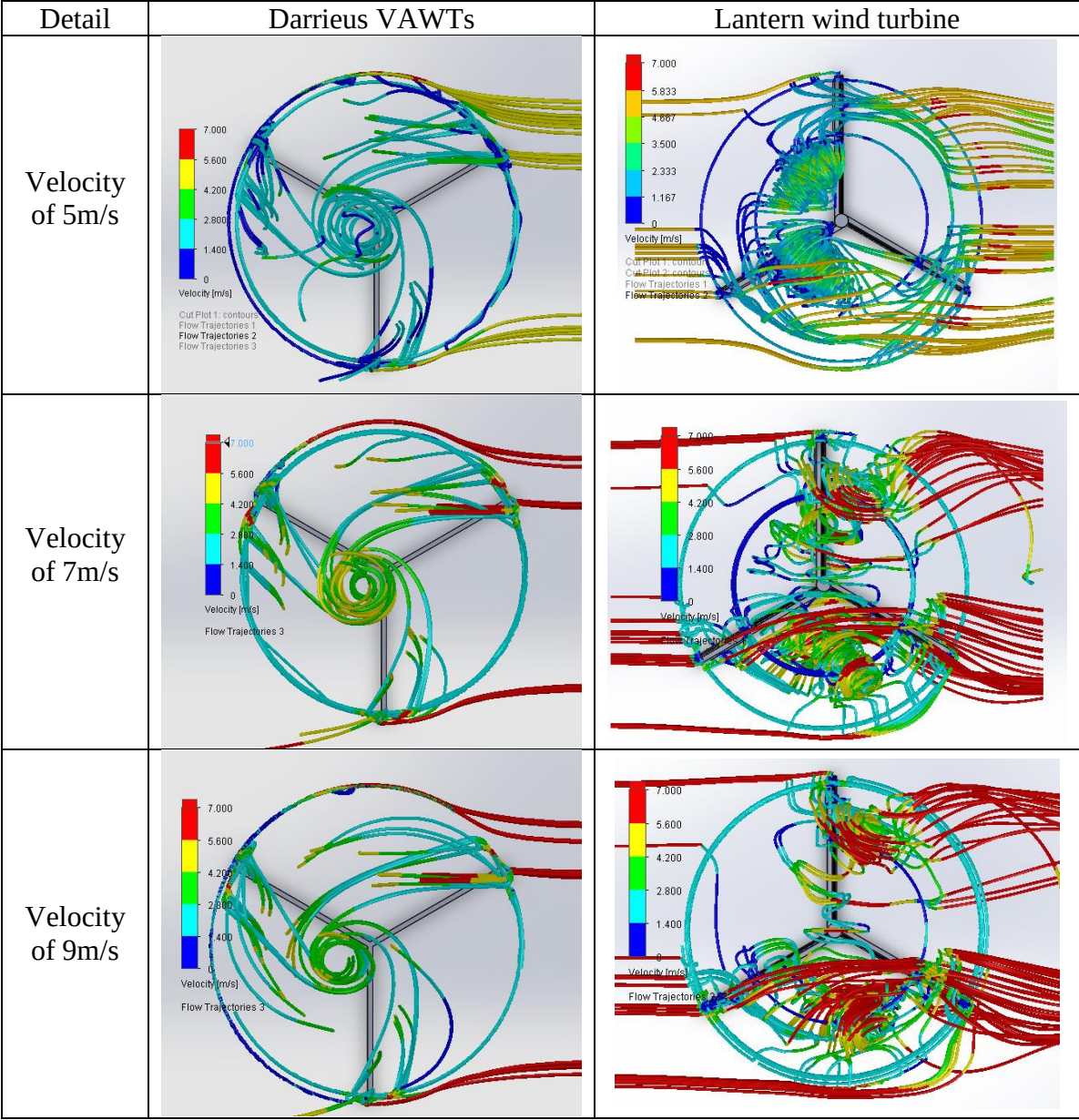
DISCUSSION

4.1 Simulation results

SOLIDWORKS[®] with flow simulation solver is being set as fluid rotational condition. Based on the results obtained in Table 36, a simulation with a velocity of 5m/s with 2 rad/s rotation shows that the lantern wind turbine has very high vortices shed. The formation of unsteady vortices shed is formed at the center of the lantern wind turbine. This unsteady shed vortices lead to vibrations and reduces the performance of the wind turbine.

Figure 52 shows the horizontal view of the flow condition with blue color, which shows the airfoil vortex wake. This increases the drag on the blade performance. However, the darrieus VAWTs with a velocity of 5m/s and a 2 rad/s rotation show a smooth pressure distributions flow on the blades and slight vortices wake at the center of the rotation. In the same Table 36 shows that the velocity of 7m/s with 2 rad/s rotation has the lantern wind turbine with a slight increase in rotating velocity value. The wind turbine design of darrieus VAWTs similarly shows a smooth pressure distributions flow on the blades and slight vortices wake at the center of rotation. The wind turbine design of darrieus VAWTs shows an increase of vortices wake on the blade as the velocity increases and reduces in the vortices wake at the center of rotation of the wind turbine. Overall distributions still shows that darrieus VAWTs has a highly more stable velocity flow distribution with low changes.

Table 36: Flow velocity and wind turbine rotation



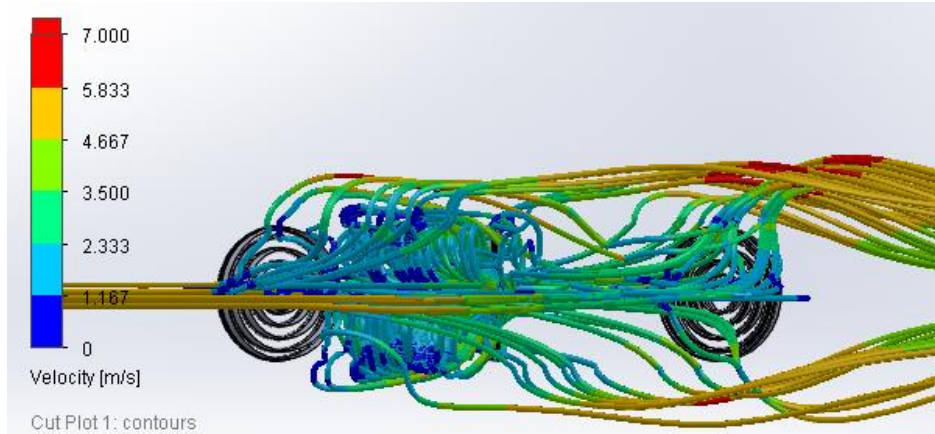


Figure 52: Lantern wind turbine streamline contour view

Table 37 shows CFD simulation of vorticity contour view and streamline vorticity view of one plane crossed at the middle of the blade. The result of the simulation shows that vorticity of lantern wind turbine design has a much higher vortex shedding than the darrieus VAWTs. It generates higher vorticity that has a higher tendency to create rotational force. For more information regarding vortex shed and blade between vortex interactions reader is referred to Tjiu (2015).

Table 38 shows the pressure difference on the blades of lantern wind turbine, which is much lower in all of the result shown above, compared to darrieus VAWTs wind turbine. There is an obvious pressure difference on the darrieus VAWTs wind turbine shown in red and green color region. Therefore, it is more likely to have aerodynamic lifting effects to take place. While, lantern wind turbine is more likely to have a drag force acting on the blade compared to lifting force.

