FLOW AND TURBULENCE CHARACTERISTICS THROUGH A VERTICAL-AXIS WIND TURBINE USING EDDY COVARIANCE METHOD

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By

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ABBREVATIONS

CFD	Computational Fluid Dynamic
HAWT	horizontal-axis wind turbine
LES	Large Eddy Simulations
VAWT	vertical-axis wind turbine
FFT	Fast Fourier Transform

LIST OF SYMBOLS

A	ampere
F	force vector (N)
$\bar{u}$	longitudinal mean velocity (m s^{-1})
$\bar{v}$	lateral mean velocity (m s^{-1})
$\bar{w}$	vertical mean velocity (m s^{-1})
u	longitudinal wind component
v	lateral wind component
w	vertical wind component
U	longitudinal instantaneous wind velocity (m s^{-1})
V	lateral instantaneous wind velocity (m s^{-1})
W	vertical instantaneous wind velocity (m s^{-1})
u'	fluctuation in longitudinal direction (m s^{-1})
v'	fluctuation in lateral direction (m s^{-1})
w'	fluctuation in vertical direction (m s^{-1})
σ_u	longitudinal turbulence (m s^{-1})
σ_v	lateral turbulence (m s^{-1})
σ_w	vertical turbulence (m s^{-1})
$\overline{w'u'}$	momentum transfer (m^2 s^{-2})

u_*	friction velocity ($m\ s^{-1}$)
I	turbulence intensity
L	the height of ultrasonic anemometer (m)
f	dimensionless frequency or normalized frequency
n	frequency (Hz)
S_p	spectra power
x_{up}	distance of flow source to ultrasonic anemometer at upwind (m)
x_{down}	distance of flow source to ultrasonic anemometer at downwind (m)
y	lateral distance (m)
z	vertical distance (m)
ρ	air density ($kg\ m^{-3}$)
V	velocity vector
μ	dynamic viscosity ($N\ m^{-2}$)
t	time scale (s)
∇	del operator
V	voltage
W	watt

CIRI-CIRI ALIRAN DAN PERGOLAKAN MERENTASI SATU TURBIN ANGIN PAKSI MENEGAK MENGGUNAKAN KAEDAH KOVARIANS EDDY

ABSTRAK

Turbin angin berjenis paksi menegak (VAWT) dipercayai berkesan dalam keadaan kelajuan angin rendah. Objektif kajian ini adalah untuk menilai ciri-ciri pergolakan dan aliran di depan dan belakang VAWT berdasarkan kelajuan aliran yang berbeza, untuk menentukan profil sisi dan menegak bagi di depan dan belakang VAWT, dan untuk menentukan ciri-ciri spektrum pergolakan di aliran belakang VAWT dengan menggunakan kaedah "kovarians eddy" untuk menentukan ciri-ciri aliran dan pergolakan bagi VAWT. Kajian dijalankan di makmal tertutup untuk mengelakkan pembolehubah yang kompleks yang hadir dalam angin di luar. Tiga 26" kipas angin industri yang diatur sebaris boleh beroperasi pada kelajuan berlainan digunakan untuk menjana sumber aliran. Naik turun pergolakan dalam tiga dimensi diukur oleh satu ultrasonik anemometer pada 10 Hz untuk memastikan kebanyakan daripada skala pergolakan dirangkumi. Kajian awal menunjukkan siri masa halaju aliran adalah sama dengan keadaan pergolakan di luar. Keputusan menunjukkan bahawa kesan penyekatan dari VAWT mempengaruhi aliran arah angina dan menghasilkan pengaliran balik bertentangan dengan sumber aliran. Pemindahan momentum menegak berlaku dari ruangan kiri ke kanan di belakang VAWT. Spektra menunjukkan pusaran bertenaga wujud di bahagian atas dan belakang VAWT mengurang dari kiri ke kanan. Kajian ini menyediakan data ukuran langsung dan berfungsi sebagai asas untuk memahami ciri-ciri pergolakan dan aliran VAWT dengan menggunakan kaedah "kovarians eddy".

FLOW AND TURBULENCE CHARACTERISTICS THROUGH A VERTICAL-AXIS WIND TURBINE USING EDDY COVARIANCE METHOD

ABSTRACT

Vertical-axis wind turbine (VAWT) is claimed to be effective in low wind speed conditions. The objectives of this research are to assess the turbulence and flow characteristics of upwind and wake of a VAWT based on different flow speeds, to determine the lateral and vertical profiles of upwind and in the wake of a VAWT and to determine the spectral characteristics of turbulence in the wake of VAWT using the eddy covariance method. To characterize the flow and obtain direct measurements of turbulence of a VAWT, the experiment is conducted in a controlled indoor laboratory to avoid the complex nature of outdoor wind. The flow source was simulated by three 26" industrial standing fans arranged in a row at different speed settings. The three dimensional flow velocities fluctuations were measured by an ultrasonic anemometer at 10 Hz in order to cover most turbulence scales. A preliminary study showed that the time series of flow velocities were similar to the outdoor turbulence condition. Results show that blocking effect of the VAWT affects the upwind flow and produced a backflow at the countercurrent direction of the flow source. Momentum transfers vertically from left to right column in the wake of VAWT. Spectra power showed that the energy carried by eddies above and in the wake of VAWT reduced from left to right. This research provides a direct measurement dataset and serves as a baseline data to understand the turbulence and flow characteristics of the VAWT using the eddy covariance method.

CHAPTER 1

INTRODUCTION

1.1 Background of Research

Development has put pressure on the environment. The issue of fossil fuel depletion has resulted in the search for energy alternatives, such as renewable energy. Wind energy is one of the clean renewable energy sources, essential when planning for sustainable development and it is deemed to have the potential to contribute to future energy demand (Shafiullah et al., 2013). The Danish government, the pioneer of the wind industry, targeted to supply 50% of its electricity from wind energy to be used in Denmark by 2020 and they are nearing to target as they achieving 39% in year 2014 (Ministry of Foreign Affairs of Denmark, 2015).

Generally, there are two categories of wind turbine systems which are vertical-axis wind turbine (VAWT) and horizontal-axis wind turbine (HAWT). Wind turbines harvest energy from the wind by converting kinetic energy into a more useful form of energy (electricity) and it has been reported growing rapidly worldwide (Wiser et al., 2014). The wind condition in Malaysia is light and variable (Salam et al., 2000, Stitt, 1999). There has been some investigations done by Malaysian researchers to estimate the potential of wind resources for power generation (Chiang et al., 2003, Darus et al., 2008, Ong et al., 2011, Sopian et al., 1995). From those assessment studies, the outcomes stated that it is possible to harvest energy from wind using small-scale wind turbines with proper assessments for potential sites before installations (Islam et al., 2011, Nor et al., 2014). Thus, we believe that the application of VAWT is more suitable compare to HAWT.

