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

BALASEM ABDULAMEER JABBAR

A thesis submitted in fulfilment of the requirement
for award of Doctor of Philosophy in Mechanical Engineering

Faculty of Mechanical and Manufacturing Engineering
Universiti Tun Hussein Onn Malaysia

NOVEMBER 2019

DEDICATION

To the lighthouse of science; Great Prophet Mohammed (peace be upon him).
To my homeland, family, supervisors and all whom have assisted me.

ACKNOWLEDGMENT

First and foremost, praise and thanksgiving to Allah for the blessing of mind and health and "the Tofiq" to complete this thesis. Also, it is with great pleasure that I wish to acknowledge several people that have helped me tremendously during the difficult, yet rewarding and exciting path towards. Without their help and support, none of this work could have been possible. I am greatly indebted to my supervisor; Assoc. Prof. Dr Nor Zelawati Binti Asmuin for the guidance, encouragement, motivation and continuous support throughout my thesis work. She has allowed me to pursue my research interests with sufficient freedom, while always being there to guide me. Working with her has been one of the most rewarding experiences of my professional life, as well as my co-supervisor. Thanks to my parents, my wife and children for supporting and giving me the freedom and opportunity to pursue my study. To UTHM and the staffs of the Faculty of Mechanical and Manufacturing Engineering: Thanks for providing me with an excellent research environment and the necessary resources to undertake this research.

Last but not least, I would like to thank each person who contributed until completion of my final thesis report, directly or indirectly. I would like to acknowledge his/her help which was necessary to complete this research.

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 the 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-ω* 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˚, 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˚flange angle (Θ_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 (Θ_f =0˚)-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 kebiasaanya 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-ω* menggunakan ANSYS 19.1, sementara kajian percubaan dijalankan dalam terowong angin gelung terbuka. Kecekapan penilaian model di perkukuhkan dalam terma kuasa, tork dan pemalar aerodimik iaitu pemalar kuasa dan pemalar tork. Analisis sistematik kuantiti ini memperlihatkan bahawa DAWT dengan peresap bebibir mencapai peningkatan yang signifikan dalam prestasi berbanding HAWT yang terdedah. Hasilnya juga menunjukkan bahawa DAWT dengan sudut flens 0˚ pada kedua-dua model rotor mencapai kuasa tambahan yang terbaik berbanding dengan konfigurasi bebibir yang lain. Selain itu, purata kuasa diperkuatkan di DAWT pada sudut bebibir 0˚ dengan pemutar awal adalah sebanyak 256% berbanding dengan HAWT yang terdedah, manakala pembesarannya mencapai 291% dalam DAWT dengan rotor yang diubahsuai pada sudut bebibir 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.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

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^2)
A_3	-	Diffuser exit area (m^2)
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_∞	-	Upstream wind velocity (m/s)
W	-	Relative wind velocity (m/s)
α	-	Angle of attack (deg)
β	-	Blade twist angle (deg)
ϵ	-	Ratio of maximum axial to upstream wind velocity in the diffuser
δ	-	Velocity speed up ratio
η_c, η_g	-	Conversion and generator efficiency
θ_f	-	Flange angle
λ	-	Tip speed ratio (TSR)
μ	-	Dynamic viscosity of air (kg /m.s)

ρ	-	Air density (m^3/s)
σ	-	Solidity ratio
φ	-	Angle of relative wind velocity (deg)
Ω	-	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

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].