Table 37: Contours 3D view for vorticity of lantern wind turbine and darrieus VAWTs

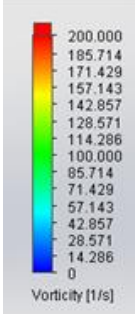
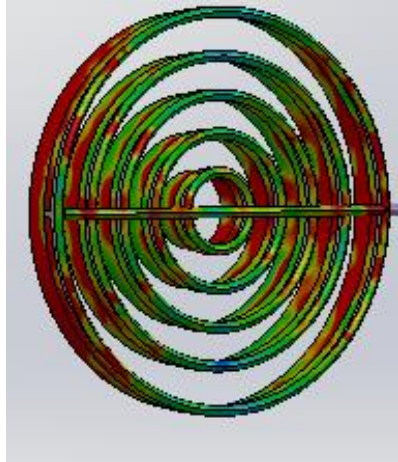
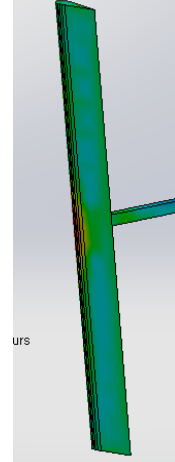
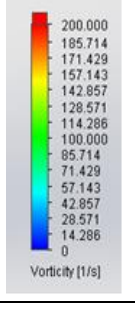
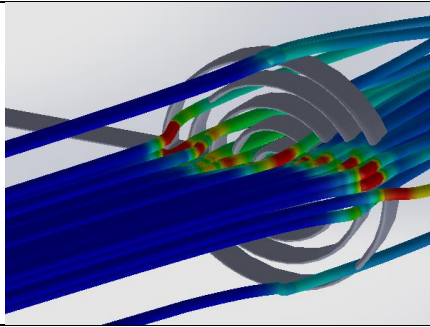
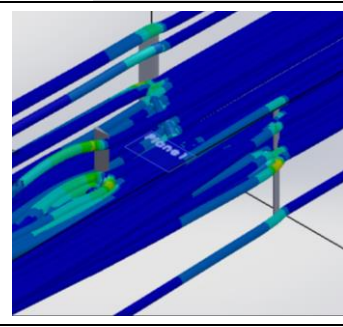
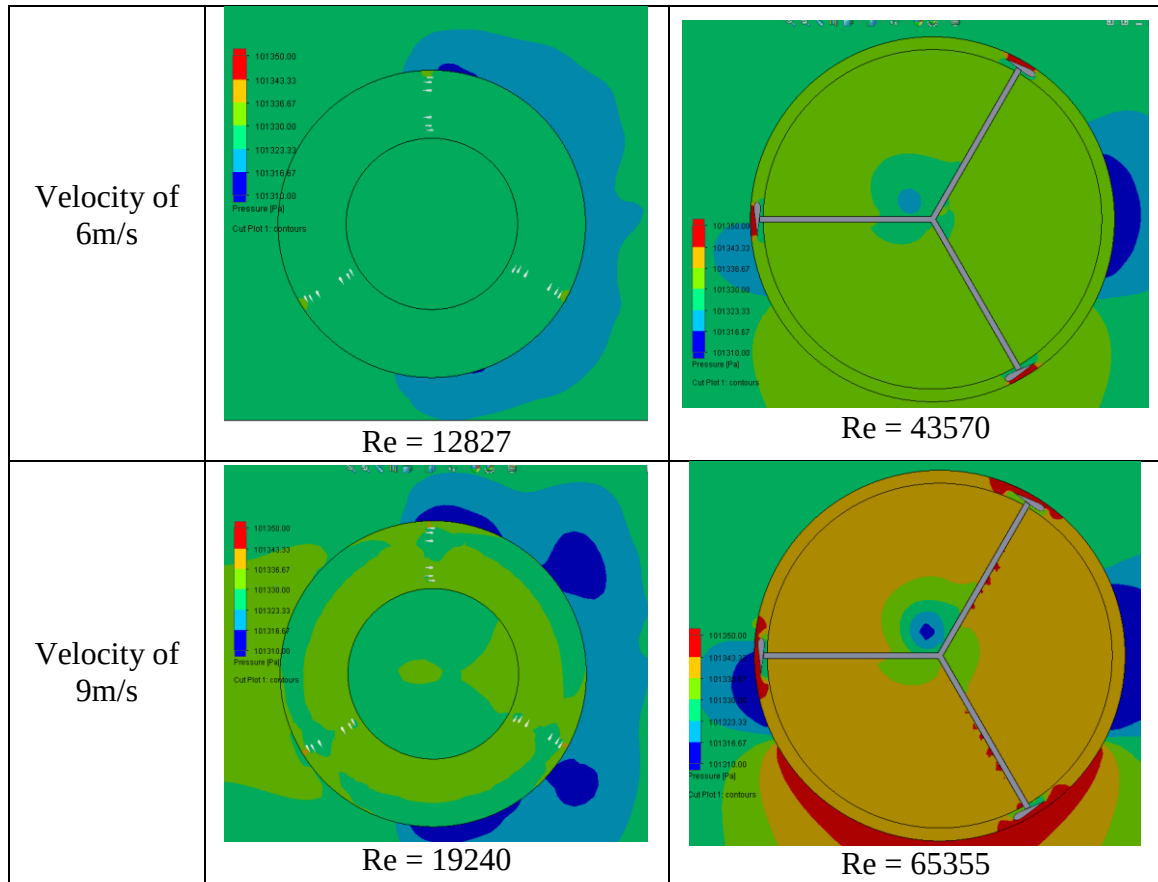
Detail	legend	Lantern wind turbine	Darrieus VAWTs
Contour view	 Vorticity [1/s] 200.000 185.714 171.429 157.143 142.857 128.571 114.286 100.000 85.714 71.429 57.143 42.857 28.571 14.286 0		
Pipe view	 Vorticity [1/s] 200.000 185.714 171.429 157.143 142.857 128.571 114.286 100.000 85.714 71.429 57.143 42.857 28.571 14.286 0		

Table 39 shows the results of waterwheel wind turbine and modern HAWT. Both show a steady distribution of pressure changes. The velocity of the wind turbine increases as the pressure slightly increases between the blades. However, the difference between these two designs was an obvious pressure difference for the waterwheel wind turbine on the blade. As shown in Figure 41, the red color on the blade is showing higher pressure with blue and green color region behind the blade. This is the pressure difference, which is more likely to generate lift and force.

Table 38: Lantern wind turbine and darrieus VAWTs rotational contour view



However, in Figure 53, less pressure differences is generated for modern HAWT with red high pressure and green average pressure.