Practically, VAWT have not been applied as widely as the conventional HAWT. However, there is a growing trend in VAWT application due to their characteristics of low noise emission, omni-directional (able to receive wind from any direction). VAWT could also perform better than HAWT in turbulent flow conditions (Mertens, 2002). Thus, VAWT is deemed to be more feasible to implement in urban areas where the turbulence is high and provided that the VAWTs are installed on building rooftops which can also provide "direct-to-user" electrical energy to the building (Balduzzi et al., 2012, Dayan, 2006). Knowing the importance of configurations and VAWT design, the merits and demerits of VAWT was reviewed and found that the results could be attributed to optimization VAWT performance (Aslam Bhutta et al., 2012). A finding stated that more kinetic energy per square meter can be harvested by placing VAWTs close to each other as the energy can be extracted through vertical transfer of kinetic energy that exists as turbulence eddies (Dabiri, 2011). Through this study, the turbulence and flow characteristics of a VAWT was identified and could serve as a platform to increase understanding on turbulence and its effect on VAWT. Some analysis works of installing a Darrieus VAWT in the rooftop of a building, has also contributed towards the knowledge in understanding the application of VAWT in the urban area better (Balduzzi et al., 2012, Cristobal et al., 2012, Tabrizi et al., 2015).

Eddy covariance method has been generally used to measure the fluxes in micrometeorology field (Roth, 2000). The idea to use this method in this research work is to explore the momentum transfer which passes through a VAWT whereby the integration of this method is seldom reported in wind turbine industry. Three dimensions flow velocities, denoted as *u*, *v* and *w* (longitudinal, lateral and vertical) which can be compared to Cartesian axes are measured. Most other studies focuses on using simulation software while this study presents direct measurements of turbulence of VAWT in a controlled setting.

1.2 Problem Statement

Wind energy has been growing fast and being utilized as renewable energy source. However, HAWT, the most common turbine, which is being used to capture wind in wind farms where the average wind speeds ranging from 5.5 to 7.5 m s^{-1} (Gipe, 2004), is not promising to be applied in built up areas under conditions with turbulent wind and low wind speeds (Stiebler, 2008). The maximum performance of a turbine happens when the air stream are relatively steady and non-turbulent. The winds in Malaysia are slow and turbulent and it is not as reliable as Germany, Denmark, Taiwan, etc. Somehow, the investigation done by some of the Malaysian researchers show a positive sign for the potential of wind power generation in a long run, using small-scale wind turbine (Islam et al., 2011, Tiang and Ishak, 2012). The design of VAWT, which able to capture wind from any direction may overcome the problem.

The distribution of wind speed and its accuracy are vital in wind energy systems. There are databases and modeling software that has been developed for large scale wind industry that could be used in predicting wind sources. However, it might not suit in predicting the urban wind due to the complexity of the surface. Hence, this experiment provides a real experimental based data set of turbulence characteristics and the comparison of upwind and in the wake of VAWT spectral characteristics of different flow speed. The turbulence characteristics analysis can be used to investigate the potential of implementation of VAWT in urban area with consideration of the turbulent structure of the urban boundary layer where such studies are rarely reported. The study on the turbulence transfer of a VAWT is essential before integrating them on rooftop; as in urban terrain, the wind is turbulent, dynamic and consists of strong vertical component (Anderson et al., 2008). A guideline on laboratory setup in initial groundwork study can be explored and Tabrizi's work (2015) has contributed some ideas on the method of wind monitoring. A study related the atmospheric stability to power performance, but only focusing on horizontal axis wind turbines in a wind farm has also reported (Wharton and Lundquist, 2012).

Investigation on the turbulence characteristics of VAWT is crucial as the configuration of the wind turbine system could help in improving the efficiency of the VAWT. There are more research focused on the turbulence generated by HAWTs compared to VAWTs due to the mainstream application of HAWTs (Ebert and Wood, 1997, Vermeer et al., 2003, Yang et al., 2012). A promising result of achieving higher power densities that is comparable to HAWTs by arranging VAWTs close to each other (Dabiri, 2011) suggests an approach to study of the characteristic of flow upwind and in the wake of VAWT. An investigation shows that the pairing of VAWTs could reduce the space of wind farm arrays (Kinzel et al., 2013).

In fact, energy conversion occurred during the entire (rotation of wind turbine) process was rarely reported in literature. This research has explored spectra power of flow velocities and turbulence at certain positions and served as a baseline data to increase the understanding of energy level at different positions.

1.3 Research Objectives

The objectives of this research are:

1. To assess the turbulence and flow characteristics of upwind and in the wake of a VAWT based on different flow speed.
2. To determine the lateral and vertical profiles of upwind and wake of a VAWT.
3. To determine the spectral characteristics of turbulence in the wake of VAWT.

1.4 Thesis Outline

This dissertation consists of five chapters. In the first chapter, it introduces the research background and discusses some of the published works that contributed some idea to this research work. The problem statement serves as the outline to develop the objectives of this study. Literature review is presented in Chapter 2, gathering most of the information and the important findings from other published works, which are then used as references to compare with the current studies. The research methodology, covering hardware and software preparation, data processing and analysis as well as the method to present the result, are included in Chapter 3. In the results and discussion chapter (Chapter 4), all of the data are presented and discussed, and shown to fulfill the objectives of this study stated in Chapter 1. Last but not least, Chapter 5 reports the important results and new findings, and also recommendations listed for future work.

1.5 Limitation of Research

This research has been carried out in an indoor laboratory to prevent the unpredictable outdoor condition. However, the control of the laboratory dimension was limited and results may affected by the effect of reflection caused by surrounding. This direct measurement experiment data was only covered a certain range of flow velocity, which are approximately ranging from 0.5 to 4.0 m s^{-1}, regardless the range when we expect a higher flow velocity at outdoor at a certain period. This research served as a platform for a better understanding of flow and turbulence characteristics on an individual VAWT, and hence the mechanism of the energy transfer was not further discussed.

