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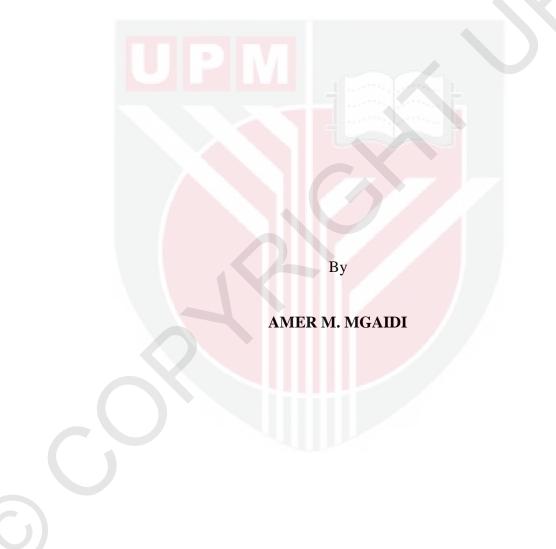
AERODYNAMIC PERFORMANCE OF MAGNUS WIND TURBINE WITH TURBINE SUPPORTIVE STRUCTURE

AMER M. MAGAIDI

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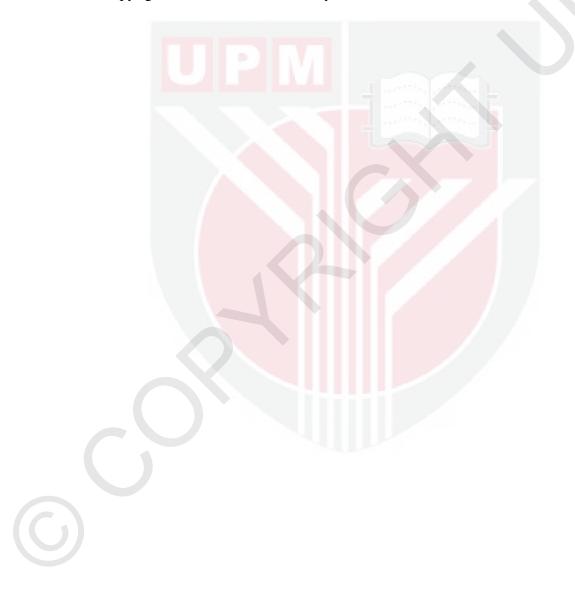
Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