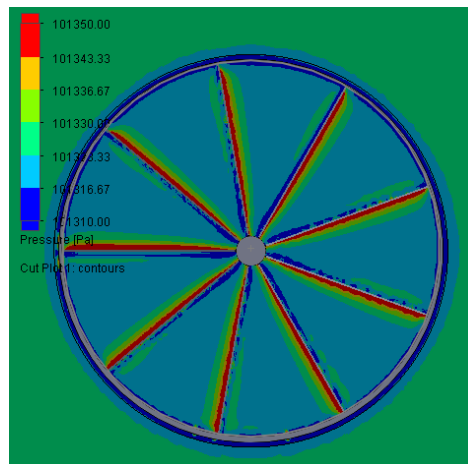
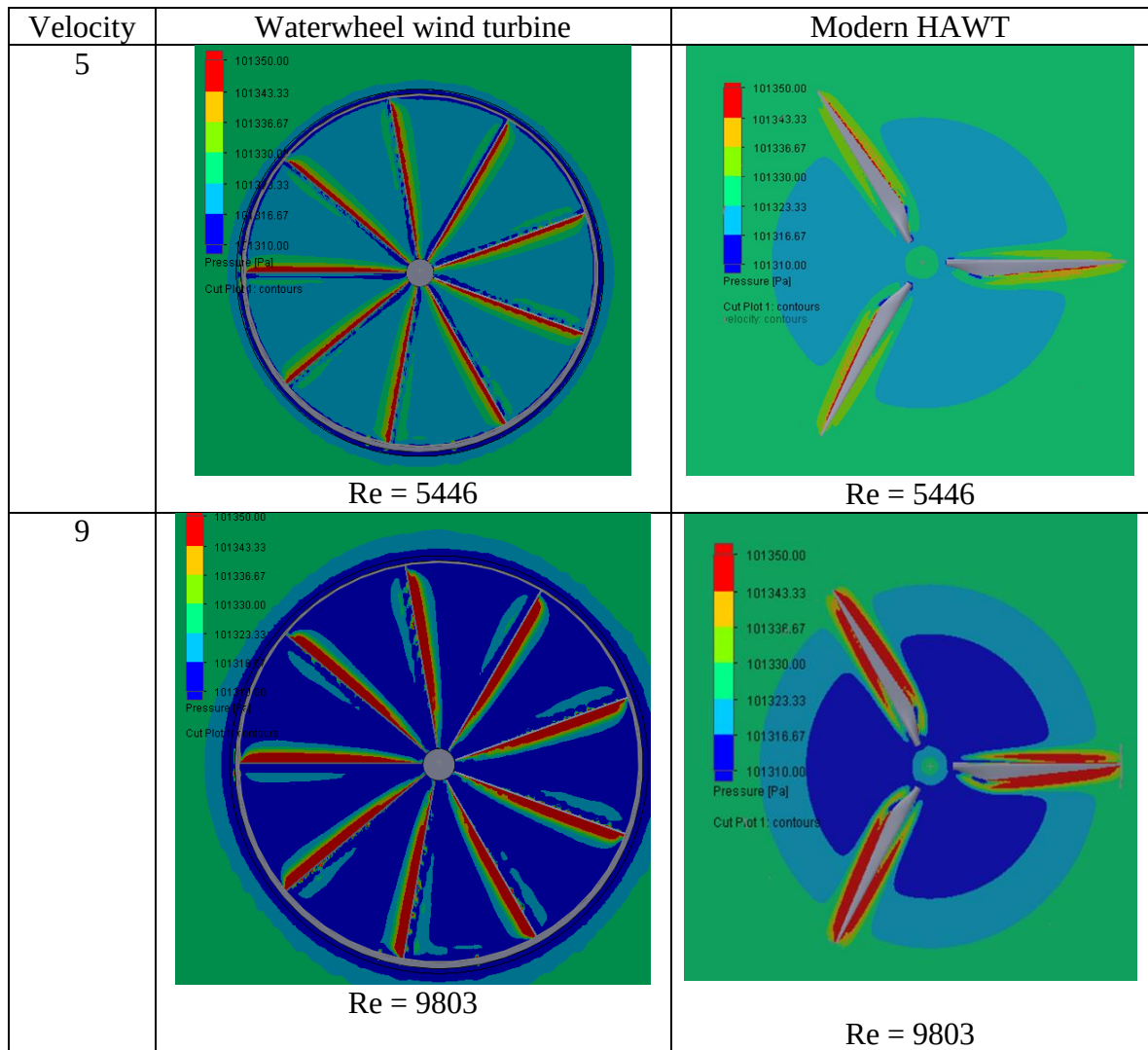


Figure 53: Pressure distribution for constant velocity 5m/s waterwheel wind turbine

Table 39: Waterwheel wind turbine and modern HAWT contour view



Based on the finding as shown above, lower wind speed with more blade of waterwheel wind turbine are more likely to capture wind as the pressure difference on each of the blades is higher compared to modern HAWT. This can be clearly seen in Figure 54.

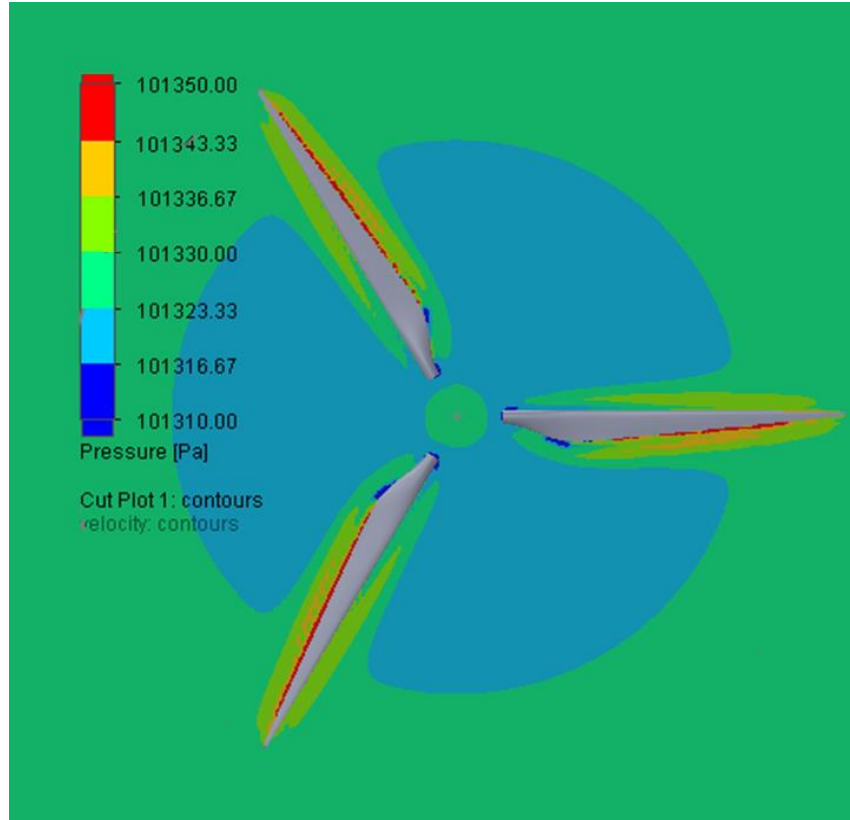
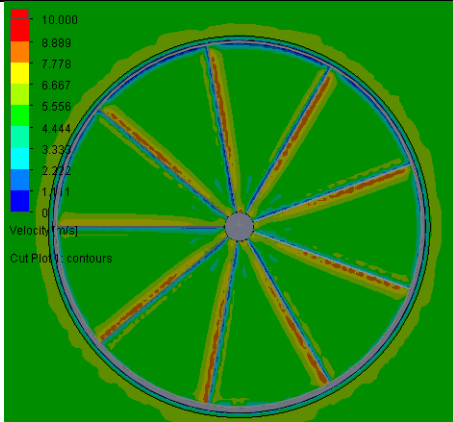
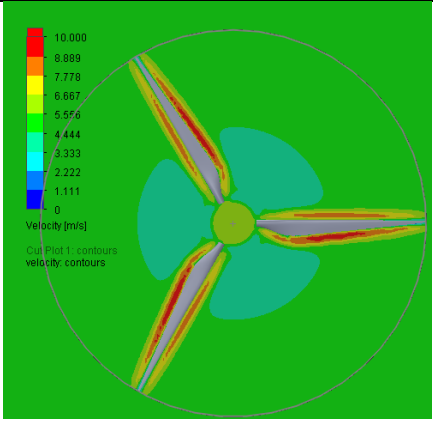
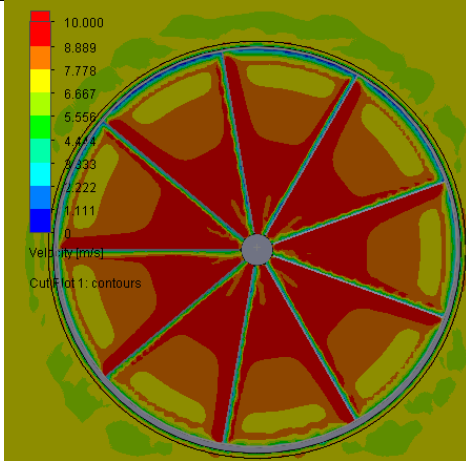
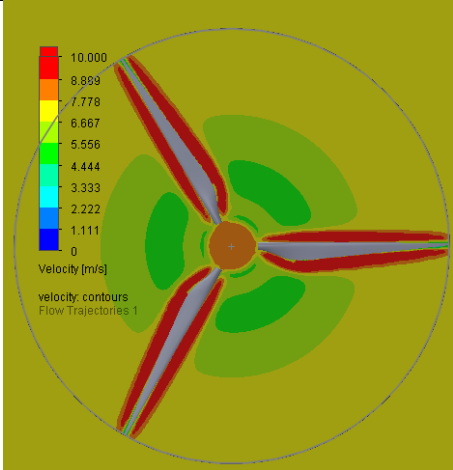


Figure 54: Pressure distribution for constant velocity 5m/s modern HAWT

Generally, velocity shows a smooth distribution flow over each of the blades for both wind turbine designs as shown in Table 40. Velocity flow of 5 m/s shows a higher velocity of rotation on the blade of modern HAWT, which has a higher region of red color as compared to the waterwheel wind turbine. At 7m /s, the velocity distribution of modern HAWT for the rotation of the blade still gives an obvious higher red color region while, waterwheel wind turbine shows an increase of velocity on each of the blades as the velocity increases. However, the result that is more accurate is placed in experiment comparison in Chapter 3.