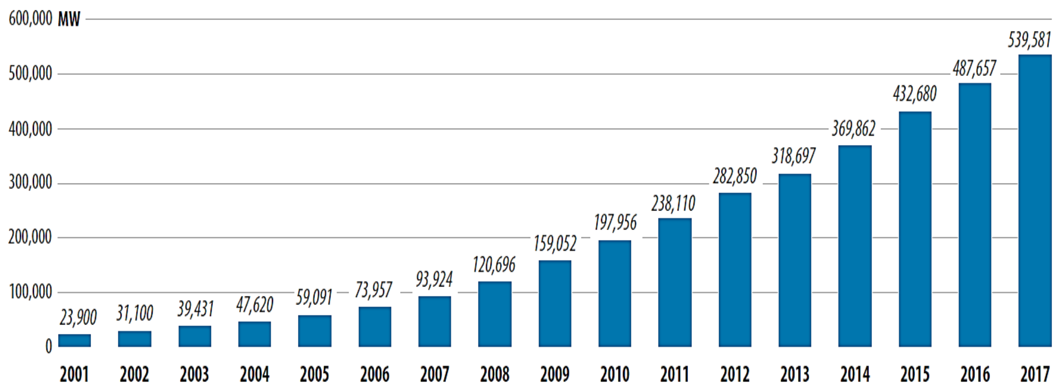

Figure 1.1: Global cumulative installed wind capacity from year 2001 to 2017 [10].

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].

REFERENCES

[1] W. Tong, *Wind power generation and wind turbine design*. 2010.

[2] K. H. Wong, W. T. Chong, N. L. Sukiman, S. C. Poh, Y. C. Shiah, and C. T. Wang, "Performance enhancements on vertical axis wind turbines using flow augmentation systems: A review," *Renew. Sustain. Energy Rev.*, vol. 73, no. June 2016, pp. 904–921, 2017.

[3] D. H. Didane, A. Ab Wahab, S. S. Shamsudin, and N. Rosly, "Wind as a sustainable alternative energy source in Malaysia - a review," *ARPN J. Eng. Appl. Sci.*, vol. 11, no. 10, pp. 6442–6449, 2016.

[4] M. Chandrala, A. Choubey, and B. Gupta, "CFD analysis of horizontal axis wind turbine blade for optimum value of power," *Int. J. Energy Environ.*, vol. 4, no. 5, pp. 825–834, 2013.

[5] D. H. Didane, N. Rosly, M. F. Zulkafli, and S. S. Shamsudin, "Evaluation of Wind Energy Potential as a Power Generation Source in Chad," *Int. J. Rotating Mach.*, vol. 2017, pp. 1–10, 2017.

[6] M. A. Arabbeiki Zefreh, "Design and CFD Analysis of Airborne Wind Turbine for Boats and Ships," *Int. J. Aerosp. Sci.*, vol. 4, no. 1, pp. 14–24, 2016.

[7] J. N. Libii and D. M. Drah, "The influence of the lengths of turbine blades on the power produced by miniature wind turbines that operate in non-uniform flow fields," *World Trans. Eng. Technol. Educ.*, vol. 10, no. 2, pp. 128–133, 2012.

[8] O. Igra, "Research and Development for Shrouded Wind Turbines," *Energy Convers. Manag.*, vol. 21, p. 13–48., 1981.

[9] S. I. Yannopoulos *et al.*, "Evolution of water lifting devices (Pumps) over the centuries worldwide," *Water (Switzerland)*, vol. 7, no. 9, pp. 5031–5060, 2015.

[10] C. Rica, "GLOBAL WIND STATISTICS 2017," *GWEC*, 2018.

[11] S. Eriksson, H. Bernhoff, and M. Leijon, "Evaluation of different turbine concepts for wind power," *Renew. Sustain. Energy Rev.*, vol. 12, no. 5, pp.

1419–1434, 2008.

[12] C. Shonhiwa and G. Makaka, "Concentrator Augmented Wind Turbines: A review," *Renew. Sustain. Energy Rev.*, vol. 59, pp. 1415–1418, 2016.

[13] A. P. Schaffarczyk, "Introduction to Wind Turbine Aerodynamics - Chapter 2," *Green Energy Technol.*, vol. 153, pp. 7–21, 2014.

[14] J. F. Manwell, J. G. McGowan, and A. L. Rogers, *Wind Energy Explained, Theory, Design and Application*, Second Edi. 2009.

[15] B. A. Jabbar, "Design and modeling of horizontal axis wind turbine rotor," Osmania University,India., 2012.

[16] J. N. Sørensen, "General Momentum Theory for Horizontal Axis Wind Turbines," *Res. Top. Wind Energy, springer*, vol. 4, pp. 43–58, 2015.

[17] T. Burton, N. Jenkins, D. Sharpe, and B. Ervin, *Wind Energy Handbook*, Second Edi. 2011.