June 2019

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

AERODYNAMIC PERFORMANCE OF MAGNUS WIND TURBINE WITH TURBINE SUPPORTIVE STRUCTURE

By

AMER M. MGAIDI

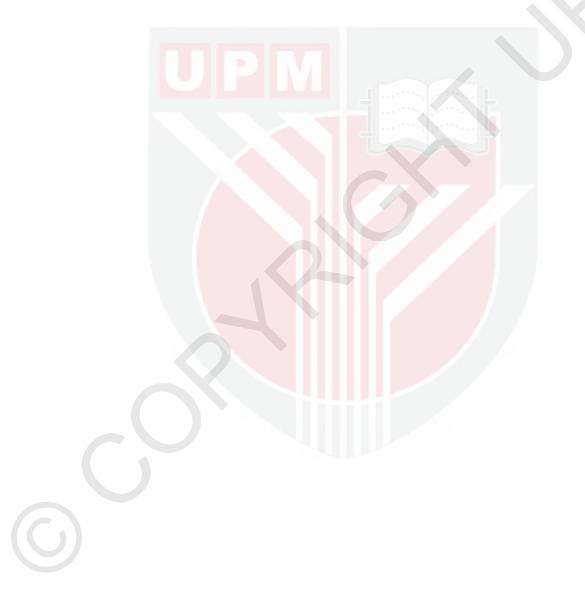
June 2019

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After going through a detailed literature review, it is perceived that the Magnus wind Turbine (MWT) can be a viable option for off grid energy conversion in certain cases of confined space and low wind speed region, where the counterpart of MWT cannot operate efficiently, However, the existing design is yet a matter of research to make it more useful in particular situation. In view of this, the main aim of present study is to improve the aerodynamic performance of MWT through adding a support structure for reduce the impact of free end status of the rotary cylinders on their aerodynamic characterises, where free end status of the cylinders depletes consumed power that uses to spin the cylinders through its impact in reduce the actual rate of cylinders rotation, and hence their tip speed ratio whose low value causes a poor performance of rotary cylinders. To overcome the above undesirable condition, this study suggests modifying magnus rotor through surrounding magnus wheel with an outer ring supported in an analogously order by supporting arms. Currently many research studies have concentrated on improving the aerodynamic performance of wind turbine through numerical, analytical and experimental studies. Computational Fluid Dynamics (CFD) offers inexpensive tool to aerodynamic blade analysis problem. Furthermore, Blade Element Moment (BEM) represents the most simplified common way to predict the overall performance of wind turbines. On the other hand, experimental studies represent the quickly assess of the computed predictive results. 2D Ansys Fluent 17.0 as a code of CFD was selected to analysis the fluid flow around the aerodynamic surfaces of the new rotor in order to predict the effectiveness of new design in improving the aerodynamic performance of MWT, where 2D simulation can provide a good result features of the fluid flow with lesser computational cost. Thereafter, BEM was directed to predict the overall performance of new designed in terms of cut-in speed and generated torque. On the other hand, experimental tests were chosen to perform on a real model of new MWT. Computed results have expected of an increase in lift force by up to 14 % which demonstrated the effectiveness of new design to improve the performance. Besides that, Analytic results of new MWT was



indicated firstly to that, the cut-in velocity decreases as the λ_2 increases in the specified range of $\lambda_2 \leq 2.8$. Also, the generated torque increases in effect of increasing both of wind speed and rotating rate of cylinders at delimited rang of 7.7 m/s and 2520RPM respectively. On other hand, experimental tests demonstrated the effect of tip speed ratio of cylinders (λ_2) on the effectiveness and variation of produced torque. Finally, the obtained results have also achieved the performance of $C_P = 0.47$ at λ_1 of 0.17, as well as disappearance of exhibiting the spinning motion of the cylinders in bell shape.



Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

MENINGKATKAN PRESTASI AERODINAMIK TURBIN ANGIN MAGNUS MELALUI PENAMBAHAN SOKONGAN BULATAN LUAR

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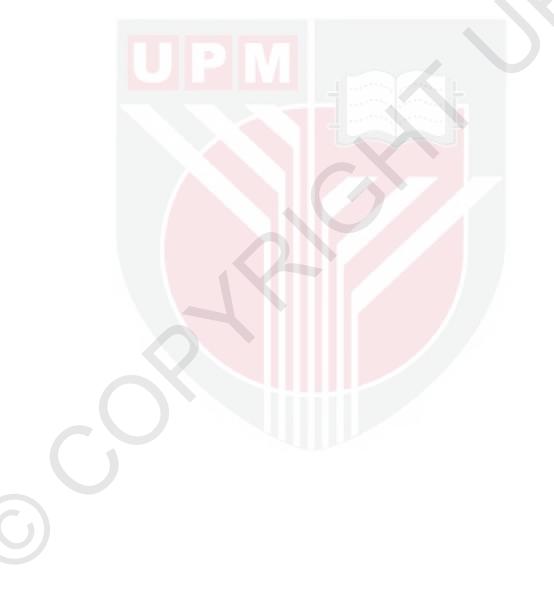
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Setelah melalui kajian literatur yang terperinci, dapat dinyatakan bahawa Turbin Angin Magnus (MWT) boleh dijadikan satu pilihan yang baik untuk penukaran tenaga luar grid bagi kes-kes tertentu seperti ruangan terhad dan kawasan halaju angin yang rendah, di mana turbin angin yang sejenis dengan MWT tidak dapat beroperasi dengan cekap. Namun, reka bentuk yang sedia ada masih lagi merupakan satu perkara penyelidikan untuk menjadikannya lebih berguna dalam keadaan tertentu. Oleh itu, matlamat utama kajian ini adalah untuk menyiasat prestasi aerodinamik MWT dengan penambahan struktur sokongan untuk mengurangkan kesan pergerakan bebas pada hujung silinder berputar terhadap ciri aerodinamik mereka, di mana daya aerodinamik telah dipengaruhi oleh gegaran silinder berputar yang disebabkan oleh tekanan turun naik yang besar. Untuk mengatasi keadaan yang tidak diingini di atas, kajian ini mencadangkan untuk mengubahsuai rotor Magnus melalui mengelilingi bulatan rotor Magnus dengan struktur luar yang bertindak sebagai menyokong lengan, di mana beberapa tenaga yang digunakan untuk memutarkan silinder itu habis kerana kesan akhir percuma, yang membawa kepada penurunan kadar pusing silinder sebenar, dan kemudian nisbah kelajuannya .Ketika ini banyak kajian penyelidikan tertumpu pada peningkatan prestasi aerodinamik turbin angin menerusi kajian berangka, analitikal dan eksperimen. Komputasi dinamik bendalir (CFD) menawarkan perkakasan yang murah untuk permasalahan analisis aerodinamik bilah. Manakala, momen unsur bilah (BEM) memperkenalkan cara umum yang paling mudah untuk menjangkakan prestasi keseluruhan turbin angin. Sebaliknya, kajian eksperimen mewakili cara paling cepat menilai hasil jangkaan yang dihitung. 2D Ansys Fluent 17.0 telah dipilih sebagai kod CFD untuk menganalisa aliran bendalir di sekeliling permukaan aerodinamik rotor yang baru untuk mengkaji keberkesanan reka bentuk tersebut dalam meningkatkan prestasi aerodinamik MWT, di mana simulasi 2D dapat memberikan hasil yang baik terhadap ciri-ciri aliran bendalir dengan kos pengiraan yang lebih rendah. Selepas itu, BEM digunakan untuk mengenalpasti prestasi keseluruhan reka bentuk yang baru dari segi halaju permulaan dan kilasan yang dihasilkan. Sebaliknya, ujian eksperimen telah



