THE DESIGN AND TESTING OF AN EXHAUST AIR ENERGY RECOVERY WIND TURBINE GENERATOR

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FACULTY OF ENGINEERING
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Abstract

An innovative system to recover part of the energy from man-made wind resources (exhaust air systems) is introduced. A vertical axis wind turbine (VAWT) in cross-wind orientation, with an enclosure is mounted above a cooling tower's exhaust fan to harness the wind energy for producing electricity. The enclosure is designed with several guide-vanes to create a venturi effect (to increase the wind speed) and guide the wind to the optimum angle-of-attack of the turbine blades. Another feature of the enclosure is the diffuser-plates that are mounted at a specific angle to accelerate the airflow. Moreover, safety concerns due to blade failure or maintenance activities are tackled by the design of the enclosure. The performance of the VAWT and its effects on the cooling tower were investigated. Laboratory test conducted on a scaled model (with a 5-bladed H-rotor with 0.3 meter rotor diameter) shows no measureable difference on the air intake speed (1.6~1.8 m/s) and current consumption of the power-driven fan (0.39 ampere) when the turbine was spinning on top of the scaled model of the cooling tower. Field test on the actual induced-draft cross flow cooling tower with 2 meters outlet diameter and powered by a 7.5 kW motor was performed using a 3-bladed Darrieus wind turbine with 1.24 meter rotor diameter. There were no significant differences on the outlet air speed of the cooling tower, i.e. the outlet speed of the cooling tower without and with wind turbine was 10.63 m/s and 10.67 m/s respectively (the rotational speed of the turbine was 881 rpm). No measureable difference was observed on the power consumption which was recorded between 7.0 to 7.1 kW for both cases. This system is retrofit-able to the existing cooling towers and has very high market potential due to abundant cooling towers and other unnatural exhaust air resources globally. In addition, the energy output is predictable and consistent, allowing simpler design of the downstream system.

Abstrak

Tesis ini memperkenalkan satu sistem yang inovatif untuk mengguna semula sebahagian daripada tenaga dari sumber angin buatan manusia (contohnya angin dari menara penyejuk). Kincir angin berpaksi menegak (VAWT) bergril dipasang di atas kipas menara penyejuk bagi memanfaatkan tenaga angin yang dilepaskan untuk menghasilkan tenaga elektrik. Gril direka bentuk dengan beberapa bilah-pandu-arah untuk mendapatkan kesan venturi (bagi meningkatkan kelajuan angin) dan mendorong angin ke sudut yang optimum apabila berinteraksi dengan bilah rotor. Satu lagi ciri yang ada pada gril ialah plat peresap yang dipasang pada sudut tertentu untuk mempercepatkan pengaliran udara keluar daripada menara penyejuk. Di samping itu, risiko keselamatan yang mungkin disebabkan oleh kegagalan bilah atau semasa penyelenggaraan ditangani oleh reka bentuk gril tersebut. Prestasi VAWT dan kesannya ke atas menara penyejuk dikaji. Ujian makmal yang dijalankan ke atas model menara penyejuk berskala kecil dengan kincir H-rotor 5-bilah berdiameter 0.3 meter, menunjukkan tiada perbezaan yang diukur pada kelajuan udara masuk (1.6~1.8 m/s) dan arus elektrik pada kipas menara penyejuk (0.39 ampere) apabila rotor berputar di atas model menara penyejuk tersebut. Ujian lapangan keatas menara penyejuk sebenar yang berkuasa 7.5 kW (motor) dengan saluran keluar angin berdiameter 2 meter dilakukan menggunakan kincir angin 3-bilah jenis Darrieus dengan diameter pusingan bersaiz 1.24 meter. Tiada perbezaan yang ketara ke atas kelajuan udara keluar dari menara penyejuk, iaitu kelajuan udara keluar pada sistem tanpa kincir angin dan sistem dengan kincir angin masing-masing adalah 10.63 m/s dan 10.67 m/s (kelajuan pusingan kincir adalah 881 rpm). Penggunaan kuasa elektrik juga tidak menunjukkan perbezaan iaitu antara 7.0 kW hingga 7.1 kW bagi kedua-dua kes. Sistem ini adalah dapat diintegrasikan dengan menara penyejuk yang sedia ada dan mempunyai potensi pasaran

yang sangat tinggi kerana bilangan menara penyejuk yang banyak didunia dan lain-lain sumber angin tidak semulajadi. Di samping itu, tenaga yang dihasilkan adalah konsisten dan boleh diramal, seterusnya boleh memudahkan reka bentuk sistem hiliran.

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Nomenclature

α	Angle of attack	[°]
A_{outlet}	Exhaust air outlet area	[m^2]
c	Cord length	[m]
C_d	Drag coefficient	-
C_l	Lift coefficient	-
C_p	Power coefficient	-
D	Rotor diameter	[m]
F_l	Lift force	[N]
F_d	Drag Force	[N]
$F_{t_{average}}$	Average tangential force	[N]
I	Electrical current	[Ampere]
$\dot{m}$	Mass flow rate	[kg/s]
N	Rotational speed (revolution per minute)	[rpm]
P	Power	[Watt]
P_{output}	Power output from the wind turbine	[Watt]
P_{input}	Power input to the exhaust air system	[Watt]
ρ	Density of the air	[kg/m^3]
r	Rotor radius	[m]
S	Solidity	-
τ	Torque	[Nm]
TSR	Tip speed ratio	-
θ	Azimuth angle	[°]
v	Wind speed	[m/s]
v_{outlet}	Wind speed at the exhaust air outlet	[m/s]
V	Voltage	[V]

$\dot{V}$	Volume flow rate	[m^3/s]
ω	Rotational speed (radian per second)	[rad/s]

CHAPTER 1: Introduction

1.1 Overview

Economic growth and energy demand are intertwined. Therefore, one of the most important concerns of the government in the world is the need for energy security. Developed countries are known as the major user of energy globally, however, the vast of increasing demand will occur in developing countries, where populations, economic activity and improvements in quality of life are growing most rapidly. Currently, the world relies on the coal, crude oil and natural gas for energy generation. However, energy crisis such as climate change and depletion of oil (which leads to the oil price inflation) becomes one of the main problems to all countries.

In Malaysia, the total primary energy supply had increased steadily over the past 18 years, and it was expected to reach 64 Mtoe in 2008, which is more than 200% increase from 1990 (Ong, Mahlia, & Masjuki, 2011). Since the past few decades, most of the power plants in Malaysia are using fossil fuel for electricity generation while only 10.7% of the electricity generation comes from the renewable sources such as hydropower, mini-hydro and biomass from the palm oil waste (Shekarchian, Moghavvemi, Mahlia, & Mazandarani, 2011). In order to meet the increasing demand on energy, the country has extensively implemented energy conservation in order to reduce the consumption growth rate. Researchers have deeply discussed and proposed possible initiative in order to promote the energy conservation programs such as fuel economy standard for motor vehicles (Mahlia, Saidur, Memon, Zulkifli, & Masjuki, 2010), energy efficiency standards and energy labels for room air conditioners and refrigerator–freezers (Mahlia & Saidur, 2010) and energy efficiency award system (Manan et al., 2010).

Besides, to meet the energy demand without damaging the planet, the energy generation from renewable sources becomes more widespread. It is proven that the renewable energy sources available can meet many times of the present world energy demand, thus their potentials are enormous (Naghavi, 2010). However, most of the current technologies on renewable energy generation still at an early stage of development and not technically mature. Thus, there is an urgent call for researchers and innovators to come out with the best possible solution for clean energy generation.

1.2 Problem statement

The provision of energy by fossil resources involves a series of undesirable side effects, which are less tolerated by industrialized societies increasingly sensitized to possible environmental and climate effect at the beginning of 21st century. Besides turning to available alternative resources for generating clean energy, energy recovery from the wastes such as heat sink, exhaust air, etc. also have a great potential in helping to address the global energy issue.

The available wind source can be divided into the natural wind and man-made wind. The man-made wind is considered as unnatural that is available from the man-made system or operation such as cooling tower, exhaust air, etc. The high-speed, consistent and predictable wind produced by the system is good to be recovered into the useful form of energy. Thus, this research is planned to prove the concept of the energy recovery system on the cooling tower by using the commercially available wind turbines.

1.3 Objectives of the research

This report presents the design and testing of an exhaust air energy recovery wind turbine generator in order to propose a new system on clean energy generation. The system is using the commercially available wind turbine to be mounted on predefined configuration facing the outlet of the exhaust air system. The objectives of this research can be presented as below:

1) To design and fabricate the energy recovery wind turbine generator for integration with an exhaust air system.
2) To perform a series of test on the energy recovery wind turbine generator installed on a scaled model and the actual exhaust air system, i.e. cooling tower.

The main aim of the research is to prove that the wind from an exhaust air system can be utilized into the useful forms of energy. Moreover, the utilization of this man-made wind energy by the energy recovery wind turbine generator is aimed to give no negative effect on the performance of the exhaust air system.

1.4 Research scopes

In this report, the design and testing of an exhaust air energy recovery wind turbine generator for clean energy generation is presented. The system is targeted to generate clean energy from the wind that is blown from the exhaust air system without giving the negative effect on the performance of the exhaust air system which is represented by a cooling tower. The design is limited to prove the concept of a recovery system to the cooling tower without optimization.

The required methodology for the study can be presented as below:

1) Literature review on wind turbine systems
2) Literature review on power augmented wind turbine systems
3) Literature review on the cooling tower systems
4) Describing the design and fabrication of the exhaust air energy recovery wind turbine generator
5) Describing the indoor and outdoor testing for the system
6) Evaluation of the obtained result on the wind turbine and cooling tower performance
7) Conclusion and recommendations

CHAPTER 2: Literature review

2.1 Wind energy

Wind energy is the fastest growing energy source in the world today. Wind power is the transformation of wind energy into electricity as more utile forms, by using wind turbines (Gipe, 2004). In the year 2010, the worldwide wind capacity reached 196,630 Megawatt, after 159,050 MW in 2009, 120,903 MW in 2008 and 93,930 MW in 2007 (Gsänger, 2010).

Wind energy is one of the earliest sources of energy when it was utilised to propel ships and boat during the ancient times. The first documented design of a wind mill dates back to 200 B.C where the Persians used wind mills for grinding grains. At the end of 18th century, experiment began in which windmills were used to generate electricity in United State and Denmark. The research continues until today and wind power generator becomes an icon for clean and sustainable energy generation.

Wind power is the kinetic energy of air in motion. The kinetic power (kinetic energy per unit time) can be expressed as

$$P = \frac{1}{2}\dot{m}v^2 \tag{2.1}$$

where P is the kinetic power, v is the air velocity and $\dot{m}$ is the air mass flow rate which can be expressed as

$$\dot{m} = \rho A v \tag{2.2}$$

where ρ is the air density and A is the swept area perpendicular to the flow direction. The combination of Eq. (2.1)and (2.2) can be expressed as

$$P = \frac{1}{2}\rho A v^3 \qquad (2.3)$$

From the equations, the power available in wind is a function of air density, swept area of the wind rotor and the wind velocity. The power in the wind is proportional to the cubic power of the velocity approaching the wind turbine, which means that even a small increment in wind speed gives a large increase in energy generation.

2.2 Wind turbine technology

Today, wind turbine becomes an icon for green energy generation. A wind turbine is a machine that converts the power in the wind into electrical (Manwell, McGowan, & Rogers, 2002). As electrical power generators, wind turbines are connected to the electrical network, including battery charging circuits, residential power systems, isolated networks and large utility grids. Large utility grids are normally using larger turbine in wind farm to generate electricity. The wind farms are mostly available in Europe and the United States where experience a strong wind throughout the year. Figure 2.1 is an example wind farm, i.e. Roscoe Wind farm in Texas, USA (the world’s largest onshore wind farm).

Figure 2.1 Wind farm for electricity generation to large utlity grid. The picture shows on of the largest on-shore wind farms is the Roscoe Wind farm in Texas, USA. The farm covers an area of 155 square miles, and its 627 turbines have a total installed capacity of 780 MW (Roos, 2011).

Wind energy conversion systems are classified into two types according to the aerodynamic force characteristic, i.e. drag-based and lift-based. The drag-based wind turbine is the earliest type of wind turbine that was been used during the ancient times. The wind turbine called the Sistan turbine (Figure 2.2) was used in Afghanistan from the year 644 A.D. up to the present time. Old structures of drag devices, however, had a very low power coefficient, C_p with a maximum value is of around 0.16 (Gasch, 1982). Aerodynamic lift is the main base for modern wind turbines, where airfoil blades are used. The lift force is supplying more than the drag force and thus, the relevant driving power of the rotor is much more for lift power rather than the drag power.

Figure 2.2 Sistan turbine for milling grain in Afghanistan (Hau, 2006).

The wind turbines also had been described by the axis of rotation. Therefore, modern wind turbines, i.e. aerodynamic lift-based wind turbines can be further divided into horizontal-axis and vertical-axis type turbines. The horizontal-axis wind turbine (HAWT) approach currently dominates the wind turbine applications where the axis of rotation is parallel to the ground. Figure 2.3 shows the schematic arrangement of a HAWT. The number of blades of a HAWT is depending on the purpose of the wind turbine. For example, two or three bladed turbines are usually used for electricity power generation. Turbines with 20 or more blades are suitable for mechanical power, e.g. water pumping.

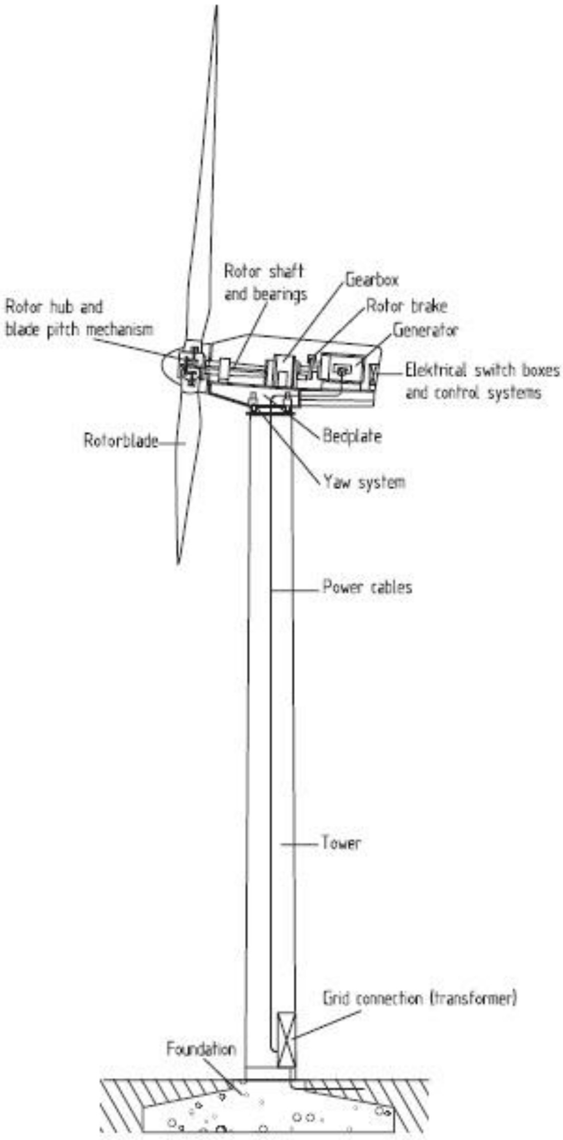

Figure 2.3 Components of a HAWT (Hau, 2006).

Another type of turbine according to the axis of rotation is the vertical axis wind turbine (VAWT). There have been many designs of vertical axis windmills over the centuries and currently the VAWT can be broadly divided into three basic types, namely the Savonius type, Darrieus type and H-rotor type (Islam, Ting, & Fartaj, 2008). The Savonius-type VAWT was invented by a Finnish engineer S.J. Savonius in 1929, and it is basically a drag force driven wind turbine with two cups or half drums fixed to a central shaft in opposing directions (Savonius, 1931). However, the Savonius turbine unfortunately has a rather poor efficiency when considering the standard design; theoretically, $C_p = 0.18$ at best (Mohamed, Janiga, Pap, & Thévenin, 2010).

The Darrieus wind turbine is another type of VAWT. Consisting of a number of aerofoil blades, the Darrieus turbine is a lift-based VAWT that uses lift forces generated by the wind hitting aerofoils to create rotation. Compared to a drag-type VAWT, e.g. Savonius turbine, a Darrieus generates less torque, but it rotates much faster. Thus, makes Darrieus wind turbines much better suited to electricity generation rather than water pumping and similar activities (REUK.co.uk, 2007).

