# DIFFUSER AUGMENTED WIND TURBINE FOR LOW-SPEED WIND

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## DEDICATION

Dedicated to Nadia Atwa, Mohamed Elsherbeiny, Ayman, Aya, and Amber

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## ABSTRACT

Wind energy is the cheapest way to create additional renewable electric generating capacity. Nonetheless, it is proportional to the cubic of wind speed, which means that regions with low wind speeds, such as countries near the equator, have limited wind energy potential. Such limitation can be addressed with Diffuser Augmented Wind Turbine (DAWT), which can accelerate the flow and increase the efficiency of the wind turbine to exceed the Betz limit. However, the flow separation that occurs on the inner walls of DAWT is the main problem in degrading the DAWT performance. Furthermore, the flow is vulnerable to laminar separation at low wind speeds. Therefore, this study aimed to develop a DAWT that can operate at wind speeds lower than 5 m/s and investigate the possibility of using the number of rotor blades as a passive boundary layer control. The design of DAWT was developed by designing a bare wind turbine and a diffuser suitable for low wind speeds. The thin airfoil SD2030 was used as the blade profile of the bare turbine, while the suction surface of the same airfoil was also used as the profile of the diffuser to overcome laminar separation. In addition, the diffuser design was completed following a parameter study that evaluated flange configuration and height, diffuser cross-section profile, and diffuser opening angle. The final diffuser configuration has a flat flange with a height to rotor diameter ratio of 0.05 to minimize the total reference area of DAWT. Velocity vector analysis revealed that employing the suction surface of the airfoil SD2030 as the diffuser cross-section profile improved the flow structure by delaying stall at a wider opening angle, allowing the opening angle to be extended to 15°. After finalizing the DAWT design and its parameters, the effects of the rotor's blade numbers and solidity were evaluated by studying the 2-blade, 3-blade, and 4-blade DAWT. This research was conducted using computational fluid dynamics (CFD) simulations with Ansys CFX. Eventually, the final design was tested in a wind tunnel to validate the CFD results. The test findings show that the developed 3-blade DAWT has a low starting speed of 1m/s and effectively operates with a power coefficient of 0.599 at a low wind speed of 5m/s, which agrees with CFD results. By analyzing the velocity contours behind the rotor's plane, it was found that increasing the number of the rotor's blades increased the kinetic energy at the rotor's tips which helped energize the flow close to the diffuser’s inner walls. Consequently, this helped the boundary layer stay attached to the diffuser's walls and avoid separation. Velocity vectors from CFD results showed that the 4-blade DAWT has the flow fully attached to the diffuser at an opening angle of 20° compared to the 3-blade and 2-blade DAWT, which had the flow completely separated at the same opening angle. These results proved that the rotor's blade number can be used as a passive boundary layer control. In conclusion, a DAWT which is suitable for low wind speeds has been successfully developed, benefiting nations with low average wind speeds like Malaysia. The potential of rotor's blade number as a passive boundary layer control has also been successfully investigated, which contributed to broadening the DAWT's understanding.

