Performance Investigation of Wind Rotor in Open and Bounded Environments

by

Zulfadhli B. Abd Majid

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Mechanical Engineering)

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Mechanical Engineering Programme
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Approved by,

(Dr. Zainal Ambri Bin Abdul Karim)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
May 2011

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

ZULFADHLI BIN ABD MAJID

ABSTRACT

Wind rotor usually operates in free surrounding condition or open environment. The efficiency of the power output is depend on how much wind energy can be converted by the wind rotor. The aim of this project is to conduct experiment which will lead to the wind rotor performance investigation upon the installation in bounded environment. Assumption made regarding the efficiency of wind rotor is that it will increase in bounded environment due to the reduction width of side escape streamline of the wind flow. Thus, this will increase the power production rate of the wind rotor. Two different types rotor blades design were tested in several methods of installation to investigate the performance. These rotor blades were tested in three types of installation which are in open, partially bounded and fully bounded environments. The data required from this experiment are the rotor blade rotation per minute (RPM) and the rotating torque of the rotor blade (N.m). Based on the data obtained during experiment, wind rotor performance criteria which are power coefficient (C_p), torque coefficient (C_T), tip speed ratio (TSR) and rotor power (P_{rotor}) can be evaluated by calculation. This report emphasis and focus on brief explanation of general and specific views and perspectives of wind rotor. This is a continuation of the "Progress Report" submitted earlier this semester for Final Year Project 2 (FYP II) and the content of this report was updated with the progress achieved. Based on analyzed data from experimental work, highest value of C_p is 0.28 and highest value of C_T is 0.74, both obtained when wind rotor operates in fully bounded environment (nozzle-diffuser casing).

ACKNOWLEDGEMENT

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CHAPTER 1: INTRODUCTION

1.1 Background of Study

Demand for energy has increased due to the rapid growth of human population globally. The conventional way of producing energy uses fossil fuel to operate turbine engine. This turbine engine drives generator to produce energy in terms of electricity. Nowadays, people begin to concern regarding environmental problem arises by this method of energy production. Moreover, fossil fuel is a limited source of energy and eventually will extinct one day.

Wind energy is one of the available alternatives considered to replace the conventional method of energy production. It is friendly to environment and this source of energy is unlimited. Device used to extract wind energy is wind rotor and the invention of wind rotor begins since the early recorded history. Among the application of wind rotor back then was to propel sailing vessel, to pump water and to grind cereal. The technology of wind rotor is growing rapidly as it is widely used for the benefit of mankind.

Figure 1.1: Wind rotor used for energy production [1]

The working principle of wind rotor is simply converting kinetic energy into electrical energy. As the wind flow through the rotor blades, it will rotate at fixed axis. Due to this rotational motion, electricity will be produced by generator connected to the wind rotor. The amount of energy in term of electricity power produced is depends on the capability of wind rotor to extract energy from the wind.

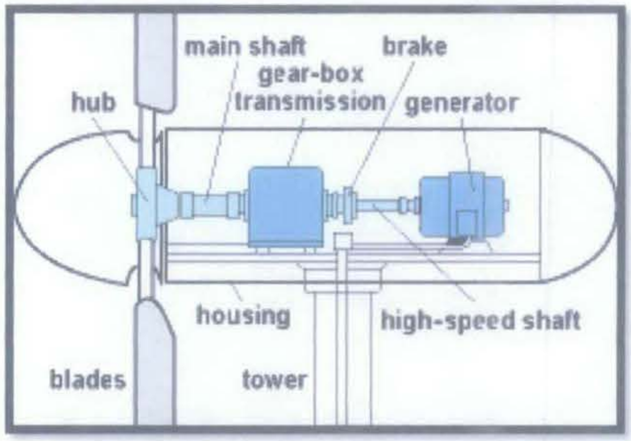


Figure 1.2: Major components in wind rotor [2]

1.2 Problem Statement

Wind rotor operates in open environment and it is generally installed at considerable height. This is because of the high availability and velocity of wind flow in open environment at higher elevation. But still the efficiency of this device is limited due to the side escape of stream-lines as the wind flow pass through the wind rotor. As a result, not all kinetic energy of the wind successfully converted into electric energy. The solution that can be taken to increase the efficiency is to reduce the side escape of stream-line. Experiment was conducted to observe the performance of wind rotor in three different installation methods, which are in open, partially bounded and fully bounded environments.

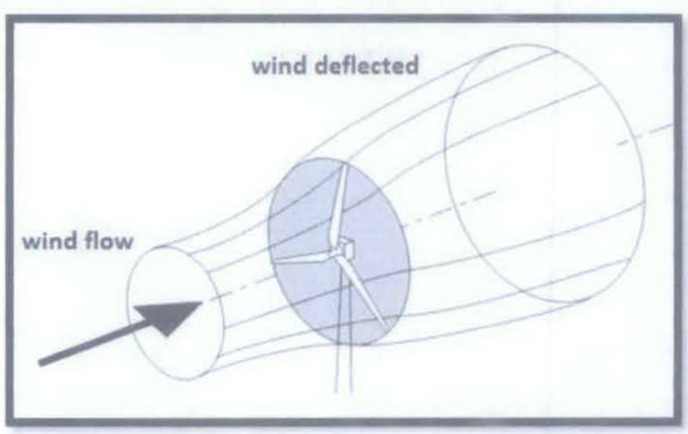


Figure 1.3: Wind deflection outward of wind rotor [3]

1.3 Objective

The objectives that have been identified to be achieved at the end of the project completion are as follow:

- To investigate the performance of rotor blade prototype in three different installation methods.
- To observe the effect of side escape stream-line reduction of wind flow in bounded installation method.
- To determine wind rotor performance based on rotation per minute (RPM) and the rotating torque of rotor blade (N.m).

1.4 Scope of Study

This project will cover several aspects of scope of study. For FYP I, the main priority was to conduct research regarding the criteria affecting the wind rotor performance. Survey had been conducted to select, at least, two possible rotor blades which are to be tested in three different environments. Design for the wind rotor prototype was made for the purpose of wind rotor prototype fabrication. The fabrication of this wind rotor prototype was done as soon as the design finalized.

For FYP2, the main activity that had been done was to conduct experiment to observe the performance of wind rotor prototype. Based on data obtained, which will be the rotation per minute (RPM) and the rotating torque produced (N.m), analysis was made to observe reduction of side escape effect on the wind rotor performance. The performance criteria of wind rotor determined and the result will be used to optimize the wind rotor that will be installed in UTP solar chimney project.

CHAPTER 2: LITERATURE REVIEW

2.1 Wind Energy Content

The kinetic energy of a moving body is directly proportional to its mass. The same concept apply to the wind flow as the kinetic energy is depends on the density of its air (mass per unit of volume). The higher the density of air, the large power can be received by wind rotor. Air density is affected by temperature. In sunny weather, air is less dense compare to cold weather [4]. The temperature effect will only give small impact to on wind power compare to the elevation effect [4]. At higher altitudes, the air pressure is low as well as the air density. Air density is inversely proportional to the temperature and elevation. 1.2 kg/m^3 is a typical value of air density at sea level [5].

Kinetic energy of wind flow is a function of its mass and speed. The kinetic energy equation is formulated as [4]:

$$K.E = \frac{1}{2} m.V^2$$

Where m is the mass of air and V is the wind speed. The mass of air can be derived from the product of the air density (ρ) and the air volume. Since air is not rigid and constantly moving, to calculate the air volume, it is necessary to include the wind speed (V) passing through the area (A) in a given time (t) [4]:

$$m = \rho.A.V.t$$

Substituting this equation into the kinetic energy equation of the wind flow will give [6]:

$$E_{wind} = \frac{1}{2} \rho.A.V^3.t$$

It can be seen that the wind energy is directly proportional to the cube of the wind speed. The power is defined as [6]:

$$P_{wind} = E_{wind}/t = \frac{1}{2} \rho.A.V^3$$

From above equation, it is also found that power in wind also directly proportional to cube of the wind speed [6].

2.2 Wind Rotor Performance Aspect

The amount of energy transfer by a wind flow that can be converted by a wind rotor is depending on several aspects which are the density of air, rotor blade swept area and the wind speed [6].

The circular area covers by the rotating wind rotor blade will determine how much energy can be extracted from wind flow. Wind rotor with larger rotor blade diameter will intercept more wind compare to smaller rotor blade hence extract more energy [4]. Doubling the swept area will double the power output:

$$A = \pi . r^2$$

Since the rotor swept area increase the square of the rotor blade radius, a twice larger wind rotor is to receive four times more energy [6]. Wind rotor with bigger rotor blade diameter will generate more electricity [4].

Wind speed is also an important aspect to the amount of energy available in wind. This is because the energy of the wind is a product of cubic value of the wind speed and change in speed will be affecting the wind energy. Doubling the wind speed does not double the wind energy, in fact it will increase the wind energy eight times bigger [4].

2.3 Wind Energy Extraction

The power output of wind rotor is only a proportion from the total wind energy which can be successfully extracted. The power available in wind flow is equal to the change in kinetic energy of the air as it passes through the wind rotor [5]. The wind rotor will slow down the wind flow as it captures the kinetic energy of the wind flow. This means that the wind will be moving slowly after leaving compare to wind speed before it passing the wind rotor [6]. The wind rotor slows the wind speed down from its original ambient speed V_0 to a final speed V_2. This deceleration of wind speed causes an increase of the static pressure before and after the wind rotor, while within the wind rotor, where energy gets extracted from the wind, its static pressure drops in correspondence. While the wind flow gets decelerated, the flow of wind correspondingly widens [6].

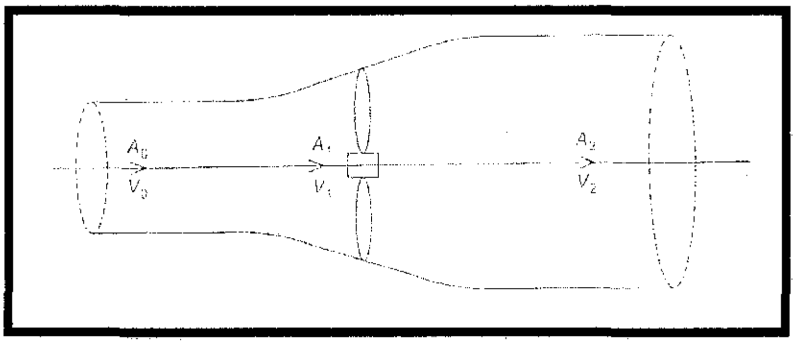


Figure 2.1: Ideal wind flow through a wind rotor [6]

For ideal wind flow, the mass flow rate (M) before passing, while passing and after passing the wind rotor is constant [5]:

$$M = \rho.A_0.V_0 = \rho.A1.V1 = \rho.A2.V2$$

The force (F) acting on the rotor blade is given by the rate of change in momentum [6]:

$$F = M\,(V_0 - V_2)$$

The power output (P_{output}) extracted by wind rotor is given by the rate of change of kinetic energy [5]:

$$P_{output} = M\,(\tfrac{1}{2}V_0^2 - \tfrac{1}{2}V_2^2) = F.V_1$$

Manipulate the equation will lead to equation for V_1 [5]:

$$V_1 = \tfrac{1}{2}\,(V_0 + V_2)$$

2.3.1 Power Coefficient

Power coefficient is defined as the fraction of wind power in a wind flow and the power output extracted by the wind rotor [8]:

$$C_p = P_{output}/P_{wind}$$

The efficiency of wind rotor will be indicated by power coefficient. The question that always being asked is how much of wind energy can be extracted by wind rotor. Conventional wind rotor extract kinetic energy from a flow of wind by means of a rotor, which is exposed to the otherwise undisturbed air flow. The concept applied is wind rotor is likely to extract energy from wind flow by reducing the speed of the wind. To get 100% efficiency of wind rotor, the wind speed is expected to reduce to zero which means it is impossible.

2.3.2 Betz's Law

In 1919, German Physicist named Albert Betz concluded that the maximum power coefficient that can be achieved is 0.5926 or 59.26% and it is known as Betz Law [6] [9]. The conclusion was proofed by him on Betz's Theorem [9]. Therefore an ideal wind rotor will slow down the wind speed by 2/3 of its original speed [3]. The reason why Betz Law is not any higher from 0.5926 is because the wind needs enough speed to flow and allow more wind to pass through the wind rotor [6]. Power coefficient will be maximized if the wind rotor operates for a particular wind speed. And it will reduce dramatically for other value of wind speed [10]. A conventional wind rotor might extract some fraction, such as 70% of the theoretical value which approximately (0.5926) (0.7) = 0.42 or 42% [8].

2.3.3 Cut In and Cut Out Speed

Rotor blade will start to rotate when a certain value of wind speed is passing through the wind rotor. This value of wind speed is called cut in speed [6]. Below the wind rotor cut in speed, there is not enough energy in the wind to overcome the mechanical losses within the wind rotor [5]. Having a wind rotor operating in high wind speed is also not preferable. This is to avoid any damages that can be done to the wind rotor. Usually wind rotor automatic to stop at certain value of wind speed and this is called cut out speed [6].