CHAPTER 2

LITERATURE REVIEW

2.1 Wind Energy and Its Potential in Malaysia

Pressure on the environment has led to climate change and its impacts are increasing. One of the contributors to this environmental issue is the combustion of the fossil fuels. Hence, reducing the emission of the polluting elements is an urgent need to achieve sustainability. Wind power is a ‘green energy’ which extracts the energy from the wind by converting the mechanical energy to electricity without emitting any pollutant to the environment. The wind industry around the world is growing rapidly and the size of the turbines has been doubling every three to four years. By year 2013, the installed capacity reached 318 GW (Wizelius, 2015, Gesino, 2011). Expecting the increasing growth of wind energy in the future, the knowledge of wind energy technology and the system of wind turbine have been reviewed (Herbert et al., 2007, Ackermann and Soder, 2000). The leading countries in the wind energy industry are Europe, or countries such as, Germany, Denmark and the United States. Asian countries such as China, has slowly getting into the track and contribute the most in wind power capacity (GWEC, 2015). Journals have been published, discussing the trend of wind energy (Damota et al., 2015, Islam et al., 2013).

Generally, the wind flow patterns in Malaysia is based on the southwest monsoon (May to September) and northeast monsoon (November to March). Wind speeds during southwest monsoon are regularly below 8 m s^{-1}; while the wind speeds may reach 15 m s^{-1} at east coast of Peninsular Malaysia (Malaysian Meteorological Department, 2012). An assessment showed that Sabah experienced a yearly averaged mean wind speed of 3.2 m s^{-1} at Kudat, while 3.3 m s^{-1} at Labuan (Islam et al., 2011).

The wind speed at Sarawak may achieve 10 m s^{-1} or above when typhoons occur in our neighboring countries, for instance, Philippines, during April to November. Thus, some regions in Malaysia still experience strong wind in a particular period even though the winds in Malaysia are generally light and variable (Malaysian Meteorological Department, 2012).

Malaysia took the initiative in involving in green energy and the government aims to reach 11% renewable energy usage by year 2020 (Engineur, 2014). Investigations have been carried out to assess the wind energy application potentiality in some places in Malaysia. SIRIM Berhad, a government agency under Ministry of Science, Technology and Innovation (MOSTI), has tested 16 wind turbines at different locations in Malaysia and the outcome was encouraging, especially at Tip of Borneo, Kudat, Sabah (Ahmad, 2013). Data from ten meteorological stations are collected for wind energy potential analysis for a duration of 10 years has been conducted by Sopian et al. (1995). An offshore wind energy potential assessment conducted in Kijal, Terengganu also showed that wind energy is feasible in Malaysia (Albani et al., 2014).

2.2 Wind in Atmospheric Boundary Layer

Atmospheric boundary layer is the layer, which is closest to the surface of the Earth, which is approximately 1 km in height. Natural wind is caused by the differences in air density and pressure due to the temperature change on the Earth's surface (Gipe, 2004). The rotation of the Earth is also one of the factors affecting the direction of prevailing wind. A atmospheric wind moves in three dimensions (non-uniform flow) that could be represented by Cartesian axes. The feature of the wind over a terrain can be characterized by computing the wind profiles, which is the changes of the horizontal wind speed with altitude (Manwell et al., 2009). The wind profiles are mainly dependent on the topography and the magnitude of wind resources. Fig. 2.1 shows the wind profiles over a different terrain with a relationship that the wind speed is proportional to the altitude. The wind in an urban area is more turbulent or unsteady due to the obstructions such as buildings and vegetation causes the roughness to be higher (Stankovic et al., 2009). The principle of turbulent flow and its characteristics will be discussed in detail in the section 2.4.

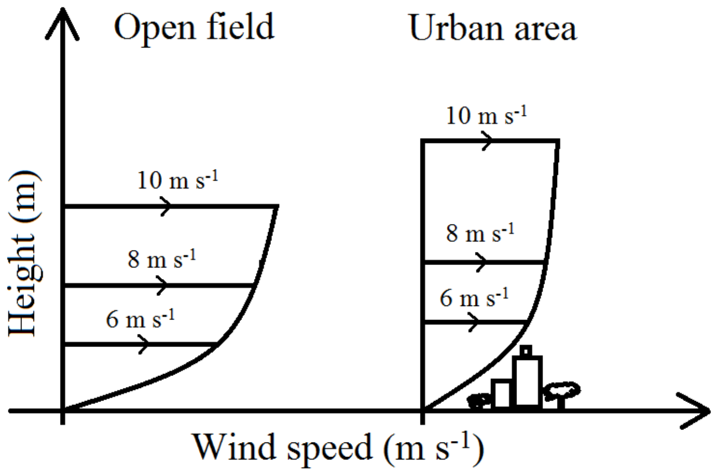

Fig. 2.1: Comparison of wind profile between open field and a terrain with obstructions such as vegetation and buildings.

2.3 Wind Turbine Designs

The machine or device used to harvest the wind energy by converting the kinetic energy to electrical energy is known as the wind turbine. Although there are various types of wind turbine designs in the market, the general types, which has been focused on are HAWT and VAWT, whereby the former one is the conventional type, which has been used for centuries and been built across the world. HAWTs were designed to have a horizontal axis of rotation, and the turbine blades are constructed in the shape of an aerofoil shaped (Manwell et al., 2009). When wind flows over the rotating aerofoil blades, the speed on top of the aerofoil increases and a force called “lift” is created. Instead of operating under turbulent condition, HAWTs need a stable wind direction and velocity for efficient performance (Stankovic et al., 2009).

VAWTs comprised of three main types, which are Darrieus (lift based), Savonius (drag based) and Giromill (H-rotor). A Darrieus wind turbine is a lift-type VAWT whereby the main rotor shaft runs vertically and the omnidirectional behavior enable it to capture wind and function effectively regardless of wind direction (Stitt, 1999, Stankovic et al., 2009). A Darrieus type of VAWT is used for this study. Fig. 2.2 illustrates the common types of wind turbine.