A variation of the Darrieus turbine is the so-called H-rotor turbine. Instead of the curved rotor blades, the straight airfoil blades connected to the rotor shaft are used. However, there are substantial drawbacks of the H-rotor VAWT, that is lower power coefficient and has a poor self-starting characteristic compared to the HAWT (Takao, Maeda, Kamada, Oki, & Kuma, 2008). The VAWTs that are discussed in this section are illustrated in Figure 2.4.

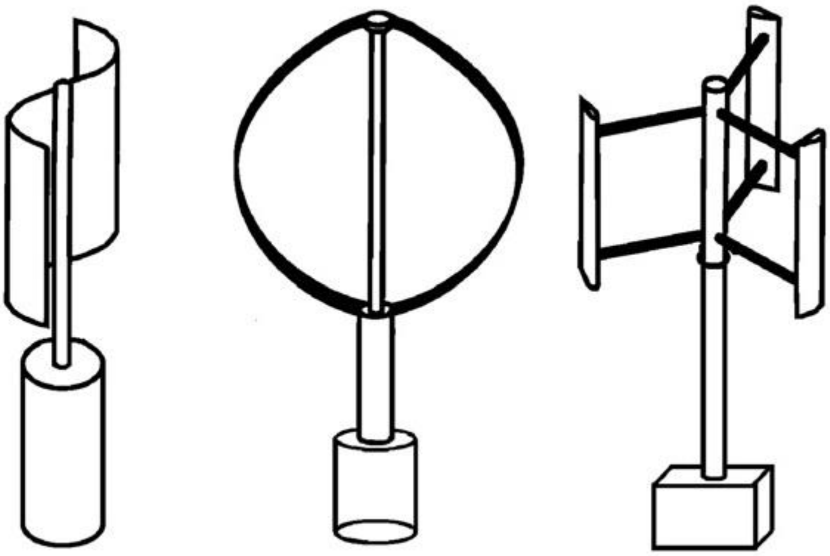

Figure 2.4 Illustrations of the VAWTs. From left, Savonius rotor, Darrieus turbine and H-rotor (Eriksson, Bernhoff, & Leijon, 2008)

The comparative studies on lift-based turbine have shown that VAWTs are advantageous to HAWTs in several aspects (Eriksson, et al., 2008; Riegler, 2003). Looking to the structural aspects, low level of maintenance can be expected from VAWT because it does not require any yaw mechanism, pitch regulation or gearbox and therefore, has few movable parts. However, the HAWT is already established on the global market and it still has to be proven that VAWTs are an interesting alternative for wind power generation.

2.3 Wind turbine theory

The wind turbine theory relates to the aerodynamic study. Aerodynamics deals with the motion of air or other gaseous fluids and the forces acting on bodies moving through them. In order to design and develop a wind energy system, understanding and interpreting the aerodynamic principles is a must. However, in this modern day, theories are specifically formulated for wind turbine which are further refined and reinforced with the help of experimental techniques.

2.3.1 Betz limit

Betz limit was first formulated in 1919 and it is applied to all types of wind turbines. According to Betz limit, no turbine can capture more than 59.3 percent of the kinetic energy in wind. That’s means the power coefficient, C_p i.e. maximum fraction of the power in a wind stream that can be extracted is 0.593.

Further explanation is based on the consideration of an ideal airflow through a wind turbine as illustrated in Figure 2.5. Treats the density changes as negligible, the streamlines must diverge as they pass through the rotor disc as the velocity reduces. In the simple momentum theory considered the pressure upstream and downstream of the rotor are constant over the rotor disc. This in the effect assumes that the two or three blades typical of a modern wind turbine have been replaced by an infinite number of thin blades, giving the same force on the approaching airflow as the average for the real rotor system.

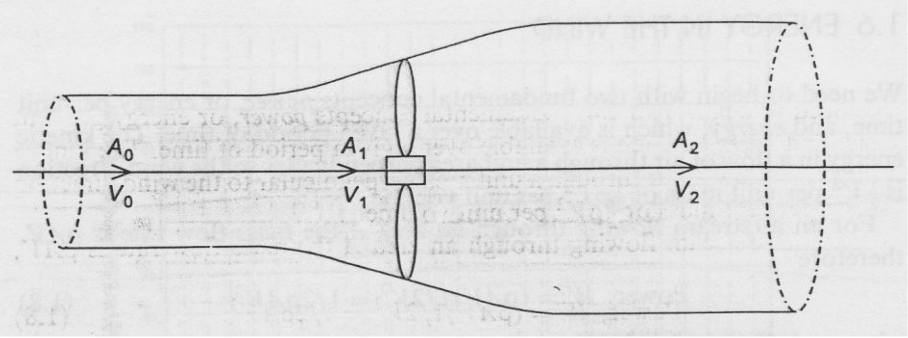

Figure 2.5 Ideal air flow through a wind turbine (Walker & Jenkins, 1997).

2.3.2 Tip Speed Ratio (TSR)

In order to obtain maximum or optimal efficiency of the wind rotor, it is necessary to match the angular velocity of the rotor to the on-coming wind speed in the design of wind turbine. If the rotor of the wind turbine turns too slowly, most of the winds will pass undisturbed through the gap between the rotor blades with a small amount of power extraction. On the other hand, if the rotor turns too fast, the rotating blades act as a solid wall obstructing the wind flow and hence reducing the power extraction.

Thus, wind turbines must be at their optimal tip speed ratio in order to extract as much as possible power from the wind stream. The tip speed ratio (TSR) is defined as the ratio of the speed of the rotor tip to the free stream wind speed as the following equation:

$$TSR = \frac{Tip\ speed\ of\ rotor\ blade}{Wind\ speed} \tag{2.4}$$

The tip speed of the rotor blade is the tangential velocity of the rotor blade tip in m/s.

However, the theory of *TSR* is only applicable to the lift type turbine, since the drag type turbine depends only to the drag force from the wind flow, which means the blade speed will either be the same as the wind speed or lower. Figure 2.6 shows the relationship between the rotor power coefficient, C_p and the *TSR* for different types of wind machines.

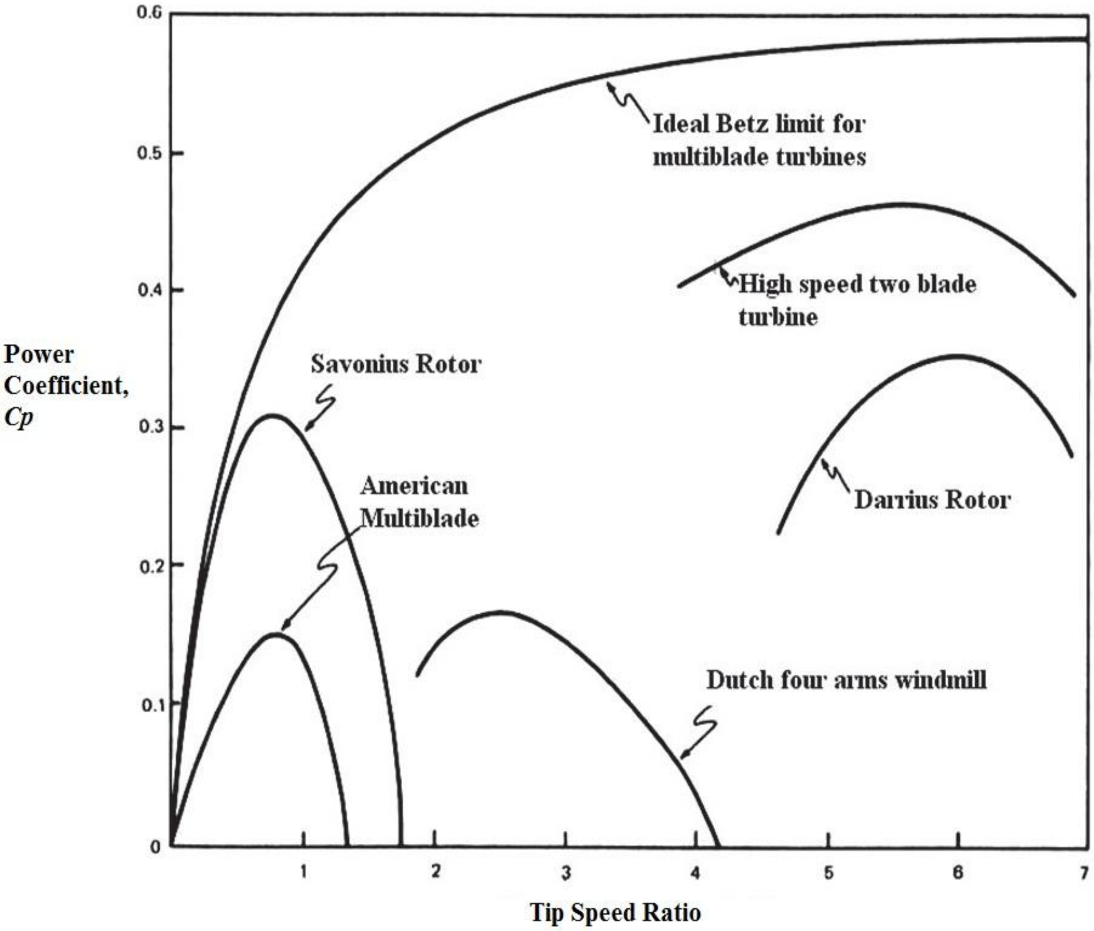

Figure 2.6 Relationship between the rotor power coefficient, C_p and the *TSR* for different types of wind machines (Ragheb & Ragheb, 2011).

2.3.3 Angle of attack

Angle of attack, α is a term used in wind turbine design to describe the angle between the chord line of an airfoil and the on-coming wind flow as shown in Figure 2.7. Lift type turbine depends completely on the shape of the airfoil blades and the angle of attack.

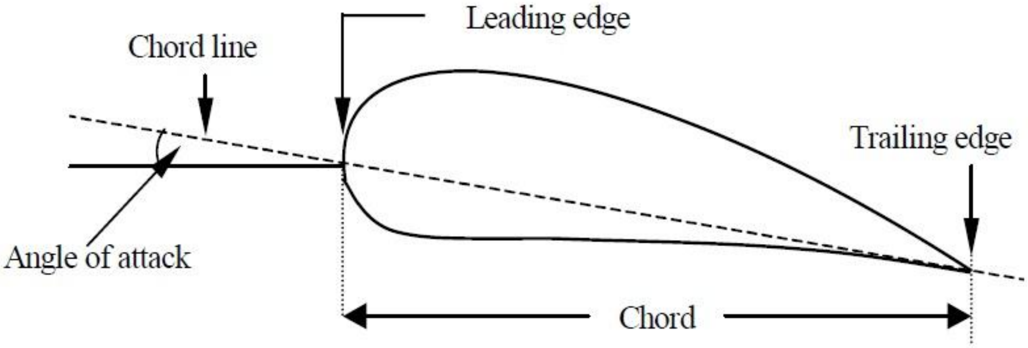

Figure 2.7 Important parameters of an airfoil (Mathew, 2006).

The lift and drag coefficient of an airfoil blade varies with every angle of attack. Lift coefficient, C_l is the factor that contributes to the elevation of the blade (always perpendicular to the wind flow). Drag coefficient C_d is used to quantify the drag, i.e. the resistance of an object in the air. These dimensionless units are expressed in the following equations:

$$C_l = \frac{F_l}{\frac{1}{2}\rho A v^2} \qquad (2.5)$$

$$C_d = \frac{F_d}{\frac{1}{2}\rho A v^2} \qquad (2.6)$$

where F_l and F_d is the lift and drag force respectively.

2.3.4 Wind turbine solidity

Solidity of wind turbine is usually defined as the percentage of the circumference area of the rotor which contains material rather than air. Solidity, S can be expressed as

$$S = \frac{Total\ blade\ area}{Swept\ \ frontal\ area} \tag{2.7}$$

$$S = \frac{nc}{D} \tag{2.8}$$

where n is the number of blades, c is the cord length and D represents the diameter of the rotor.

High-solidity wind turbines carry a lot of material and have coarse blade angles. They generate much higher starting torque than low-solidity wind turbines. However, the high-solidity turbines are inherently less efficient than low-solidity machines. Figure 2.8 depicts the example of torque that can be achieved by several turbines with solidity variation.

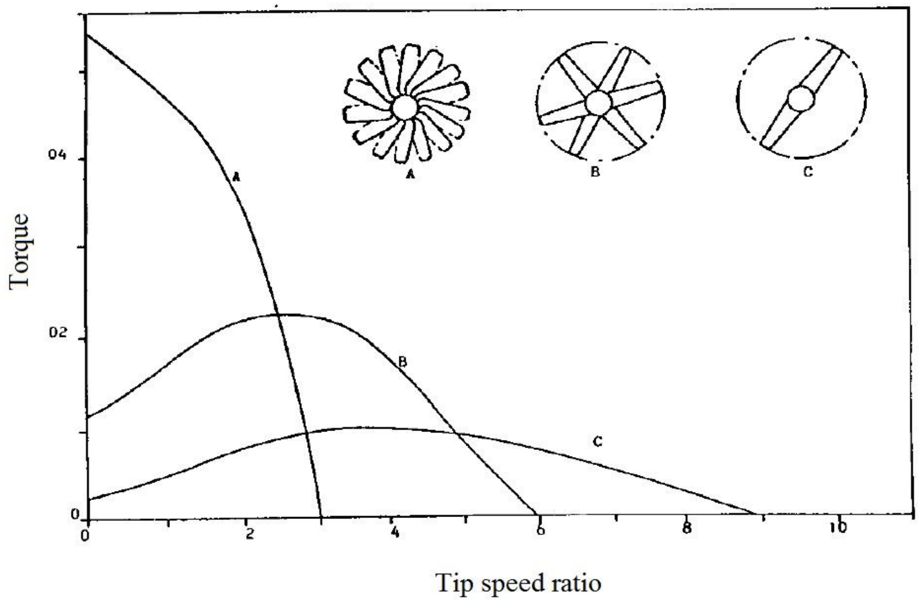

Figure 2.8 Example of torque versus tip speed ration on the wind turbines with high-solidity (A), intermediate (B) and low-solidity (B) (Neilnob, 2005).

2.3.5 Output power

The tangential and normal forces of wind turbine are developed for every azimuthal position, so, they are considered as a function of azimuth angle, θ (Islam, et al., 2008). The tangential force, $F_{t_{average}}$ on a single blade can be expressed as the following equation

$$F_{t_{average}} = \frac{1}{2\pi}\int_0^{2\pi} F_t(\theta)d\theta \tag{2.9}$$

With the multiple number of blades, n, the total torque, τ can be obtained by the following equation

$$\tau = n \cdot F_{t_{average}} \cdot r \tag{2.10}$$

The output power, P_{output} of the rotor can be expressed as

$$P_{output} = \tau \cdot \omega \tag{2.11}$$

where ω is the rotational speed of the wind turbine in rad/s.

2.4 Wind turbine with diffuser

Besides focusing on improving the performance of wind turbine by the aerodynamic study of the turbine blades, increasing the on-coming wind speed before it interacts with the wind turbine also provides a significant result in power generation increment. As mentioned before, the power in the wind is proportional to the cubic power of the wind speed, which means that even a small increment in wind speed gives a large increase in energy generation. Therefore, many researchers had studied and reported different designs of ducted or diffuser augmented wind turbines, which increase the on-coming wind speed hence increasing the efficiency and performance of turbines.

(Dhanasekaran & Govardhan, 2005) have shown that the efficiency and starting characteristics of the Wells turbine (horizontal axis wind turbine) have improved when compared with the respective turbines without guide vanes. A study conducted in Taiwan also revealed that a bucket-shape ducted wind turbine tested in the field was able to improve the flow around the generator. It was estimated that the power extraction efficiency increases by about 80% (Hu & Cheng, 2008). Another research revealed that by adopting the guide vane row, the power coefficient of a straight-bladed VAWT was 1.5 times higher than a wind turbine which has no guide vane (Takao, et al., 2008). In order to address the low wind speed condition in Malaysia, local researchers designed an innovative device called the power-augmentation-guide-vane (PAGV) to increase the wind speed and guide it before interacting with the rotor blades.

The techno-economic analysis of the PAGV integrated wind turbine shows that the PAGV is able to increase the operating hour by 58% and hence the power increment by 327% (Chong, Naghavi, Poh, Mahlia, & Pan, 2011).

2.4.1 Diffuser theory

The basic function of the diffuser is to convert the kinetic energy of the flow downstream of the rotor into a pressure rise. This lowers the pressure level behind the rotor, and makes it possible for the rotor to capture airflow from a free-stream tube area that is greater than that of the rotor itself. The inlet area need not be large, as the stream tubes will converge naturally to the inlet if the diffuser is sufficiently effective. The flow velocity through the rotor is typically 20 to 60 percent greater than the free wind velocity as opposed to 67 percent less than the free wind for the enshrouded case (Oman & Foreman, 1973). In addition, to offer more output per unit rotor area, this fundamental change in stream tube configuration enables practical rotor designs to operate even at very low wind speeds.