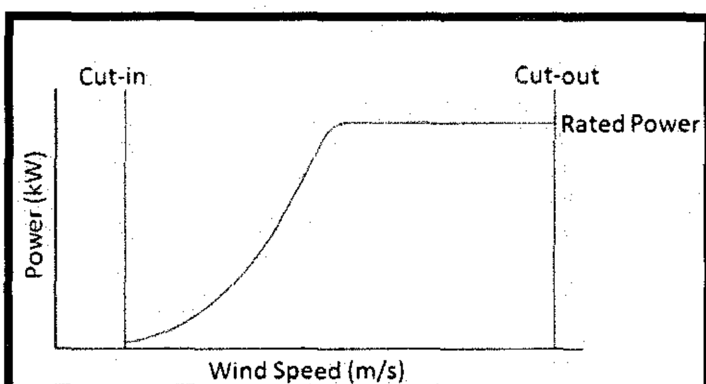


Figure 2.2: Theoretical power curve of wind rotor [11]

2.3.4 Tip Speed Ratio

Tip speed ratio is actually the ratio between the wind speed and the speed of rotor blade tips, λ_S [10]. This ratio is relating the circumferential speed of rotor blade tips, V_{tip} and the wind speed, V_{wind} and given by the tip speed ratio [5]:

$$TSR = V_{tip}/V_{wind} = (\omega R)/V_0$$

Where ω is the rotational speed in rad/s and R is the rotor blade radius. The efficiency of wind rotor is strongly influenced by tip speed ratio. Slow rotation of wind rotor will result small tip speed ratio. This will cause huge angle of attack, α_A and if it is bigger that critical angle, the wind flow will break away from rotor blade profile. The wind flow will become turbulent and dramatically reducing the lift force of the rotor blade [6].

Most of the wind will flow through the wind rotor undistributed because of huge gap between the blades and wind rotor may stall. If the tip speed ratio is too high, the lift force reaches its maximum value and decrease afterwards. The rotor will act like a solid wall thus reducing the power efficiency of converter [6]. Power will not optimally extract and wind rotor will be highly stressed. Therefore, wind rotor is to be design with optimal tip speed ratio to extract the maximum power of the wind flow possible. Different number of blades will have different optimum tip speed ratio value. Wind rotor with less number of blades has larger optimum tip speed ratio value. This is because the rotor blade has to rotate faster to extract maximum power from the wind flow [12].

2.4 Wind Rotor in Bounded Environment

The concept of having a wind rotor in a bounded installation method is not a new idea. If the widening effect of the wind stream can be avoided, the efficiency of a wind rotor could increase. There have been several attempts in the past to increase the power of wind rotor by means of shroud systems. Research regarding this method of installation was conducted by many and it is still in developing process. In a research on calculation method conducted by Bernard Frankovic′ and Ivan Vrsalovic′, they proposed a new type of wind rotor which is installed in a nozzle-type bounded environment [13]. The nozzle shell which lies close to the blade tips will induce considerable radial speed. The design of this nozzle shell follows the aerodynamic principle because of wing-ring shape will cause lower pressure side pointed towards the centre of the nozzle as the lift force on each part of the wing is directed radially towards the centre. This create a centrifugally directed reaction force in the air flow which cause the stream field to expand strongly downstream of the rotor and includes a greater number of stream-lines in the active stream in front of the rotor (upstream).

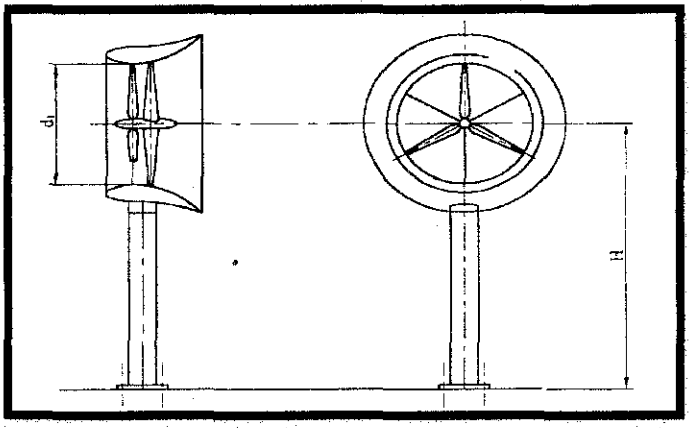


Figure 2.3: Wind rotor in wing profile nozzle shell [13]

Thus, the nozzle forces a greater air mass flow to pass through the wind rotor. The higher mass flow and higher velocity reduction behind the rotor result in a higher energy output from the wind rotor in the nozzle. In this way the wind rotor efficiency is multiplied. This new method of installation will generate more power from a slow and a medium wind speed because of the relation wind power (P_{wind}) corresponds to cubic value of wind speed. Based on calculation method, they claim the wind rotor in nozzle installation produces more energy than open environment wind rotor. Thus, a wind rotor in nozzle installation can produce an energy output which is approximately 3.28 times higher than the energy output obtained from a wind rotor in the free air stream of the same diameter [13].

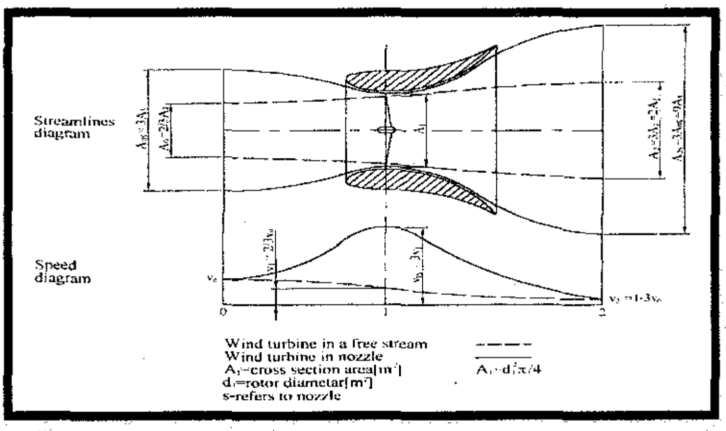


Figure 2.4: The aerodynamic impact of shaped nozzle shell on the stream field [13]

When approaching open environment wind rotor, the wind flow is slowed down and widened. This effect causes a loss in the efficiency of the wind rotor. In a research by simulation conducted by F. Bet and H. Grassmann, they propose an idea to create a field of low pressure behind the wind rotor [7]. With this loss in efficiency can be avoided. Based on their research, it is found that to increase the power output of the wind rotor, the pressure drop at the rotor blade must be increased. This can be achieved by decreasing the pressure behind the rotor blade.

To maintain this pressure drop in a flow of wind, work must be done by flow of wind which passes near to the wind rotor, but does not pass through it. If a wing profile structure is installed to a wind rotor, field of low pressure behind the wind rotor can be created as the bended side of the wing profile structure pointing to the wind rotor will decrease the pressure behind the turbine. As a consequence, the air passing between the wing and wind rotor will be decelerated.

Based on these considerations, a model of a wind rotor with a wing profile structure around it was simulated. The simulation conducted shows how the field of low pressure, which forms over the bended side of a wing, attached with the field of low pressure behind the wind rotor. It is found that the power of the wind rotor is increased by the wing system by a factor of 1.6 [7].

Figure 2.5: Simulation done with added wing structure [7]

An additional, outer cylindrical wing structure is added. Again, the field of low pressure, created by this structure, attached to the low pressure field inside the first cylinder, behind the wind rotor. Compared to the open surrounding wind rotor, the power again increases a factor of 2.0.

Figure 2.6: Added outer wing structure [7]

The shroud system widen up the low pressure field behind the wind rotor. It is also found that it is not necessary to have a long wing profile for the operation. This suggests that the wings can be made much smaller. They conducted simulation with smaller wing profiles but the outer cylinder covers about as much cross-section as before. Also the power of the device is again about the same: the smaller wind profile configuration increase the power output by the factor of 2.0 [7].

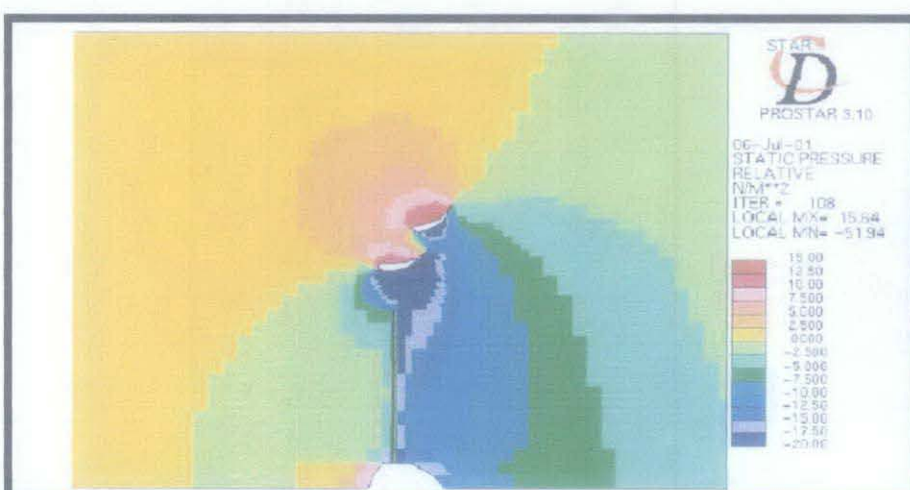


Figure 2.7: Smaller outer wing structure installed to wind rotor [7]

Therefore, to double the power of a wind rotor, it can be achieved by inserting it into a wing profile structure of about the same total area as the area which is covered by the rotor blade of the wind rotor itself.

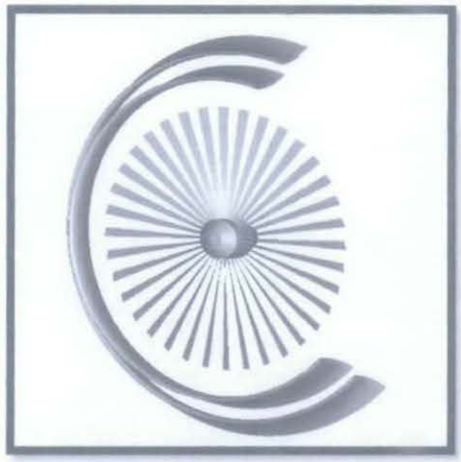


Figure 2.8: Outer wing structure installed to wind rotor [7]

A slight increase of wind velocity can influence the power output produced. If we are able to concentrate the wind energy, the power output will increase significantly. A unique research by experiment was conducted in the past regarding a diffuser-augmented wind rotor [14]. Yuji Ohya et al. examined three hollow structures which are cylindrical-type, diffuser-type and nozzle-type.

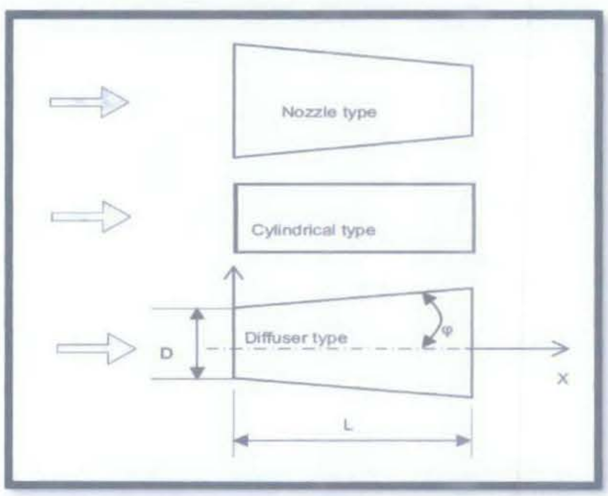


Figure 2.9: Three types of hollow structures [14]

Wind distribution and static pressure along the centre axis was measured. From this experiment, it is known that a diffuser-type model has a remarkable ability on the collection and acceleration of the approaching wind entering the body. The wind tends to avoid entering the nozzle-type model, where as the wind flows into the diffuser-type model as it is sucked inside. Thus, it was confirmed that the diffuser structure is most effective for collecting and accelerating the wind.

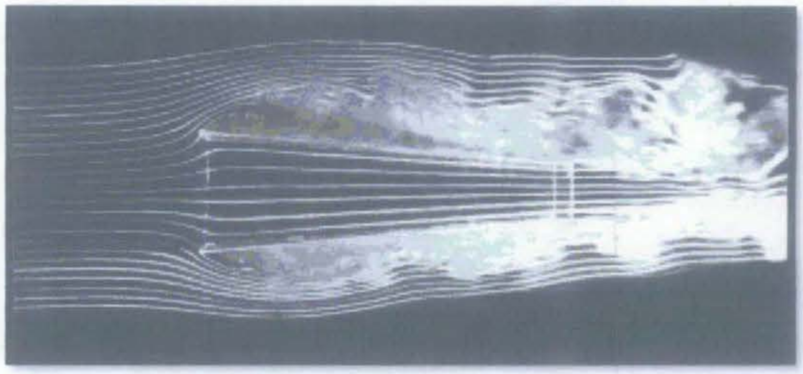


Figure 2.10: Nozzle-type structure [14]

Figure 2.11: Diffuser-type structure [14]

A remarkable increase in wind speed was obtained if a long diffuser body. However, in the practical point of view, it is preferable to have a short diffuser body. Therefore, they examined a short diffuser-type structure which is capable of providing more effective performance by applying various ideas to the short body. Although the main concern of the experiment is to observe acceleration performance using diffusers, it is also found that square sections and circular sections of diffuser will have similar performance.