Table 40: Velocity distribution contour view

Velocity	Waterwheel wind turbine	Modern HAWT
5	 Re = 5446	 Re = 5446
7	 Re = 7625	 Re = 7625

4.2 Comparison between simulation and experimental for lantern wind turbine and darrieus VAWTs

Figure 55 indicates the results obtained from velocity of wind flow and angular velocity of wind turbine. However, based on the table, it shows that the lantern wind turbine has no rotational motion in experimental results. Even though the velocity of the wind speed is

increased up to 10m/s, there was no sign of rotational motion. Darrieus VAWTs shows an outstanding performance of up to 900 RPM.

Lantern wind turbine could not be rotated. It has no rotation due to the blade design with a very high mass and there is possibility that the rotor used have too much resistance. It is believed that angle of attack should be increased to produce higher pressure differences so that higher lifting force could act on the blade. This can be seen in Figure 56. There is no obvious pressure difference at the front of top blade or bottom of the blade design flow as compared to Figure 57. Modern HAWT show an obvious pressure difference based on the color shown in the figure; where green color shows lower pressure and red color shows higher pressure.

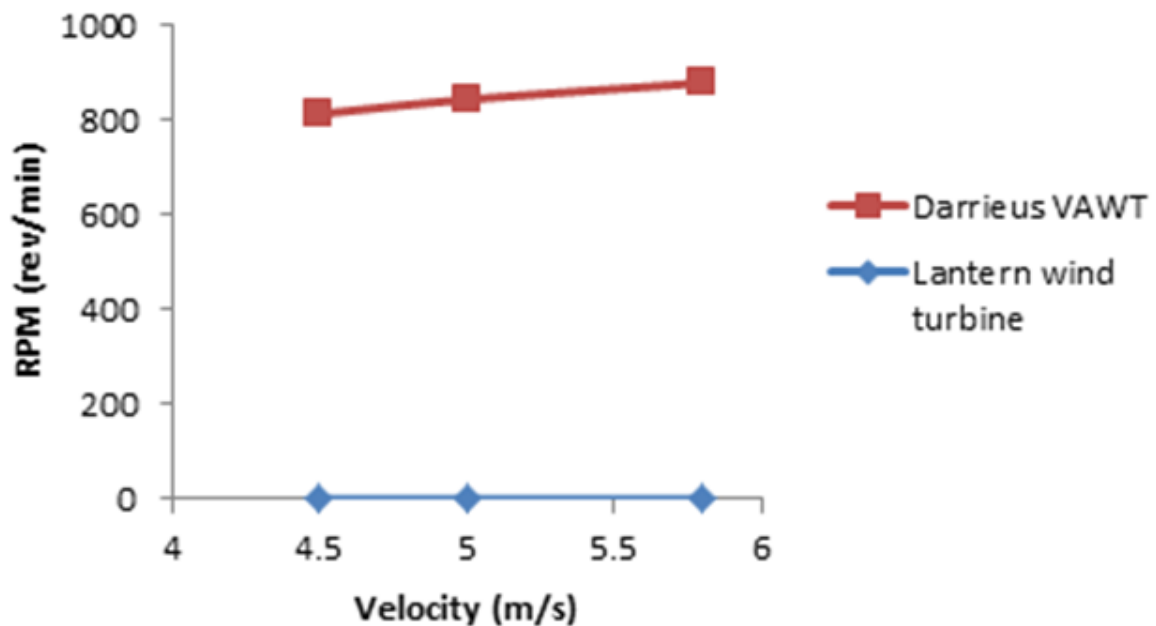


Figure 55: Experimental results of RPM vs velocity of darrieus VAWTs and lantern wind turbine

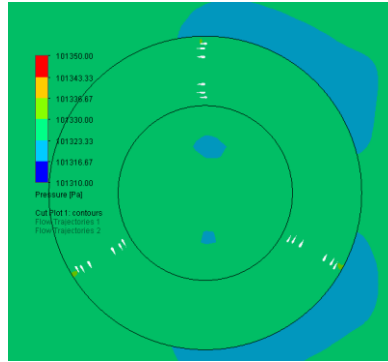


Figure 56: Velocity of 5 m/s with 2 rad/s rotation of lantern wind turbine.

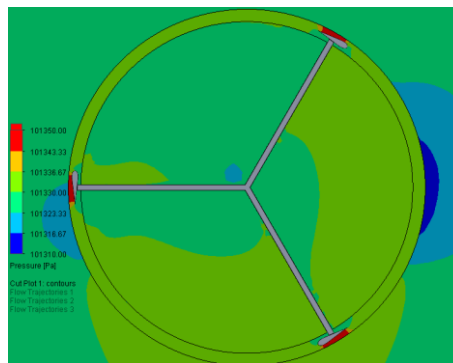


Figure 57: Velocity of 5 m/s with 2 rad/s rotation of darrieus VAWTs

4.3 Comparison between simulation and experimental for modern HAWT vs waterwheel wind turbine

Figure 58 shows the results generated from calculation based on theory as mentioned in Chapter 3. This graph compares the velocity of the wind blowing and the revolution per minutes of the wind turbine rotating when the wind is blowing. Compared results shows that the modern HAWT is not rotating at low wind speed, which is less than 4m/s. However, it shows a high increase in RPM as it exceeded 4 m/s. Waterwheel wind turbine shows that it has a constant increase of RPM from lower wind speed. The experimental for velocity less than 3 m/s is not conducted because this research is conducted based on the reference of an average wind speed of Malaysia, as previously mentioned in Section 2.2.