A diffuser has a duct surrounds the turbine blades and are essentially raised at the back pressure of the turbine and causing negative pressure at the back. The back pressure draws more accelerated wind through the blade plane, and hence more power can be generated compare to a turbine without diffuser at the same rotor blade size. Such mass flow augmentation can be achieved through two basic principles: increase in the diffuser exit ratio and/or by decreasing the negative back pressure at the exit (Bussel, 2007). The anticipated effect on the stream-tube passing through the blade on a diffuser augmented wind turbine can be seen at Figure 2.9. Without the diffuser, there is a smaller area of wind flow that interacts with the wind turbine as sketched by typical bare turbine stream tube boundary lines. While with the integration of diffuser, the amount of wind that passes through the wind turbine is more and this can be shown as typical diffuser augmented wind turbine (DAWT) stream tube boundary lines. The wind speed at the wind turbine is higher than the free stream wind due to the venturi effect.

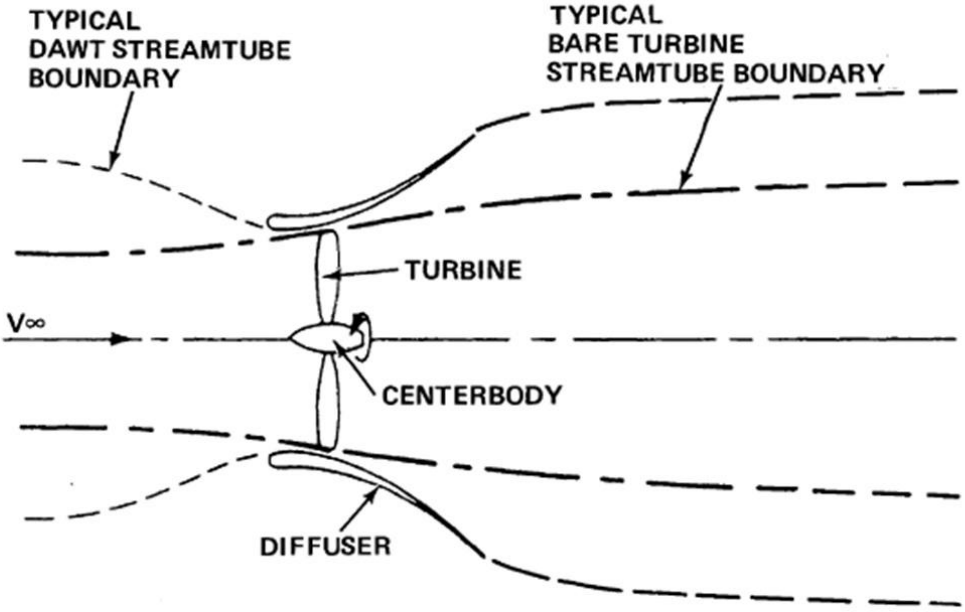

Figure 2.9 Effect of diffuser on stream-tube passing through (Foreman, 1980)

2.5 Cooling towers

Most air-conditioning systems and industrial processes generate heat that must be removed and dissipated. Water is commonly used as a heat transfer medium to remove heat from refrigerant condensers or industrial process heat exchangers. Cooling towers are commonly used to dissipate heat from water-cooled refrigeration, air-conditioning systems, and industrial process systems. Cooling towers are heat removal devices used to transfer waste heat to the atmosphere; large office buildings, hospitals and schools typically installed one or more cooling towers for buildings ventilation system.

A cooling tower cools water by a combination of heat and mass transfer. Water to be cooled is distributed in the tower by spray nozzles, splash bars, or film-type fill, which exposes a very large water surface area to atmospheric air. Atmospheric air is circulated by fans, convective currents, natural wind currents, or induction effect from sprays. A portion of the water absorbs heat to change from a liquid to a vapor at a constant pressure. This heat of vaporization at the atmospheric pressure is transferred from the water remaining in the liquid state into the airstream.

There are two basic types of cooling towers are used. The first type is the direct-contact or open cooling tower where the source of heat is transferred directly to the air by exposing water to the cooling atmosphere. The second of these, the closed circuit cooling tower that combines a heat exchanger and cooling tower into one relative compact device, the heat is dissipated by indirect contact between heated fluid and atmosphere. Induced-draft towers, chimney towers and non-mechanical-draft towers are the types of direct-contact cooling towers while the types of indirect-contact cooling towers are closed-circuit cooling towers and coil shed towers (both are mechanical-draft).

Direct-contact induced-draft cooling towers are the most common cooling tower in Malaysia. Figure 2.10 shows an example of cross-flow direct-contact induced-draft cooling tower. This type of cooling tower relies on power-driven fans to draw or force the air through the tower. The air enters the cooling tower through the louver at the sides of the tower. Then, it is forced to flow upwards until the exit on top of the tower and at the same time, it is in contact with the water that flowing downwards. The cross-flow heat transfer from water to the air happens when they are in contact. The heat in the air is then released to the atmosphere in high speed through the outlet channel. Wind speeds up to 18 m/s is recorded at the distance 0.3 meter above the outlet of cooling tower, which is preferable to generate the electricity.

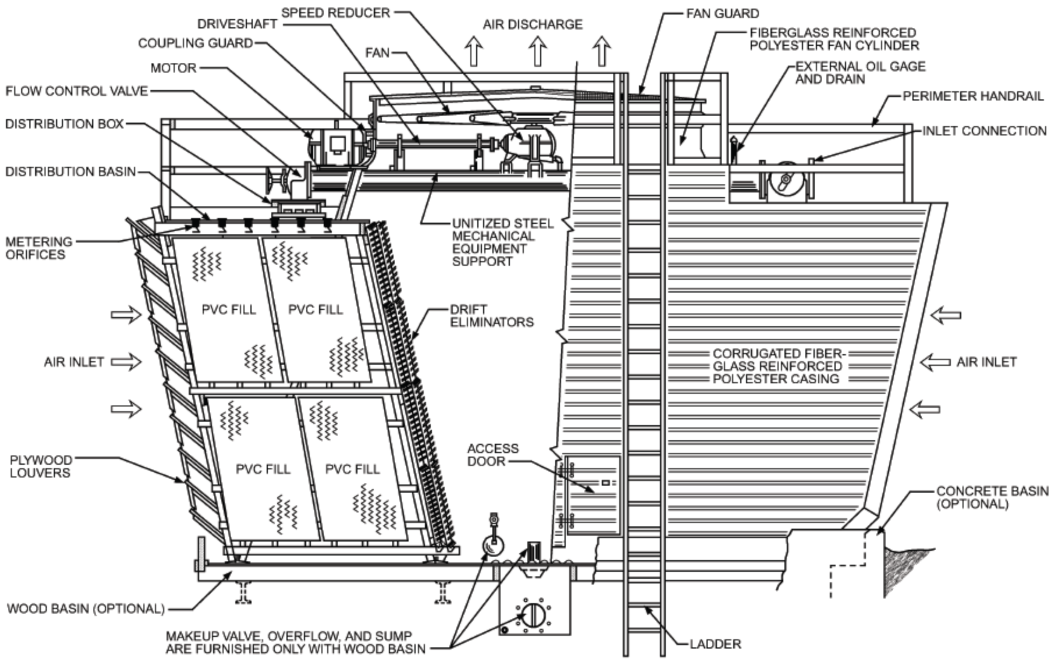

Figure 2.10 Cross-flow direct-contact induced-draft cooling tower (ASHRAE, 2008)

2.5.1 Factors affecting cooling tower performance

There are a lot of factors which affect the cooling tower performance. However, those factors whose effects predominate and related to the air flow are identified and discussed in this section.

2.5.1.1 Interference

Figure 2.11 depicts a phenomenon called “interference” that happens when a portion of the wind from the outlet of a cooling tower contaminates with the air intake of the other cooling tower. Therefore, a proper design especially on the discharge height and the distance between the cooling towers is necessary to minimize the interference. The study on the local wind condition will be a baseline for the design.

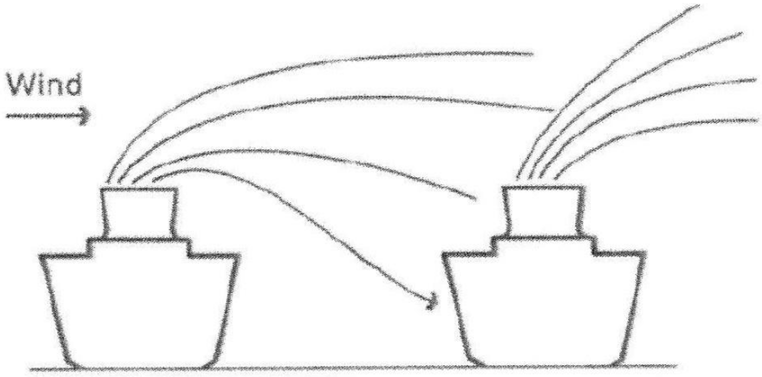

Figure 2.11 Interference phenomenon on cooling towers (Hensley, 2009)

2.5.1.2 Recirculation

Recirculation or re-entrainment as shown in Figure 2.12 is another undesirable situation that affecting the cooling tower performance. The basic principle of the cooling tower is to take the fresh ambient air into the compartment for the air to absorb and carry the heat out of the cooling tower through the outlet. If the discharged air recirculated by contamination with the intake air, the performance of the cooling tower will be affected. The potential for recirculation is primarily related to wind force and direction. It is tending to increase as the wind velocity increases. Therefore, accepted code under which cooling towers are thermal performance limit wind velocity during the test to 4.5 m/s (Hensley, 2009).

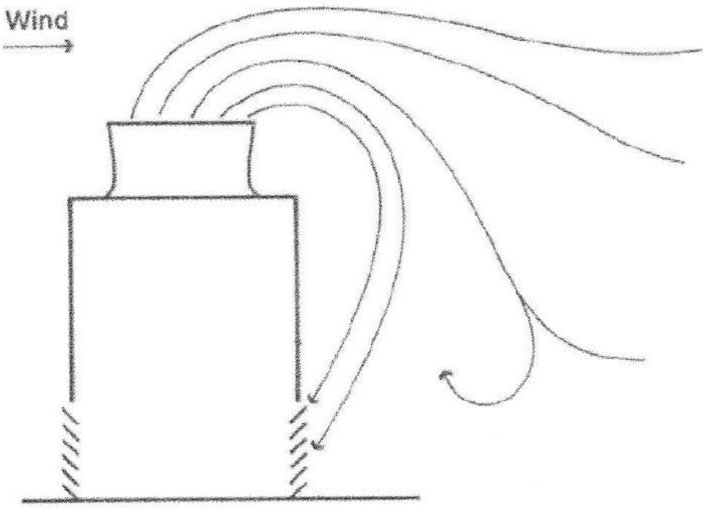

Figure 2.12 Recirculation phenomenon on cooling towers (Hensley, 2009).

2.5.2 Performance testing on an induced-draft cooling tower

There are many factors affect the cooling tower performance such as water distribution, air distribution, the amount of surface and fill, etc. However, in case of troubleshooting, fan flow characteristic is one of the first items to be investigated. In order to evaluate the performance of the fan, the parameters to be measured are the air flow rate, power input to motor and fan speed (Herrman, 1962).

2.5.2.1 Air flow rate

The air flow rate for an induced-draft cooling tower shall be measured at the discharge side (Herrman, 1962). The calibrated vane-type anemometer is preferable for the measurement instead of pitot-tube and hot wire anemometer. The water contains in the air discharged from the cooling tower will easily fills the small hole of the pitot-tube makes it unsuitable for measurement in moist environment. In addition, the hot wire anemometer is useless in the wet air. The volume flow rate of the air delivered by the fan is calculated by the outlet velocity (as measured by the anemometer) times the area of discharge.

2.5.2.2 Power input to motor

Only cooling tower with electrical powered motor is considered in this research report. The parameter needed in the measurement is the power input to the motor. Manufacturer’s efficiency curve for the electrical motor can be used for the evaluation. A three-phase wattmeter or two single phase wattmeters is preferred for the measurement. Alternatively, a voltmeter, ammeter, and power factor meter can be used.

2.5.2.3 Fan speed

To measure the fan speed directly to the blade or shaft is a bit difficult due to the size and physical limitation. So, using a tachometer, the rotational speed of the pulley that connected to the fan shaft is measured. Then by using the gear ratio, the fan speed can be calculated.

CHAPTER 3: Methodology

3.1 Design description of the exhaust air energy recovery wind turbine generator

This section describes the design and features of the exhaust air energy recovery wind turbine generator. The system is registered as patent with the patent number of PI 2011700168 in 2011 (Chong, Kong, & Fazlizan, 2011).

3.1.1 Patent Description

The design of features and requirements of the exhaust air energy recovery wind turbine generator is done under the supervision of Dr. Chong Wen Tong. The invention relates to a system to reuse exhaust air from an exhaust outlet as well as natural wind energy to generate electricity. The study is focusing on a vertical axis wind turbine (VAWT) with enclosure to be mounted above the outlet to harness the wind energy. The general arrangement of this system is shown Figure 3.1.

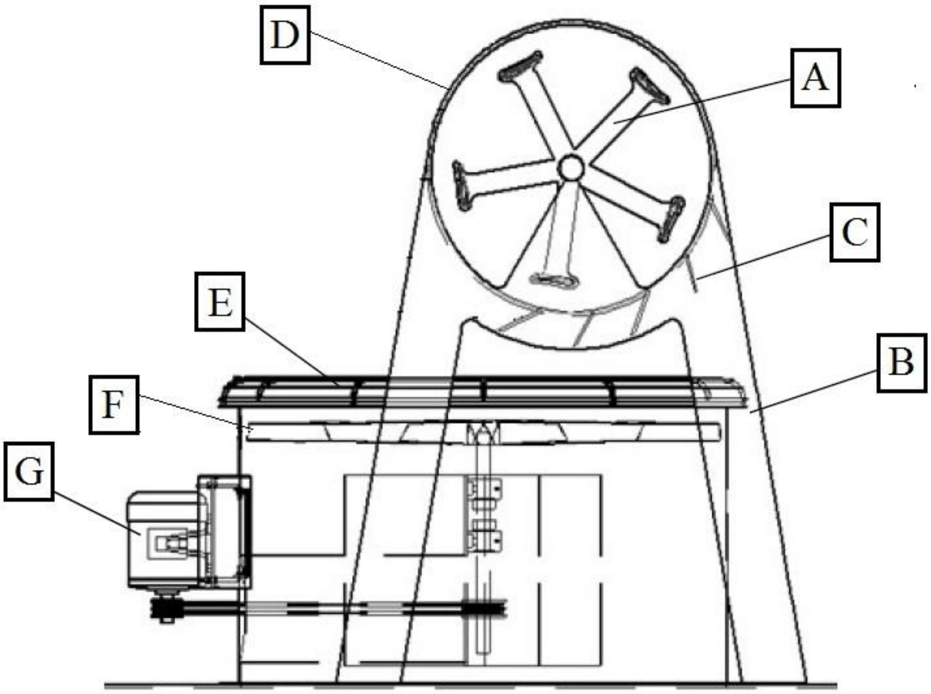

Figure 3.1 General arrangement of the exhaust air energy recovery wind turbine generator

A VAWT, [A] is mounted on the supportive structure, [B] and being able to rotate about a horizontal axis above the exhaust air outlet. The turbine can be any type of available VAWT in the market such as a Darrieus turbine, H-rotor turbine, etc. or a combination of more than one VAWT in one axis such as Darrieus turbine pair with a Savonius turbine. To recover maximum amount of wind energy, the system can be in multiple axis of wind turbine (an axis is considered holding a VAWT or a combination of VAWTs) with a maximum of four axes. The VAWT is positioned at predefine orientation above the exhaust air outlet to avoid any negative effect to performance the exhaust air system.

Guide-vanes, [C] are arranged in between the exhaust outlet and the VAWT at a predetermined angle. The vanes form multiple flow channels, which are utilized to guide the wind stream to an optimized angle of attack on the VAWT blades. In addition, the guide-vanes create a venturi effect where velocity of the exhaust air flow is increased after gone through the channels. This feature improves rotational speed of the

VAWT, thus generating a large amount of electricity. The enclosure, [D] is mounted surrounding the VAWT (other than occupied by the guide-vanes) to improve the safety of the system. A mesh can also be used to cover the enclosure (to avoid the bird strike problems and danger caused by blade failure). Diffuser-plates form parts of the enclosure (Figure 3.2. at both sides of the VAWT and are mounted at a specific angle facing the exhaust air outlet. The placement of diffuser plates improves the aerodynamic properties by enhancing the transition between the low velocity of exhaust air flow from the exhaust outlet and the high velocity exhaust air flow towards the VAWT; hence accelerate the exhaust air flow impinging on the turbine.