As a result of several attempts, it was found that wind speed is increased by adding an appropriate entrance (called an inlet shroud) and a ring-type flange at the exit periphery to the diffuser body. When both the inlet shroud and flange are installed, a remarkable increase in wind speed can be obtained, exceeding the case of a diffuser model only, and achieving a high speed that is 1.6–2.4 times greater than that of the approaching wind speed. The effect of the inlet shroud is found to restrains flow separation at the entrance fairly well and the wind flows in more smoothly.

The vortex formation like the Karman vortex street is observed at downstream of the flange. Due to the vortex formation, the static pressure of the diffuser equipped with a flange falls to a fairly low pressure compared to that of the upstream flow in comparison to the case of diffuser without a flange.

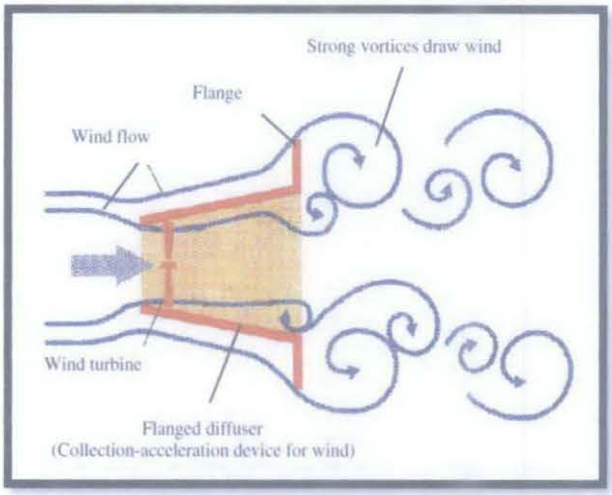


Figure 2.12: Flow mechanism around a flanged diffuser [14]

The approaching flow is inhaled into the diffuser near the entrance. As the wind outside the diffuser hit the flange, vortices created and a low pressure region was generated at the back of the diffuser. Generally, a flange may be thought to be an obstacle against the flow coming smoothly. However, this flange generates large size of separation behind it and this will cause the wind speed to be accelerated inside the diffuser as the wind flowing into the low pressure region. Due to this effect, the flow coming into the diffuser can be effectively concentrated and accelerated.

This method prevents pressure loss by flow separation and increases the mass flow inside the diffuser. The development of a shrouded wind rotor with an inlet shroud and flange structure shows an increase of power output by a factor of 2 compare to conventional wind rotor. An optimal shape of flange diffuser was found to acquire higher power output. When a flanged concept applied, a significant increase of power coefficient achieved compare to conventional wind rotor.

CHAPTER 3: METHODOLOGY

3.1 Methodology

To conduct the "Performance Investigation of Wind Rotor in Open and Bounded Environments" project, several aspects were identified. This will include project planning, research and study, rotor blade survey, design and fabrication, performance investigation and data analysis:

- Project Planning

The major execution plan of the project was started at the early final year 3rd semester. The design software, fabrication equipment and experiment tools need to be used are prepared. Project activities had already been scheduled, utilizing the time frame for May 2011 semester. The experiment scheduled to be completed in week twelve. Data analysis was planned to be done right after data obtained from experiment. The early scheduling during FYP I will not be applicable and the new planned scheduling can be observed in updated Gantt chart.

- Research and Study

Research related to this experiment was studied to understand the principle of wind rotor operating in three different installation methods. Research conducted regarding the performance based on rotor blade rotation per minute (RPM) and rotor blade torque produced (N.m) obtained by experiment and was used to determine wind rotor performance. With reference from journal, books and relevant web, calculation required to obtain performance criteria was applied. This is also to improvise the understanding of wind rotor based on the requirement of the project. Obtained knowledge was included in Literature Review. Related calculation model applied for data analysis. The data was obtained and final conclusion was made.

- Rotor Blade Survey

Since the design and fabrication of rotor blade is difficult and need more time to complete, decision to obtain rotor blade which is already available to on market was taken as solution. Rotor blade with different dimension, number of rotor blade and rotor blade type made as guideline for selection. Two different rotor blades were selected. These rotor blades were slightly modified during fabrication to suit the design of overall wind rotor prototype.

- Design and Fabrication

The overall design for wind rotor prototype was made by using Auto-CAD 2007 software. Bounded casings, rotor blade mounting and tower and base were included in overall design. Three different bounded casings which are cylindrical type, diffuser type and nozzle type fabricated. Proper dimension and structure had been considered in designing this wind rotor prototype. After finalizing the design, the fabrication of the wind rotor prototype was done by outside fabricator. The fabrication completed within a month and a half which is in week 10. The experiment began as soon as the fabrication completed.

- Performance investigation

The performance investigation of the three installation methods of wind rotor prototype was conducted using industrial fan. The reduction of side escape effect on performance of wind rotor prototype had been observed by manipulating several factors which are the number of blade, type of rotor blade and method of installation. The wind rotor prototype tested with seven variations of wind speed (1m/s – 7 m/s). Based on determined wind speed, the rotation per minute (RPM) and torque produced of rotor blade evaluated to obtain performance criteria of wind rotor prototype.

- Data analysis

Data obtained in experiment was recorded and analyzed. Comparison between performances of wind rotor in open, partially bounded and fully bounded environments was made. Performance of wind rotor in different bounded casings also had been compared. Based on the result, discussion included in report, conclusion was made and for the future reference of this project.

3.2 Project Work Flow

The development that will be made within 'FYP I' and 'FYP II', the project activities are explained in flow chart below:

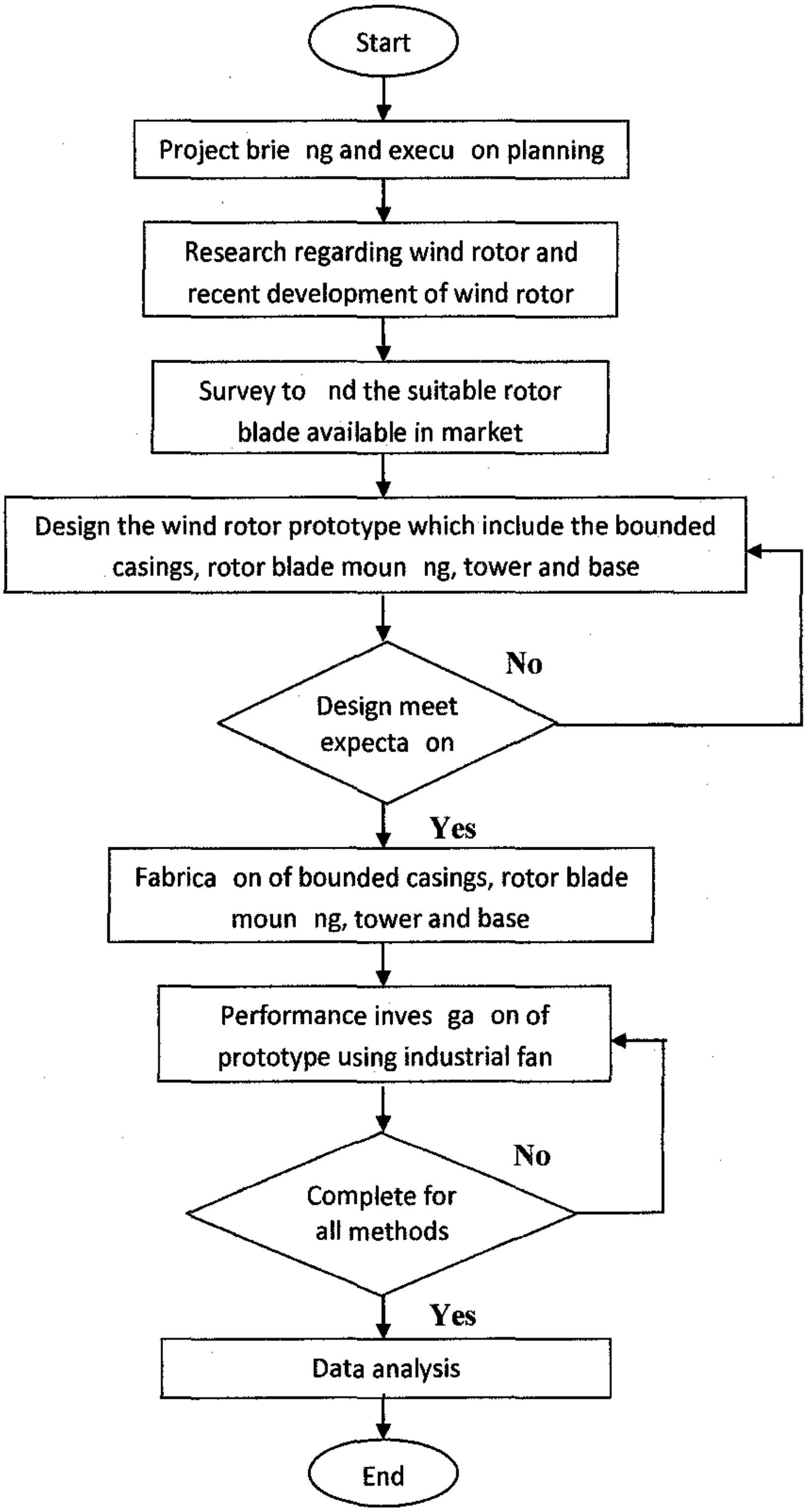


Figure 3.1: Project work flow

3.3 Tool required

- Anemometer
- Tachometer
- Torque meter
- Industrial fan

3.4 Software required

- Auto-Cad 2007
- Microsoft Word 2007
- Microsoft Excel 2007

3.5 Gantt Chart

**The Gantt chart is attached in Appendices*

3.6 Rotor Blades for Experiment

For this project, the rotor blade that used in the experiment was not designed and fabricated. This is because on the difficulty of designing a rotor blade and it requires a high skilled designer with deep knowledge regarding the design criteria such as rotor blade aerofoil shape, the angle of twist, pitch angle and so forth. To acquire this skill and knowledge, it will take longer period to complete this project. After discussion with project supervisor, instead of designing and fabricating the rotor blade, alternative taken was to use available rotor blade in market.

Several criteria of rotor blade were decided before survey for suitable rotor blade being conducted. Rotor blades with similar diameter need to be different in number of blade to observe the effect of rotor blade number on the performance of wind rotor. Having different type of rotor blades (the lift and drag type) can also be beneficial as the effect on wind rotor performance can be studied.

Based on these considerations, two different rotor blades were selected. These rotor blades fulfil the requirement of having different number of blades and different rotor blade types as shows in Table 3.1:

Table 3.1: Rotor blades selection

Rotor Blade	Description
 A	Dimension: 152.0 mm Number of blade: 3 Rotor blade type: drag
 B	Dimension: 152.0 mm Number of blade: 13 Rotor blade type: lift

3.7. Wind Rotor Prototype Component Design

The most vital step need to be taken to execute this project is the design and fabrication of wind rotor prototype that was utilized in the experiment. To get the best design, several design constraints were identified as below:

- Suitable dimensioning of wind rotor prototype

The dimension of wind rotor prototype components such as bounded casings, rotor blade mounting, rotor blade tower and base required to follow rotor blade scale, which is 152.0 mm in diameter. Acceptable tolerance had been included in dimension analysis and dimension was finalized for each component considering the ease of working during experiment.

- Weight of the wind rotor prototype component

Weight of each component had been taken into consideration since it will affect the wind rotor prototype. Heavy component will lead to difficulty of assembling and dismantling wind rotor prototype for experiment purpose. Accurate dimension and components design was made to reduce overall weight wind rotor prototype to a value considered to be acceptable.

- Material cost and ease of fabrication

Material that was used for fabrication is expected to be low cost and easy to fabricate. This is to reduce the overall project cost as low as possible. Since the design for wind rotor prototype includes sweep shape, formability of material is an important factor. Mechanical properties of material are evaluated. Mild steel and aluminium were the two materials which already shortlisted to be used for fabrication.

- Stability of wind rotor prototype

Design of the wind rotor prototype evaluated to ensure the stability of wind rotor prototype during experiment. Proper structure and support design had been finalized and suitable material with appropriate mechanical properties was selected. Since the experiment is utilizing considerably high speed wind flow with from industrial fan, stability of wind rotor prototype is essential factor in design and fabrication.

3.7.1 Bounded Casing

After oral presentation for FYP1, the design was invalid since the concept of the bounded casing is poorly understood. Based on old design, the rotor blade will be placed at the middle of all bounded casings. After discussion with supervisor and internal examiners, the concept of bounded casing was then fully understood. For each bounded casing, the placement of rotor blade is different:

Cylinder Casing: the rotor blade will be placed at the end of the casing
Diffuser Casing: the rotor blade will be placed the front of the casing
Nozzle Casing: the rotor blade will be placed at the end of casing

A new design of all bounded casings was produced to replace the old design. After the new design revealed, permission to continue fabricating these bounded casings granted.

To obtain the best design for bounded casing, proper dimension analysis was made based on the dimension of rotor blade prototypes. These rotor blades have a maximum diameter of 152.0 mm. The diameter for all bounded casings should not less than or equal to 152.0 mm.

$$D_{casing} > 152.0mm$$

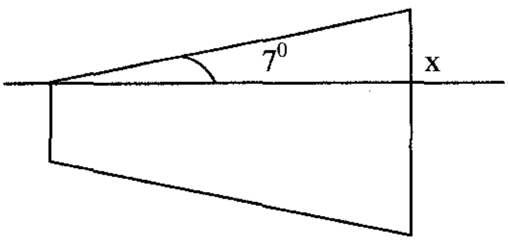
Based on rotor blades diameter, the dimension for casing diameter set to be 160.0 mm since some tolerance should be provided to avoid the casing from interrupting these rotor blade rotating motions.