dipilih untuk melaksanakan analisis prestasi model sebenar MWT yang baru. Hasil keputusan yang dikira telah menunjukkan peningkatan daya angkat sebanyak 14% yang mana menunjukkan keberkesanan reka bentuk baru bagi meningkatkan prestasi turbin angin MWT. Selain itu, keputusan analitik bagi MWT yang baru ditunjukkan terlebih dahulu, di mana halaju permulaan menurun apabila λ_2 meningkat dalam julat yang dinyatakan $\lambda_2 \leq 2.8$. Kilasan yang dijana meningkat berikutan peningkatan kedua-dua halaju angin dan kadar pusingan silinder pada julat batas masing-masing 7.7 m/s dan 2520 RPM. Sebalik itu, ujian eksperimen menunjukkan kesan nisbah halaju hujung silinder (λ_2) ke atas keberkesanan dan variasi kilasan yang dihasilkan. Akhir sekali hasil yang diperoleh juga telah mencapai prestasi C_P = 0.47 pada λ_1 = 0.17, serta menunjukkan kehilangan pergerakan silinder berputar dalam bentuk loceng.



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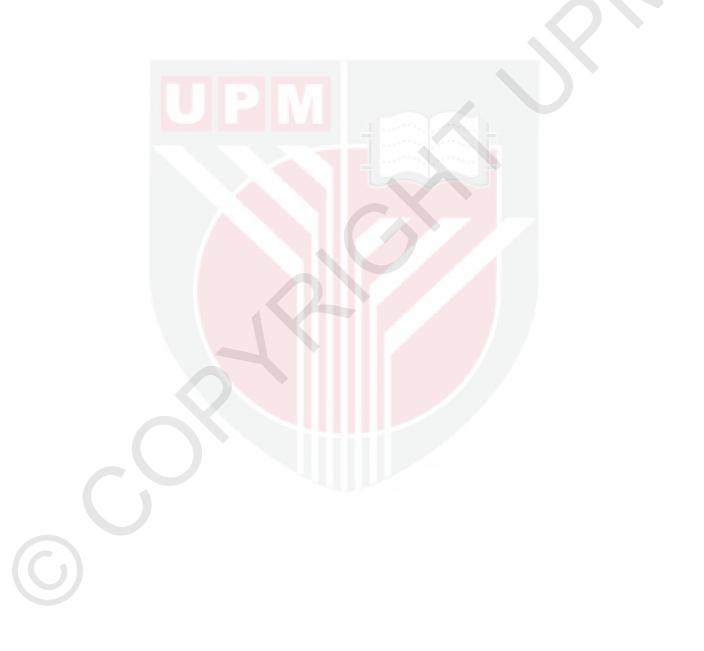
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LIST OF SYMBOLS

	a ₁	Axial Indictor Factor
	a ₂	Radial Indictor Factor
	AR	Aspect ratio
	В	Number of blades
	C _D	Drag coefficient
	CL	Lift coefficient
	C _Q	Torque coefficient
	CP	Power coefficient
	d	Diameter of the cylinder
	P∞	Atmospheric pressure
	Р	Mechanical produced power
	Q	Generated Torque
	R	Diameter of the rotor
	Rg	Universal gas constant
	Re	Reynolds number
	S	Rotor Swept Area
	S _{ref}	Reference Area
	Т	Atmospheric temperature
	U_{∞}	Wind speed
	с	Chord of airfoil
	h	Height of airfoil
	t	Thickness of airfoil
	α	Angle of attack
	β	Angle of relative wind speed