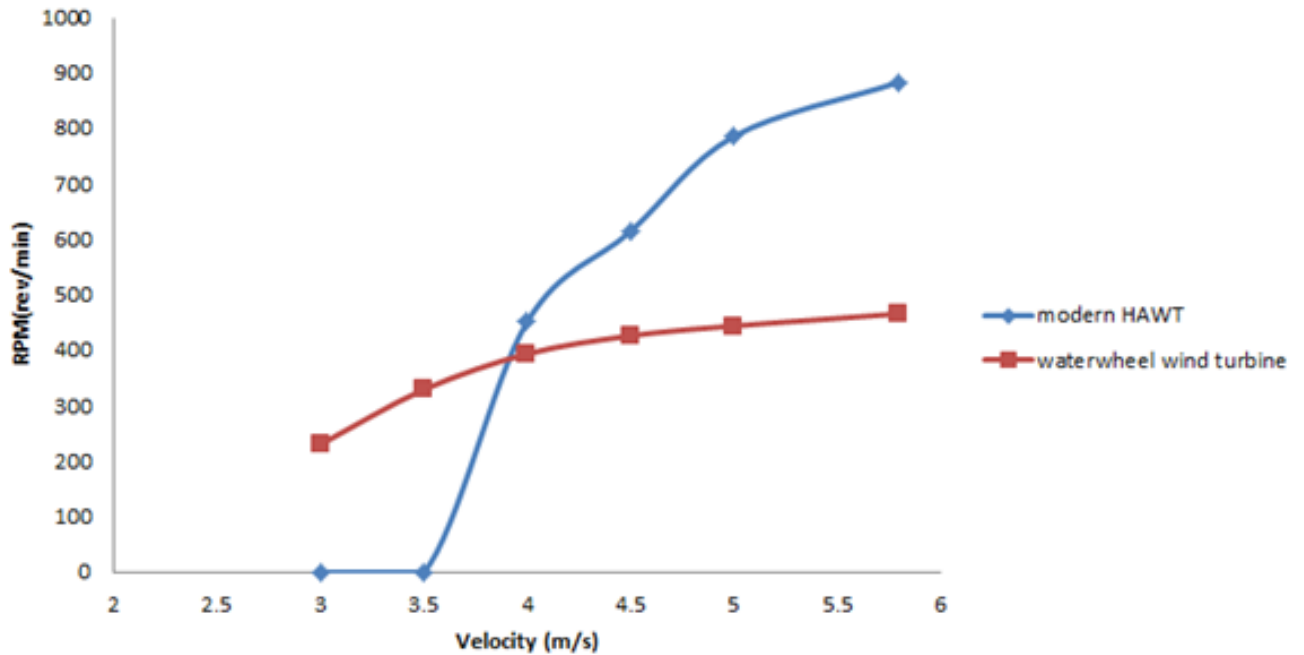


Figure 58: Velocity vs angular speeds of experimental

The C_p and TSR in figure 59 shows the experimental result which was generated according to the same chord length, radius and angle, which was previously mentioned in Chapter 3.5. For a tip speed ratio, (TSR) < 1 , the wind turbine is dependent on drag force, while TSR > 1 , the wind turbine depends on lifting force. The result of the velocity studied is in the range between 3-6 m/s. Waterwheel wind turbine shows lower C_p . The water wind turbine's TSR depends on drag force instead of lifting force. Modern HAWT depends on lifting force. This results shows that modern HAWT has higher C_p compared to waterwheel wind turbine. It can also be stated that modern HAWT has higher rotor performance compared to the others.

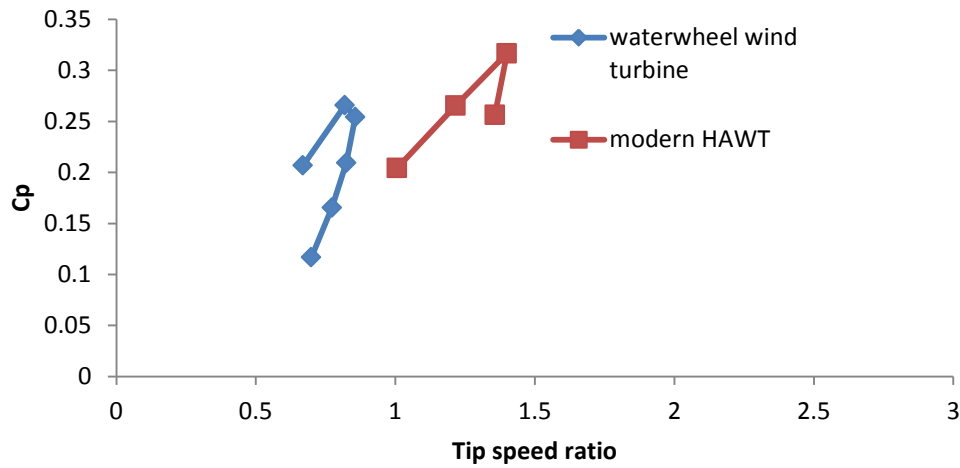


Figure 59: C_p vs TSR, Radius = 0.08 m and Chord = 0.01 m

Figure 60 shows a tabulation of results of our two novel design wind turbine compared to Menet & Bourabaa results (Menet & Bourabaa, 2004). Ideal wind turbine is known as the Betz limit, the maximum C_p is 59.2% and the maximum of C_p obtained in practice was 46 %, shown in the same figure 60 (Çetin et al, 2005). Ideal wind turbine is plotted with purple colour in figure 60. The real practice C_p is less than the theoretical value; this is due to the losses that are not considered in theory. Whirlpool losses are the mass of the air changes as it approaches the rotating blade which is also shown by Betz limit. TSR is basically acted as an independent variable which is fixed. However, this experimental study proved that some wind turbine design does not rotate even with the present of high wind speed. Therefore, when there is no rotation TSR would always be zero. Hence, there is no power extracted from the wind. Part of the result is generated by Menet & Bourabaa (2004) with C_p generated by moment and TSR (Menet, 2004; Ragheb & Ragheb, 2011). It does not supply sufficient information for blades chord, radius angles or velocity for each of the machine designed. Figure 60 is added with the results for waterwheel wind turbine and modern HAWT which is tabulated based on experimental result of angular velocity of wind turbine. The modern

HAWT model gives the maximum power coefficient of 0.27 at a wind speed of 5 m/s and tip speed ratio of 0.6 which is higher than the waterwheel wind turbine model. This gives the maximum power coefficient of 0.32 at a wind speed of 3.5 m/s and tip speed ratio of 1.4. Besides that, Menet & Bourabaa (2004) results show that the savios rotor optimal TSR where C_p is lower than the waterwheel wind turbine but higher than the modern HAWT design. The American multiple blade wind turbine has a very low TSR of 1.5 and 0.7 C_p as compared to others. 3 blade air screw has highest optimal C_p and TSR compared to others. The result for modern HAWT highly reduced in TSR and C_p at the red last point due to the increase of vibration of the model when it reached 884 revolutions per second for the small-scale model.

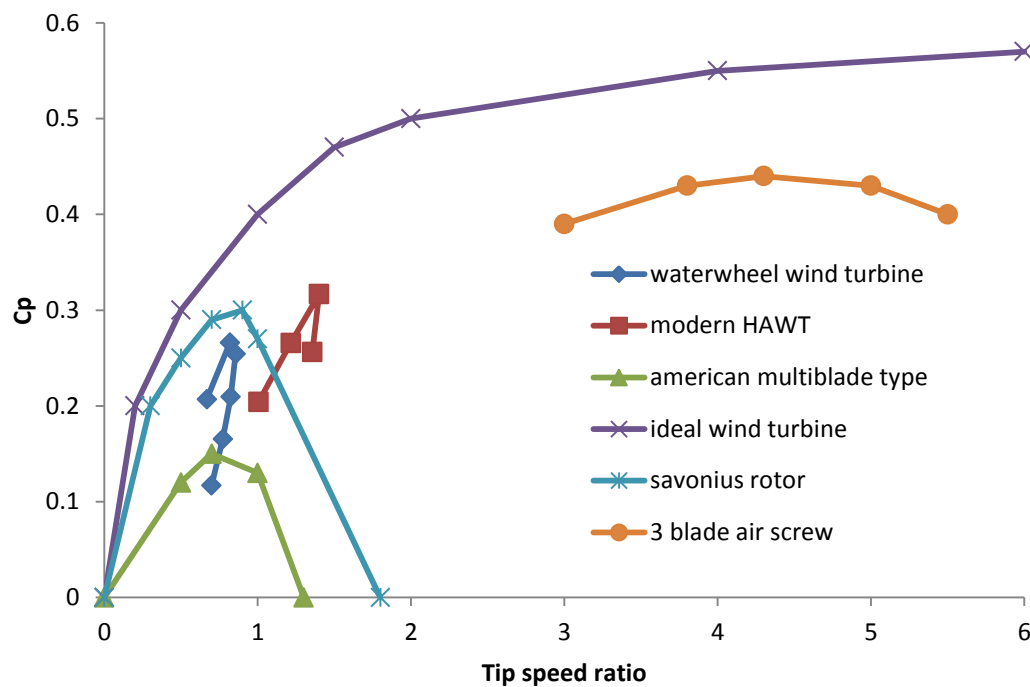


Figure 60: Combination results between marketed product, waterwheel and modern HAWT designs C_p vs TSR (Menet, 2004)

The simulation results obtained from SOLIDWORKS® is generated. The results, which are shown in Figure 61, expressed the relation between the torque and RPM at a constant Re

number for each pair of comparison. The torque value shown in the figure is representing the rotating force of the wind turbine. The modern HAWT has the optimum torque of 0.01N and 540 RPM. The water waterwheel wind turbine has the optimum torque of 0.01N and 900 RPM. Both simulation results for the modern HAWT and waterwheel wind turbine shows higher reading of torque compared to experimental readings. This is undoubtedly due to energy losses caused by the surface roughness of model parts printed with 3D printer. The surface roughness reduces the performance of the wind turbines. This leads to surface frictional forces that reduce the performance of the wind turbine. Different types of rotating rotor also influence the torque of the experimental wind turbines. However, the comparison between numerical and experimental shows very similar trends as the RPM increases. This verifies that the numerical models have very convincing results.