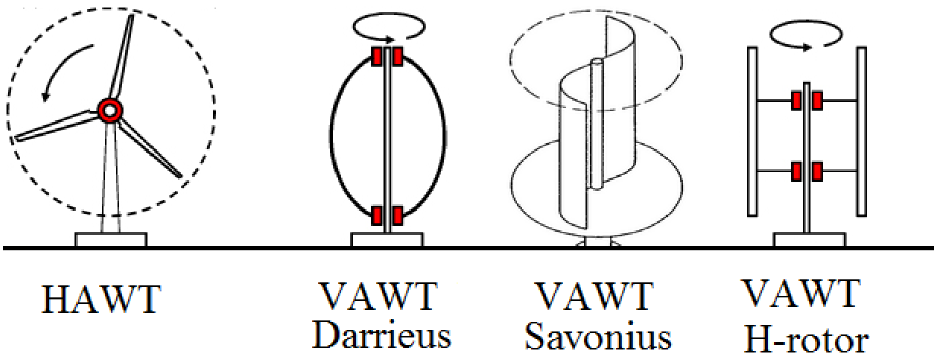

Fig. 2.2: General types of wind turbines (Hill, 2011).

2.3.1 Advantages and Disadvantages of Vertical-axis Wind Turbine (VAWT)

Both VAWT and HAWT convert kinetic energy (via rotating the shaft) to electrical energy, but they are different from the outlook and the mechanism of operation. The pros and cons of VAWTs over HAWTs are discussed below.

Firstly, VAWTs is able to capture turbulent winds effectively in urban area compared to HAWT as they could handle wind from any direction (Pope et al., 2011). The placement of VAWT could be closer to the ground, thus making it more user-friendly for residential purposes. The costs of construction are lower and maintenance is easier to carry out as the turbine generator and gearbox can be placed lower to the ground. VAWT produces less noise as the blades operate at low rotational speeds. Therefore, VAWT is found economical and suitable for energy production especially in urban environment (CleanfieldEnergy, 2013). However, these advantages are being said as misunderstanding and some explanations are listed by Ian (Woofenden, 2009). Some drawbacks doubted the feasibility of VAWT, such as the low efficiency due to the installation at low height, and hence lesser wind speed available to generate the turbine and lead to less energy extracted. In efficiency aspect, VAWT is less efficient than HAWT for their swept area. Due to the limitations of VAWT, an interest in designing a new turbine which is known as Zephyr turbine, has been developed at the University of Ontario Institute of Technology, which claimed to be able to operate in high turbulence and low wind speeds conditions by placing them close to each other, that can be implemented in urban areas (Dincer, 2011, Pope et al., 2010).

2.4 Principles of Turbulent Flow

Turbulence is an irregular movement of air, or a three dimensions (longitudinal, lateral and vertical) fluctuating components in a wind velocity, caused by buoyancy and mechanical effect in atmospheric boundary layer (Wyngaard, 2010). Unsteady flow comprised of numerous different sizes of swirling units of air, known as "eddies". The unsteady flow passed through a wind turbine affects the performance of the turbine, thus it is essential in wind monitoring for wind turbine installation. Turbulence intensity level can be calculated according to Eq. (1), where u' is the standard deviation of the turbulence velocity of fluctuations and $\bar{u}$ is the mean wind speed. The higher the intensity of turbulence, I, the more unstable the flow would be.

$$I = u' / \bar{u} \qquad (1)$$

Flows in motion develop a force known as shear stress with a unit of force per unit area (Douglas, 2005) and turbulence is proportional to shear. The basic of turbulence equations are discussed in the next sections.

2.4.1 Incompressible Navier-Stokes Equations

The incompressible Navier-Stokes equations are deemed to be suitable to be implemented in the wakes study of turbine, as it's positioned within the range of 5 to 25 m s^{-1} in the atmosphere (Sanderse et al., 2011). This equation has been used by most of the VAWT studies. The equation shown in Eq. (2) is applied for the vectors in three directions (longitudinal, lateral and vertical).

$$\rho \frac{D\boldsymbol{V}}{Dt} = \rho F - \nabla \rho + \mu \nabla^2 \boldsymbol{V} \tag{2}$$

ρ is the air density; $\boldsymbol{V}$ is the velocity vector; F is the force vector; μ is the dynamic viscosity and t is the time scale (Wang et al., 2012, Sanderse et al., 2011, Troldborg et al., 2007).

2.4.2 Reynold's Decomposition and Characteristics of Turbulence

In urban area, the irregular topography due to buildings and other obstructions causes the wind speed to change and thus the wind flow is turbulent (Grimmond and Oke, 2002). Fig. 2.3 shows the schematic diagram of the flow condition in an urban area.

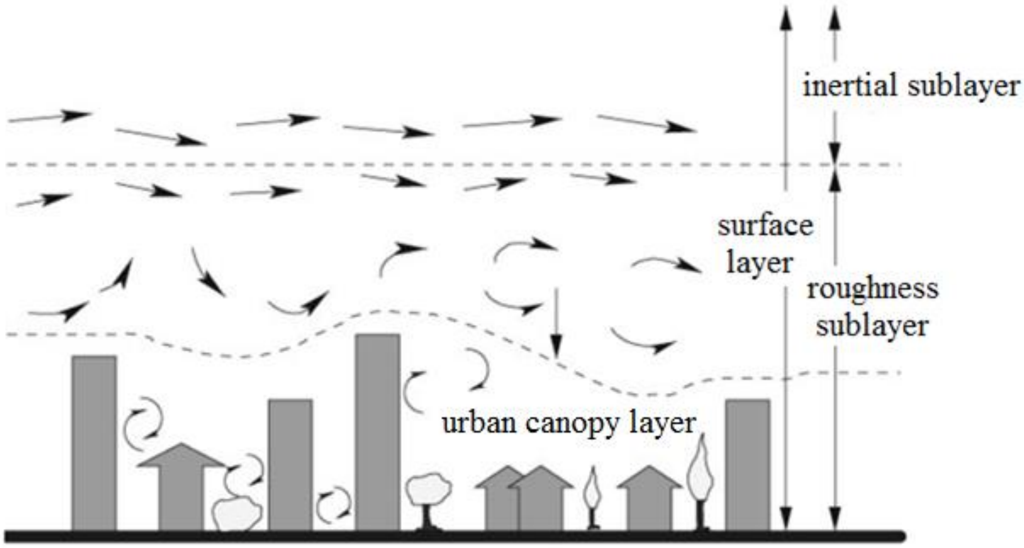

Fig. 2.3: Schematic diagram of an urban area (Grimmond and Oke, 2002).

The three fluctuations components (longitudinal, lateral and vertical), denoted as u', v' and w' can be defined using a mathematical technique, known as Reynold's decomposition. Instantaneous wind velocity (*U*, *V* or *W*) is computed by combination of the mean velocity ($\bar{u}$, $\bar{v}$ or $\bar{w}$) and the turbulent fluctuations components (u', v' or w'). This Reynold's decomposition is then implemented into Navier-Stokes equations to derive the ensemble average of a fluctuation. The ensemble averaged is used in the eddy covariance method that will be discussed in section 2.6.