- δ Boundary layer thickness
- μ Viscosity
- ρ Density

 λ_1

- v Kinematic viscosity
- Ω₂ Angular Velocity of Cylinder
- Ω_1 Angular Velocity of Rotor
- λ_2 Tip speed ratio of cylinder
 - Tip speed ratio of Rotor

LIST OF ACRONYMS

- 2D Two Dimensional
- 3D Three Dimensional
- BEM Blade Element Momentum
- CFD Computational Fluid Dynamic
- EFD Experimental Fluid Dynamic
- HAWT Horizontal Axis Wind Turbine
- GIT Grid Independency Test
- NACA National Advisory Committee for Aeronautics
- NREL National Renewable Energy Laboratory
- OBWT Open Jet Wind Tunnel
- VAWT Vertical Axis Wind Turbine

CHAPTER 1

INTRODUCTION

1.1 Background

The extraction of energy from the wind defines one of the major sources of alternative energies. Wind energy as a source of the power is being favoured widely as an alternative to fossil fuels, as it is renewable, plentiful, clean, and so widely distributed. Wind turbine is a configuration, which transforms the kinetic energy from the wind into mechanical energy that can be used to generate electricity via a mechanical rotor, a drive train and a generator (Biadgo, 2017). Several types of wind turbines have been developed in some of categories such as the number of blades and rotating axis orientation, where horizontal axis wind turbines (HAWT) have been widely used due to the advantage of highly efficient in terms of extracted energy. Magnus rotor knows one of the main types that belong to HAWT kind. It distinct from other types by spinning cylinder that creates a whirlpool of fluid around itself and generates a lift force perpendicular to the flow direction as its boundary layer is influenced (Ramjatan and Fitz-coy, 2018), where the producing force defines the Magnus lift force, that has been much larger than streamlined airfoils (Gupta et al., 2017; Borg, 1986). This has motivated a large number of researchers and scientist to use the Magnus lift in aerospace, naval, and wind turbine industries.

From its very inception, the beginning of Magnus effect goes back to the early of nineteen- century when it was used to propel a ship using the Magnus force (De Marco et al., 2016; Nuttall and Kaitu, 2016). Given the success it had by generating high values of lift forces on spinning cylinders compared with airfoil. Flettner rotor was not commercialized due to low fuel prices at that time (De Marco et al., 2016). The potential of generating high lift forces then attracted many researchers in engineering applications, where many patents on using of Magnus forces were appeared. However, very few configurations were operated successfully. The renew interest in the Flettner device is becoming again a hot topic in naval engineering due to the increase in fuel costs and problems of environmental pollution.

Continually to research in related areas, researchers have been compelled to study more about the application of this physical phenomenon. As a result, the Magnus wind turbine which follows the Magnus effect theory had gained proportionate popularity in recent years as a new method of harnessing and exploiting wind for power generation (Bychkov and Dovgal, 2008). The technology actually solves the locationconstraint encountered by traditional wind turbines due to the idea that the configuration can operate even at low wind speeds, which is the case in urban areas. Due to these benefits, Magnus wind turbine offers great potential in producing power as an evolving renewable energy, especially in low wind speed countries like Malaysia. In the broader scope, use of Magnus effect in wind turbine is appeared in Russia and Japan in past decade. Japanese Akita Magnus Association proved that a wind turbine could rotate in effect of the mentioned phenomena Magnus impact, their cylindrical blades were necessary to spin by electric motors (Borg, 1986; Seifert, 2012).

1.2 Problem Statement

Compatible with development of modern life in all fields, the demand of energy has increased significantly. An estimation data by the International Energy Agency IEA (2014) mentioned to that over 80 percent of the world's total energy production results from the burning of fossil (Tietenberg and Lewis, 2016), and with the huge increasing consumption of energy in the world today, the focus of reliable may hurt to risk depletion of this source, Fossil fuels besides is limited, also it takes millions of years to form. In addition to the risk of depletion of fossil fuel, the increase in fuel price is another factor of the problem of energy sources, and more importantly, the factor of environmental pollution; where studies have shown that exceeds the amount of 35 billion metric tonnes of carbon monoxide has been escalating into the atmosphere yearly as a result of fuel combustion (Perera, 2017), that could pose other risks to environment and the balance of nature. Therefore, all of the above are mainly reasons that have promoted the human populations to search for alternative sources of energies and encouraged them to develop through engineering applications in accordance with the applied research and specialized studies and be at the same time are not harmful to nature.

