

EXPERIMENTAL AND SIMULATION STUDY OF A DIFFUSER AUGMENTED  
WIND TURBINE TO ENHANCE THE PERFORMANCE BY MODIFYING  
DIFFUSER AND ROTOR

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## DEDICATION

To the lighthouse of science; Great Prophet Mohammed (peace be upon him).

To my homeland, family, supervisors and all whom have assisted me.



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## ABSTRACT

Wind energy technology represented in wind turbines is one of the fastest growing alternative energy technologies, especially horizontal axis wind turbine (HAWT) type which is more efficient, compared to other conventional wind turbines. However, it is less utilized in urban areas due to the relatively low wind velocity in these areas. In this work, a technique of augmenting wind by the concept of diffuser augmented wind turbine (DAWT) has been presented to improve the efficiency of small scale of HAWT by enclosing it with a suitable diffuser. The study included two stages for performance improvement; first, developing the diffuser design in three configurations, and second, developing the design of HAWT rotor blades based on the maximum increase of wind velocity in the modified diffuser; at the rotor position, a Modified Theory was used. Two models of DAWT were obtained; one of them was installed with the preliminary rotor, while the other one was installed with the modified rotor where aerodynamic performance predictions of the diffuser, bare HAWT, and DAWTs models have been studied through experimental and simulation approaches. The simulation study was performed using 3-D CFD models based on the *SST k- $\omega$*  turbulence model using ANSYS 19.1, while the experimental study was conducted in an open-loop wind tunnel. The performance evaluations of the models were established in terms of power, torque and aerodynamics coefficient which were power coefficient and torque coefficient. The systematic analysis of these quantities showed that DAWT with a flanged diffuser achieved a significant increase in performance compared to bare HAWT. The results also demonstrated that DAWT with flange angle of  $0^\circ$ , at both rotors models, achieved the best augmented in power, compared to other flange configurations. On the other hand, the average power was augmented in the DAWT at  $0^\circ$  flange angle ( $\Theta_f$ ) with the preliminary rotor (FDAWT-PR) by around 256%, compared to bare HAWT, while the augmentation reached up to 291% in DAWT with the modified rotor (FDAWT-MR) at same flange angle. In addition, FDAWT ( $\Theta_f=0^\circ$ )-MR has a simple shape, economic, and compact size. Furthermore, the simulation was conducted to visualize the fluid flowing around the chosen models, as well as giving precise details that difficult to obtaining them practically.

## ABSTRAK

Teknologi tenaga angin yang digunapakai dalam turbin angin merupakan salah satu teknologi tenaga alternatif yang paling pesat berkembang terutama turbin angin paksi (HAWT) yang lebih efisien berbanding turbin angin konvensional yang lain. Walaubagaimanapun, ia kurang digunakan sepenuhnya di kawasan berpendudukan padat kerana kebiasaannya angin di situ adalah berkelajuan rendah. Dalam kerja-kerja ini, satu teknik penambahan angin melalui konsep turbin penyebar angin tambahan (DAWT) telah dipersembahkan dengan melengkapkannya dengan penyebar yang sesuai untuk meningkatkan kecekapan skala kecil HAWT. Kajian ini merangkumi dua peringkat penambahbaikan prestasi; pertama, membangunkan reka bentuk penyebar dalam tiga konfigurasi, dan yang kedua, mengembangkan reka bentuk bilah pemutar HAWT berdasarkan kenaikan maksimum kelajuan angin di peresap yang diubahsuai pada kedudukan pemutar dengan menggunakan bilah yang diubah suai berdasarkan teori momentum unsur. Dua model DAWT diperolehi, salah satunya adalah dengan menggunakan pemutar awal, manakala yang kedua adalah dengan pemutar yang diubah suai, yang mana ramalan prestasi aerodinamik penyebar, model HAWT dan DAWT terdedah telah dikaji melalui pendekatan percubaan dan simulasi. Kajian simulasi dilakukan menggunakan model 3-D CFD berdasarkan model pergolakan SST  $k-\omega$  menggunakan ANSYS 19.1, sementara kajian percubaan dijalankan dalam terowong angin gelung terbuka. Kecekapan penilaian model di perkukuhkan dalam terma kuasa, tork dan pemalar aerodinamik iaitu pemalar kuasa dan pemalar tork. Analisis sistematik kuantiti ini memperlihatkan bahawa DAWT dengan peresap bibir mencapai peningkatan yang signifikan dalam prestasi berbanding HAWT yang terdedah. Hasilnya juga menunjukkan bahawa DAWT dengan sudut flens  $0^\circ$  pada kedua-dua model rotor mencapai kuasa tambahan yang terbaik berbanding dengan konfigurasi bibir yang lain. Selain itu, purata kuasa diperkuatkan di DAWT pada sudut bibir  $0^\circ$  dengan pemutar awal adalah sebanyak 256% berbanding dengan HAWT yang terdedah, manakala pembesarannya mencapai 291% dalam DAWT dengan rotor yang diubahsuai pada sudut bibir yang sama. Selain itu, simulasi telah dijalankan untuk menggambarkan aliran di sekitar model yang dipilih; serta memberikan butiran yang tepat yang sukar untuk mendapatkannya secara praktikal.