In vertical wind profile, wind speed is proportional to height but the shear stress is inversely proportional to height. Friction velocity, u_*, is used to characterize the surface shear stress and Eq. (3) shows the calculation (Britter and Hanna, 2003). The overbars are denoted as ensemble average of the local momentum fluxes in longitudinal and lateral directions.

$$u_* = \sqrt[4]{\overline{w'u'}^2 + \overline{w'v'}^2} \quad (3)$$

2.5 Eddies in Turbulent Flow

In the process of energy extraction, energy content reduces while the turbulence in the wake of the wind turbines increases. Eddy is a swirling unit of air in turbulent flow and each of them are in different sizes, play a role in energy and momentum transfer over the large range of length and time scales. Energy is transferred from the large to small scale and thus energy cascade existed. The hierarchy of eddies can be divided into three categories, which are large scale, intermediate scale (Taylor-scale), and small scale; where by the mechanism of the energy transfer for each eddies varies at different frequencies range (Alexandrova et al., 2013). Most of the large scale eddies (or known as energy containing eddies) drain kinetic energy from the main flow and feed to the smaller eddies through interactions and loses the energy via dissipation (Wyngaard, 2010). Table 2.1 shows the three major spectra regions at different frequencies (Alexandrova et al., 2013, Aubinet et al., 2012).

Table 2.1: Three major regions of eddies at a wide range of length scale.

Frequency range	Properties
Low (typically $< 10^{-4}$ Hz)	Energy containing range. Eddies in large scale and energy is produced.
Intermediate (inertial subrange) (within 10^{-4} to 10^{-1} Hz)	Passes down the energy of eddies from large to small scale without dissipation and no energy is produced. Essential in energy and momentum transfer.
High (typically $> 10^{-4}$ Hz)	Dissipation range where eddies are in small scale. Approaching homogeneous state.

Wind turbines not only generating energy but also produces wakes downstream. The wakes are invisible ripples and waves in the atmosphere that could eventually damage the turbines due to the increased load and reduce the efficiency

(Manwell et al., 2009, Stark, 2011). The wakes comprised of a near, intermediate and far wake. Near wake is the downstream region of the turbine whereby the pattern of the flow field is mainly depends on the turbine geometry. In intermediate wake, the flow is unsteady and it combines to form large scale structure. Far wake is dependent on the wake and turbulence modeling, as well as the topographical aspect (Vermeer et al., 2003, Jha et al., 2015, Sanderse et al., 2011).

2.6 Eddy Covariance Method

Eddy covariance method is a statistical technique that has been widely used in micrometeorology field to measure and calculate the vertical turbulent fluxes within the atmospheric boundary layer (Baldocchi, 2003, Aubinet et al., 2012). The heat, mass and momentum fluxes can be measured and the estimation of gas exchange and emission rate could be calculated using this method (Aubinet et al., 2012). The turbulent motions are measured using fast response system such as an ultrasonic anemometer and the correlation exchange rate of a scalar in vertical transport can be determined. The covariance of $\overline{w'u'}$ also known as momentum transfer is explored in this research. The overbar denotes ensemble average and w' and u' represent the fluctuations from the mean.

2.7 Experimental and Numerical Simulation

Experimental evaluation is deemed to achieve higher accuracy compared to the simulation modelling. In fact, there are limited studies are focus on the direct measurements of the quantification of turbulence and flow characteristics. The turbulence characteristics of the wind have been slowly getting the attraction from researchers. The wake studies have so far conducted using modeling simulation such as Large Eddy Simulation (LES) and most studies are focused on HAWT (Hasager et al., 2013, Werle, 2015, Troldborg et al., 2007). A comparison between the modeling and the measurement results show that the accuracy of the modeling appears not to be high as the models tends to perform a higher or lower prediction (Barthelmie et al., 2006). The wake characteristics of a wind farm was examined and the Computational Fluid Dynamic (CFD) modeling result is compared with the pilot photographs (Hasager et al., 2013). A study on power deficit of wind turbine due to the wakes is determined by conducting meteorological measurement, and result shows that power deficit affected by the ambient turbulence intensity (Hansen et al., 2012). Simulation and numerical analysis had been done on Savonius type vertical-axis wind turbines for the past 20 years (Dobrev and Massouh, 2011, Fernando and Modi, 1989). The effect of turbulence towards performance of VAWT also has been analyzed (Yao et al., 2012). A review on Savonius wind turbine has been published, and some vital information such as the factors affecting the performance, has been assembled which are useful knowledge for further studies (Akwa et al., 2012).

An indoor facility testing on a wind turbine in low wind condition has been done and the work has contributed some idea in this research work (Wahab and Chong, 2003). A study on the turbulence characteristics of a Darrieus-type VAWT has been carried out and eddy frequencies after the VAWT are determined (H'ng et al., 2014). An overview of the fish schooling concept implemented in VAWT is also discussed by Islam (2013). Inspired by the fish schooling of red herring, Dabiri (2011) imitated this configurations by an array of VAWTs by placing them close to each other in counter-rotating direction. Kinzel et al. (2013) continued this work from Dabiri by analyzing the flow field of 18 counter-rotating VAWTs. Rooftop monitoring of VAWT are conducted by Tabrizi et al. (2015) and Breton et al. (2014) found that both simulation and experimental data are sharing a same observation where the distance between turbines gives an impact on the performance of turbine at upstream.

CHAPTER 3

METHODOLOGY

The turbulence quantification of upwind and in the wake of VAWT was conducted in four different phases. The flow chart of the research was depicted in Fig. 3.1. In phase 1, laboratory setup and the preparation of the research materials, including the calibration of the ultrasonic anemometer, were carried out. During the preliminary study (phase 2), data collection was done and a MATLAB script was developed to manage the data before data analyses stage. Data quality checking would decide the necessity of repeating the data collection step. In phase 3, experimental data was collected and analyzed. Data management and processing would produce the results for all measurement of upwind and in the wake of VAWT turbulence and flow characteristics as well as the spectral analysis.

3.1 Laboratory Setup

To avoid the variable and complexity of uncontrolled flow fields outdoors caused by the interaction between wind turbines and the atmospheric boundary layer, this research was conducted in a controlled indoor laboratory. The atmospheric boundary layer is the atmospheric layer closest to the surface of Earth and it is not commonly "neutral" where the buoyancy effects cause "unstable" flow field conditions. Neutral is defined as when mechanical shear dominates buoyancy effects on turbulence production.