# ABSTRAK

Tenaga angin adalah cara termurah untuk menghasilkan kapasiti penjanaan elektrik tambahan yang dapat diperbaharui. Tetapi, tenaga angin adalah berkadar dengan kelajuan angin kuasa tiga yang mana kawasan dengan kelajuan angin rendah seperti negara-negara berhampiran khatulistiwa, mempunyai potensi tenaga angin yang terhad. Kekangan ini mampu diatasi dengan Turbin Angin Tambahan Peresap (DAWT) yang berupaya untuk mempercepatkan dan meningkatkan kecekapan turbin angin melebihi had Betz. Walau bagaimanapun, pemisahan aliran yang berlaku pada dinding dalaman DAWT adalah masalah utama yang menjejaskan prestasi DAWT. Tambahan pula, aliran udara terdedah kepada pemisahan lamina pada kelajuan angin yang rendah. Oleh itu, kajian ini bertujuan untuk membangunkan DAWT yang boleh beroperasi pada kelajuan angin lebih rendah daripada 5m/s dan menyiasat kemungkinan untuk menggunakan bilangan bilah pemutar sebagai kawalan lapisan sempadan pasif. Reka bentuk DAWT telah dibangunkan dengan mereka bentuk turbin angin kosong dan peresap yang sesuai untuk kelajuan angin rendah. Kerajang udara nipis SD2030 digunakan sebagai profil bilah turbin kosong tersebut, sementara permukaan sedutan bagi kerajang udara yang sama juga digunakan sebagai profil peresap untuk mengatasi pemisahan lamina. Reka bentuk peresap merangkumi kajian parameter untuk menilai konfigurasi bebibir dan ketinggian, profil keratan rentas, dan sudut bukaan peresap. Konfigurasi akhir peresap mempunyai nisbah ketinggian bebibir berbanding diameter pemutar dengan nilai 0.05 untuk meminimumkan jumlah keluasan kawasan rujukan DAWT. Analisis vektor halaju menunjukkan bahawa profil peresap SD2030 telah melengahkan tegun pada sudut bukaan setinggi 15°. Selepas memuktamadkan reka bentuk DAWT dan parameternya, kesan nombor bilah pemutar dan kepejalannya dinilai dengan mengkaji DAWT 2-bilah, 3-bilah dan 4-bilah. Penyelidikan ini dijalankan menggunakan simulasi pengiraan dinamik bendalir (CFD) dengan Ansys CFX. Akhirnya, reka bentuk akhir telah diuji dalam terowong angin untuk mengesahkan keputusan CFD. Penemuan ujian menunjukkan bahawa DAWT 3 bilah yang dibangunkan mempunyai kelajuan permulaan yang rendah iaitu 1m/s dan berkesan beroperasi dengan pekali kuasa 0.599 pada kelajuan angin serendah 5m/s, konsisten dengan keputusan CFD. Dengan menganalisis kontur halaju di belakang satah pemutar, didapati bahawa menaikkan bilangan bilah rotor dapat meningkatkan tenaga kinetik pada hujung pemutar yang membantu memberi tenaga aliran dekat dengan dinding dalam peresap. Seterusnya ia membantu lapisan sempadan kekal melekat pada dinding peresap dan elakkan pemisahan. Vektor halaju daripada keputusan CFD menunjukkan bahawa DAWT 4-bilah mempunyai aliran yang melekat sepenuhnya pada peresap pada sudut bukaan 20° berbanding DAWT 3-bilah dan 2-bilah, yang mempunyai aliran dipisahkan sepenuhnya pada sudut bukaan yang sama. Keputusan CFD ini membuktikan bahawa nombor bilah pemutar boleh digunakan sebagai kawalan lapisan sempadan pasif. Kesimpulannya, reka bentuk DAWT yang sesuai untuk angin berkelajuan rendah telah berjaya dibangunkan, memberi manfaat kepada negara-negara yang mempunyai kelajuan angin purata rendah seperti Malaysia. Potensi bilangan bilah rotor sebagai kawalan lapisan sempadan pasif juga telah berjaya diselidiki, yang menyumbang untuk memperluas pemahaman DAWT.

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| | | |
|---|---|---|
| CFD | - | Computational Fluid Dynamics |
| DAWT | - | Diffuser Augmented Wind Turbine |
| BEM | - | Blade Element Momentum |
| RANS | - | Reynolds Averaged Navier Stokes |
| TSR | - | Tip Speed Ratio |
| RPM | - | Rotation Per Minute |
| Re | - | Reynolds Number |
| BL | - | Boundary Layer |
| SST | - | Shear Stress Transport |
| KKL | - | Koo Kleinstreuer Li |

## LIST OF SYMBOLS

| | | |
|---|---|---|
| Cp | - | Power Coefficient |
| Cp* | - | Normalized Power Coefficient |
| $\theta$ | - | Diffuser opening angle |
| L | - | Diffuser length |
| $D_e$ | - | Diffuser exit diameter |
| H | - | Flange height |
| r | - | Augmentation ratio |
| W | - | Watt |
| $B_R$ | - | Blockage ratio |
| Yplus | - | Non-dimensional distance |

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# CHAPTER1

# INTRODUCTION

## 1.1 Introduction

Wind energy is one of the fastest expanding sources of new energy capacity. In 2020, the globe generated 743 GW of electricity (1), accounting for 6% of global production. Wind energy production increased by 93 GW compared to 2019, with an almost 14% growth rate. Many nations, such as Denmark, achieved 20% wind energy output, with wind energy accounting for 57 % of total power generation in 2019. (2). Figure 1.1 shows the share of renewable energy in the world's electricity production by 2020.

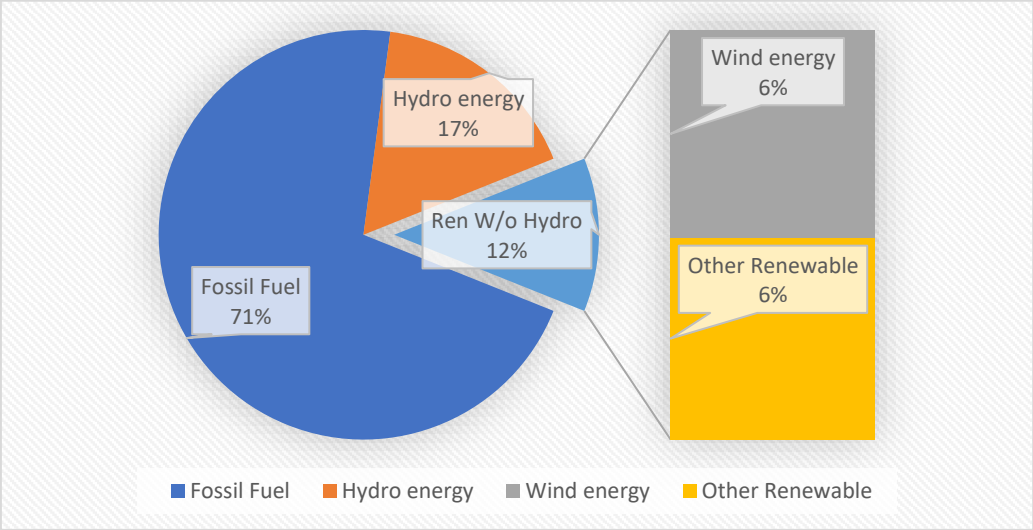


Figure 1.1 Global Electricity Production End-2020 (1).