Discussion about the length of casing also was made with supervisors. It is decided that the length of these bounded casings is to:

$$L_{casing} = 2D_{rotor}$$

The decided length of casing (L_{casing}) is twice the value of rotor blade diameter (D_{rotor}). From calculation, the minimum length should be 304.0 mm.

Cylinder casing will be having same diameter for both ends which is 160.0 mm including tolerance. For diffuser and nozzle, the diameter for front and end is different due to the shape of these casings. Inclination angle is decided to be 7^0 for both casings.



$$\text{Tan } 7^0 = x / L_{casing}$$

The front diameter (D_{front}) is 160.0 mm. The end diameter (D_{end}) is:

$$D_{end} = 2x + D_{front}$$

Based on calculation, the end diameter is 234.5. Calculation for nozzle casing front diameter will be the same by applying the same equation used to calculate the end diameter of the diffuser casing. Table 3.2 and Table 3.3 describe the bounded casing designs:

Table 3.2: Old design for bounded casings

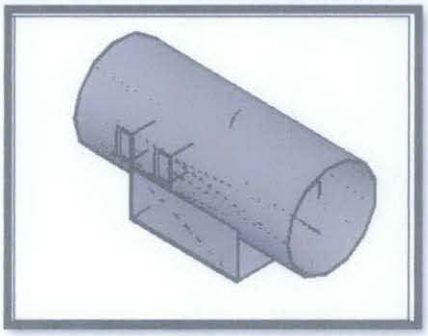
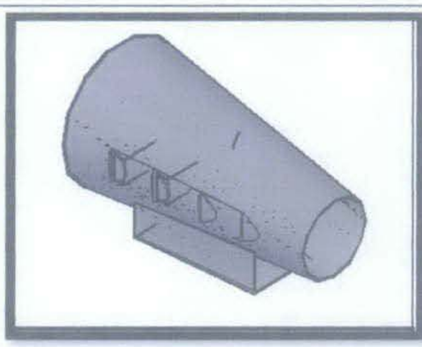
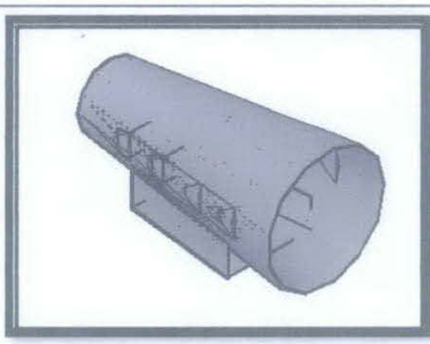
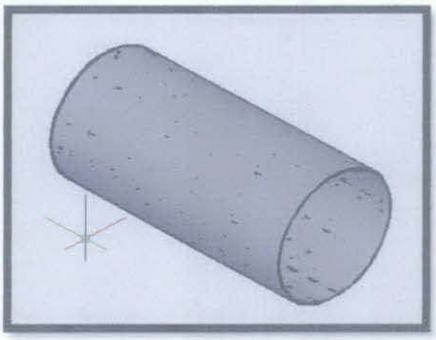
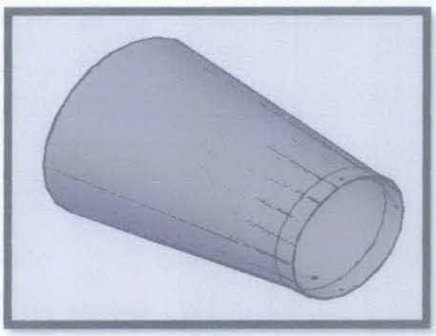
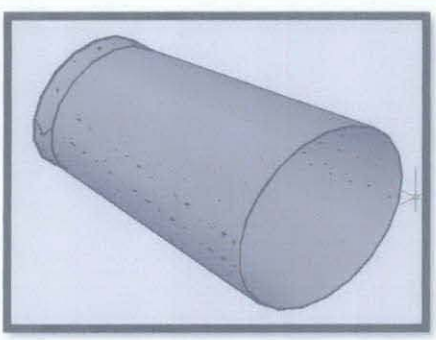
Casing	Dimension
 Cylindrical	Casing type: Cylindrical Conduit length: 400.0 mm Conduit diameter: 165 mm
 Diffuser	Casing type: Diffuser Inclination Angle: 7^0 Conduit length: 400.0 mm Conduit diameter: 115.9 mm inlet 214.1 mm outlet
 Nozzle	Casing type: Nozzle Inclination Angle: 7^0 Conduit length: 400.0 mm Conduit diameter: 214.1 mm inlet 115.9 mm outlet

Table 3.3: New design for bounded casings

Casing	Dimension
 Cylindrical	Casing type: Cylindrical Conduit length: 304.0 mm Conduit diameter: 160.0 mm
 Diffuser	Casing type: Diffuser Inclination Angle: 7^0 Conduit length: 304.0 mm Conduit diameter: 160.0 mm inlet 234.5 mm outlet
 Nozzle	Casing type: Nozzle Inclination Angle: 7^0 Conduit length: 304.0 mm Conduit diameter: 234.5 mm inlet 160.0 mm outlet

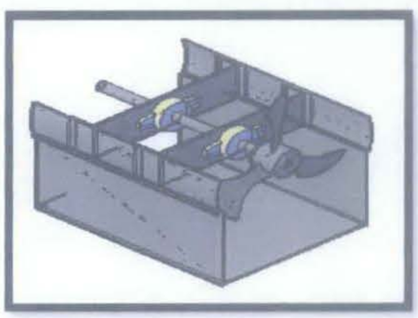
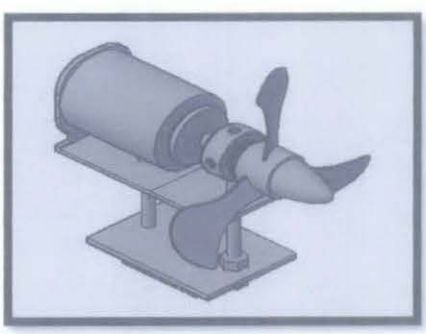
3.7.2 Rotor Blade Mounting

Since the concept for bounded casing was poorly understood earlier, the old design for rotor blade mounting was also made by mistake. The old design was done to suit the idea of placing rotor blade at the middle for all bounded casings. The other issue discussed with supervisor is the wide area of the plate connecting the bearing and mounting that might block the wind flow.

After discussion, this area is to be reduced since the blocking of wind flow will affect the efficiency of wind rotor. This new design version was made to correct the mistake and to suit the new design of bounded casing. Bearing, shaft, and rotor blade is included in the rotor blade mounting. The mounting attached at the top of rotor blade tower.

The dimension for this new rotor blade mounting was decided based on the determined bounded casing dimension. There are several factors that need to be considered when deciding the proper dimension for rotor blade mounting. The main factor is the alignment of rotor blade rotational axis and the central axis of the bounded casing. Other than that is the suitable dimension of joint connection between bounded casing and rotor blade mounting. The appropriate scale of rotor blade mounting was also a factor to be considered since the design is to follow the diameter of rotor blade. Table 3.4 shows the old and new design for rotor blade mounting:

Table 3.4: Rotor blade mounting design

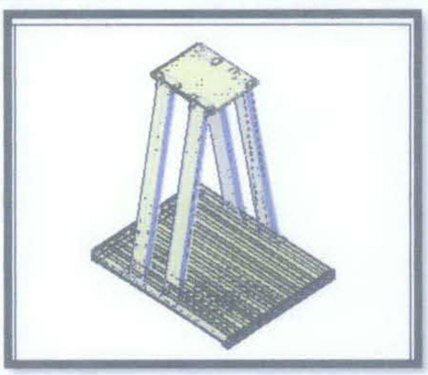
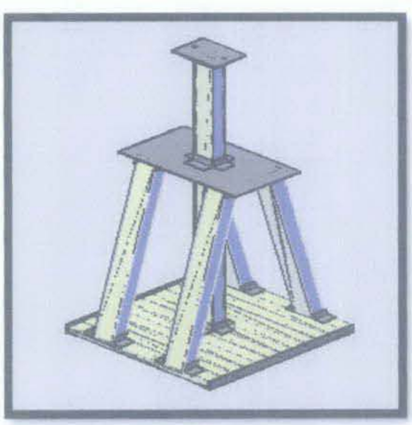
Rotor Blade Mounting	Dimension
 Old design	Height: 112.26 mm Base length: 200 mm Base width: 156 mm
 New design	Height: 112.26 mm Base length: 110 mm Base width: 65 mm

3.7.3 Tower and Base

The earlier design concept for the wind prototype was made based on rotor blade mounting design and for easier fabrication. This is to reduce the cost and time taken to complete the fabrication of wind rotor prototype. After discussion with supervisor, the tower and base structure of wind rotor prototype needs to be improved.

These tower and base will be supporting the rotor blade mounting and bounded casings. The height of the tower increased to make the rotor blade mounting axis is closely parallel to the outlet axis of industrial fan without neglecting stability factor. With this, more organize wind flow pattern can be achieved. The design for tower support will be maintained. The width and length of the wind rotor prototype base is reduced based on the new design of bounded casing and rotor blade mounting. Table 3.5 shows old and new design for tower and base structure:

Table 3.5: Tower and base structure design

Casing	Dimension
 Old design	Height: 472.7 mm Base length: 456 mm Base width: 355.6 mm Mounting base length: 200 mm Mounting base width; 256 mm Support angle: 78^0
 New design	Height: 762.8 mm Base length: 306 mm Base width: 304.8 mm Mounting base length: 89.9 mm Mounting base width; 65.2 mm Support angle: 78^0

3.7.4 Wind Rotor Prototype Material Selection

Table 3.6: Material selection for wind rotor prototype

Materials / Design criterion	Weightage	Mild Steel Plate	Aluminium Plate
Overall cost	0.35	5	2
Ease of fabrication	0.25	5	4
Weight issue	0.25	3	5
Material availability	0.15	5	4
Total	1.00	4.5	3.55

From Table 3.6, two materials were shortlisted for fabrication of wind rotor prototype. Decision was made to use mild steel as material for fabrication. This material was used for all components fabrication which are bounded casing, rotor blade mounting, tower and base. The most important criterion is the overall cost of material and the ease of fabrication. Mild steel is a lot cheaper than aluminium and it will reduce the overall project cost. Apart from that, it is easier to be fabricated compare to aluminium as joint connection can be done by welding rather than using rivet or screw. The weight of these bounded casings fabricated using mild steel is heavier than using aluminium. Despite that, it will be beneficial to stabilize wind rotor prototype during experiment especially for the fabrication of tower and base.

3.8 Wind Rotor Prototype Fabrication

The fabrication started on the 4th week of this semester. After finalizing the design of the wind rotor prototype at the end of 3rd week, the fabrication phase executed. Originally, the fabrication is to be done in lab 21. After surveying the material available equipment available, it is advisable to continue the fabrication outside UTP. Since the fabrication was done outside, the progress of fabrication is a bit slow.

This is due to the fabrication queues that need to be followed. On the 10th week of this semester, wind rotor prototype fabrication was completed. The fabricated wind rotor prototype is slightly different from original design because there is some critical modification need to be made after discussion with fabricator. The experiment started right after the fabrication completed which is early week 11. All the experiment tools required was prepared in advance to ensure the experiment can be conducted smoothly. Figures 3.2 – 3.6 below show completed wind rotor components after fabrication:

Figure 3.2: Completed bounded casings

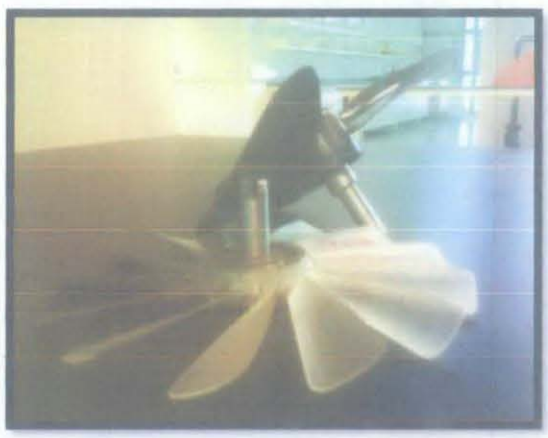


Figure 3.3: Modified rotor blades for experiment

Figure 3.4: Rotor mounting with bearing

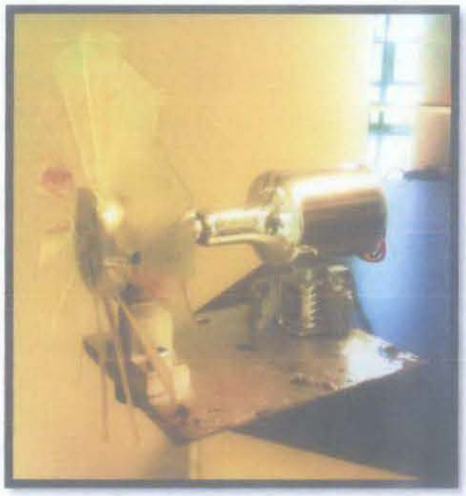


Figure 3.5: Assembly of rotor blade mounting with dynamo

Figure 3.6: Tower and base structure

3.9 Wind Rotor Experimental Procedure

Based on early planning, the experiment will be conducted using wind tunnel. This is because of the high speed wind flow is required to operate wind rotor prototype with a small generator connected through a shaft from rotor blade. This high speed wind flow from wind tunnel manages to provide sufficient torque to rotate rotor blade connected with a generator shown in Figure 3.7.