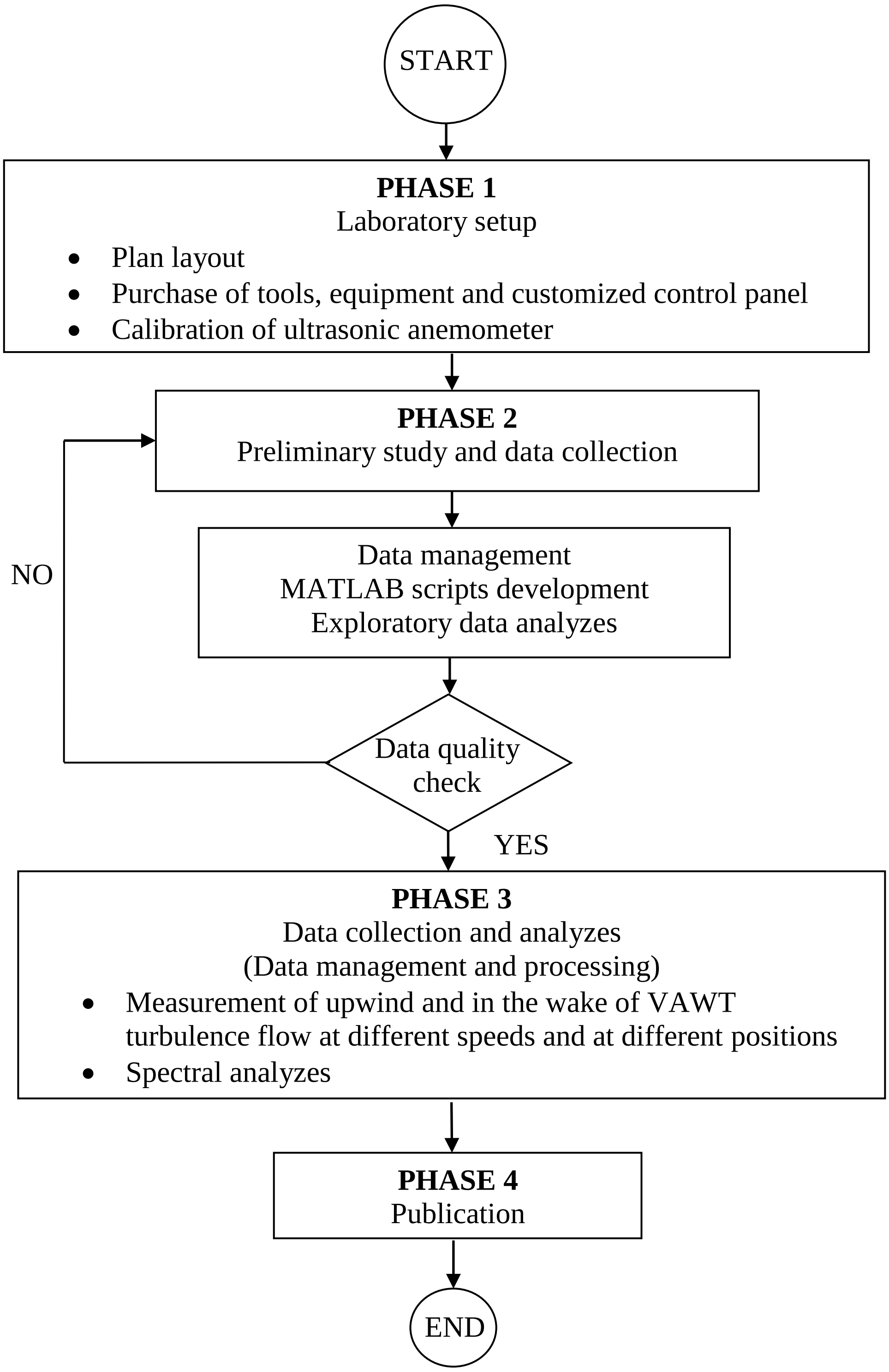

Fig. 3.1: Research methodology flow chart.

Fig. 3.2 shows the three-dimensional side view of the laboratory layout with the dimensions of 3.0 m × 5.5 m where the flow fields were generated by three units of 26" industrial standing fans which arranged in a row. The height of the middle fan was lowered in order to provide a uniform flow over the swept area when the flow disperses downwind as recommended by Wahab and Chong (2003). A sketch of the front and top view of the fans is shown in Fig. 3.3.