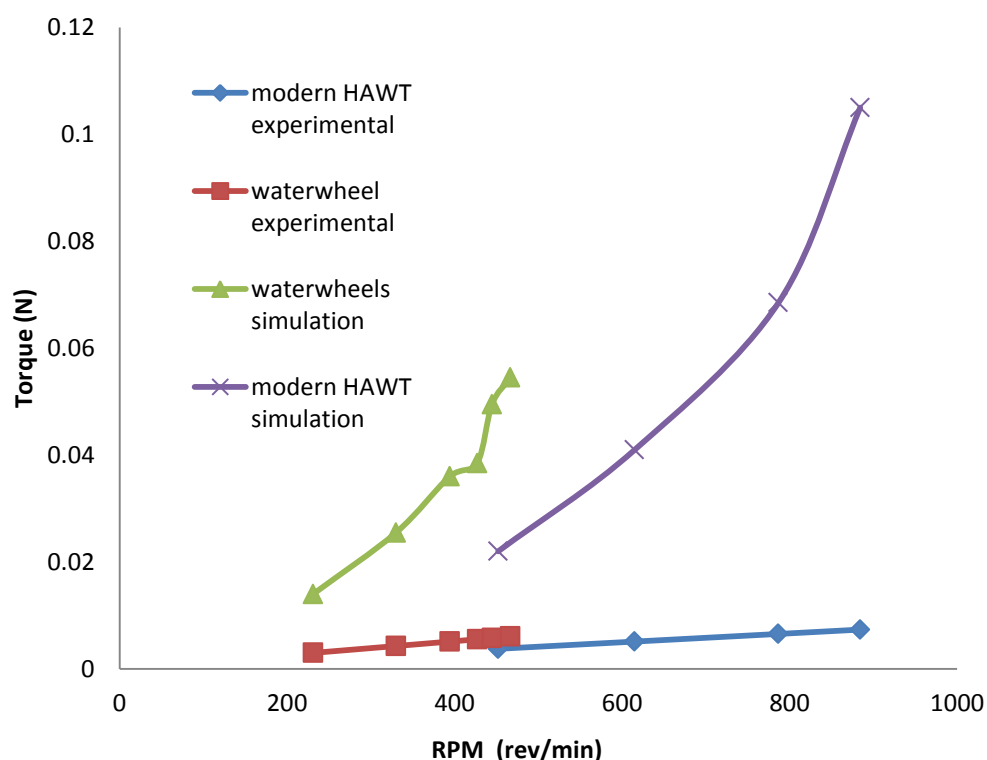


Figure 61: Experimental analysis compared to numerical model results

CHAPTER 5

SUMMARY AND CONCLUSION

5.1 Conclusion

The lantern wind turbine has wide range of improvement since it is a new design in development process. The lantern wind turbine shows no rotation when it is compared to darrieus VAWTs. Simulation and experimental results for HAWT shows that modern HAWT has higher efficiency and performs at higher velocity. The results are shown in the form of power coefficient vs tip speed ratio for wind velocities between 3 m/sec to 6 m/sec. The performance of the model is compared with different type of wind turbines operating on the drag force and each having three blades, available in the methodology. The modern HAWT model gives the maximum power coefficient of 0.27 at a wind speed of 5 m/s and tip speed ratio of 0.6 which is higher than the waterwheel wind turbine model. This gives the maximum power coefficient of 0.32 at a wind speed of 3.5 m/s and tip speed ratio of 1.4. The modern HAWT has the optimum torque of 0.01N and 540 RPM. The water waterwheel wind turbine has the optimum torque of 0.01N and 900 RPM. The proposed water wheel wind turbine can be plant at rural area in Malaysia that has low wind speed. It also can prevent the wind turbine from exploding due to high rotating speed as mentioned in the problem statements previously.

5.2 Recommendations and suggestions for future work

The full-scale waterwheel wind turbine should be built. Wind turbine can be placed in rural areas in Malaysia that has lower wind speed. The blades of a wind turbine should be tested under 0- 45 degree angles of attack. The design should be tested for lower speed of 1- 3m/s.