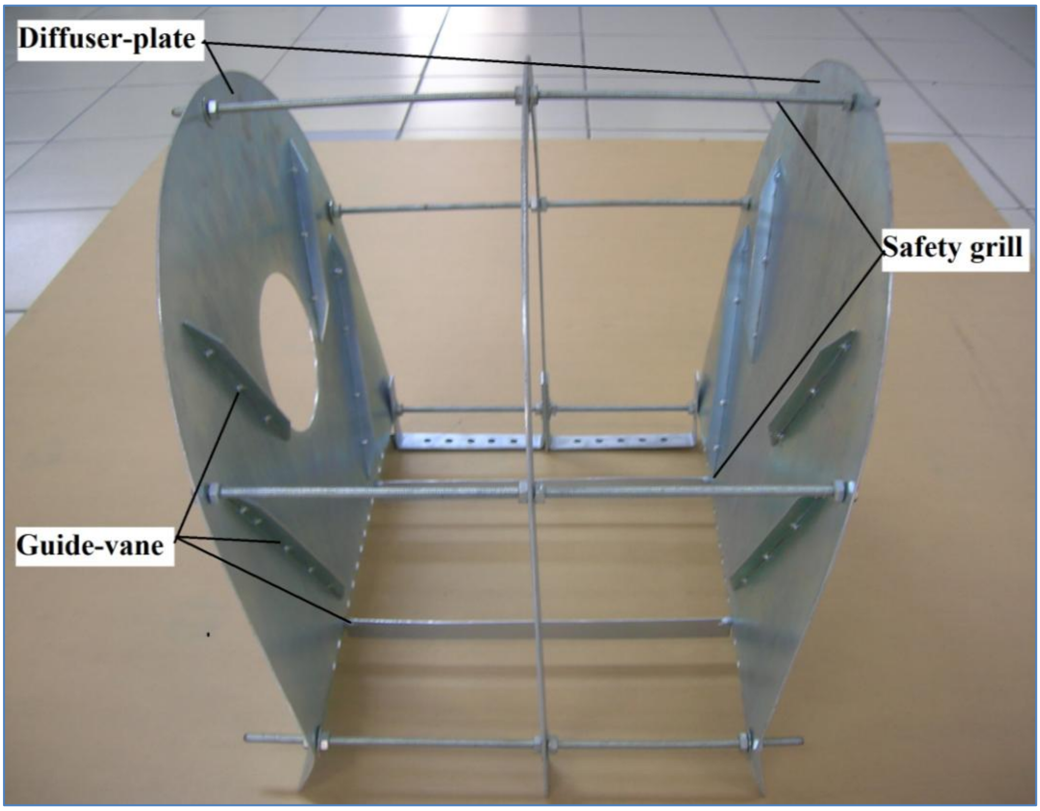

Figure 3.2 The enclosure with guide-vanes, safety grills and diffuser-plates on both sides.

Supporting structure, [B] is the main structure to hold the VAWT, guide-vanes, diffuser-plates and enclosure. It can be mounted on the tower's body without obstructing the exhaust air flow. The entire system can be either in horizontal or vertical direction depends on the direction of the wind. To capture the wind blown from the bottom (or top), the system can be installed horizontally with supporting structure at both end of the power-transmission shaft of the VAWT with generator at one side and a (set of) bearing at the other. If the exhaust air is blowing from side, the system can be either in horizontal or vertical. The generator can sit on the floor (or ground) for vertical installation of the system.

Besides, when the wind turbine is spinning at high rotational speed, a low pressure region is created at the exhaust outlet and this is expected to induce more air out from the exhaust air system. Consequently, the power consumption of the power-driven fan is also expected to be reduced.

3.1.2 Features of the system

The innovative design of the exhaust air energy recovery wind turbine generator is purposely to harness energy exhausted from an exhaust air system. The high-speed air diffused from the exhaust air system has a great potential to be extracted instead of it is only released to atmosphere. The idea for this invention comes from the observation of the wind speed in Malaysia that is low and unsuitable for energy generation from conventional wind turbine systems especially for urban environment. From an analysis of data from several weather stations, the wind speed in Malaysia is less than 4 m/s more than 90% of the total hours throughout the year (Tong, Chew, Abdullah, Sean, & Ching, 2011).

The main concern to place a wind turbine facing the cooling tower outlet is to ensure there is no negative effect on the cooling tower performance such as the amount of air to be exhausted to the atmosphere and the power consumption by the fan motor. Therefore, the optimum position and solidity for the wind turbine is very important. Besides, if the position is right, the performance of the wind turbine would be maximized and it also can help the cooling tower to induce more air. This is expected to happen because of the highest wind speed (based on the wind profile from the cooling tower) is directed to the positive torque area of the wind turbine and hence, help the wind turbine to spin faster. When the wind turbine is rotating at high rotational speed, the top of the cooling tower will experience a low pressure region which will be beneficial to help the fan to draw the air to the outlet faster and its power consumption would be decreased.

Since the system is targeted to be installed at urban area, the concern on safety is undeniable. To address this issue, the system is designed with enclosure. Besides acts as a safety feature to the system, the enclosure is equipped with a number of guide-vanes and a pair of diffusers plates. The guide-vanes are to guide the wind flow to the correct angle of attacks of the turbine blades so that improve the performance of the wind turbine. The diffuser-plates are tilted at a predefined angle to act as a diffuser to accumulate a higher amount of wind to interact with the turbine. Details on the diffuser theory are discussed in previous section (Section 2.4.1).

3.1.3 Advantages of the system

This exhaust air energy recovery wind turbine generator is aimed to generate clean energy from a wasted energy released by the cooling tower. The high-speed air that contains a tremendous amount of energy from the cooling tower is utilized into the useful forms of energy by the installation of the system. This resource of energy is readily available whenever the air-conditioning system of a building is in operation which is operating for more than 8 hours per day.

The wind that is blown by the fan has a better quality than the natural wind. In the conventional wind turbine applications, a series of wind data at a period of time need to be statistically analysed before deployment of the turbine due to variation on the natural wind characteristic. On the other hand, the wind from the unnatural resources is more constant, predictable and concentrated. These qualities are giving the advantage for wind turbine operation. From the wind characteristic, the wind turbine selection for the system would be simplified, i.e. the rated wind speed of the turbine is according to the wind speed of the cooling tower and the power output from the system can be easily predicted. Steady rotational speed of the turbine could be expected and the life span of the wind turbine is maximized due to less fatigue.

The enclosure (with guide-vanes and diffuser-plates) is a novel device that helps to improve the performance of the wind turbine. The guide-vanes are functioning to guide the air flow to the optimum angle of attack of the turbine blades and the diffuser-plates create the suction effect to induce more air to be interacted with the turbine. These features will improve the efficiency of the wind turbine.

The design of the energy recovery wind turbine generator takes into accounts the problems and people’s concerns on the wind turbine system especially when it is planned to be installed in urban environment. Besides improve the performance of the wind turbine, the enclosure acts as a safety cover. The danger that may cause by blade failure is tackled; if the blades fail, it will not fly-off since it is blocked by the enclosure’s grill.

The system has a very high market potential due to abundant cooling towers and other unnatural wind sources globally. Besides, it is retrofit-able to the existing cooling towers and other exhaust air systems.

3.2 Experimental testing

A series of experimental testing is conducted in order to validate the concept of energy recovery using this system. The experiments are preliminary testing, laboratory testing on a scaled model and field testing on the actual cooling tower.

3.2.1 Preliminary testing

The preliminary testing is performed to assess the effect of blockage that is applied facing the exhaust air system to the air flow and current consumption of the exhaust fan. A scaled model of exhaust air system, i.e. cooling tower is fabricated for the testing. An industrial fan is used to represent the exhaust fan to blow the air through the outlet of the exhaust air system. The blockage is fabricated by using a perspex plane. The preliminary testing set-up and the plan view of the blockage is shown in Figure 3.3 and Figure 3.4.

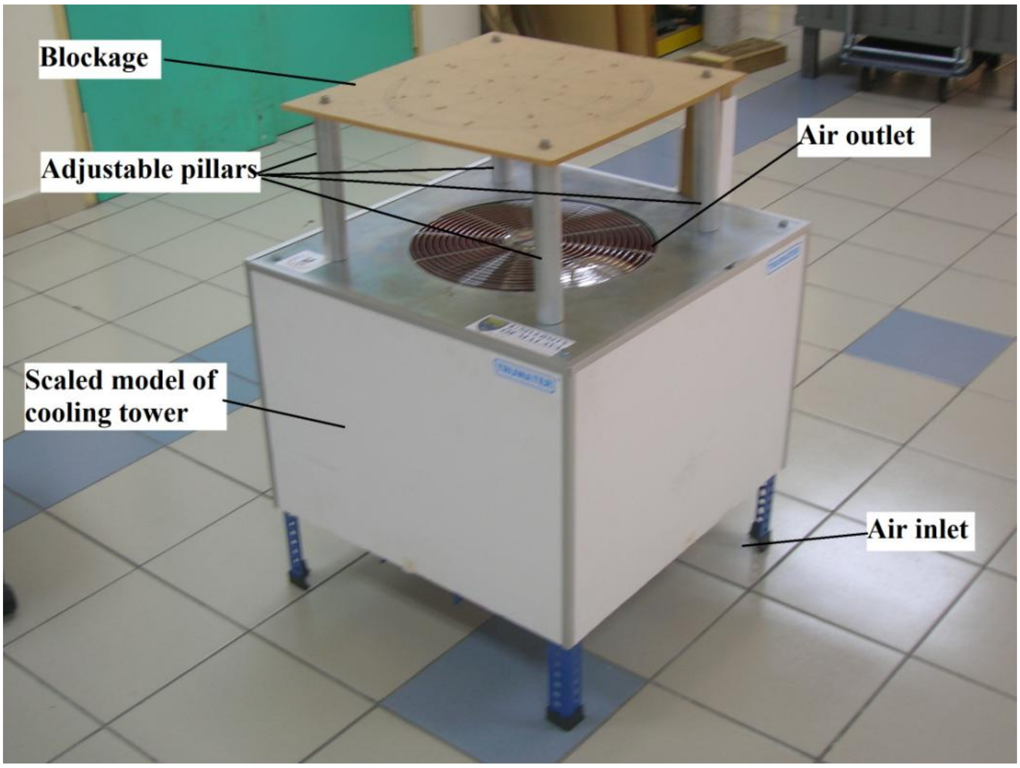

Figure 3.3 Preliminary test setup

Figure 3.4 Plan view of the blockage

The desired outcome for this experiment is to obtain the amount and distance of blockage that will not cause the increment of the current drawn by the fan motor and reducing the air flow rate. With the existence of the blockage, the current consumption of the fan is expected to increase. The current consumption is measured using a mini clamp-on meter. The air intake speed is measured at four intake points using a hot-wire anemometer. The amount of blockages is reduced gradually as well as the blockage distance to the exhaust air outlet until the desired result achieved.

3.2.2 Indoor testing on the scaled model of cooling tower

A series indoor testing has been conducted on the exhaust air energy recovery wind turbine generator. The testing was held in the Fluid Mechanics Laboratory, Department of Mechanical Engineering, University of Malaya. The indoor testing is performed as an initial experiment to analyze the feasibility of the system. The main parameters are the effect of the system on the exhaust air performance and the performance of the wind turbine.

The experiment was carried out on a small scaled model as shown in Figure 3.5. A 5-bladed H-rotor wind turbine with a rotor diameter of 0.3 meters is used in the experiment. The cooling tower is simulated by using a 0.4 meters diameter industrial fan enclosed in a 0.6 meters diameter cylinder duct. There is a gap at the bottom of the cooling tower with the distance of 0.1 meter from the floor (with air inlet area of 0.4096 m^2). The fan speed is set to the maximum speed (number 3 on selection buttons). The air flows through the inlet of the cooling tower (at the bottom gap) and is blown out to atmosphere through the exit opening (on the top surface). Then, the air interacts with the turbine blades and forces the turbine to rotate.

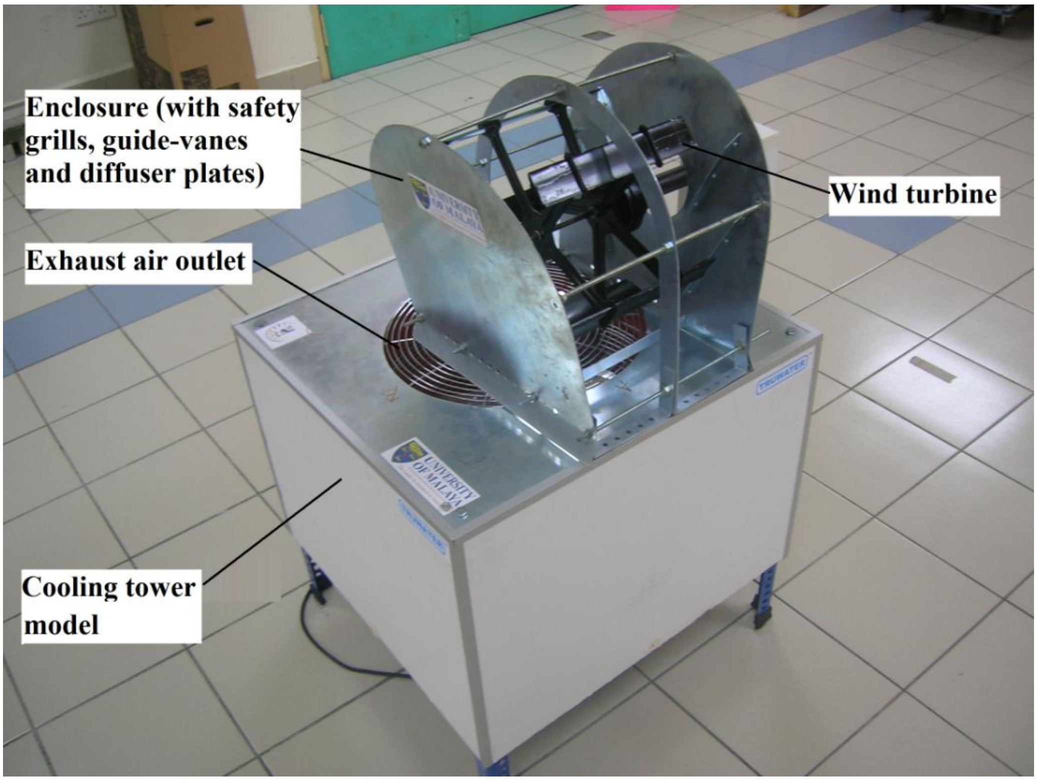

Figure 3.5 Picture of the laboratory test model

The diffuser-plates (Figure 3.6) are fabricated to be mounted at both sides of the wind turbine. The shape of the diffuser plates are the combination of a semi-circle and a square. The straight edge at the bottom of the diffuser plate is to be sitting on the cooling tower outlet while the semi-circle follows the outer radius of the rotor but in greater diameter. The diffuser plates are inclined at 7° relative to the horizontal axis as recommended by (Bleier, 1997).

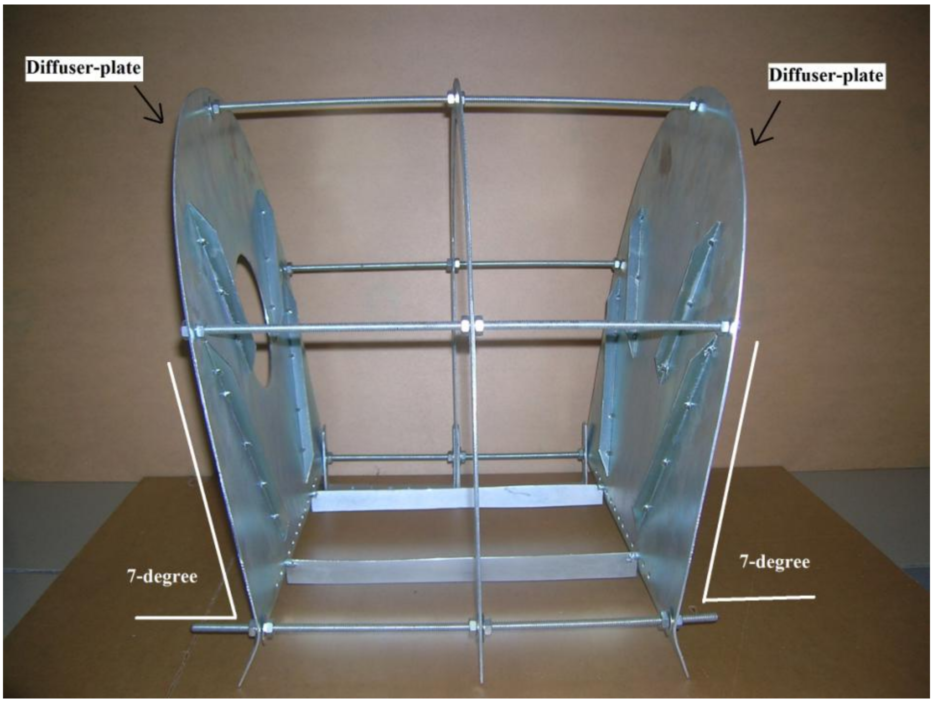

Figure 3.6 Diffuser plate for laboratory testing

The experiment is performed in three conditions as follows:

1) cooling tower without wind turbine
2) cooling tower with wind turbine
3) cooling tower with wind turbine surrounded by enclosure

Several measurements are needed to identify the difference between these three set-ups. Current drawn by the fan motor is measured at the power cable using a multimeter. A hot-wire anemometer is used to measure the air intake speed of the small scaled model of cooling tower. The rotational speed of the wind turbine is measured by a hand-held laser tachometer.