But the problem arises was fluctuated measurement of power generated in terms of current and voltage. This is due to the inconsistent wind flow of the wind tunnel. Besides that, the direct current motor operating wind tunnel was reported to be easily overheated. Discussion was held with supervisor regarding this problem and it was then decided to conduct the experiment without using generator. Since the experiment is conducted without using generator, less torque is required to rotate the rotor blade. A smaller size industrial fan was used replacing wind tunnel to get the wind flow required for this experiment. Moreover, the wind flow is more consistent compare to wind flow from inefficient wind tunnel.

Figure 3.7: Modified dynamo used as generator

The industrial fan is 700 mm in diameter, having a central axis height of 1600 mm from the ground. The height of wind rotor prototype from central axis to the ground is 768.2 mm which is less than half the height of industrial fan central axis. This is because dimension consideration for wind rotor prototype stability factor. To ensure both wind rotor prototype and central axes are parallel, a small table was used as a platform. A speed switch is placed on the left side of the industrial fan body to control desired wind flow speed for experiment. Figure 3.8 shows experiment set up:

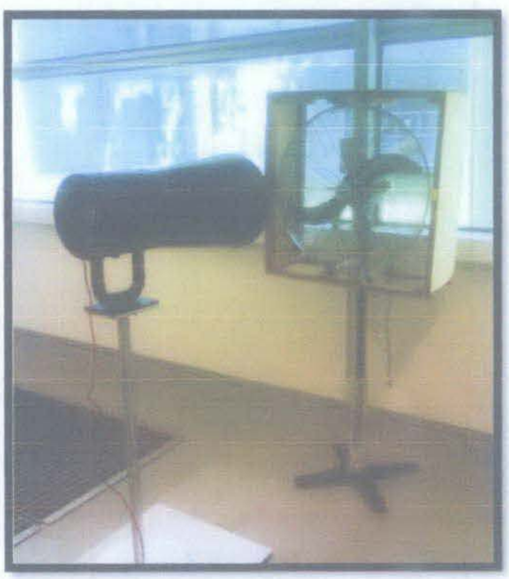
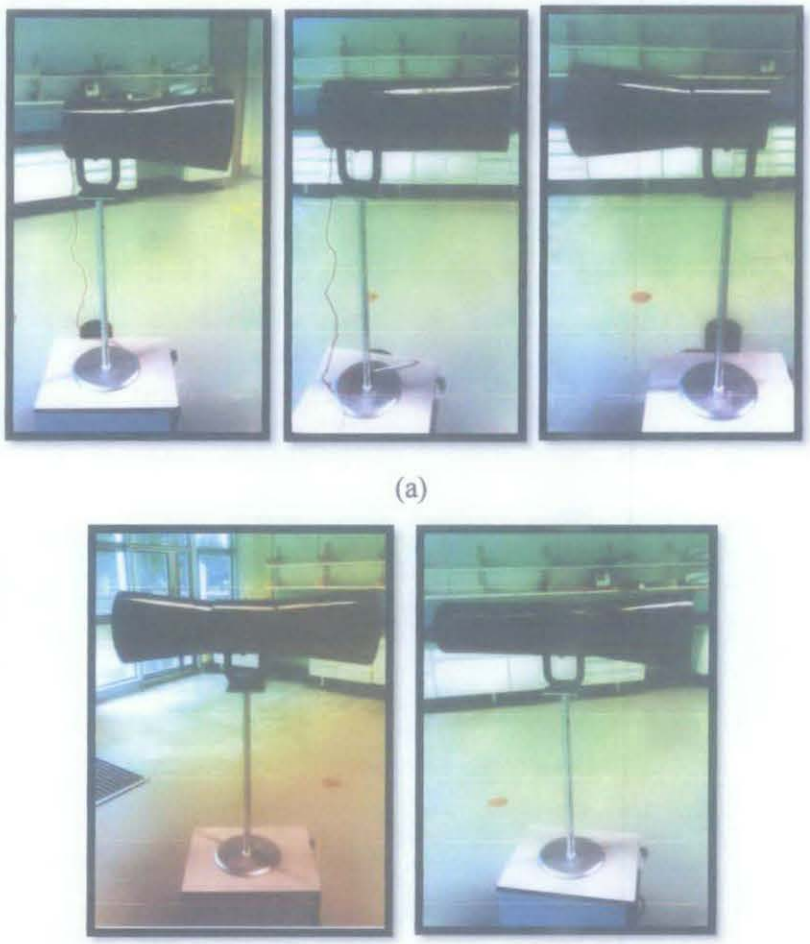


Figure 3.8: Experiment set up for wind rotor

To conduct this experiment, three environment of wind rotor prototype will be tested using two different rotor blades. The desired wind flow speed is from 1m/s to 7m/s which can be achieved by controlling the speed switch on industrial fan. The wind flow speed measured and determined by using digital anemometer. It is impossible to obtain the exact wind flow output speed because of the inconsistent of wind flow. Some tolerance of wind flow speed was considered acceptable. Bounded casings fabricated will be used to create partially bounded and fully bounded environments. All the three types of casings which are cylinder, diffuser and nozzle were used in decided orientation. Figure 3.9 shows wind rotor installation methods:



(a)

(b)

Figure 3.9: Installation method for partially (a) and fully bounded (b) environments

3.10 Data Recording and Analyzing Procedure

A digital tachometer was used to measure the rotation per minute (RPM) of rotor blade during experiment. This can be done by pointing laser tip to a reflective strip attached to the near center of rotation of rotor blade. As the rotor blade rotates, the reflected laser beam will be captured by tachometer and measured rotational speed value will appear on monitor. The measurement can only be made once the rotor blade prototype rotation finally stable. Figure 3.10 shows a digital tachometer used for experiment:

Figure 3.10: Digital tachometer to measure rotation speed (RPM)

Torque meter is used to measure torque (N.m) produced by a rotating rotor blade. It will be clamped on the shaft connected to rotor blade. Due to inconsistent wind flow output speed, the measurement will be slightly fluctuated. The average peak value of torque produced will be taken as final measurement. Figure 3.11 shows a digital torque meter used for experiment:

Figure 3.11: Digital torque meter to measure torque produced (N.m)

The experiment was conducted for all three different installation methods which are open, partially bounded and fully bounded environments using two different rotor blades. All data recorded and analyzed using Microsoft Excel software.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Data Recording and Analysis

The experiment was conducted in a laboratory (Block 18) under standard room condition of 1 atm atmospheric pressure and 24-25^{0}C ambient room temperature. During experiment, two measurements which are rotation per minute (RPM) and torque produced (N.m) were successfully recorded for two different rotor blades. These rotor blades operated in three different installation methods which are open, partially bounded and fully bounded environments at wind speed range of 1m/s to 7m/s. based on recorded data, analysis was conducted in order to determine and compare the wind rotor performance. Related equations were studied and applied in calculating wind rotor performance criteria. The equations are listed below:

- Air density, $\rho = 1.2$ kg/m^3
- Rotation per minute, N (measured using tachometer)
- Torque of rotor blade, T (measured using torque meter)
- Wind speed, V (measured using anemometer)
- Wind Power, $P_{wind} = ½\rho V^3 A_{rotor}$
- Tip Speed Ratio (TSR), $\lambda = (\omega.r)/V$
- Rotor rotational speed, $\omega = 2\pi N/60$
- Rotor Power, $P_{rotor} = \omega.T$
- Power Coefficient, $C_p = P_{rotor} / P_{wind}$
- Torque Coefficient, $C_T = T/ (1/2\ \rho V^3 A_{rotor}(D/2))$

Based on data obtained during experiment, equations above were applied to determine five performance criteria. These performance criteria were tabulated for each installation methods and graphical data comparison was presented to be observed and analysed. The data was recorded and analyzed in tables 4.1 – 4.12 below:

Table 4.1: Data from wind rotor experiment in open environment

No	Wind Speed, m/s	Rotor Blade A		Rotor Blade B	
		Rotational speed, RPM	Torque, N.m	Rotational speed, RPM	Torque, N.m
1	1.00	0	0.0003	0	0.0001
2	2.00	0	0.0007	0	0.0005
3	3.00	0	0.0015	136	0.0012
4	4.00	363	0.0025	247	0.0023
5	5.00	466	0.0046	361	0.0031
6	6.00	586	0.0056	483	0.0047
7	7.00	704	0.0068	604	0.0066

Table 4.2: Result for wind rotor experiment in open environment

Wind Speed.	P_{wind}	P_{rotor}	TSR	C_p	C_t
Rotor Blade A					
1	0.011	0	0	0	0.38
2	0.087	0	0	0	0.11
3	0.29	0	0	0	0.067
4	0.70	0.091	0.72	0.13	0.047
5	1.36	0.23	0.74	0.17	0.045
6	2.35	0.34	0.78	0.15	0.031
7	3.74	0.50	0.80	0.13	0.024
Wind Speed.	P_{wind}	P_{rotor}	TSR	C_p	C_t
Rotor Blade B					
1	0.011	0	0	0	0.15
2	0.087	0	0	0	0.082
3	0.29	0.017	0.36	0.058	0.054
4	0.70	0.060	0.49	0.085	0.043
5	1.36	0.12	0.58	0.086	0.030
6	2.35	0.24	0.64	0.10	0.026
7	3.74	0.42	0.69	0.11	0.023

Table 4.3: Data from wind rotor experiment in partially bounded environment (cylinder)

No	Wind Speed, m/s	Rotor Blade A		Rotor Blade B	
		Rotational speed, RPM	Torque, N.m	Rotational speed, RPM	Torque, N.m
1	1.00	0	0.0003	0	0.0002
2	2.00	0	0.0016	0	0.0014
3	3.00	0	0.0035	156	0.0030
4	4.00	355	0.0047	252	0.0041
5	5.00	519	0.0062	338	0.0058
6	6.00	632	0.0069	421	0.0065
7	7.00	816	0.0075	560	0.0076

Table 4.4: Result for wind rotor experiment in partially bounded environment (cylinder)

Wind Speed.	P_{wind}	P_{rotor}	TSR	C_p	C_t
Rotor Blade A					
1	0.011	0	0	0	0.40
2	0.087	0	0	0	0.24
3	0.29	0	0	0	0.16
4	0.70	0.18	0.71	0.25	0.089
5	1.36	0.34	0.83	0.25	0.060
6	2.35	0.46	0.84	0.19	0.039
7	3.74	0.64	0.93	0.17	0.026
Wind Speed.	P_{wind}	P_{rotor}	TSR	C_p	C_t
Rotor Blade B					
1	0.011	0	0	0	0.29
2	0.087	0	0	0	0.21
3	0.29	0.049	0.41	0.17	0.13
4	0.70	0.11	0.50	0.16	0.077
5	1.36	0.21	0.54	0.15	0.056
6	2.35	0.29	0.56	0.12	0.036
7	3.74	0.45	0.64	0.12	0.027

Table 4.5: Data from wind rotor experiment in partially bounded environment (diffuser)

No	Wind Speed, m/s	Rotor Blade A		Rotor Blade B	
		Rotational speed, RPM	Torque, N.m	Rotational speed, RPM	Torque, N.m
1	1.00	0	0.0005	0	0.0004
2	2.00	0	0.0016	0	0.0013
3	3.00	273	0.0023	204	0.0025
4	4.00	365	0.0046	305	0.0037
5	5.00	476	0.0066	413	0.0043
6	6.00	656	0.0071	517	0.0055
7	7.00	869	0.0083	615	0.0064

Table 4.6: Result for wind rotor experiment in partially bounded environment (diffuser)

Wind Speed.	P_{wind}	P_{rotor}	TSR	C_p	C_t
Rotor Blade A					
1	0.011	0	0	0	0.54
2	0.087	0	0	0	0.24
3	0.29	0.066	0.72	0.22	0.10
4	0.70	0.18	0.74	0.25	0.087
5	1.36	0.33	0.76	0.24	0.064
6	2.35	0.49	0.87	0.21	0.040
7	3.74	0.76	0.99	0.20	0.029
Wind Speed.	P_{wind}	P_{rotor}	TSR	C_p	C_t
Rotor Blade B					
1	0.011	0	0	0	0.44
2	0.087	0	0	0	0.20
3	0.29	0.053	0.54	0.18	0.11
4	0.70	0.12	0.61	0.17	0.070
5	1.36	0.19	0.66	0.14	0.042
6	2.35	0.30	0.69	0.13	0.031
7	3.74	0.41	0.70	0.11	0.023

Table 4.7: Data from wind rotor experiment in partially bounded environment (nozzle)