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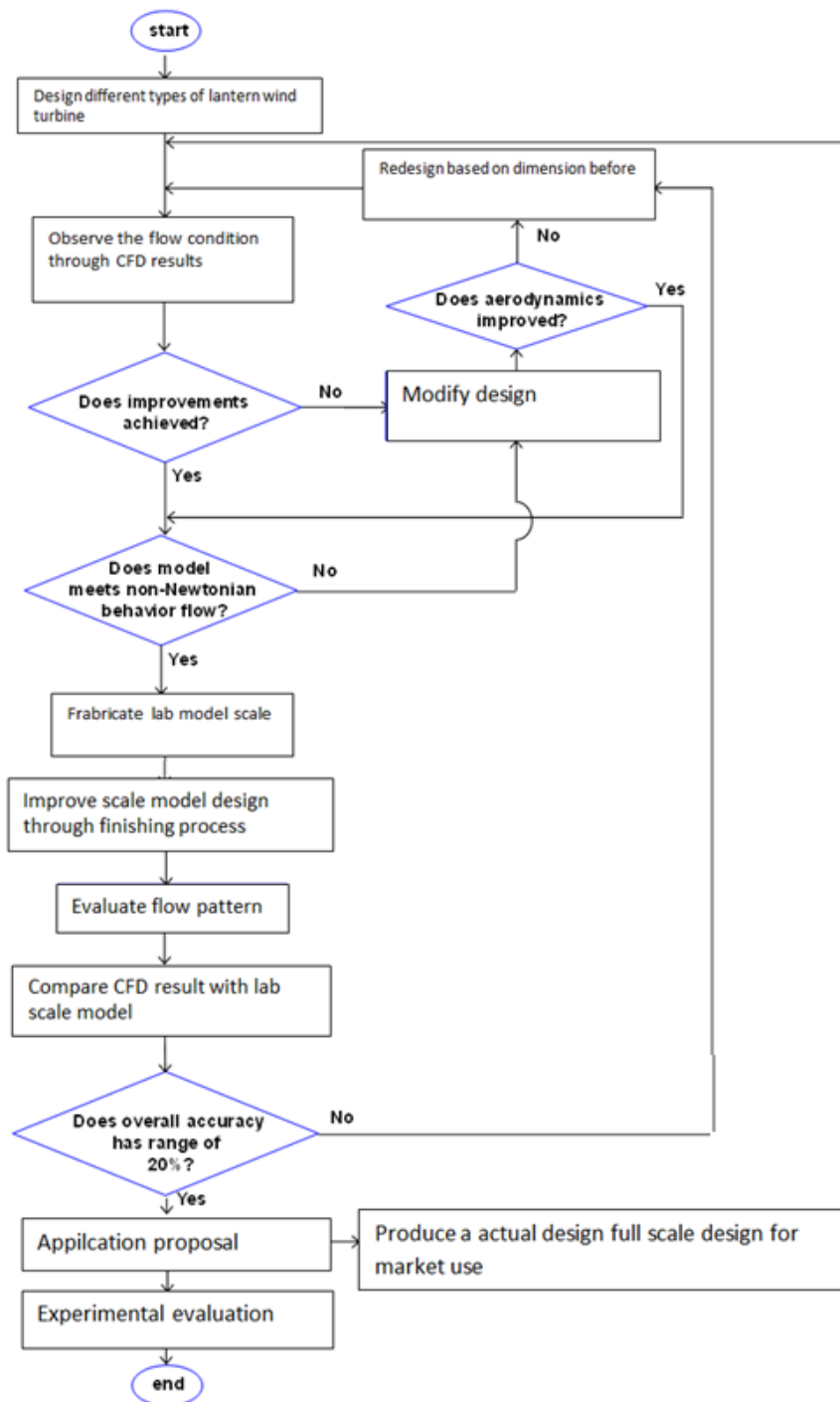
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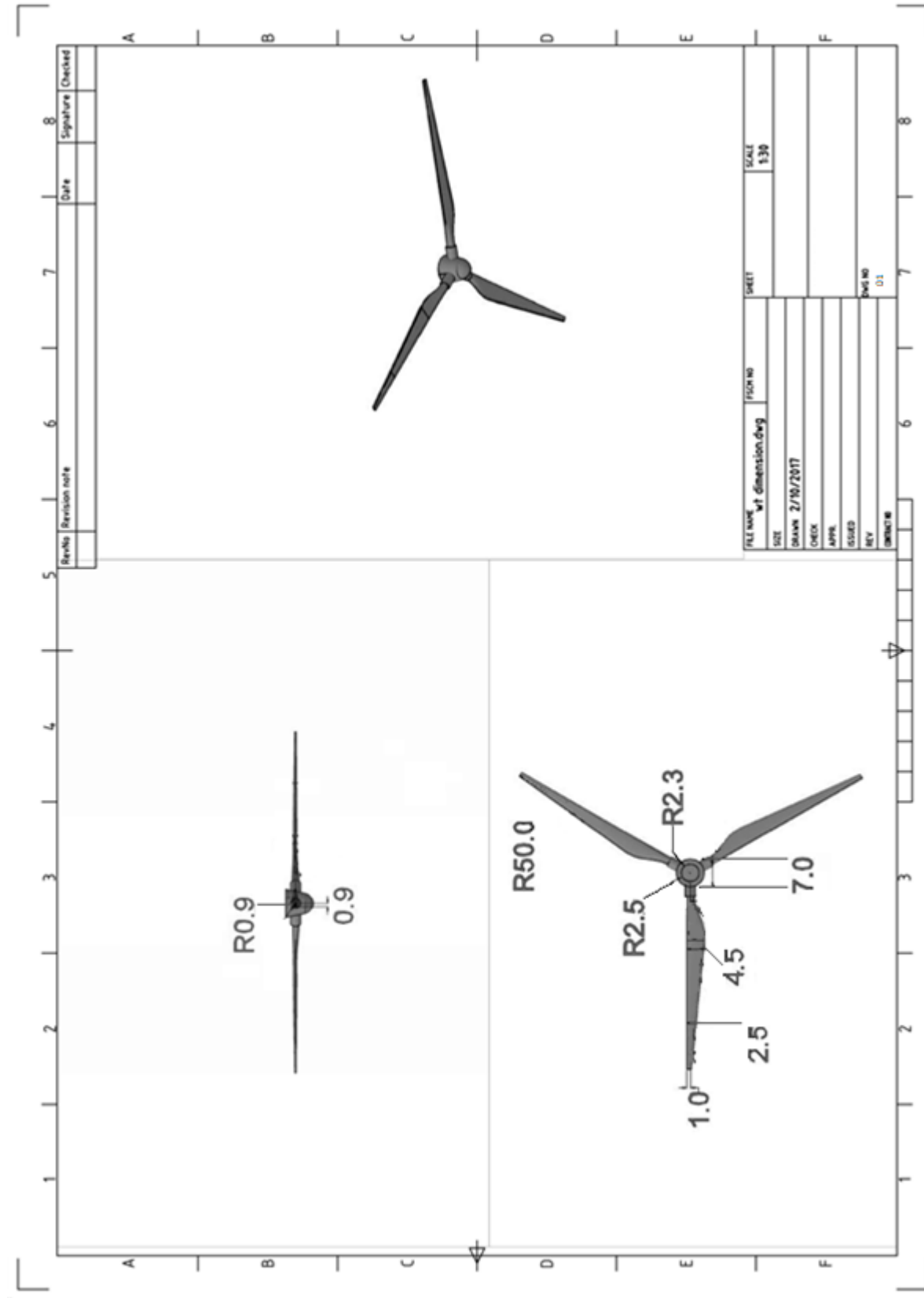
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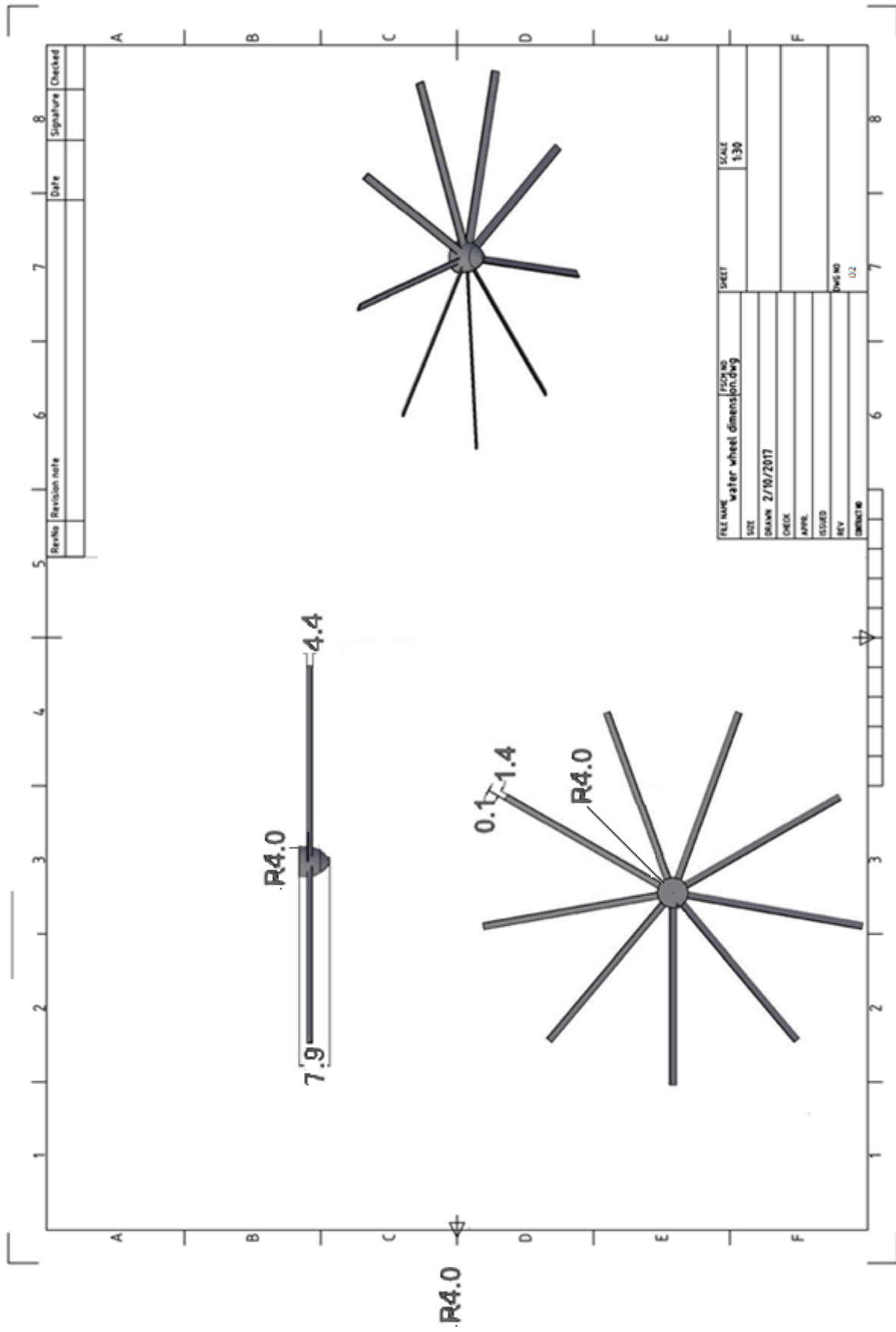
APPENDICES