3.2.3 Outdoor testing on the actual cooling tower

Truwater Cooling Tower Sdn. Bhd., as an industrial partner for this project provides the facilities to perform the outdoor testing that include an actual cooling tower, fabrication materials and manpower. There is a demo unit of cooling tower (Model: TXS300 - 1S) as shown in Figure 3.7 available at the company's factory ready for testing. The outlet diameter of the cooling tower is 2 meters and the fan is powered by a 7.5 kW motor.

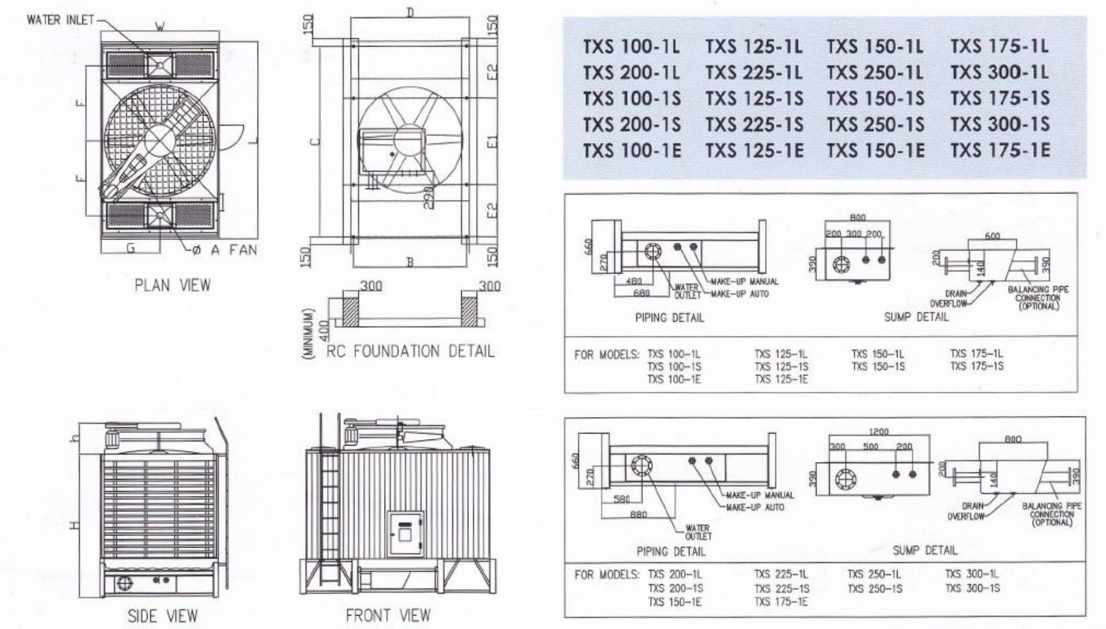

Figure 3.7 The cooling tower model: TXS300 – 1S used in the outdoor testing (Truwater, 2011)

To integrate the exhaust air energy recovery wind turbine generator with the existing cooling tower, the supporting structure for the wind turbine needs to be designed and fabricated first. The design and installation of wind turbine on top of cooling tower supported by the supporting structure is shown in Figure 3.8. A combination of a 3-bladed Darrieus type VAWT with the rotor diameter of 1.24 meters with two layers of Savonius rotor at the centre shaft is used in this experiment. The shaft of the rotor is shifted from the centre of the cooling tower outlet at a predefine distance in order to get the better performance of the wind turbine based on the measured velocity profile of the outlet wind. The horizontal distance between the nearest circumference of the VAWT to the outlet of the cooling tower is set to be half of the diameter of the rotor. The system is mounted to the supporting structure at both end of the power-transmission shaft with generator at one side and a bearing at the other. The diffuser plates are not included in this outdoor testing due to time constraint and the shape is complicated.

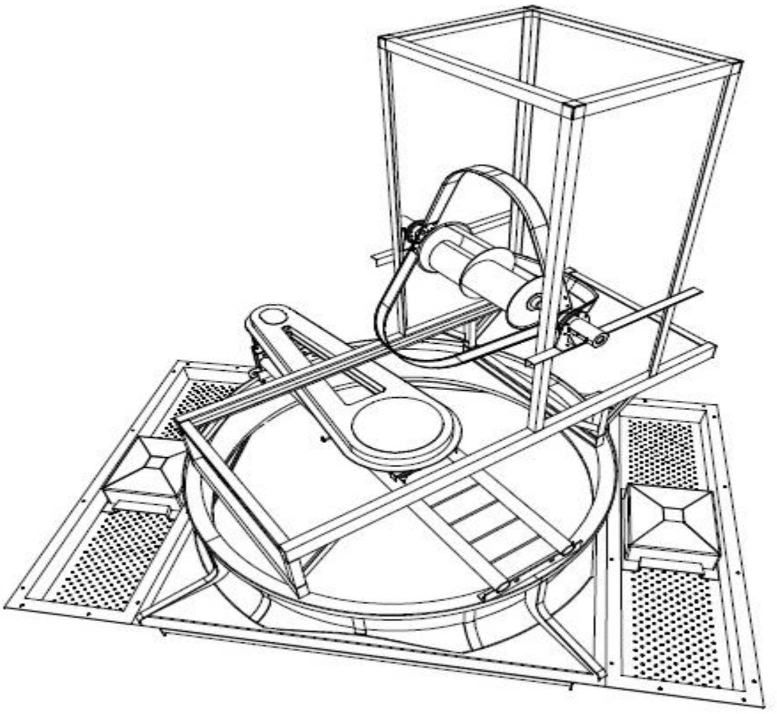

Figure 3.8 The design and installation of wind turbine on top of cooling tower supported by the supporting structure .

The outdoor testing is performed in two configurations as follows:

1) cooling tower without wind turbine
2) cooling tower with wind turbine

The desired data is measured by the similar method as the indoor testing and will be deeply discussed in the next section.

3.3 Measurement methods

3.3.1 Volume flow rate

Volume flow rate is an important parameter to measure the amount of blockages when any object is placed at the outlet of the exhaust air system. The volume flow rate is calculated as following equation

$$\dot{V} = v_{outlet} \times A \tag{3.1}$$

where $\dot{V}$ is the volume flow rate, v_{outlet} is the average wind speed measured at the outlet of the exhaust system and A is the outlet area.

The wind speed will vary from point to point over the cross section of the exhaust air outlet duct. A suitable method for circular ducts is to divide the area into several concentric parts of equal area and the wind speed at the outlet, v_{outlet} is calculated by averaging six velocities taken at 60° intervals round the circle. Therefore, if the circular duct is divided into three concentric part of an equal area, the total points to be measure are 18 points as shown in Figure 3.9 with $d_1/D = 0.032$, $d_2/D = 0.135$ and $d_3/D = 0.321$ (Daly, 1979). The wind speed is measured by using a hot-wire anemometer for laboratory testing and vane-type anemometer for outdoor testing.

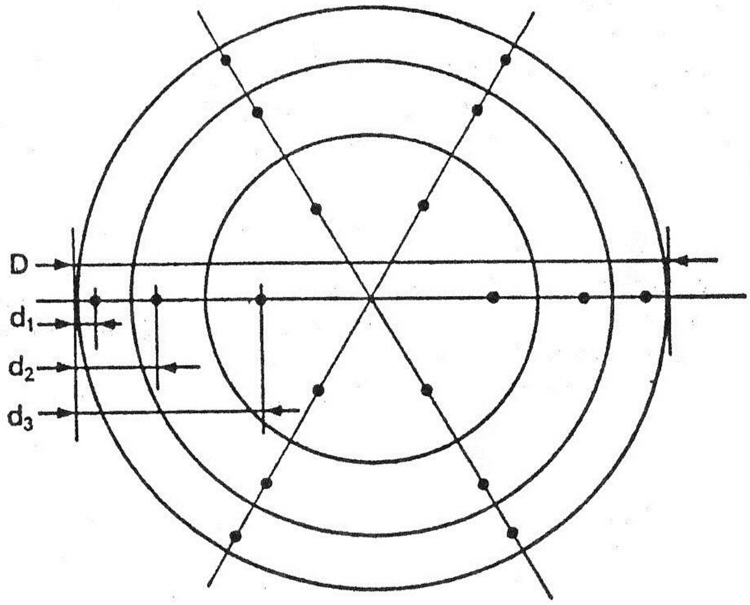

Figure 3.9 Air velocity measurement points on a circular duct (Daly, 1979)

3.3.2 Power input to the exhaust air system

The power input to the exhaust air system is measured at the electrical source. For the laboratory testing, the simulated cooling tower is powered by an industrial fan that connected to the electrical source. The fan is propelled by using a single phase motor. Since the power consumption by the fan is relatively small, a small-scale device, i.e. mini clamp-on meter is used for the measurement. The device is clamped at the life or neutral cable for the voltage and current measurement as shown in Figure 3.10.

Figure 3.10 Voltage and current measurement on a single phase motor

The mini clamp-on meter only displays the value of voltage and current. The power input, P_{input} to the exhaust air system is calculated as the following equation

$$P = I \times V \tag{3.2}$$

where I is the electrical current and V is the voltage.

For the field testing, the cooling tower's fan is powered by a 3-phase motor. Power consumption for the motor is measured using a power meter that capable to show the data for power (Watt), the voltage and the current at once.

3.3.3 Fan speed

To measure the fan speed directly to the fan of the actual cooling tower is very dangerous due to the limitation of space and the fan rotates at high speed. Therefore, the measurement is done on the pulley that connected to the fan through a belting system by using a hand-held laser tachometer. The measuring process and set-up is shown in Figure 3.11.

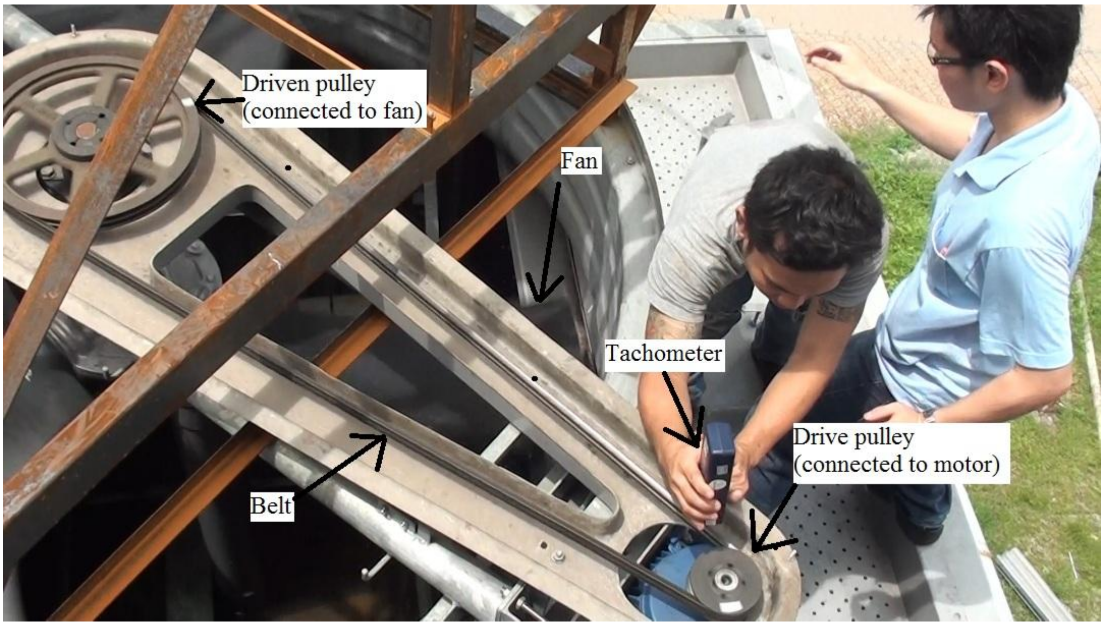

Figure 3.11 Fan speed measurement on actual cooling tower

The rotational speed of the fan is equivalent to the rotational speed of the driven pulley that connected to the fan via the same shaft. Since the rotational speed of the driving pulley is obtained by measurement, the rotational speed of the driven pulley can be calculated by the pulley speed ratio as follows

$$N_1 = N_2 \times \frac{D_2}{D_1} \qquad (3.3)$$

where N_1 is the rotational is the rotational speed of the driven pulley and N_2 is the rotational speed of the driving pulley. D_1 and D_2 are the diameter of the driven pulley and driving pulley respectively.

3.3.4 Wind turbine rotational speed

The wind turbine rotational speed is measured directly to either the rotating shaft of the wind turbine or the turbine blade. The instrument used in the measurement is a laser tachometer. Figure 3.12 and Figure 3.13 shows the wind turbine rotational speed measurement for field testing and laboratory testing respectively.

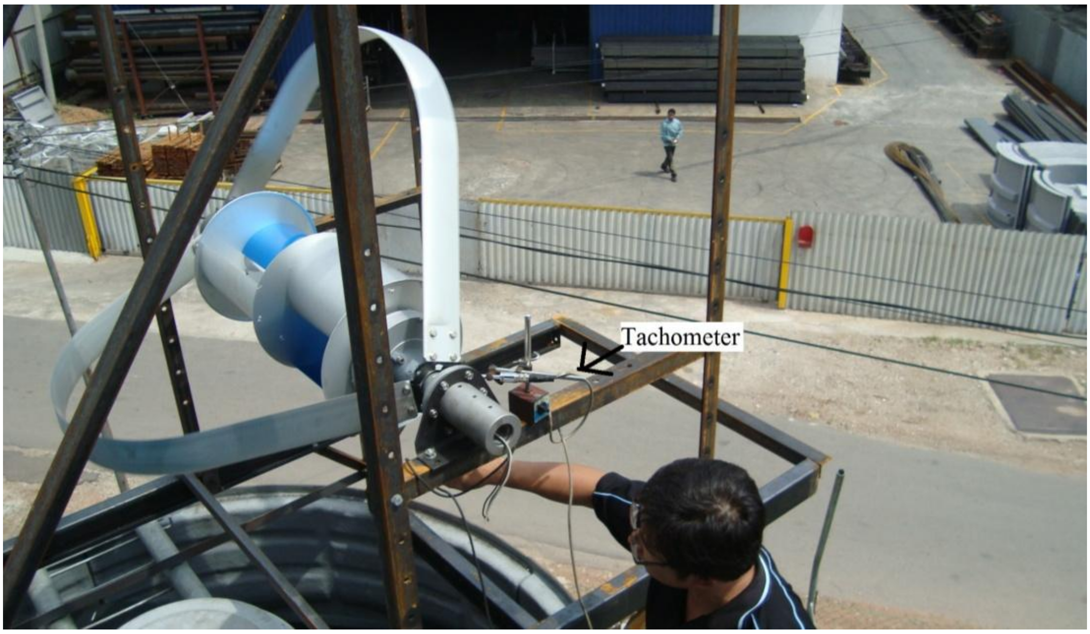

Figure 3.12 Wind turbine rotational speed measurement at field testing. The tachometer is pointed to the roatating shaft of the wind turbine.

Figure 3.13 Wind turbine rotational speed measurement at laboratory testing. The tachometer is pointed to the turbine blade.

CHAPTER 4: Results and discussions

4.1 Preliminary study

The main concern to place any object facing the outlet of an exhaust air system is to avoid any negative impact on the performance of the system, i.e. the increment of current consumption and the reduction of the air flow rate. This preliminary study is to get the minimum distance and blockage area that not causing negative impact on the exhaust air system. The impact of the blockage application facing the exhaust air outlet on the current consumption is shown Figure 4.1 and Figure depicts the blockages pictures that been used in the experiment.