No	Wind Speed, m/s	Rotor Blade A		Rotor Blade B	
		Rotational speed, RPM	Torque, N.m	Rotational speed, RPM	Torque, N.m
1	1.00	0	0.0006	0	0.0004
2	2.00	0	0.0021	0	0.0013
3	3.00	195	0.0037	163	0.0026
4	4.00	320	0.0048	259	0.0042
5	5.00	488	0.0065	351	0.0051
6	6.00	622	0.0077	492	0.0062
7	7.00	922	0.0081	636	0.0073

Table 4.8: Result for wind rotor experiment in partially bounded environment (nozzle)

Wind Speed.	P_{wind}	P_{rotor}	TSR	C_p	C_t
Rotor Blade A					
1	0.011	0	0	0	0.69
2	0.087	0	0	0	0.32
3	0.29	0.076	0.52	0.26	0.17
4	0.70	0.16	0.64	0.23	0.091
5	1.36	0.33	0.78	0.24	0.063
6	2.35	0.50	0.83	0.21	0.043
7	3.74	0.78	1.05	0.21	0.029
Wind Speed.	P_{wind}	P_{rotor}	TSR	C_p	C_t
Rotor Blade B					
1	0.011	0	0	0	0.46
2	0.087	0	0	0	0.20
3	0.29	0.044	0.43	0.15	0.12
4	0.70	0.11	0.52	0.16	0.080
5	1.36	0.19	0.56	0.14	0.049
6	2.35	0.32	0.65	0.14	0.035
7	3.74	0.49	0.72	0.13	0.026

Table 4.9: Data from wind rotor experiment in fully bounded environment (nozzle-cylinder)

No	Wind Speed, m/s	Rotor Blade A		Rotor Blade B	
		Rotational speed, RPM	Torque, N.m	Rotational speed, RPM	Torque, N.m
1	1.00	0	0.0005	0	0.0003
2	2.00	0	0.0019	0	0.0013
3	3.00	0	0.0031	161	0.0021
4	4.00	326	0.0044	273	0.0026
5	5.00	543	0.0052	392	0.0032
6	6.00	712	0.0063	473	0.0043
7	7.00	990	0.0071	630	0.0051

Table 4.10: Result for wind rotor experiment in fully bounded environment (nozzle-cylinder)

Wind Speed.	P_{wind}	P_{rotor}	TSR	C_p	C_t
Rotor Blade A					
1	0.011	0	0	0	0.59
2	0.087	0	0	0	0.29
3	0.29	0	0	0	0.14
4	0.70	0.14	0.65	0.20	0.083
5	1.36	0.30	0.86	0.22	0.050
6	2.35	0.47	0.94	0.20	0.035
7	3.74	0.74	1.13	0.20	0.025
Wind Speed.	P_{wind}	P_{rotor}	TSR	C_p	C_t
Rotor Blade B					
1	0.011	0	0	0	0.36
2	0.087	0	0	0	0.20
3	0.29	0.034	0.43	0.12	0.094
4	0.70	0.074	0.54	0.11	0.049
5	1.36	0.13	0.62	0.097	0.031
6	2.35	0.21	0.63	0.091	0.024
7	3.74	0.34	0.72	0.090	0.018

Table 4.11: Data from wind rotor experiment in fully bounded environment (nozzle-diffuser)

No	Wind Speed, m/s	Rotor Blade A		Rotor Blade B	
		Rotational speed, RPM	Torque, N.m	Rotational speed, RPM	Torque, N.m
1	1.00	0	0.0006	0	0.0003
2	2.00	0	0.0024	0	0.0018
3	3.00	0	0.0032	203	0.0035
4	4.00	376	0.0046	325	0.0044
5	5.00	560	0.0065	436	0.0056
6	6.00	715	0.0080	540	0.0055
7	7.00	896	0.0096	710	0.0063

Table 4.12: Result for wind rotor experiment in fully bounded environment (nozzle-diffuser)

Wind Speed.	P_{wind}	P_{rotor}	TSR	C_p	C_t
Rotor Blade A					
1	0.011	0	0	0	0.74
2	0.087	0	0	0	0.36
3	0.29	0	0	0	0.14
4	0.70	0.18	0.75	0.26	0.087
5	1.36	0.38	0.89	0.28	0.063
6	2.35	0.60	0.95	0.26	0.045
7	3.74	0.90	1.02	0.24	0.034
Wind Speed.	P_{wind}	P_{rotor}	TSR	C_p	C_t
Rotor Blade B					
1	0.011	0	0	0	0.39
2	0.087	0	0	0	0.27
3	0.29	0.064	0.54	0.22	0.16
4	0.70	0.15	0.65	0.22	0.083
5	1.36	0.26	0.69	0.19	0.054
6	2.35	0.31	0.72	0.13	0.031
7	3.74	0.47	0.81	0.13	0.022

4.1.1 Rotor Blades Performance Comparison

The experiment was conducted using two rotor blades, Rotor A and Rotor B. These rotor blades have different criteria in terms of number of blades and blade type. This will affect the rotor blades performance and it can be seen in the result. Rotor A is a drag type need higher wind speed to start rotating compare to Rotor B which is lift type. Since Rotor B has 13 blades, the rotation per minute (RPM) is lower compare to Rotor A which has three blades.

Experiment was conducted for three types of environments which are open, partially bounded and fully bounded. Figure 4.1 shows the result of power coefficient versus tip speed ratio for these rotor blades in open environment. The maximum power coefficient for Rotor A is 0.17 at tip speed ratio of 0.74. For Rotor B, the maximum power coefficient is 0.11 at tip speed ratio of 0.69. Form the result, it is clearly determined that Rotor A has higher power coefficient value compare to Rotor B.

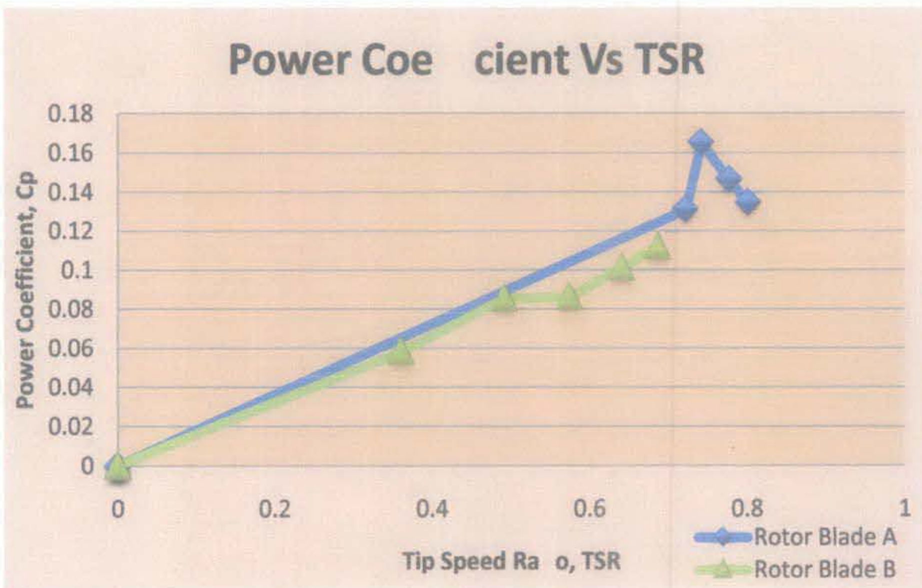


Figure 4.1: C_P versus TSR for rotor blades in open environment

From Figure 4.2, it can be seen that the highest torque coefficient value for both Rotor A and Rotor B happen at tip speed ratio is equal to zero. The maximum torque coefficient for Rotor A is 0.38 and for Rotor B is 0.15. These values will be decrease as the tip speed ratio value increases. Rotor A has higher torque coefficient value compare to Rotor B. Based on result obtained from open environment experiment, further discussion of result will be focusing on Rotor A.

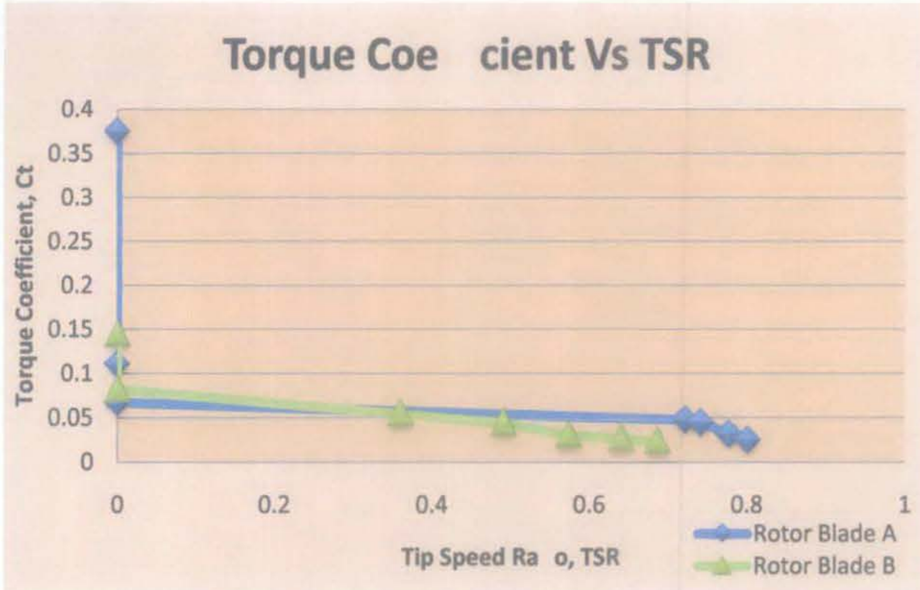


Figure 4.2: C_T versus TSR for rotor blades in open environment

4.1.2 Performance of Rotor A in Partially Bounded Environment

Experiment for partially bounded environment conducted using cylinder, diffuser and nozzle casing. Based on Figure 4.3, Rotor A reaches highest power coefficient value when using nozzle casing with power coefficient of 0.26 at tip speed ratio of 0.52. The maximum power coefficient obtained when Rotor A operated in diffuser casing is 0.25 at tip speed ratio of 0.74. Lastly for cylinder casing, the maximum power coefficient is 0.25 at tip speed ratio of 0.71. In general power coefficient increases in partially bounded environment operations and the highest power coefficient is achieved at a range of tip speed ratio from 0.5-0.8.

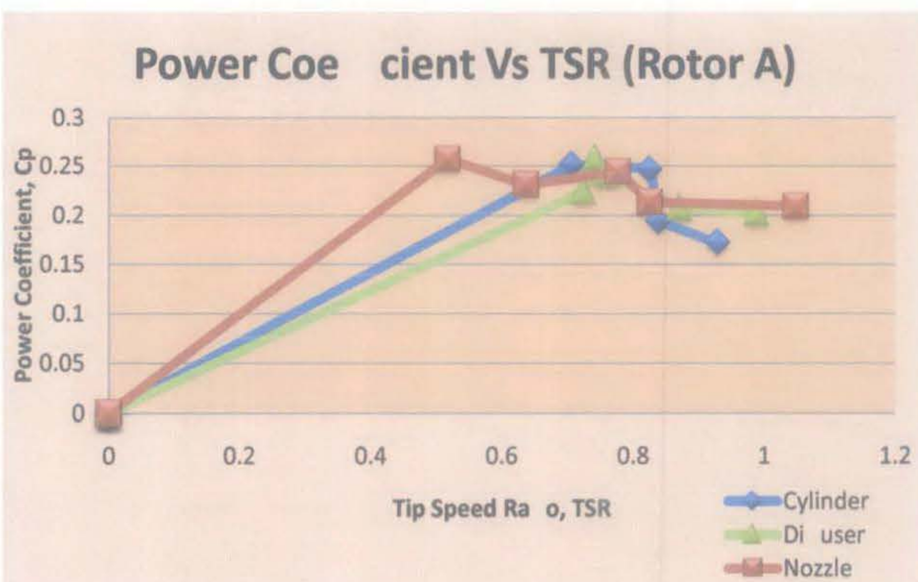


Figure 4.3: C_P versus TSR for Rotor A in partially bounded environment

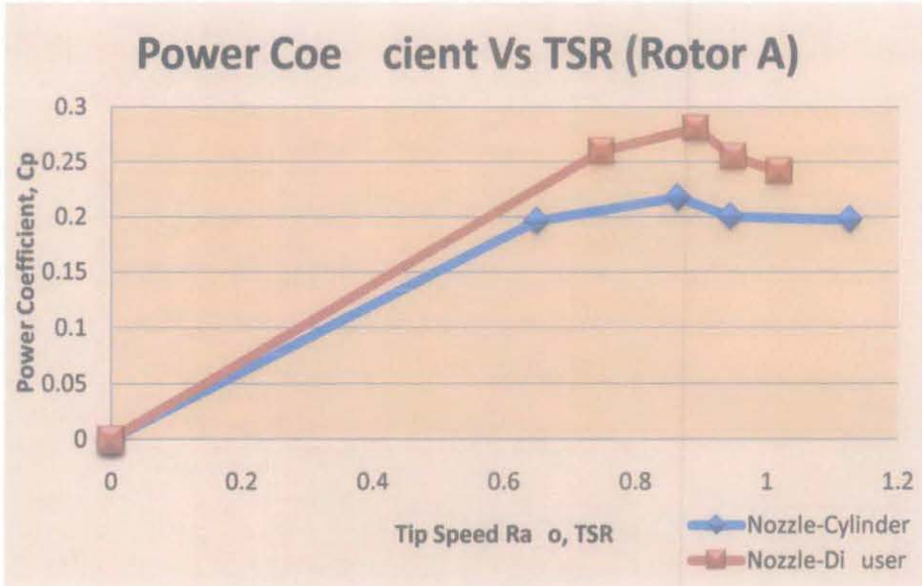


Figure 4.5: C_P versus TSR for Rotor A in fully bounded environment

For fully bounded environment, the highest torque coefficient value was also obtained when the tip speed ratio is equal to zero. Based on Figure 4.6, the maximum torque coefficient when Rotor A operated in nozzle-diffuser is 0.74. For nozzle-cylinder casing installation, the value highest value of torque coefficient is 0.59. During operation in fully bounded environment, higher torque coefficient and tip speed ratio can be achieved. Based on significant result obtained, further discussion will be focusing on nozzle-diffuser casing installation for fully bounded environment.