Being one of the alternative energy sources, wind energy has therefore aroused a great deal of interest. Wind energy systems have been improved rapidly and advanced considerably to become an essential energy source. There are still researches and projects in process aiming to improve the wind energy systems and make a more efficient use of the wind rotors which could define the most important part of the wind power stations. Consequently, a number of different wind rotors and configurations have been designed, tried and used during this period. Large amounts of research and resources have been spending in order to improve the performance of wind turbines through determining of optimum specifications that should suite to certain operating conditions (Gupta et al., 2017; Pujol et al., 2018; Sedaghat, 2014; Sedaghat et al., 2014). According to some of guidelines and specific restrictions of the researches on the Magnus rotor specifications as a configuration, it could classify through the factors that has effect on the amount of power extracted, Power generated through applications of wind turbines mainly dependent on the size of the turbine, the wind speed and wind direction. This means that this source of renewable energy is not a stable supply of energy and requires creating some of modification to achieve the requests through special researches. According to the above causes and effects with some of a brief detail, there was a comprehensive incentive in searching to provide a new source of energy. At the same time, a relative underperformance of spindle cylinders within the region of a low- speeds in effect of lift force and the negative impact of flow-induced vibrations in terms the risks of vibrations arising particularly on rotary cylinders, have highlighted to special importance to the field of aerodynamics. Both reasons have embodied an incentive encouraging for researchers

to contest the searching development for spindle cylinders and Magnus rotor through proceeding of some modifications to the geometrical configuration in order to achieve improved performance. As the free end rotating cylinders is the main tool for generating lift and then producing torque in MWT, the free end status of magnus rotary cylinder is the cause of depletion in consumed power that used to spin the cylinders, which lead to reduce the available rotational speed of cylinders and thus their speed ratio that considers one of the main factors determining the effectiveness of the rotating cylinders and their aerodynamic characteristics. Besides that, each cylinder exhibit alternating vortex shedding causing large fluctuating pressure force that could lead to structural failure.

Therefore, the present work is aimed to overcome the above deficiency through new design of surrounding magnus rotor with an outer ring supported in an analogously order by beams or supporting arms mounted on the hub of the rotor, in order to transfer the consumed power to spin the cylinders without depletion by preventing the emergence of each cylinder's spinning motion in bell shape that refers to the issue of power depletion. As the damping amplitude arising, the aerodynamic characteristics of the rotary cylinders predicated to be directly influenced, where the fluctuation of the generator lift force has been increased and hence the quality of the generated torque and produced power. Commonly there is no power generation without angular speed and a gyre torque, hence, there is no torque without aerodynamic forces.

1.3 Aims and Objectives

The main aim of this research work is to study the aerodynamic performance of the design of MWT through the implementation of numerical and analytic studies and then experimental, through which to investigate the effectiveness of new added support structure. Therefore, to achieve the above aim four objectives have to be achieved in the following sequence:

- To design new MWT by adding the support structure in order to improve the performance through reducing the depletion of consumed power.
- To investigate the aerodynamic characteristics of new MWT using computational method in terms of lift force generated on cylindrical blades and supporting arms.
- To analyse the performance of new MWT using BEM method due to the complexity of the computational method.
- To conduct the experimental work in order to validate the BEM method and obtain predictive results that can contribute for estimation of wind turbine performance. performance.

1.4 Scopes of Study

The limitation of the research could be mainly summarized in

- The specifications of both of chosen work section of Open Jet Wind tunnel at aerodynamic laboratory in University Putra Malaysia and used power supply to spin the rotating cylinder. Where the cross-section area of circular geometrical shape with diameter of 2.0 m and delimited range of wind speed of less than or equal 7.74m/s were identified the specifications of mentioned work section. Besides that, the wind flow was assumed to be uniform in order to simplify analysing computed results and obtained experimental results, where the velocity inlet represents one of major input parameters in both of CFD code, BEM and experimental tests; as well the influence of some other relevant factors that included the drag force and the effect of the hub dimensions on the performance of the rotor was ignored.
- As all modern electricity-generating wind turbines use the lift force derived from the blades to drive the rotor and generate the torque, of interest was directed to compute the lift force, where MWT mainly rotate due to exertion of lift force generated on the cylindrical blades when they rotate around a main horizontal shaft.
- On the other hand, the maximum an available power to spinning the cylinders of 0.84W was represent the other major limitation source in this research work. Moreover, there were dependent limitations in some of performance parameters such as rotor tip speed ratio, tip speed ratio of cylinders and Reynolds number, where the mentioned limitation was on the range of results limitation and not on their effectiveness and importance