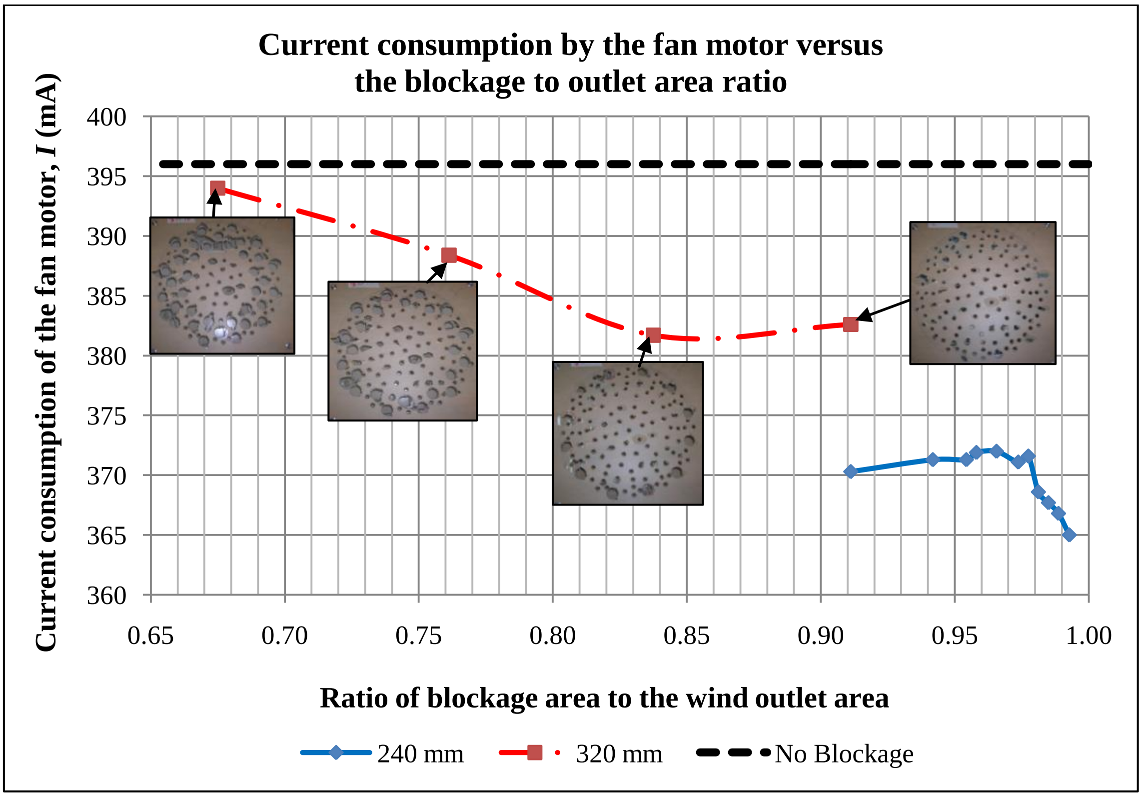

Figure 4.1 Current consumption of the fan motor versus the ratio of blockage area to the wind inlet area for the distance of 240 mm and 320 mm. The black dash-line is the condition without blockage.

At the ratio of blockage area to the wind outlet area equals to 1, the wind outlet area is considered as totally blocked. The current consumption by the simulated cooling tower without blockage is measured as 396 mA and it is used as the baseline for this experiment. At the distance of 240 mm between the blockage and the air outlet, there was an instant reduction on the current consumption (365 mA) at the area ratio of 0.9928. The current consumption increased gradually with the reduction of blockage until the blockage was reduced to 98.1%. From this point to the blockage ratio of 0.911, small difference was observed and the current consumption at this range is considered as constant. When the distance was increased, a significant increment of current consumption was recorded. The trend continued until the current consumption of the system with blockage equivalent with the exhaust air system without blockage. This condition (i.e. blockage percentage of 67.5% at a distance of 320 mm) is considered as causing no effect on the cooling tower current consumption.

Figure 4.2 depicts the effect of blockage to the air flow rate of the cooling tower. At the blockage ratio of 0.993 and distance of 240 mm, the air flow rate was measured as 0.5591 m^3/s which was a 41% reduction compared to the cooling tower without blockage (0.9421 m^3/s). The air flow rate was increasing with the reduction of the blockage until it reached the relatively constant level at the range of blockage from 98.1% to 91.1%. When the blockage distance was increased to 320 mm from the outlet, the increasing trend continued and reached the volume flow rate of 0.9708 m^3/s that is approximately same level with the cooling tower without blockage.

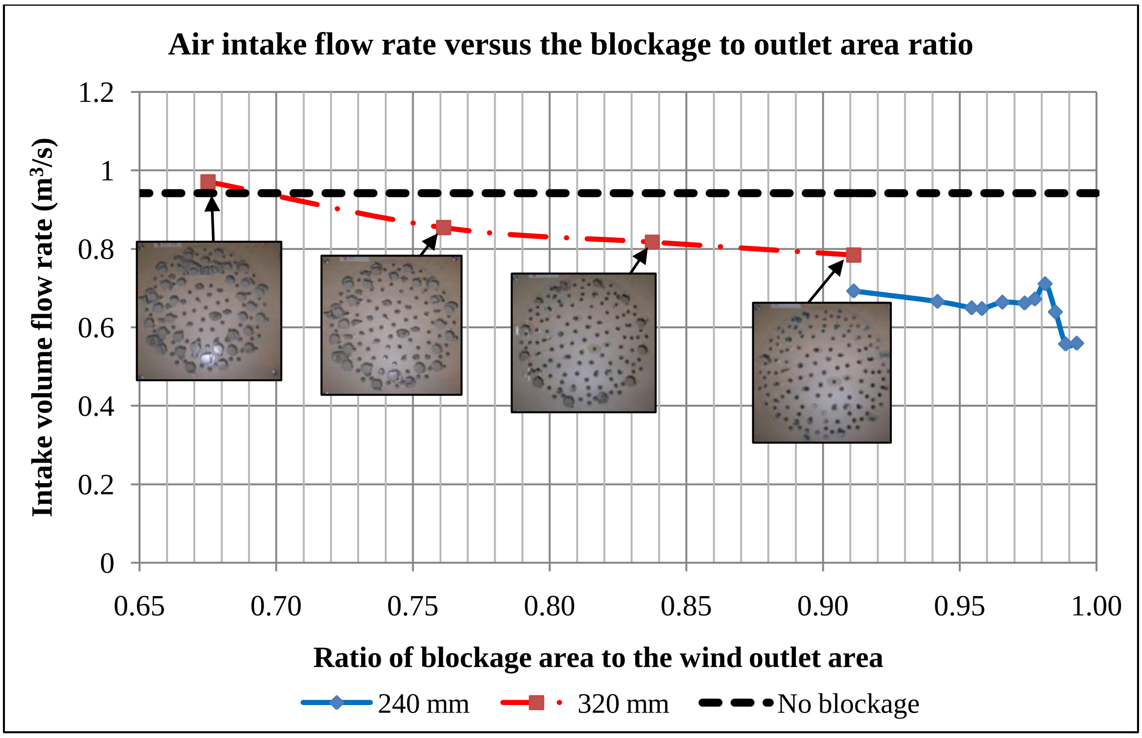

Figure 4.2 Air intake volume flow rate versus the ratio of blockage area to the wind inlet area for the distance of 240 mm and 320 mm. The black dash-line is the condition without blockage.

From the above figures, the trend of the current consumption and the air flow rate with respect of blockage percentage is similar. The relationship between these two parameters (Figure 4.3) shows that the volume flow rate of the intake air is proportional to the current consumption by the fan motor. When the air flow rate is low, the exhaust fan will handle less amount of air and this is may be the reason why the current consumption by the fan motor is low. The exhaust fan needs more power when it's handling higher volume of air. Since the voltage of the electrical source is constant (average voltage = 246.5 V), the only electrical parameter that varies is the current. Therefore, when the power demand from the exhaust fan increases, the current consumption will increase as well.

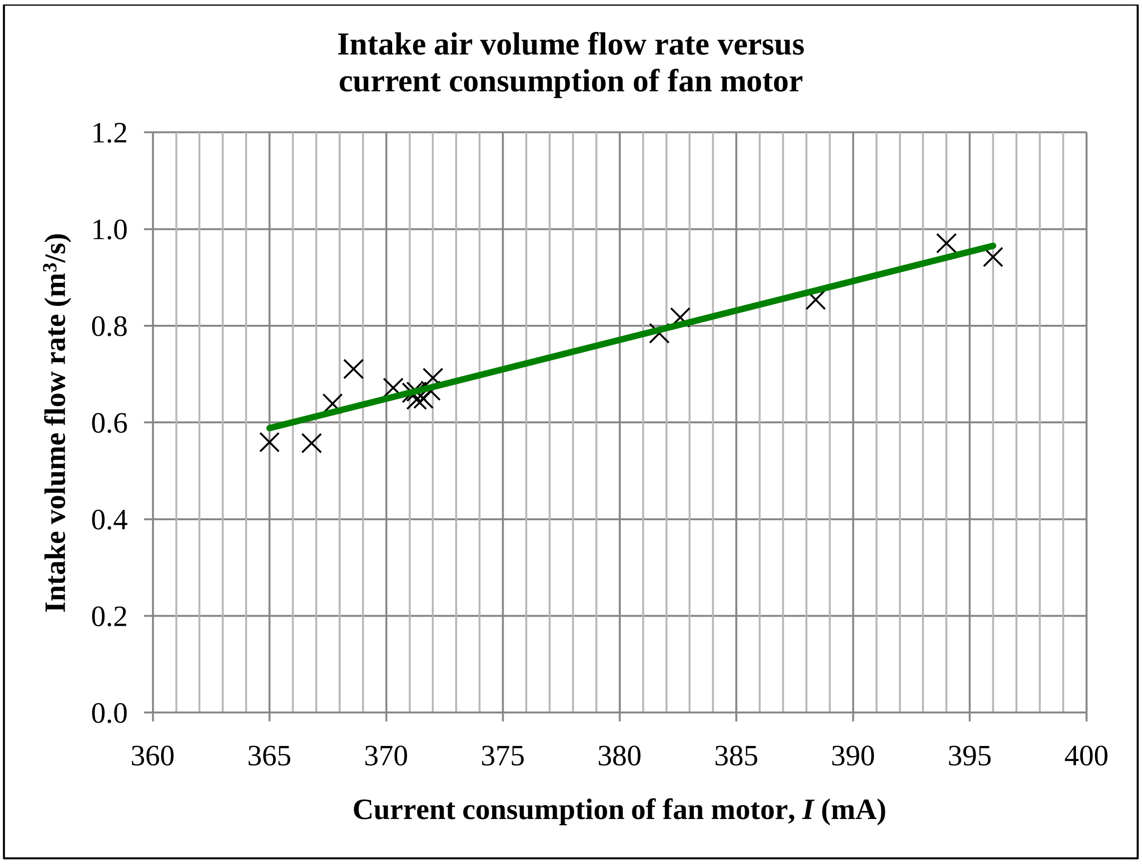

Figure 4.3 The relationship between intake volume flow rate to the cooling tower and current consumption by the fan motor

This preliminary study proves that the existence of the blockage facing the outlet of the exhaust air system will affect the performance of the exhaust air system. In order to eliminate or minimize the negative effects, the amount and distance of the blockage to the system must be in right position. However, this scenario would be different if the blockage is a wind turbine that spinning in the wind stream. The repetition of this experiment on the spinning wind turbine is recommended for future study. An adjustable supporting structure (to adjust horizontal and vertical position of wind turbine) and a motor speed regulator to control the rotational speed of the wind turbine might be used in the experiment. The outcomes would be the optimum position and the desired tip speed ratio of the wind turbine. However, due to time and equipment limitation, the experiment cannot be materialised at this moment.

4.2 Indoor testing on the scaled model of cooling tower

Based on the initial set-up of the small scaled model of cooling tower, the wind speed at the outlet of the cooling tower was 8.0 m/s. Other data obtained for all the set-up conditions are tabulated in Table 4.1.

Table 4.1 Results from the laboratory testing on the scaled model of cooling tower

Laboratory testing of scaled model of cooling tower	**Cooling tower without wind turbine**	**Cooling tower with wind turbine**	**Cooling tower with wind turbine and diffuser**
Fan motor current consumption	0.39 ampere	0.39 ampere	0.39 ampere
Intake air velocity	1.6 – 1.8 m/s	1.6 – 1.8 m/s	1.6 – 1.8 m/s
Wind turbine speed	-	115 rpm	150 rpm

For cooling tower without wind turbine and diffuser (considered as in normal condition), the current drawn by the fan motor was 0.39 ampere and the intake air velocity is in the range of 1.6 to 1.8 m/s. This condition was used as a baseline of the experiment. After the wind turbine was installed above the cooling tower’s outlet, the wind turbine rotated at 115 rpm without any difference on the cooling tower. For the third configuration, i.e. wind turbine with diffuser, the rotational speed of the rotor was recorded as 150 rpm and no measurable difference was observed on the cooling tower compared to the normal condition.

The results show that the high-speed exhaust air at the outlet of the cooling tower is possible to be extracted into electricity without adding extra load to the fan motor by using wind turbine that is placed at a correct position and distance. In order to improve the performance of the wind turbine, the use of the diffuser has effectively increases the speed of the wind turbine by 30.4%. Since there are no differences on fan motor current consumption and intake air velocity for all three test conditions, the system with this wind turbine model is considered as in correct configuration.

4.3 Outdoor testing on the actual cooling tower

In order to have a reliable result on the performance of the exhaust air energy recovery wind turbine generator and the cooling tower, an outdoor testing on the actual cooling tower is conducted. The experiment is to study the wind characteristic from the cooling tower, effect of the system to the cooling tower and performance of wind turbine.

4.3.1 Wind speed profile

The discharge air velocity was measured in five bands on every quarter. The average wind speed from each band and tabulated in Figure 4.4. From the trend line, the highest wind speed was obtained between band 3 and band 4. The wind speed is relatively low at band 5 located near the outer radius and even lower at band 1 that close to the centre of the outlet opening. The position of the belting system on top of the cooling tower outlet is the reason why the wind speed close to the centre is low. The fan rotation would cause the air tend to swirl and spread out when it discharged from the outlet. However, approaching to the outer radius of the outlet, the wind speed is drastically reduced might be because of the reflection of the air after hitting the inner wall of the cooling tower outlet.

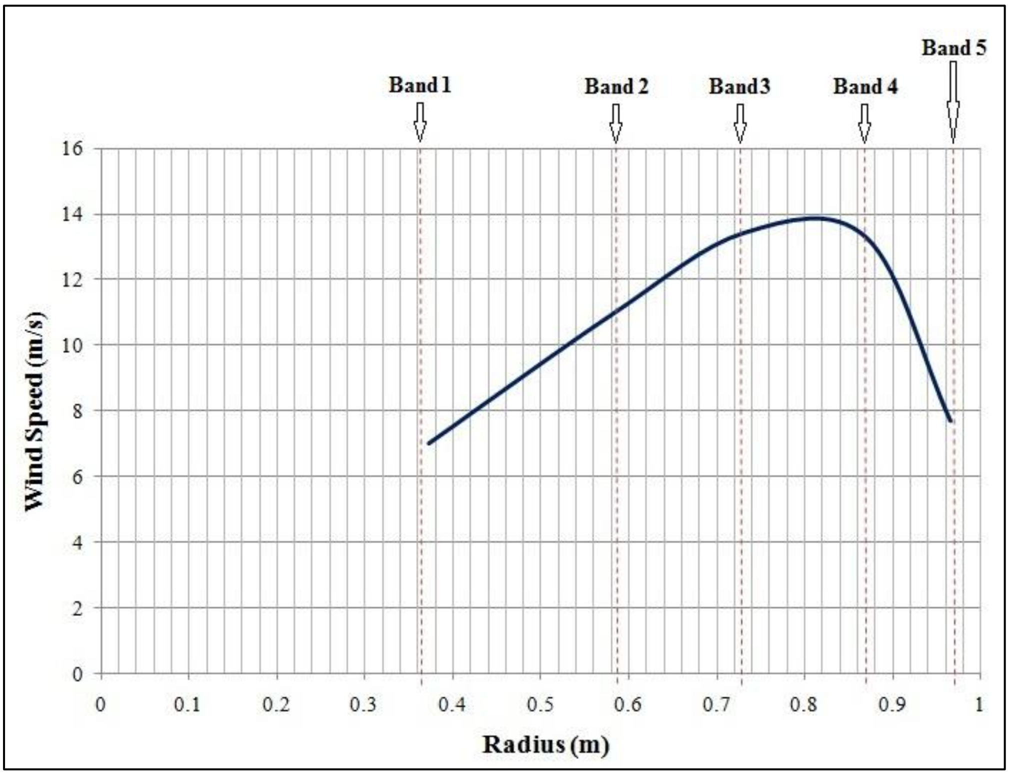

Figure 4.4 Wind velocity profile discharge from cooling tower

Based on wind profile, the wind turbine is preferably to be positioned at approximately between band 3 and band 4 where the wind speed at those areas is the highest.