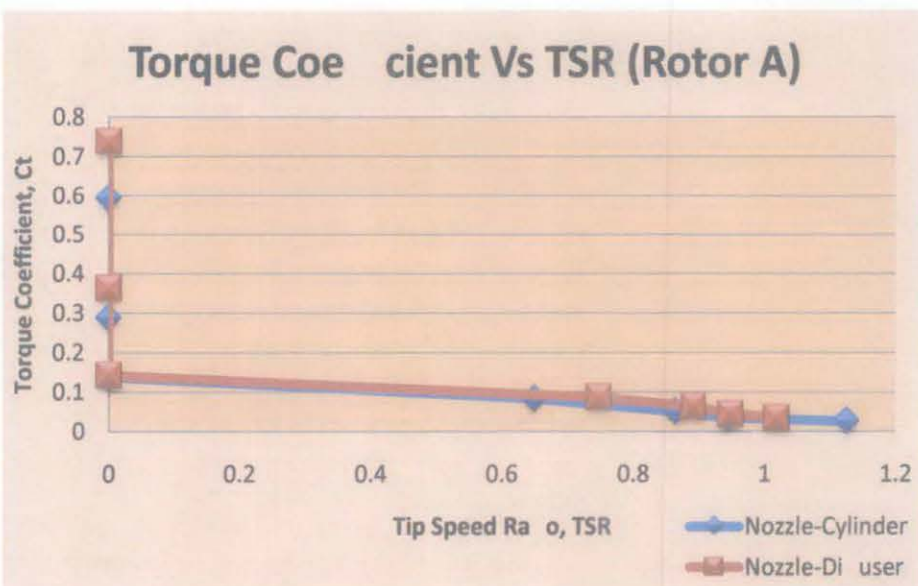


Figure 4.6: C_T versus TSR for Rotor A in fully bounded environment

For partially bounded environment, the highest torque coefficient value is achieved when tip speed ratio is equals to zero. From figure 4.4, the maximum torque coefficient achieved by operating Rotor A in nozzle casing where the value is 0.69. This value followed by torque coefficient reached when using diffuser casing which is 0.54. For operation in cylinder casing, the maximum torque coefficient obtained is 0.40. If comparing tip speed ratio at a range from 0.4-0.6, operation in nozzle casing is much better compare to diffuser and cylinder casings. Focus will be given to nozzle casing when evaluating Rotor A performance in partially bounded environment.

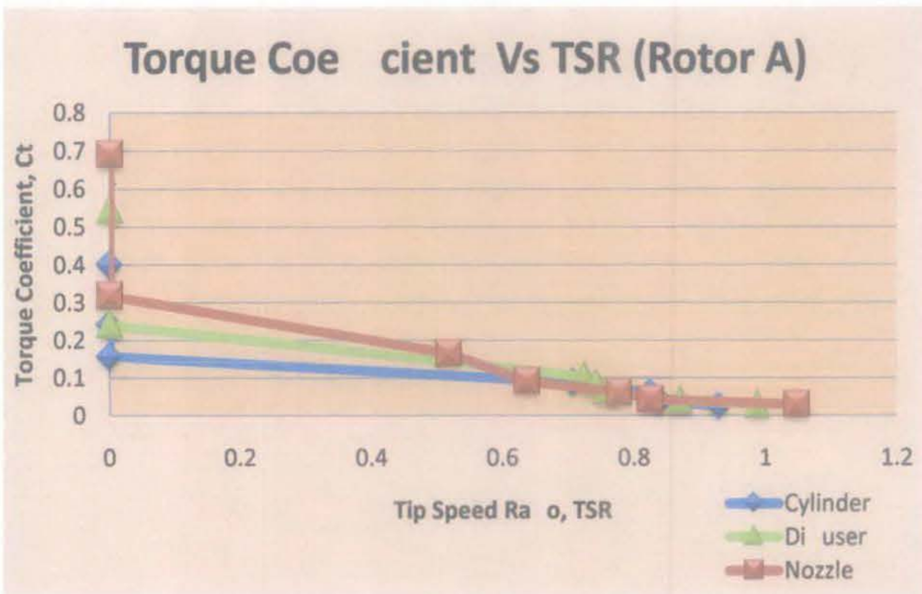


Figure 4.4: C_T versus TSR for Rotor A in partially bounded environment

4.1.3 Performance of Rotor A in Fully Bounded Environment

For experiment of wind rotor in fully bounded environment, two installations will be uses which are nozzle-cylinder casing and nozzle-diffuser casing. From Figure 4.5, the maximum power coefficient for Rotor A is 0.28 at tip speed ratio of 0.89 operating in nozzle-diffuser casing installation. For nozzle-cylinder installation, the maximum power coefficient is 0.22 at tip speed ratio of 0.86. If compare the range of tip speed ratio between 0.6-1.0, it can be seen that nozzle-diffuser casing installation achieved higher power coefficient with increasing tip speed ratio compare to nozzle-cylinder casing installation.

4.1.4 Performance of Rotor A in Different Environments

Comparison of Rotor A power coefficient for three different environments which are open partially bounded and fully bounded was made. Figure 4.7 shows that the maximum power coefficient of 0.28 at tip speed ratio of 0.89 is achieved when Rotor A operating in fully bounded environment (nozzle-diffuser casing). In partially bounded environment (nozzle casing), Rotor A obtain power coefficient of 0.26 at tip speed ratio of 0.52. In open environment, the maximum power coefficient is 0.17 at tip speed ratio of 0.74. When Rotor A operating in partially bounded environment, it reach maximum power coefficient at lowest tip speed ratio compare to open environment and fully bounded environment.

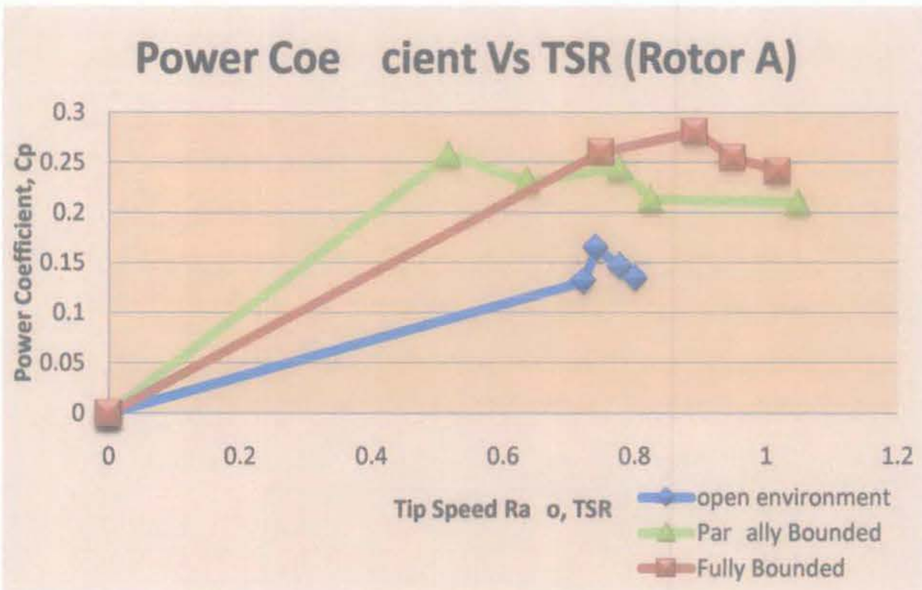


Figure 4.7: C_P comparison for different environments

During data analysis, comparison for torque coefficient for the three different environments also was made. Based on Figure 4.8, the maximum torque coefficient for each environment achieved when tip speed ratio is equal to zero. The maximum torque coefficient is 0.74 for fully bounded environment. The maximum torque coefficient for partially bounded environment is 0.69 and 0.38 for open environment. The torque coefficient decrease as tip speed ratio increase. At the range of 0.0-0.6, operation in fully bounded environment has the highest value of torque coefficient compare to other environments.

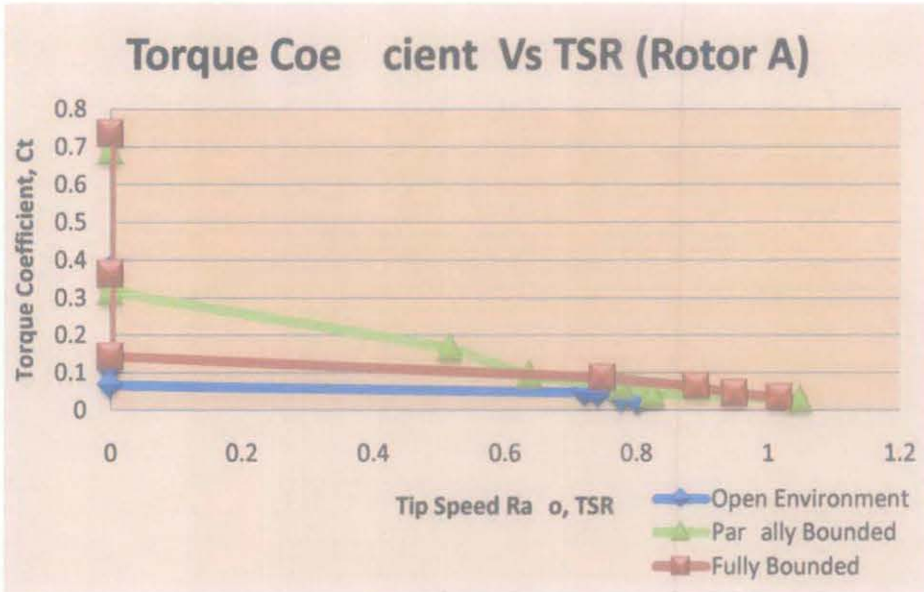


Figure 4.6: C_T comparison for different environments

As discussed earlier, Rotor A operating in fully bounded environment with nozzle-diffuser casing installation performed as predicted, having the highest value of power and torque coefficient. This is because of the side escape stream-line reduction of wind flow passing through wind rotor. Wind flow was concentrated by these bounded casings hence more wind energy was extracted, improving the overall wind rotor performance.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

This project was executed to investigate the performance of wind rotor in three different installation methods which are open, partially bounded and fully bounded environments. For the bounded environments installation method, three different bounded casings was used which are cylinder, diffuser and nozzle.

Comparison of performance for wind rotor in these different installation methods can lead to the development of bounded wind rotor in near future. Two rotor blades were selected and some modification was made to make sure these prototypes can be used for the experiment.

The result obtained was compared for each type of rotor blades operating in different environment. The experiment was successfully conducted and conclusion was made as below:

- Enhance Starting Potential

  The starting wind speed for Rotor A to rotate is 3.7 m/s while for Rotor B is 3 m/s when operating in open environment. When operating in partially bounded environment (nozzle casing), Rotor A starts rotating at 3 m/s and Rotor B starts at 2.7 m/s. For fully bounded environment (nozzle-diffuser casing), Rotor A starts at approximately 2.7 m/s and Rotor B starts approximately 2.4m /s. the starting wind speed for both rotor blades was reduced thus increasing the starting potential

- Enhance Coefficient of Performance, C_P

  As observed in result, there is an increment of power coefficient value for both rotor blades when operating in bounded environment. Rotor blades also manage to reach higher tip speed ratio value in whether in partially or fully bounded environments as compared to open environment. Rotor A achieved maximum power coefficient value in fully bounded environment (0.28).

- Enhance Coefficient of Torque, C_T

  From result, higher torque coefficient vlue was obtained when Rotor A operating in bounded environment. The highest value of torque coefficient is achieved by Rotor A is when operating in fully bounded environment (0.74).

The investigation of wind rotor performance was successfully done by obtaining required data which are rotor blade rotation per minute (RPM) and rotor blade torque produced (N.m). The data obtained by experiment was analyzed to determine performance criteria of wind rotor using related equations. The effect of side escape stream-line reduction by operating wind rotor in partially and fully bounded environments was observed based on result obtained. To get a better understanding regarding this effect, simulation of wind flow can be used for critical analysis. For future continuation of this project, simulation using Computational Fluid Dynamics (CFD) is highly recommended.