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## LIST OF SYMBOLS AND ABBREVIATIONS

$a$	-	Axial induction factor for bare turbine
$a^*$	-	Axial induction factor for DAWT
$a_{opt}$	-	Optimum axial induction factor for bare turbine
$a_{apt}^*$	-	Optimum axial induction factor for DAWT
$a_t$	-	Tangential induction factor for bare turbine
$a_t^*$	-	Tangential induction factor for DAWT
$A$	-	Rotor swept area (m <sup>2</sup> )
$A_3$	-	Diffuser exit area (m <sup>2</sup> )
$B$	-	Number of turbine blades
$c$	-	Chord length (m)
$C_D$	-	Drag coefficient
$C_l$	-	Lift coefficient
$C_n$	-	Normal force coefficient
$C_P$	-	Power coefficient for bare turbine
$C_{P,d}$	-	Power coefficient for DAWT
$C_{P,max}$	-	Maximum power coefficient for bare turbine
$C_{P,d,max}$	-	Maximum power coefficient for DAWT
$C_Q$	-	Torque coefficient for bare turbine
$C_{Q,d}$	-	Torque coefficient for DAWT
$C_t$	-	Tangential force coefficient
$C_T$	-	Thrust coefficient for bare turbine
$C_{T,d}$	-	Thrust coefficient for DAWT
$dF_n$	-	Normal force per blade section (N)

$dF_t$	-	Tangential force per blade section (N)
$dQ$	-	Torque per blade section for the bare turbine (N.m)
$dQ_d$	-	Torque per blade section for DAWT (N.m)
$dT$	-	Thrust force per blade section for the bare turbine (N)
$dT_d$	-	Thrust force per blade section for DAWT (N)
$F$	-	Correction losses factor
$F_{tip}$	-	Tip losses factor
$P$	-	Output power for the bare turbine (W)
$P_d$	-	Output power for DAWT (W)
$Q$	-	Rotor torque (N.m)
$r$	-	Radial position (m)
$R$	-	Radius of the turbine (m)
$Re$	-	Reynolds number
$T$	-	Thrust force for the bare turbine (N)
$T_d$	-	Thrust force for DAWT (N)
$V_1, V_2$	-	Wind velocity at rotor plane (m/s)
$V_1^*$	-	Maximum axial wind velocity in the diffuser (m/s)
$V_3$	-	Wind velocity at diffuser exit (m/s)
$V_d$	-	Downstream wind velocity (m/s)
$V_\infty$	-	Upstream wind velocity (m/s)
$W$	-	Relative wind velocity (m/s)
$\alpha$	-	Angle of attack (deg)
$\beta$	-	Blade twist angle (deg)
$\epsilon$	-	Ratio of maximum axial to upstream wind velocity in the diffuser
$\delta$	-	Velocity speed up ratio
$\eta_c, \eta_g$	-	Conversion and generator efficiency
$\theta_f$	-	Flange angle
$\lambda$	-	Tip speed ratio (TSR)
$\mu$	-	Dynamic viscosity of air (kg /m.s)