Countries located in the equatorial zone, such as Malaysia, considered one of the Doldrums countries (located slightly to the north of the equator), are characterized by frequent showers, thunderstorms, heavy rainfall, and light wind speed. Malaysia's average offshore wind speed is between 1.2 m/s to 4.1 m/s, while many regions

worldwide have an average wind speed of 10 m/s (3–6). The East Coast of Peninsular Malaysia has the highest potential, with an annual resultant wind speed vector of 4.1 m/s (6). In the wind energy equation, wind speed is essential. The wind power is proportional to the cube of the wind speed and the square of the blade's diameter (7), as shown in Equation 1.1. Thus, countries with low wind speeds might have limited wind energy potential.

$$P = \frac{1}{2}\rho V^3 A \qquad \text{Equation (1.1)}$$

Diffuser ducts have been proved to speed up the airspeed in a free flow by suction effect. A diffuser is a duct that serves pressure recovery (8); a pressure difference is created across its length. The diffuser inlet has a pressure lower than the atmosphere, encouraging the upstream air to flow through the diffuser (9).

The efficiency of wind turbines is limited to what is known by the Betz limit, which is 59.3% (7). Many researchers have demonstrated that adding a diffuser behind the turbine significantly increases power output, exceeding the Betz limit (10,11). Wind turbines shrouded with a diffuser are called diffuser augmented wind turbines (DAWT).

The diffuser increases the mass flow rate through the rotor. It causes a pressure gradient downstream after the rotor because the diffuser must end up with Sub-atmospheric pressure at its exit; the pressure directly behind the rotor is decreased. Hence, the pressure difference across the turbine increases, which increases the speed of air and hence the power(12,13). Diffuser augmented wind turbines (DAWT) have been proven to have enhanced performance compared to bare turbines at low wind speeds (10).

Two main parameters can increase the efficiency of the diffuser; the first one is increasing the area ratio between its inlet and outlet. However, increasing the area ratio is limited by the flow separation inside the diffuser walls. It was noticed that the turbine's wake mixed with the boundary layer shedding and reduced the separation (11,14). The second parameter is to decrease the exit pressure of the diffuser. Using

flanges at the exit of the diffuser creates vortex shedding behind it, which produces a low-pressure region at the diffuser exit (9,15).

The aerodynamics of DAWT turbines at low wind speed could be challenging because of the laminar separation that happens at a low Reynolds number. Airflow usually separates at a low Reynolds number below $5 \times 10^5$, even though the boundary layer is still laminar and before the transition to turbulent. The laminar separation is usually accompanied by laminar separation bubbles, which cause extra drag force to the airfoil, known as the bubble drag (16,17).

## 1.1 Problem Statement

Diffuser Augmented wind turbines DAWT outperform bare turbines at low wind speeds. Flow separation happens at the inner walls of the diffuser walls because of the adverse pressure gradient. Laminar flow separation occurs at a low Reynolds number. Flow separation changes the effective shape of the diffuser, which limits its function. The number of the rotor's blades influences the energy and turbulent intensity of the wakes behind the turbine. The interaction between the turbine's wake and the flow passing inside the diffuser is critical to overall performance (14). There is insufficient knowledge about how the turbine's wake energy could be a factor in determining whether the flow separates the diffuser walls.

## 1.2 Objectives

The primary aim of the research is to develop a DWAT that can operate at low wind speed, which is conducted by achieving the following objectives:

1. To design a small horizontal axis wind turbine that can operate at low wind speeds.
2. To design a diffuser with a flange suitable for wind speeds below 5 m/s.
3. To evaluate the turbine's number of blades and the solidity impact on the flow separation inside the diffuser.
4. To investigate the possibility of using the number of rotor blades as a passive boundary layer control.

## 1.3 Scope

1. The influence of the geometrical parameter of the diffuser is investigated using 3D CFD simulation. The parameters studied are the flange height, turbine position, opening angle, and diffuser profile.
2. The optimum number of turbine blades that can help suppress the flow separation is investigated by studying 2-blade,3-blade, and 4-blade rotors.
3. Wind tunnel testing is conducted for the prototype of the DAWT to measure the torque of the turbine using a torque sensor.

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