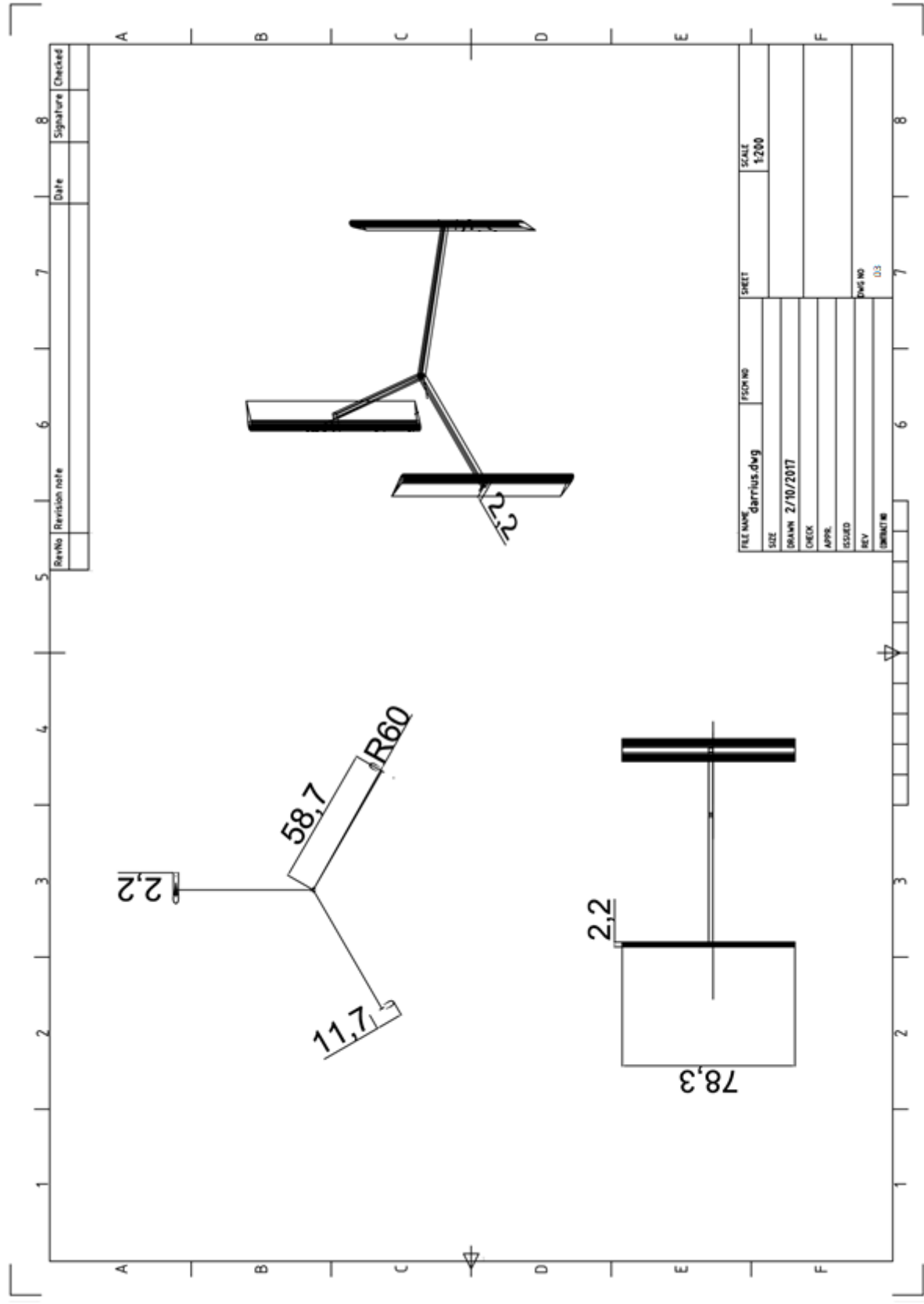
Appendix A1: Flow chart of wind turbine research



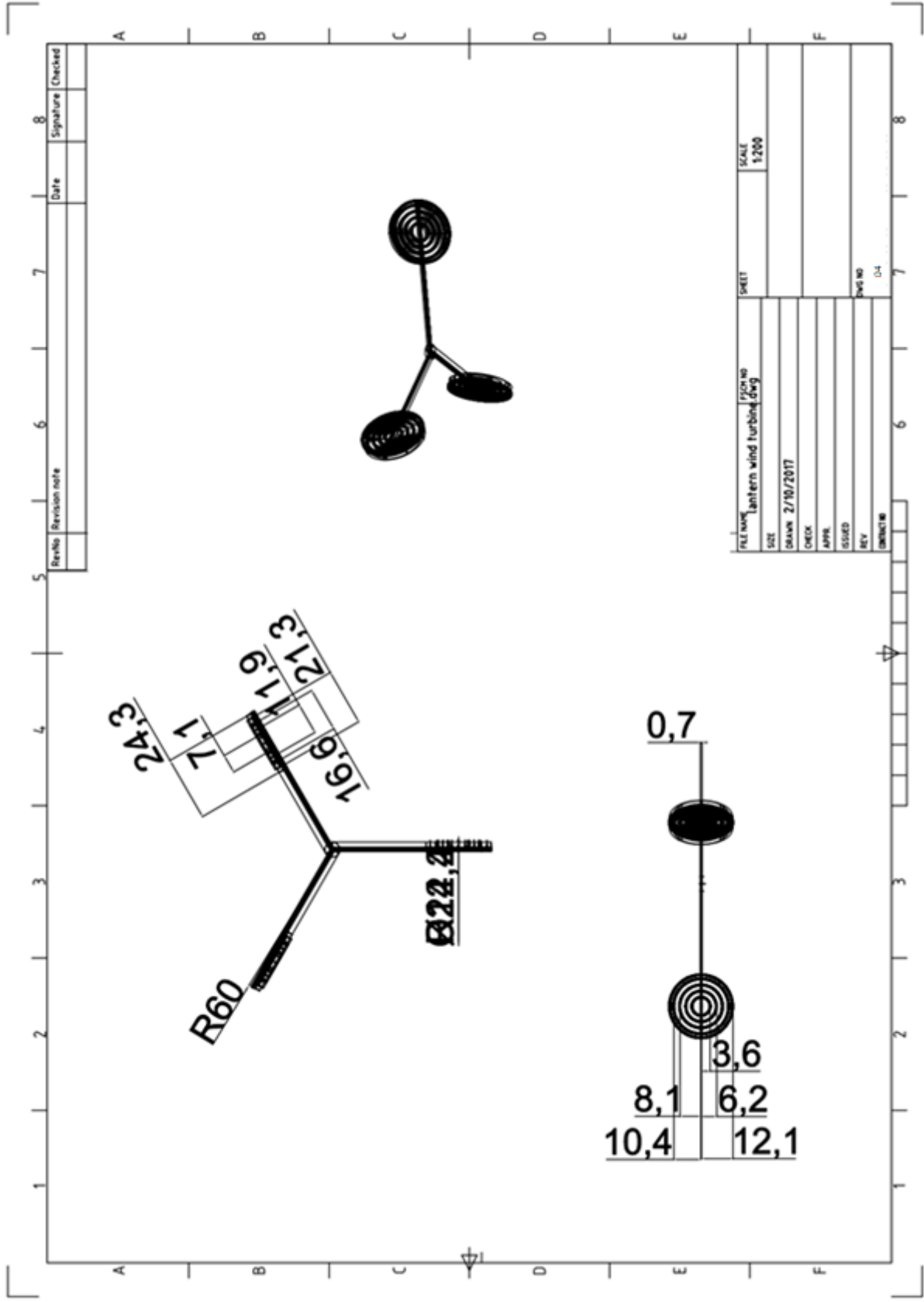
Appendix A2: Modern HAWT



Appendix A3: Water wheel wind turbine



Appendix A4: Darrius VAWTs



Appendix A5: Lantern wind turbine