$\rho$	-	Air density ( $\text{m}^3/\text{s}$ )
$\sigma$	-	Solidity ratio
$\varphi$	-	Angle of relative wind velocity (deg)
$\Omega$	-	Angular velocity of the rotor (rad / s)

### Acronyms

ADM	-	Actuator Disk Model
ALM	-	Actuator Line Model
BEM	-	Blade element momentum theory
BHAWT	-	Bare horizontal axis wind turbine
BVAWT	-	Bare vertical axis wind turbine
CAWT	-	Concentrators Augmented Wind Turbine
CDAWT	-	Collector - Diffuser Augmented Wind Turbine
CFD	-	Computational fluid dynamic
DAWT	-	Diffuser augmented wind turbine
ESAWT	-	Ejector Shroud Augmented Wind Turbine
FD	-	Flanged diffuser
FDAWT	-	Flanged diffuser augmented wind turbine
FRM	-	Fully Rotor Model
HAWT	-	Horizontal axis wind turbine
MR	-	Modified rotor
NACA	-	National Advisory Committee for Aeronautics
NFD	-	Non-flanged diffuser
NFDAWT	-	Non-flanged diffuser augmented wind turbine
PR	-	Preliminary rotor
RANS	-	Reynolds- Averaged Navier-Stokes
rpm	-	Revolution per minute
SHAWT	-	Shrouded horizontal axis wind turbine
SST	-	Shear stress transport
SVAWT	-	Shrouded vertical axis wind turbine
VAWT	-	Vertical axis wind turbine

**LIST OF APPENDICES**

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PTTA UTHM  
PERPUSTAKAAN TUNKU TUN AMINAH

## CHAPTER 1

### INTRODUCTION

#### 1.1 Research background on wind turbines

The need for energy in societies is increasing as technologies are advancing in certain areas. Thus, the capability to produce energy must keep pace with those increasing demands. Due to the rapid depletion of fossil energy sources, there is a necessary obligation to seek alternative and sustainable sources of energy [1], [2], [3]. As such, wind energy as a renewable and inexhaustible source of energy is now the fastest growing energy technology worldwide. Compared to conventional energy sources, wind power has many advantages. Unlike fossil fuels that emit harmful gases, or nuclear power that generates radioactive wastes, wind power on the other hand is a clean and environmentally friendly energy source. As an inexhaustible and free energy source, it is available plentiful in most regions of the earth. In addition, more extensive use of wind power would help reducing the demands for fossil fuels, which may run out within some times in this century according to present levels of consumption [1], [2], [4], [5], [6]. Wind power systems, represented by wind turbines, have been the focus of interest by scientists and researchers in the past decades. Flowing of wind through the turbine rotor leads to production of mechanical energy which can be utilized in many applications especially when it comes to producing electricity. However, power produced by a wind turbine is dependent on the Betz limit; an ideal type can extract only 59.3% of incoming energy in stream-tube by turbine blades [7], [8].

## 1.2 Development of wind turbines

Wind energy is abundant, clean, cheap, and has been made the most of by mankind for centuries in agriculture for water pumping, crop irrigation and grain grinding [9]. Wind turbine is a rotary machine that extracts energy from the wind. Rotor blade is a key element in a wind turbine generator system which converts wind energy into mechanical energy [1]. These days, wind energy is acknowledged as a mainstream form of energy in electrical power generation and is has been an increasing trend. According to the global wind energy outlook, global cumulative installed wind capacity has increased significantly since the year 2001, and reached 539,581 MW in the year 2017 as shown in Figure 1.1 [10].