1.5 Organization of the Thesis

This thesis has been organized in five chapters, the details of which could be summarized following:

Chapter 1: Introduction that includes background, problem statement, aims and Objectives, scopes of study and the organization of the thesis.

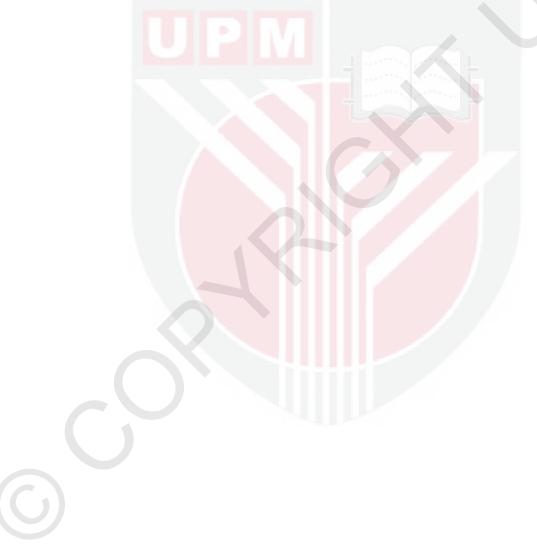
Chapter 2: Literature review which chosen to present a brief on wind turbines, then moves to historical evolution of magnus wind turbine, and then displays the aerodynamic components of magnus rotor.

Chapter 3: methodology, it includes calibration of wind flow speed at work section, 3.3. Technical specification of new Magnus rotor, three chosen approaches of numerical, analytical and experimental. Where numerical approach includes Information about turbulence models, geometrical design using of work bench Ansys, domain details, the boundary conditions, grid independence test and parametric study

on Sn-airfoil, while analytical approach include Information about blade element theory and determine the aerodynamic performance of new magnus wind turbine. On the other hand, the experimental approach covers the fabrication of new magnus turbine equipment setup and the experiment methods.

Chapter 4: results and discussion: this chapter presents analysis and discussion of obtained results, and also the computed and experimental results were Compared. This chapter is important to validate the solver used and also to choose the most suitable turbulence model for further simulations.

Chapter 5: conclusion and future work, where concluding remarks are stated and recommendations for future work are addressed.



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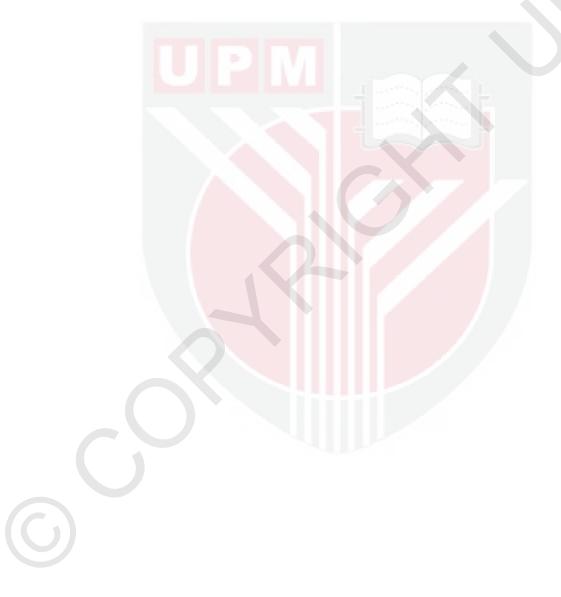
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BIODATA OF STUDENT

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LIST OF PUBLICATIONS

- Numerical and Experimental Analyses of the Flow around a Rotating Circular Cylinder at Subcritical Regime of Reynolds number using k-ε and k-ω-sst Turbulent Models. A. M. Mgaidi, A. S. Mohd Rafie, K. A. Ahmad, R. Zahari, M. F. Abdul Hamid and O. F. Marzuki. Published, VOL. 13, NO. 3, FEBRUARY 2018, ISSN 1819-6608. www.arpnjournals.com.
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