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APPENDICES

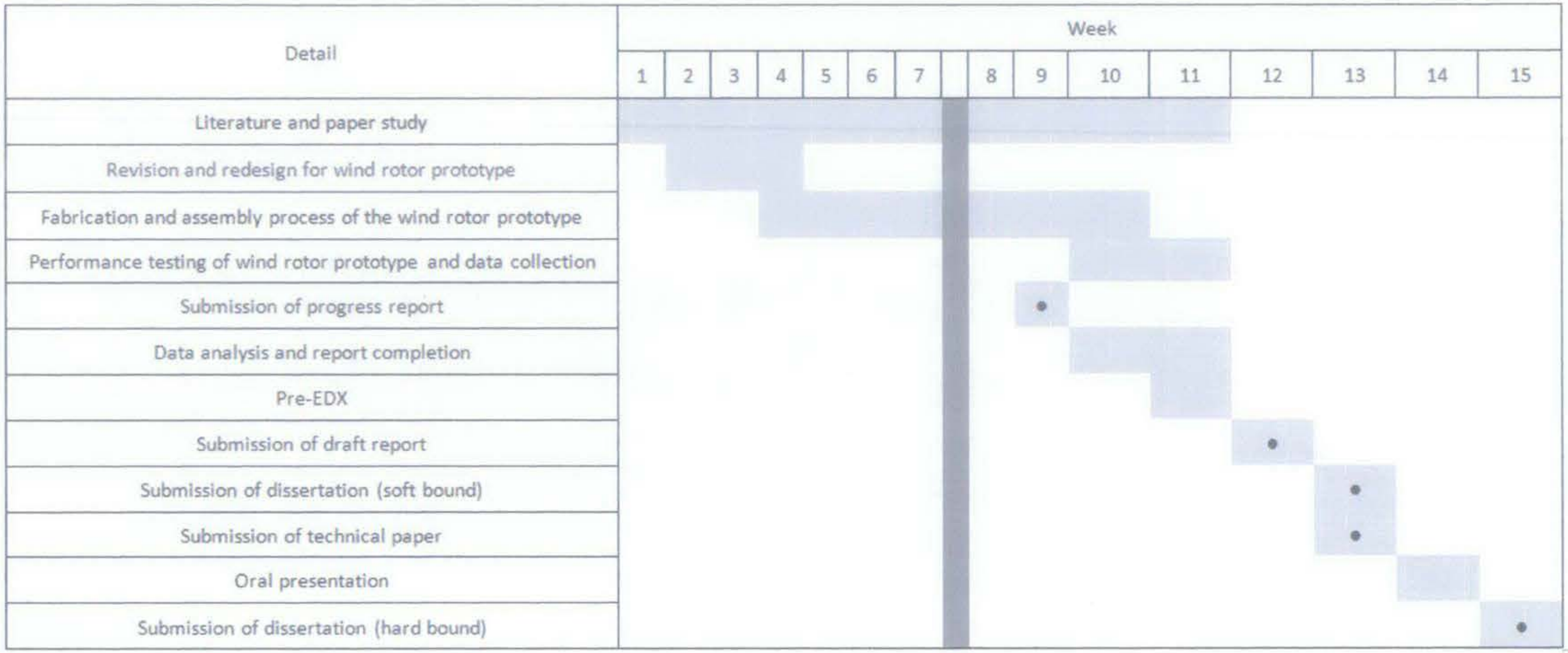


Figure 5: Updated Gantt Chart

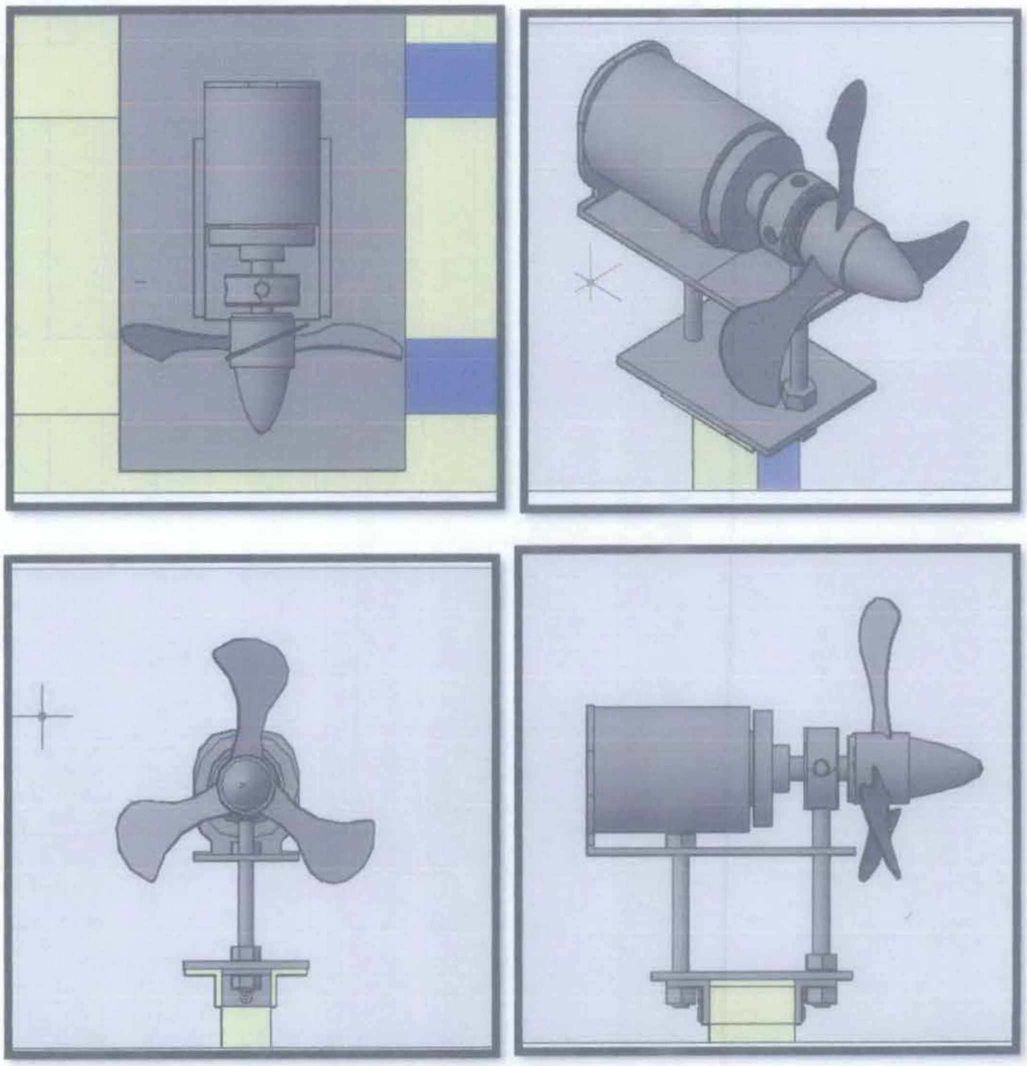
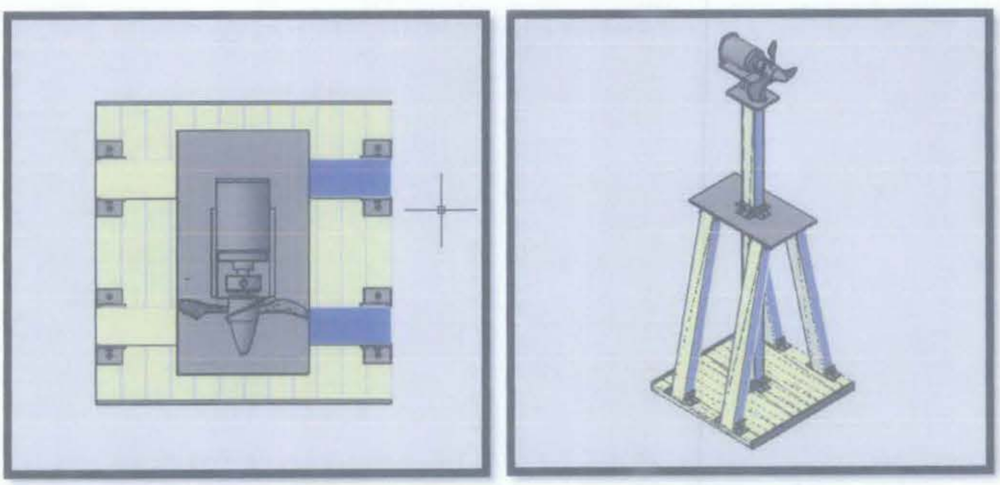


Figure 6: Rotor blade mounting design



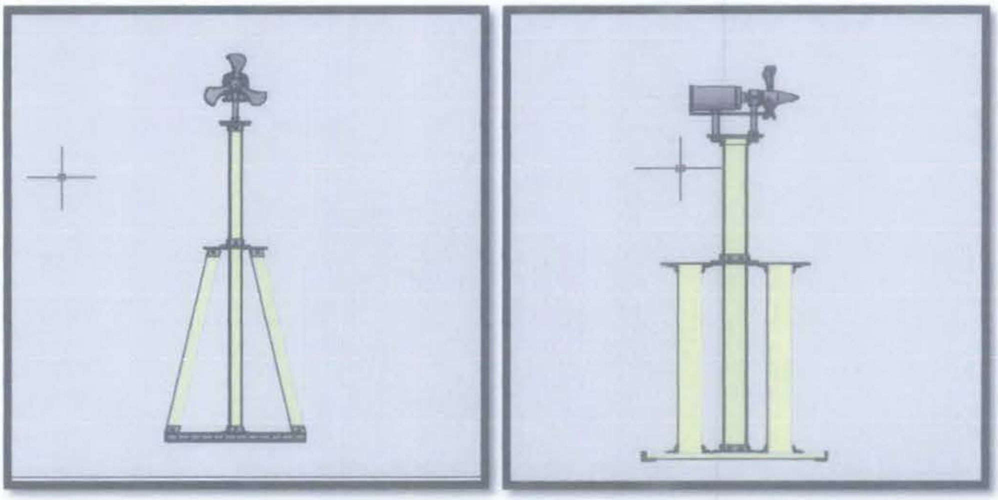
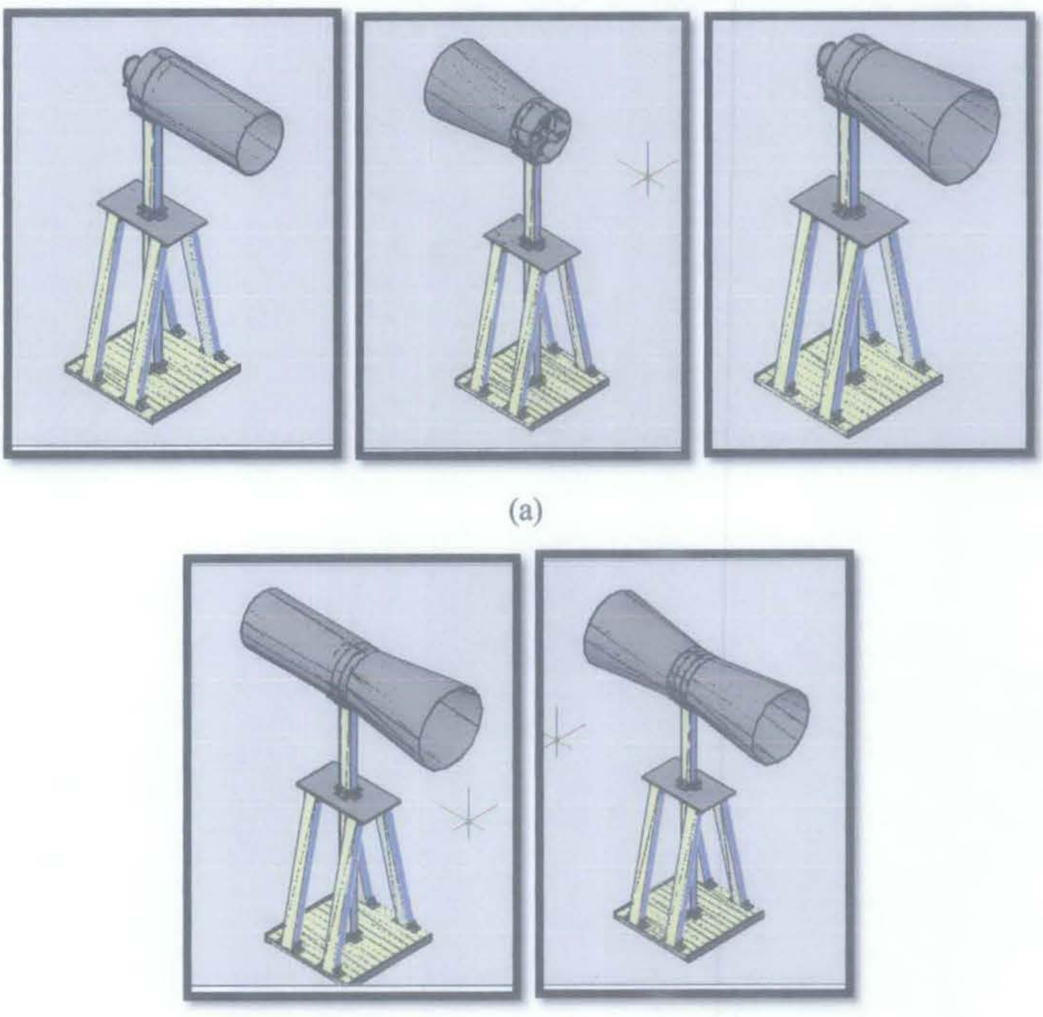


Figure 7: Wind rotor prototype design



(a)

(b)

Figure 8: Installation method design for paritally (a) and fully (b) bounded environments