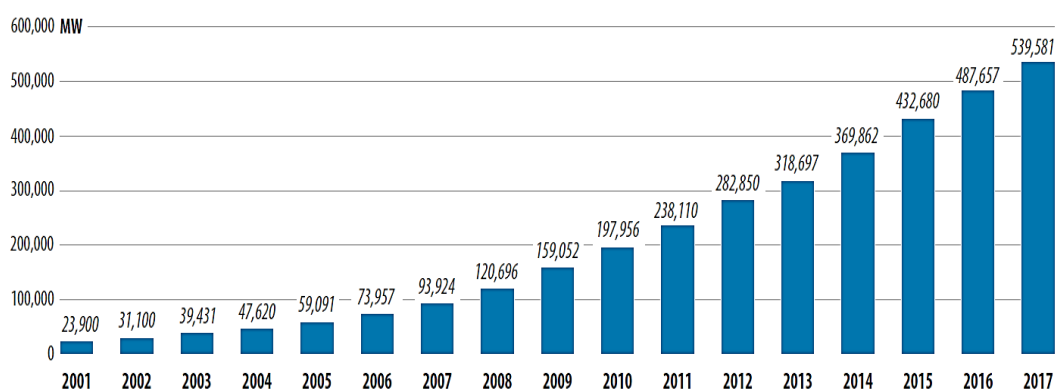


Figure 1.1: Global cumulative installed wind capacity from year 2001 to 2017 [10].

## 1.3 Classification of wind turbines

There are various types of wind turbines currently have made use of; they are grouped into different classes based on diverse factors. Wind turbine types can be classified either as drag and lift. For drag turbines, rotor moves slowly but at high force, hence, this type of wind turbines is suitable to be used for irrigation and pumping. Contrarily, lift turbines have high rotational speeds, thus, they are used in electricity production process [6]. The blades of this type of turbine work similarly as wings of a plane. They are designed with a cambered airfoil, in order to create a pressure difference between the lower and upper surfaces. High pressure is created in the lower surface of the blade, while the upper surface is exposed to low pressure. This is because of the fact that air has to travel a longer distance on the upper side of the airfoil, but shorter distance on

the lower surface airfoil from the top surface, as well as bottom surface has to meet at the same instant at the trailing edge of airfoil to have a circulation which results in lift generation [6]. Typical classifications of wind turbines include Horizontal Axis Wind Turbines (HAWTs) and Vertical Axis Wind Turbines (VAWTs). The following section discussed these two significant types of wind turbines which depended on the orientation of the shaft and rotor axis of rotation; upwind or downwind turbines depended on rotor position in relation to oncoming wind, while small or large wind turbines depended on wind turbine power output [2], [11], [12], [13].

### **1.3.1 Vertical Axis Wind Turbines (VAWTs)**

Vertical axis wind turbine is a turbine type that rotates perpendicularly axis to wind direction. The center axis of the tower in modern VAWTs is connected to a speed escalating gearbox. This shaft drives a generator that converts the mechanical power of the rotor to electrical power. There are several innovations of VAWTs in which the power is generated in such a design either drag (Savonius) or lift (Darrieus) [14]. Moreover, VAWT can be operated in two configurations namely bare VAWT (BVAWT) and shrouded VAWT (SVAWT).

### **1.3.2 Horizontal Axis Wind Turbines (HAWTs)**

The most common design of wind turbines is HAWT, generally classified according to the rotor orientation (upwind or downwind of the tower). Figure 1.2 shows a blade articulation (rigid or teetering), number of blades (generally two or three blades), rotor control (pitch stall) and how they are aligned with wind (free yaw or active yaw). HAWT is one of the most common design for electricity production, particularly the three-bladed rotor. Most of the commercial wind turbine fall under this category [14], [15]. Currently, most of manufactures are HAWT that is due to their relatively high efficiency, low cut-in speed, easy furling, self-start and aerodynamic stability. The HAWT consist of three major components, namely rotor, nacelle, and tower. The major components of a HAWT are the rotor consisting of blades and a supporting hub. The power-train includes the rotating parts of the wind turbine (exclusive of the rotor); it usually consists of shafts, gearbox, coupling, a mechanical brake and generator. The nacelle structure and main frame include wind turbine housing and yaw system [14].



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