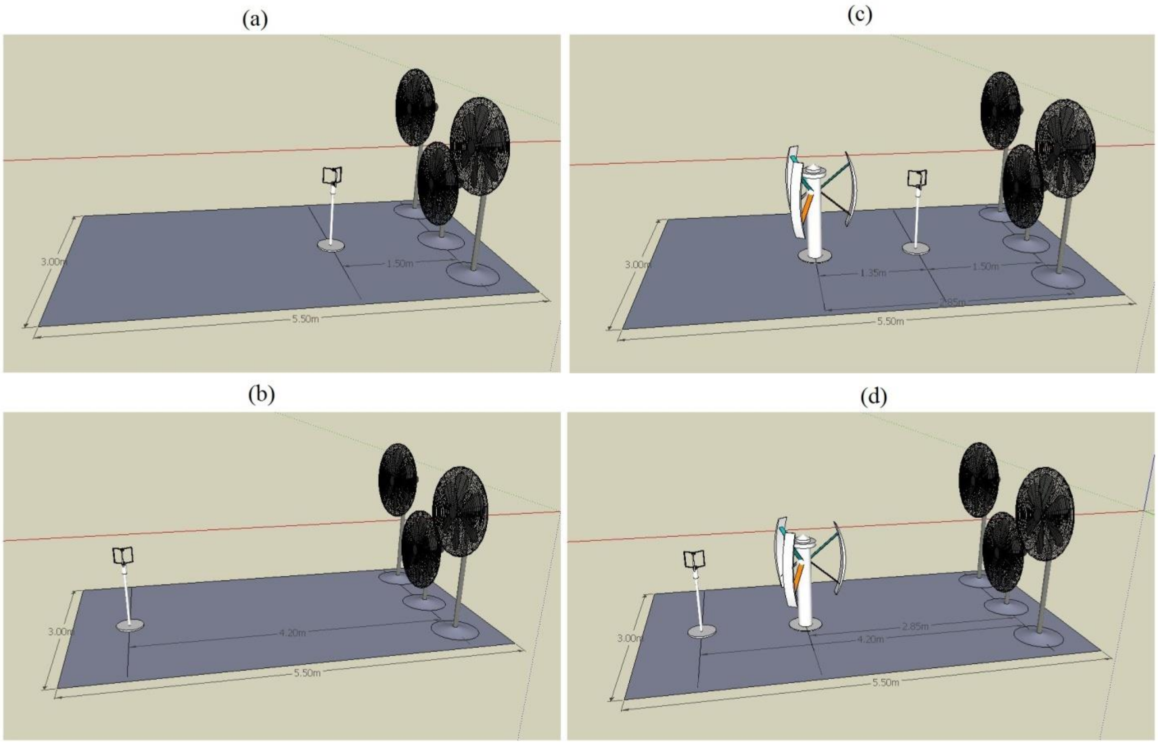

Fig. 3.2: Laboratory setup depicting the arrangement of the ultrasonic anemometer, VAWT and the three 26" industrial standing fans at four different positions: (a) upwind position without VAWT (b) downwind position without VAWT (c) upwind position with VAWT and (d) downwind position with VAWT; upwind at a distance of x_{up} = 1.50 m and downwind at a distance of x_{down} = 4.20 m.

A 300 W Darrieus-type VAWT (iW301, iWind Energy, Taiwan) was used to study the turbulence and flow characteristics of a VAWT and its specification is listed in Table 3.1. Fig. 3.4 depicts the design of the VAWT with total swept area of 1.44 m^2. The VAWT was placed within the flow and turbulence was measured at two different speed settings (“low” and “high” speeds) by adjusting the control button of the industrial standing fans. The averaged mean flow velocity (cells C4, C5 and C6) at low speed setting is approximately 3.2 m s^{-1} and 4.0 m s^{-1} at high speed setting.

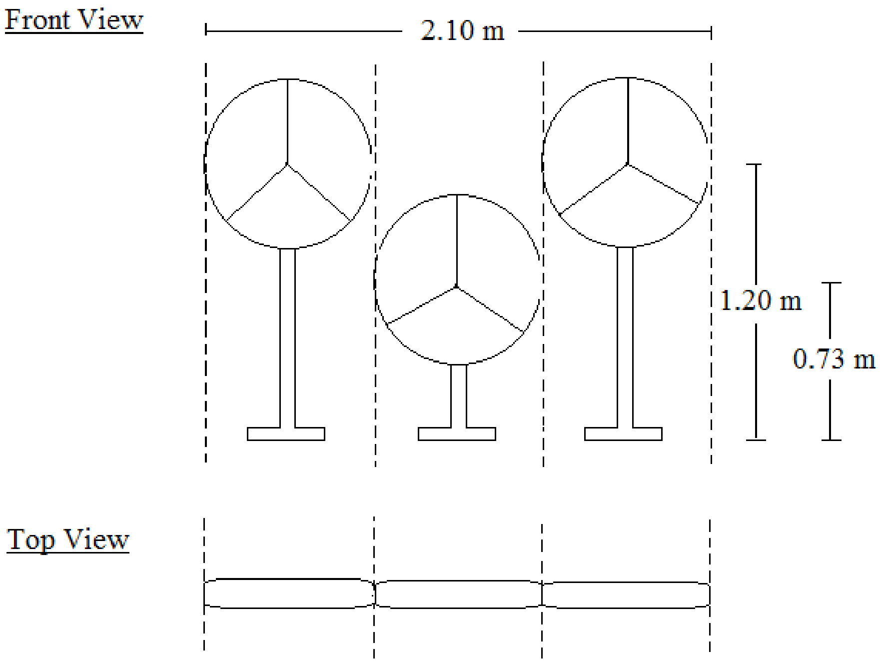

Fig. 3.3: The front and top view of the arrangement of the three 26" industrial standing fans.

Table 3.1: Specifications of the three-bladed Darrieus-type (iW301, iWind Energy, Taiwan) VAWT.

Specification	Model: iW301
Rated Power Output	300 W
Rated wind speed	12 m s^{-1}
Cut-in wind speed	2.5 m s^{-1}
Survival wind speed	30 m s^{-1}
Total swept area	1.44 m^2

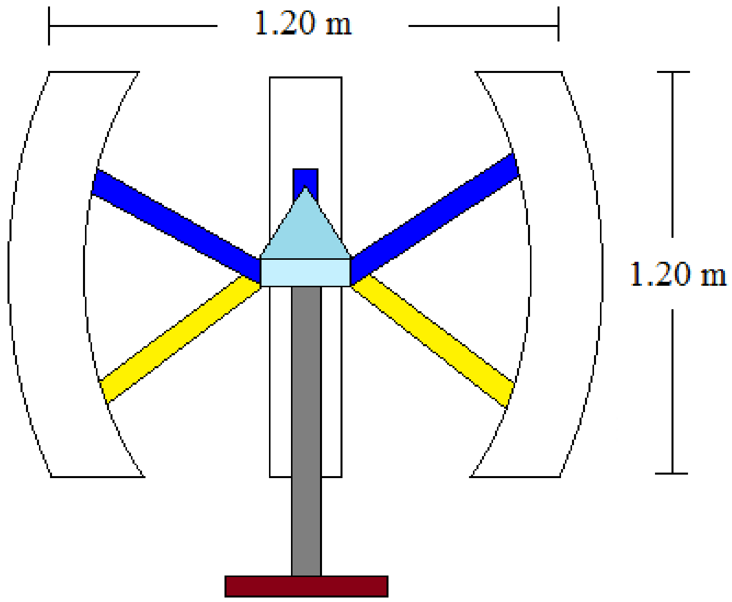

Fig. 3.4: Schematic of the three-bladed Darrieus-type (iW301, iWind Energy, Taiwan) VAWT.

The three dimensional flow velocity components (*u*, *v* and *w*) was measured using an ultrasonic anemometer (81000, Young, USA). The accuracy of the ultrasonic anemometer was ±1% root mean square. A grid shelf marked with 30 data collection positions (shown in Fig. 3.5), which covered the flow source area was fabricated to assist the positioning of the ultrasonic anemometer throughout the experiment and this idea was modified from an indoor testing facility methodology developed by Wahab and Chong (2003). The front view of grid shelf was positioned facing upwind of the flow source and the results were discussed according to the positions shown in Fig. 3.5. Each filled circle positions are represented as blocks or cells in heat map shown in the results, depicting the flow speed and turbulences distribution covering the windswept area for four different positions.