4.3.2 Cooling tower and wind turbine performance

The outdoor testing was performed on the cooling tower (model: TXS300 - 1S) fabricated by Truwater Cooling Tower Sdn Bhd. The measured data to compare the performance of the cooling tower before and after the integration with the wind turbine is summarized in Table 4.2.

Table 4.2 Results from the outdoor testing on the demo unit of cooling tower (Model: TXS300 -1S)

Parameter	**Cooling tower without wind turbine**	**Cooling tower with wind turbine**	**Percentage of difference**
Average discharge wind speed (m/s)	10.63	10.67	0.4 %
Air volume flow rate (m^3/s)	33.40	32.52	0.4 %
Cooling tower fan rotational speed (RPM)	386	387	0.3 %
Power consumption by the cooling tower (kW)	7.0 ~ 7.1		0.0 %
Wind turbine rotational speed (RPM)	-	881	-

From the outdoor testing, the discharge air speed increased by an average of 0.4% that is proportional with volume flow rate of the air (volume flow rate = wind speed x area). This small increment shows that the installation of the energy recovery wind turbine generator facing the cooling tower outlet would help the cooling tower to draw more air to the atmosphere which able to improve the cooling tower performance. The rotational speed of the cooling tower's fan also showed an increment by 0.4%. The power consumption by the cooling tower system was measured at the electrical switch board by using a wattmeter. There was no difference in power consumption the cooling tower with both configurations which was ranging between 7.0 to 7.1 kW. This result shows that the presence of energy recovery turbine generator facing the cooling tower with this configuration gives no effect to the power consumption of the cooling tower. These figures (discharge air speed, air flow rate, fan rotational speed and power consumption) on the cooling tower would be further improved by the optimization of the energy recovery wind turbine generator where the turbine position plays an important role.

Based on the manufacturer's specification of the wind turbine that been used in this experiment, the rated wind speed is 13.5 m/s, the rated power is 300 W and the rated rotor rotational speed is 835 rpm. From testing, the wind speed from the cooling tower at about 10.6 m/s was able to spin the turbine (without loading) at 881 rpm. By referring to the power curve, the wind turbine would produce power at 200W. However, these entire figures could be further improved by the optimization of this exhaust air energy recovery wind turbine generator.

4.4 Estimation of energy generation

Truwater Cooling Tower Sdn. Bhd. is the largest manufacturer of cooling tower in Malaysia. The company installed thousands unit of cooling tower in Malaysia as well as overseas. The induced-draft cooling tower is the common cooling tower for the air conditioning system of office buildings in Malaysia. In this study, an estimation of 3000 units of cooling tower is used in energy generation calculation.

The optimized system with 2 units of wind turbine that integrates with a cooling tower is expected generate 500 W from each of the rotor. Assuming a 2 meters diameter cooling tower requires 7.5 kW power for 16 hours operation per day, 131.4 GWh/year of power consumption will be utilized to operate 3000 similar units of cooling tower. With 1 kWh of power generation by this exhaust air energy recovery wind turbine generator, a total of 17.1 GWh is expected to be recovered by the system in a year which is equivalent to 13% of the power consumption of the cooling tower. The electricity generated from this micro wind generation system can be utilized for commercial purposes, stored in battery or fed into the electricity grid.

CHAPTER 5: Conclusions and recommendations

5.1 Conclusion

An idea on harnessing clean energy from unnatural wind resources is presented. The implementation of the exhaust air energy recovery wind turbine generator facing the outlet of cooling towers can recover a portion of the unused exhaust air for electricity generation. The performance of the VAWT is boosted with the additional shrouded device surrounding the turbine, i.e. the enclosure.

The enclosure is designed with several guide-vanes to create a venturi effect (to increase the wind speed) and guide the wind to the optimum angle-of-attack of the turbine blades. Another feature of the enclosure is the diffuser-plates that are mounted at a specific angle to accelerate the airflow. Besides enhance the performance of the VAWT, the enclosure can also act as a safety cover. Safety concerns due to blade failure and maintenance activities are tackled in the design of the whole system.

From the indoor testing done on the small scale model of a cooling tower; when the VAWT was spinning on top of the exhaust air outlet, there were no measureable differences in the air intake speed (1.6 – 1.8 m/s) and current consumption of the power-driven fan (0.39 ampere). In addition, the enclosure significantly improves the wind turbine rotational by 30.4%.

Field test on the actual induced-draft cooling tower with 2 meters outlet diameter and powered by a 7.5 kW motor was performed using a 3-bladed Darrieus wind turbine with 1.24 meter rotor diameter. There were no significant differences on the outlet air speed of the cooling tower, i.e. 10.63 m/s for cooling tower without wind turbine and 10.67 m/s for the cooling tower with the presence of the wind turbine (rotational speed of the wind turbine is 881 rpm). No measureable difference was observed on the power consumption which was recorded between 7.0 to 7.1 kW for both cases.

The system is expected to recover 13% of the energy consumption by the cooling tower. Assuming a 2 meters diameter cooling tower requiring 7.5 kW power for 16 hours operation, 131.4 GWh/year of power consumption will be utilized to operate 3000 similar units of cooling tower. The amount of energy that is expected to be recovered is 17.1 GWh/year.

The electricity generated from this system can be utilized for commercial usage or fed into the electricity grid. This system is retrofit-able to the existing cooling towers and has very high market potential due to abundant cooling towers and other unnatural exhaust air resources globally. In addition, the energy output is predictable and consistent, allowing simpler design of the downstream system.

5.2 Recommendations

Up to this moment, this report proves that the energy recovery wind turbine generator is applicable to be integrated with the exhaust air system without negative impact. An optimization is needed for this system in order to generate as much as possible energy from the unused exhaust air. Thorough study and analysis on the turbine’s solidity, tip speed ratio and angle of attack is needed to achieve this.

The optimization study of the system can be listed as follows:

1) The distance of turbine to the outlet of the cooling tower
2) The horizontal position of the wind turbine
3) The number and angle of the guide-vanes

4) The configuration of the diffuser-plates
5) The number and size of the turbine blades
6) The type of wind turbine

Besides, the design of the system configuration can be further aesthetically improved for commercialization.

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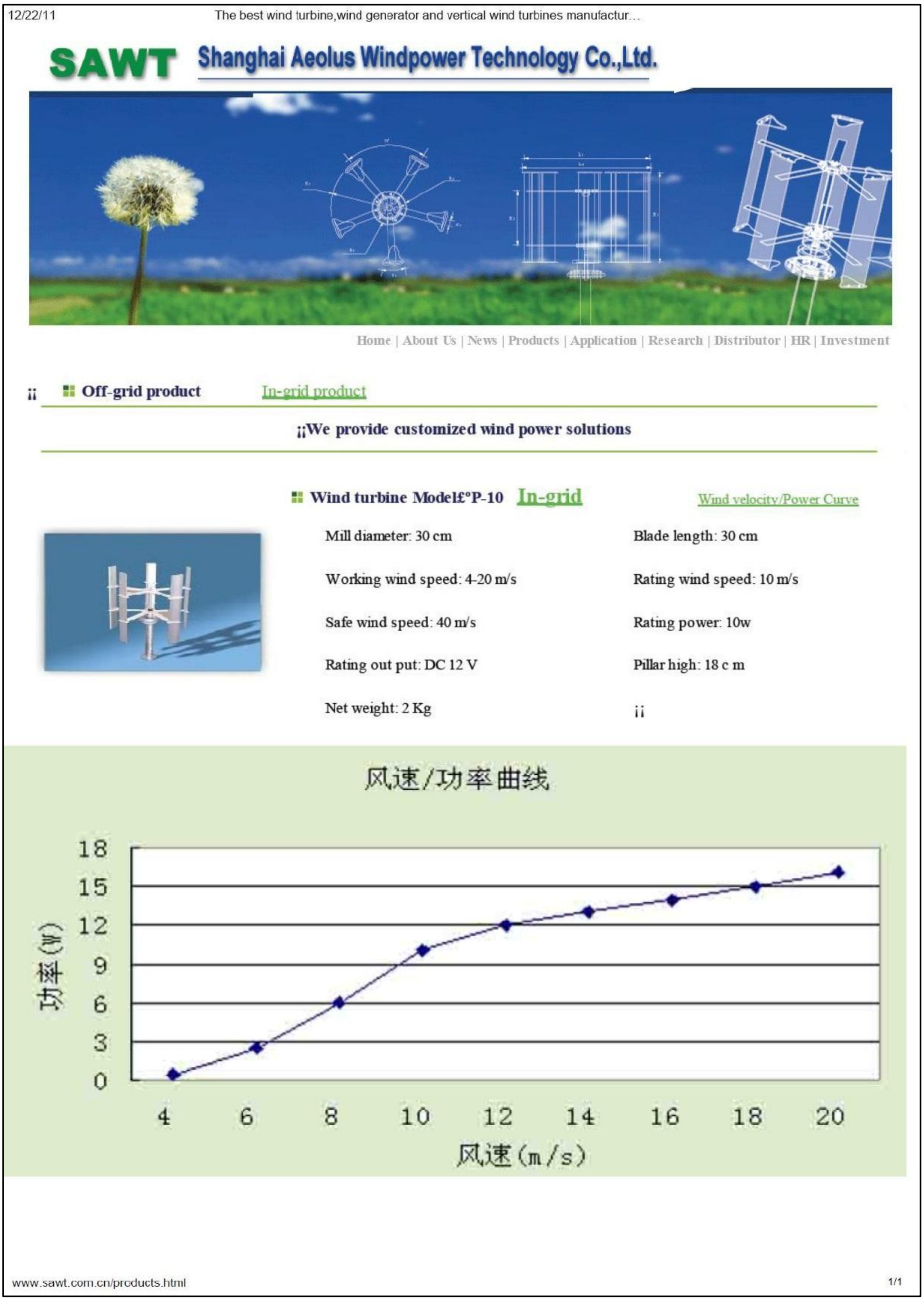
Appendix A

Wind turbine and cooling tower specifications

Figure A1: Specification of H-rotor wind turbine



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¡¡ **Off-grid product** In-grid product

¡¡We provide customized wind power solutions

Wind turbine Model£°P-10 In-grid Wind velocity/Power Curve

Mill diameter: 30 cm

Blade length: 30 cm

Working wind speed: 4-20 m/s

Rating wind speed: 10 m/s

Safe wind speed: 40 m/s

Rating power: 10w

Rating out put: DC 12 V

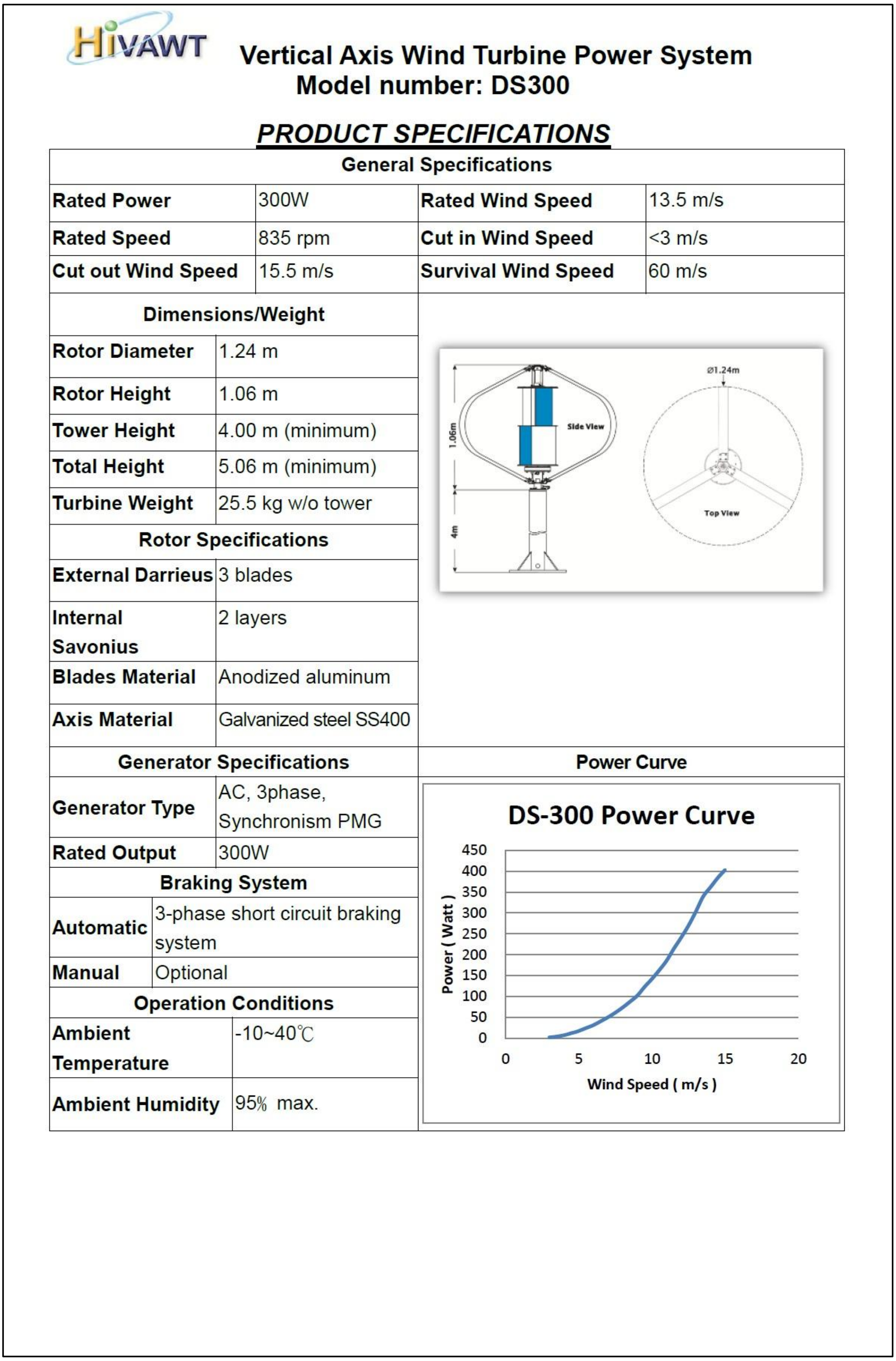
Pillar high: 18 c m

Net weight: 2 Kg

¡¡

www.sawt.com.cn/products.html 1/1

Figure A2: Specification of Darrieus wind turbine



HIVAWT

Vertical Axis Wind Turbine Power System
Model number: DS300

PRODUCT SPECIFICATIONS

General Specifications			
Rated Power	300W	**Rated Wind Speed**	13.5 m/s
Rated Speed	835 rpm	**Cut in Wind Speed**	<3 m/s
Cut out Wind Speed	15.5 m/s	**Survival Wind Speed**	60 m/s

Dimensions/Weight	
Rotor Diameter	1.24 m
Rotor Height	1.06 m
Tower Height	4.00 m (minimum)
Total Height	5.06 m (minimum)
Turbine Weight	25.5 kg w/o tower

Rotor Specifications	
External Darrieus	3 blades
Internal Savonius	2 layers
Blades Material	Anodized aluminum
Axis Material	Galvanized steel SS400