An RPM magnet is attached to the rotor of the VAWT and its sensor is installed on the VAWT stand. The VAWT is connected to a customized wind turbine control panel shown in Fig. 3.6, to display the readings of ampere (A), voltage (V) and revolution per minute (RPM) outputs from the VAWT. The voltage and ampere of a battery is displayed on the control panel once the battery with 12 W is switched on. Table 3.2 shows the ampere, voltage and the RPM outputs from VAWT, displayed by the control panel at both low and high speed settings.

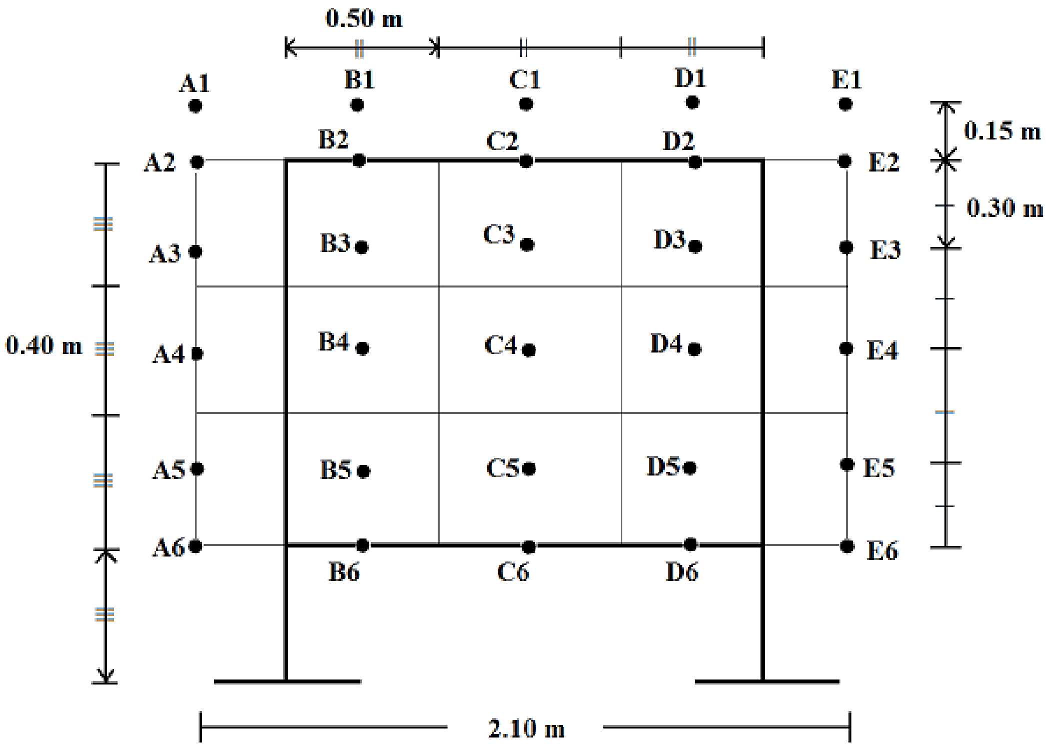

Fig. 3.5: Fabricated shelf grid with 30 data measurement positions (A1 to E6) represented in filled circles; covering the entire windswept area of the flow source, which represents the flow field.

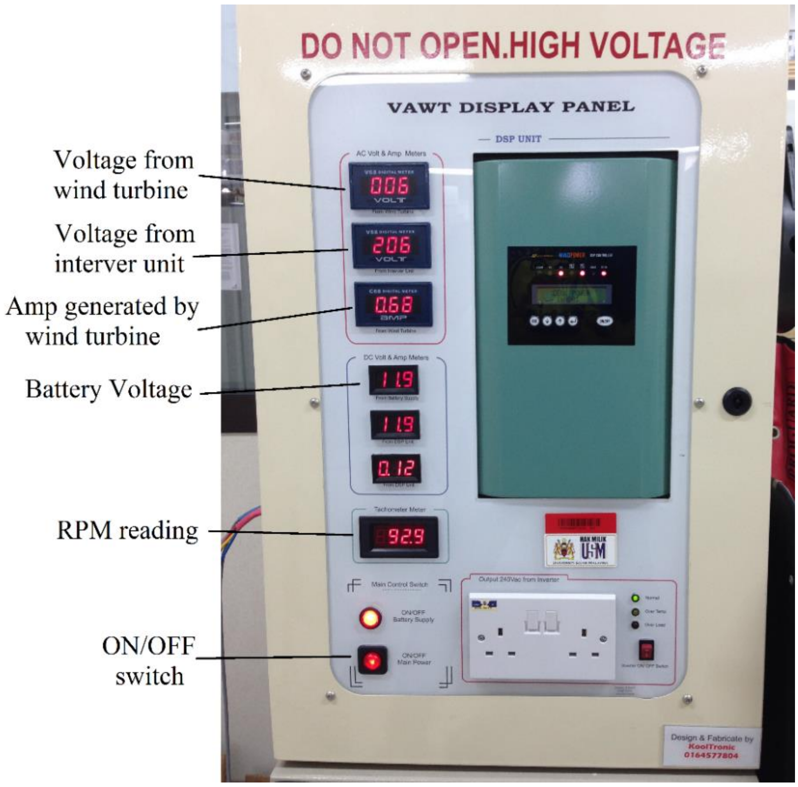

Fig. 3.6: Customized wind turbine control panel which connected to the wind turbine displaying the voltage, ampere and rpm readings.

Table 3.2: Ampere (A), voltage (V) and revolution per minute (RPM) outputs from VAWT at low and high speed settings.

Properties \ Speed settings	Low ($3.2\ m\ s^{-1}$)	High ($4.0\ m\ s^{-1}$)
Ampere (A)	0.01 - 0.02	0.01 - 0.03
Voltage (V)	5 - 6	7 - 8
Revolution per minute (RPM)	75 - 79	101 - 105

The three flow velocity components for both upwind and in the wake of VAWT flows were collected by an ultrasonic anemometer connected to a personal computer via RS232 cable. “Hyperterm” (Microsoft®, USA) was used as the interface to log the data set of 36000 points over 30 min for preliminary analysis. Data was sampled at a frequency of 10 Hz for a period of 60 min. From the preliminary analysis, it was discovered that this time average is sufficient to obtain all relevant turbulence scales including the one second period. This method in