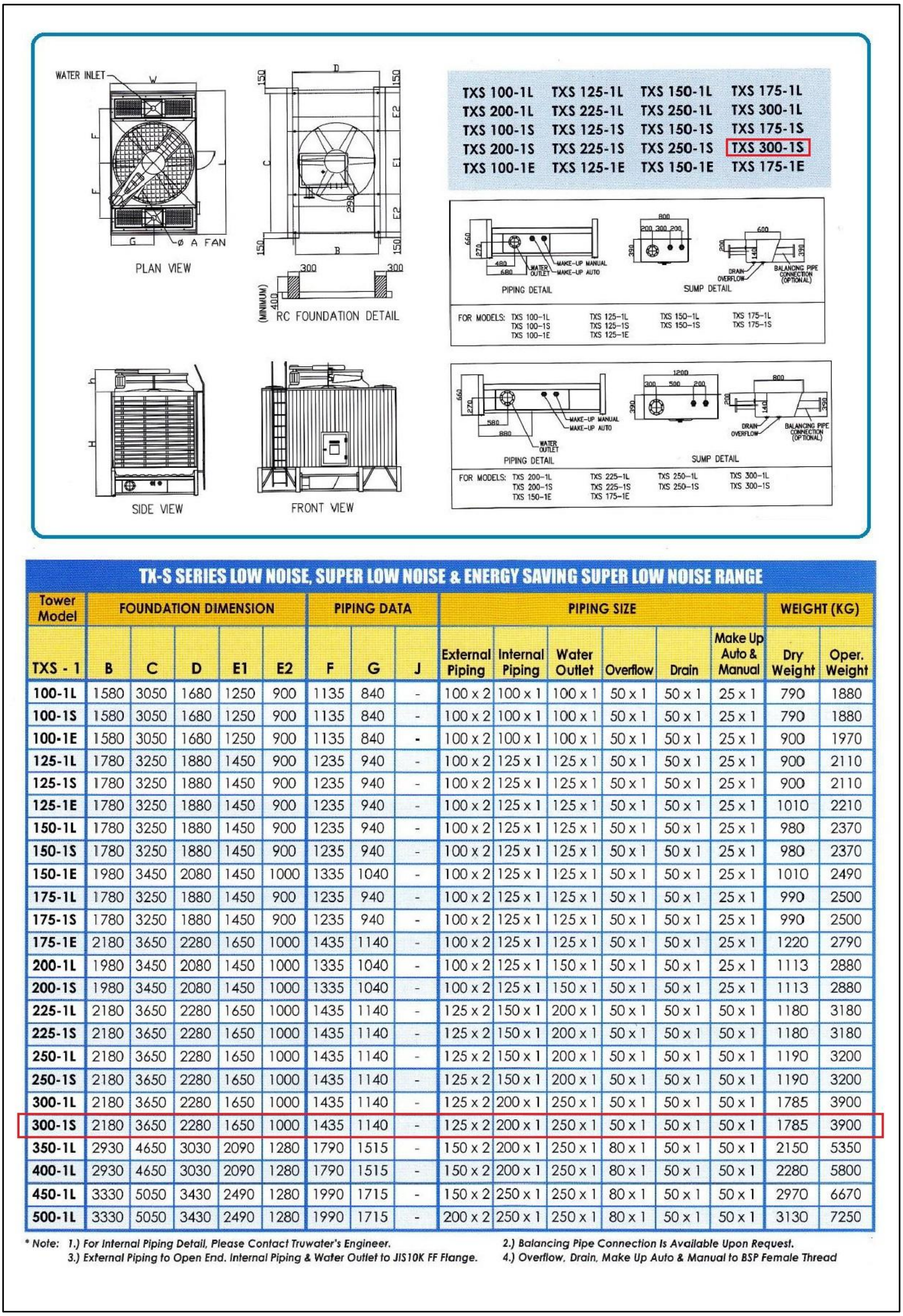
Generator Specifications	
Generator Type	AC, 3phase, Synchronism PMG
Rated Output	300W

Braking System	
Automatic	3-phase short circuit braking system
Manual	Optional

Operation Conditions	
Ambient Temperature	-10~40℃
Ambient Humidity	95% max.

Power Curve

Figure A3: Cooling tower specification



TX-S SERIES LOW NOISE, SUPER LOW NOISE & ENERGY SAVING SUPER LOW NOISE RANGE

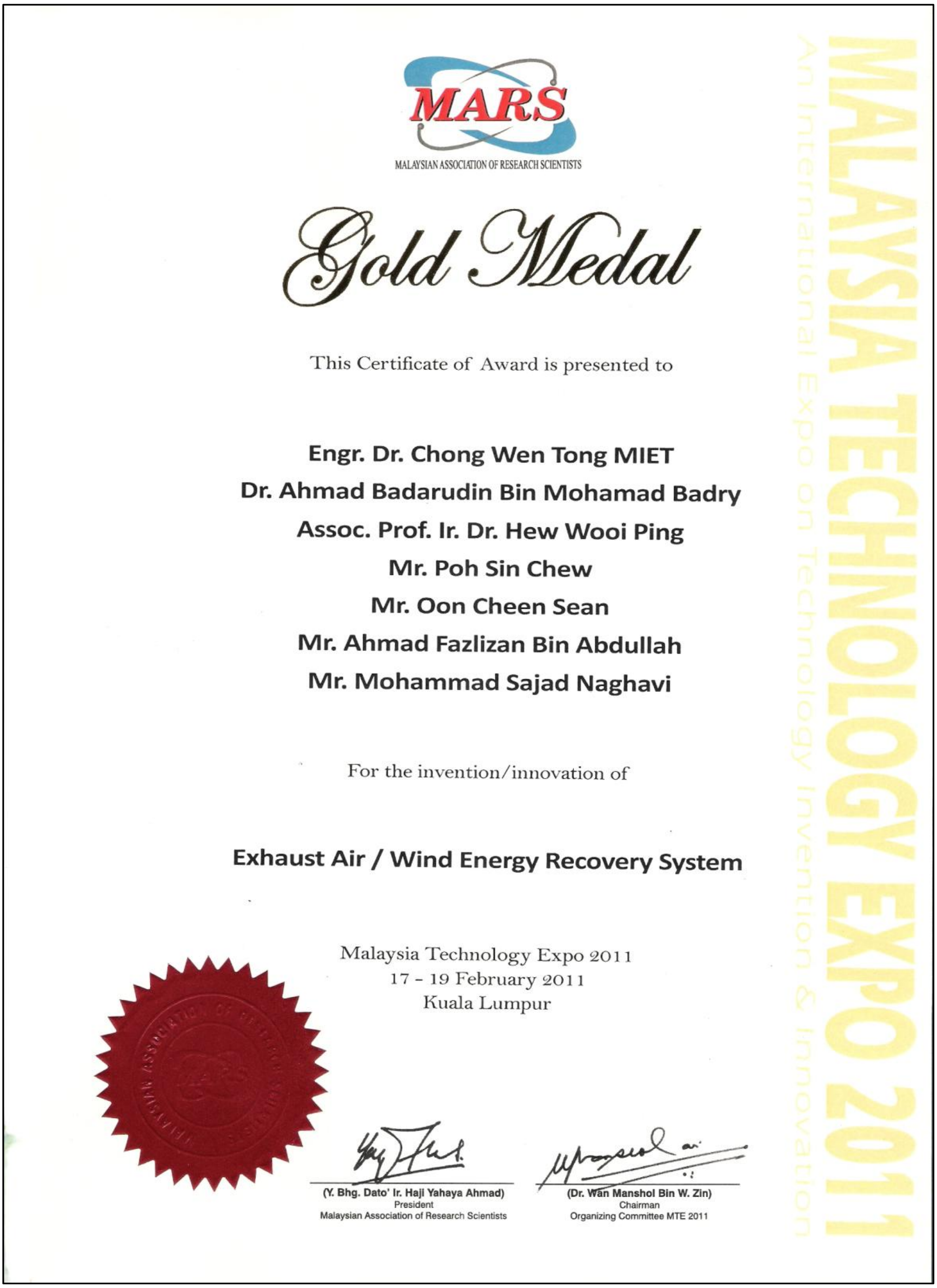
Tower Model	FOUNDATION DIMENSION					PIPING DATA			PIPING SIZE						WEIGHT (KG)	
TXS - 1	B	C	D	E1	E2	F	G	J	External Piping	Internal Piping	Water Outlet	Overflow	Drain	Make Up Auto & Manual	Dry Weight	Oper. Weight
100-1L	1580	3050	1680	1250	900	1135	840	-	100 x 2	100 x 1	100 x 1	50 x 1	50 x 1	25 x 1	790	1880
100-1S	1580	3050	1680	1250	900	1135	840	-	100 x 2	100 x 1	100 x 1	50 x 1	50 x 1	25 x 1	790	1880
100-1E	1580	3050	1680	1250	900	1135	840	-	100 x 2	100 x 1	100 x 1	50 x 1	50 x 1	25 x 1	900	1970
125-1L	1780	3250	1880	1450	900	1235	940	-	100 x 2	125 x 1	125 x 1	50 x 1	50 x 1	25 x 1	900	2110
125-1S	1780	3250	1880	1450	900	1235	940	-	100 x 2	125 x 1	125 x 1	50 x 1	50 x 1	25 x 1	900	2110
125-1E	1780	3250	1880	1450	900	1235	940	-	100 x 2	125 x 1	125 x 1	50 x 1	50 x 1	25 x 1	1010	2210
150-1L	1780	3250	1880	1450	900	1235	940	-	100 x 2	125 x 1	125 x 1	50 x 1	50 x 1	25 x 1	980	2370
150-1S	1780	3250	1880	1450	900	1235	940	-	100 x 2	125 x 1	125 x 1	50 x 1	50 x 1	25 x 1	980	2370
150-1E	1980	3450	2080	1450	1000	1335	1040	-	100 x 2	125 x 1	125 x 1	50 x 1	50 x 1	25 x 1	1010	2490
175-1L	1780	3250	1880	1450	900	1235	940	-	100 x 2	125 x 1	125 x 1	50 x 1	50 x 1	25 x 1	990	2500
175-1S	1780	3250	1880	1450	900	1235	940	-	100 x 2	125 x 1	125 x 1	50 x 1	50 x 1	25 x 1	990	2500
175-1E	2180	3650	2280	1650	1000	1435	1140	-	100 x 2	125 x 1	125 x 1	50 x 1	50 x 1	25 x 1	1220	2790
200-1L	1980	3450	2080	1450	1000	1335	1040	-	100 x 2	125 x 1	150 x 1	50 x 1	50 x 1	25 x 1	1113	2880
200-1S	1980	3450	2080	1450	1000	1335	1040	-	100 x 2	125 x 1	150 x 1	50 x 1	50 x 1	25 x 1	1113	2880
225-1L	2180	3650	2280	1650	1000	1435	1140	-	125 x 2	150 x 1	200 x 1	50 x 1	50 x 1	50 x 1	1180	3180
225-1S	2180	3650	2280	1650	1000	1435	1140	-	125 x 2	150 x 1	200 x 1	50 x 1	50 x 1	50 x 1	1180	3180
250-1L	2180	3650	2280	1650	1000	1435	1140	-	125 x 2	150 x 1	200 x 1	50 x 1	50 x 1	50 x 1	1190	3200
250-1S	2180	3650	2280	1650	1000	1435	1140	-	125 x 2	150 x 1	200 x 1	50 x 1	50 x 1	50 x 1	1190	3200
300-1L	2180	3650	2280	1650	1000	1435	1140	-	125 x 2	200 x 1	250 x 1	50 x 1	50 x 1	50 x 1	1785	3900
300-1S	2180	3650	2280	1650	1000	1435	1140	-	125 x 2	200 x 1	250 x 1	50 x 1	50 x 1	50 x 1	1785	3900
350-1L	2930	4650	3030	2090	1280	1790	1515	-	150 x 2	200 x 1	250 x 1	80 x 1	50 x 1	50 x 1	2150	5350
400-1L	2930	4650	3030	2090	1280	1790	1515	-	150 x 2	200 x 1	250 x 1	80 x 1	50 x 1	50 x 1	2280	5800
450-1L	3330	5050	3430	2490	1280	1990	1715	-	150 x 2	250 x 1	250 x 1	80 x 1	50 x 1	50 x 1	2970	6670
500-1L	3330	5050	3430	2490	1280	1990	1715	-	200 x 2	250 x 1	250 x 1	80 x 1	50 x 1	50 x 1	3130	7250

** Note: 1.) For Internal Piping Detail, Please Contact Truwater's Engineer.*
2.) Balancing Pipe Connection Is Available Upon Request.
3.) External Piping to Open End. Internal Piping & Water Outlet to JIS10K FF Flange.
4.) Overflow, Drain, Make Up Auto & Manual to BSP Female Thread

Appendix B

Awards

Figure B1: Gold Medal Award at Malaysia Technology Expo 2011 (MTE 2011)



MARS

MALAYSIAN ASSOCIATION OF RESEARCH SCIENTISTS

Gold Medal

This Certificate of Award is presented to

Engr. Dr. Chong Wen Tong MIET
Dr. Ahmad Badarudin Bin Mohamad Badry
Assoc. Prof. Ir. Dr. Hew Wooi Ping
Mr. Poh Sin Chew
Mr. Oon Cheen Sean
Mr. Ahmad Fazlizan Bin Abdullah
Mr. Mohammad Sajad Naghavi

For the invention/innovation of

Exhaust Air / Wind Energy Recovery System

Malaysia Technology Expo 2011
17 - 19 February 2011
Kuala Lumpur

(Y. Bhg. Dato' Ir. Haji Yahaya Ahmad)
President
Malaysian Association of Research Scientists

(Dr. Wan Manshol Bin W. Zin)
Chairman
Organizing Committee MTE 2011

MALAYSIA TECHNOLOGY EXPO 2011
An International Expo on Technology Invention & Innovation

Figure B2: Gold Medal Awards at 22nd International Invention, Innovation and Technology Exhibition (ITEX ’11)

MINISTRY OF SCIENCE,
TECHNOLOGY & INNOVATION

ITEX '11
MALAYSIA
22nd INTERNATIONAL
INVENTION, INNOVATION
AND TECHNOLOGY EXHIBITION
UNDER THE PATRONAGE OF THE MINISTER
OF SCIENCE, TECHNOLOGY AND INNOVATION

MINDS

Certificate of Award

This is to certify that

DR. CHONG WEN TONG, DR. AHMAD BADARUDIN MOHAMAD BADRY, ASSOC. PROF. IR. DR. HEW WOOI PING, POH SIN CHEW, AHMAD FAZLIZAN ABDULLAH

has been awarded the

ITEX GOLD MEDAL

for the invention

DIFFUSER AUGMENTED DUAL-ROTOR TURBINE GENERATOR

at the

22nd International Invention, Innovation & Technology Exhibition
ITEX 2011
Kuala Lumpur, Malaysia
20th – 22nd May 2011

Academician Emeritus Professor Tan Sri Datuk
Dr Augustine Ong Soon Hock
President
Malaysian Invention and Design Society

Figure B3: Finalist for Patent Competition “Innovative Solutions for Everyday Life” organized by WIPO, KIPO and MyIPO

특허청
KOREAN INTELLECTUAL PROPERTY OFFICE

WIPO
WORLD
INTELLECTUAL PROPERTY
ORGANIZATION

WIPO - KIPO CERTIFICATE OF MERIT

CHONG WEN TONG,
POH SIN CHEW,
AHMAD FAZLIZAN ABDULLAH,
OON CHEEN SEAN

are hereby awarded
the WIPO - KIPO CERTIFICATE OF MERIT

for being shortlisted in the competition
“INNOVATIVE SOLUTIONS FOR EVERYDAY LIFE”

organized by
the World Intellectual Property Organization (WIPO)
the Korean Intellectual Property Office (KIPO)

in collaboration with
the Intellectual Property Corporation of Malaysia (MyIPO)

Kuala Lumpur
June 2011

Lee Soowon

Soowon Lee
Commissioner
KIPO

Francis Gurry
Director General
WIPO

Figure B4: Silver Medal at International Conference and Exposition on Inventions of Institutions of Higher Learning (PECIPTA 2011)

Pecipta 2011
Malaysia
INCORPORATING BUSINESS PARTNERING SESSIONS

International Conference and Exposition on Inventions of Institutions of Higher Learning

Certificate of Appreciation

This is to certify that

CHONG WEN TONG, HEW WOOI PING,
AHMAD BADARUDIN MOHAMAD BADRY,
POH SIN CHEW AND AHMAD FAZLIZAN ABDULLAH
(TWIN-ROTOR ENERGY RECOVERY TURBINE GENERATOR)

have been awarded a

SILVER MEDAL

PECIPTA 2011
Kuala Lumpur Convention Centre
13-15 September 2011

YB. Dato' Seri Mohamed Khaled Nordin
Minister of Higher Education

UNIVERSITI
TEKNOLOGI
MARA

Appendix C

Related publication

This project was presented in International Conference on Environment and Industrial Innovation 2011, Kuala Lumpur. The conference paper was accepted for publication in International Journal of Environmental Science and Development (IJESD). The acceptance letter and the original paper is presented below:

Date	Fri, 1 Jul 2011 10:59:40 +0800 (CST)
From	IJESD <ijesd@vip.163.com>
Reply-To	IJESD <ijesd@vip.163.com>
To	chong_wentong@um.edu.my; a.fazlizan@siswa.um.edu.my
Subject	IJESD Notification of Acceptance – Paper ID: C027

International Journal of Environmental Science and Development (IJESD)

http://www.ijesd.org/index.htm

Frequency: Bimonthly
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Dear Chong Wen Tong, Poh Sin Chew, Ahmad Fazlizan Abdullah, Oon Cheen Sean and Tiah Chai Ching

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Paper Title: Exhaust Air and Wind Energy Recovery System for Clean Energy Generation

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