[18] & T. Holten, V., "Windmills with diffuser effect induced by small tipvanes," *International Symposium on Wind Energy Systems, Cambridge, England*, 1977.

[19] O. de Vries, *Fluid Dynamic Aspects of Wind Energy Conversion*. 1979.

[20] Y. Ohya and T. Karasudani, "A shrouded wind turbine generating high output power with wind-lens technology," *Wind Turbine Technol. Princ. Des.*, vol. 3, pp. 634–649, 2010.

[21] R. W. Y. Habash, Y. Yang, C. Blouin, P. Guillemette, and V. Groza, "Performance of a Contrarotating Small Wind Energy Converter," *ISRN Mech. Eng.*, vol. 2011, pp. 1–10, 2011.

[22] F. A. van Dorst, "An Improved Rotor Design for a Diffuser Augmented Wind Turbine," Delft University of technology, 2011.

[23] V. Holten and Th., "Concentrator systems for wind energy, with emphasis on tipvanes," *Wind Eng.*, vol. 5, p. 29–45., 1981.

[24] E. Dick, "Power Limits for Wind Energy Concentrator Systems. Wind Engineering," *Wind Eng.*, vol. 10, no. 2, pp. 98–115, 1986.

[25] J. N. Sørensen, "Aerodynamic Aspects of Wind Energy Conversion," *Annu. Rev. Fluid Mech.*, vol. 43, no. 1, pp. 427–448, 2011.

[26] M.Natesan, Dr.S.Jeyanthi, and U. Sivasathya, "A Review on Design of Augmented Wind Turbine Blade for Low Wind Speed Urban area," *Int. J. Mech. Eng. Technol.*, vol. 8, no. 7, pp. 685–691, 2017.

[27] R. F. Ghajar and E. A. Badr, “An Experimental Study of a Collector and Diffuser System on a Small Demonstration Wind Turbine,” *Int. J. Mech. Eng. Educ.*, vol. 36, no. 1, pp. 58–68, 2013.

[28] U. Göltenbott, Y. Ohya, S. Yoshida, and P. Jamieson, “Aerodynamic interaction of diffuser augmented wind turbines in multi-rotor systems,” *Renew. Energy*, vol. 112, pp. 25–34, 2017.

[29] B. Kosasih and A. Tondelli, “Experimental study of shrouded micro-wind turbine,” *Procedia Eng.*, vol. 49, pp. 92–98, 2012.

[30] A. M. El-Zahaby, A. E. Kabeel, S. S. Elsayed, and M. F. Obiaa, “CFD analysis of flow fields for shrouded wind turbine’s diffuser model with different flange angles,” *Alexandria Eng. J.*, vol. 56, no. 1, pp. 171–179, 2017.

[31] M. H. Lee, Y. C. Shiah, and C. J. Bai, “Experiments and numerical simulations of the rotor-blade performance for a small-scale horizontal axis wind turbine,” *J. Wind Eng. Ind. Aerodyn.*, vol. 149, pp. 17–29, 2016.

[32] R. E. N. Members, *Renewables 2019 global status report 2019*. 2019.

[33] A. Sadikin *et al.*, “A Comparative Study of Turbulence Models on Aerodynamics Characteristics of a NACA0012 Airfoil,” *Int. J. Integr. Eng.*, vol. 10, no. 1, pp. 134–137, 2018.

[34] M. F. M. M. D H Didane, S Mohd, Z Subari, N Rosly, M F Abdul Ghafir, “An aerodynamic performance analysis of a perforated wind turbine blade,” *Int. Eng. Res. Innov. Symp, 2016.*

[35] R. L. U. de F. Pinto and B. P. F. Gonçalves, “A revised theoretical analysis of aerodynamic optimization of horizontal-axis wind turbines based on BEM theory,” *Renew. Energy*, vol. 105, pp. 625–636, 2017.

[36] A. H. Abdullah and F. Wang, “Modelling Thermal Environmental Performance In Top-lit Malaysian Atrium Using Computational Fluid Dynamics (CFD),” *Int. J. Integr. Eng.*, vol. 1, pp. 27–42, 2011.

[37] A. Sadikin *et al.*, “Numerical Simulation in Transient Flow of Non-Newtonian Fluid in Nozzles during Filling Process,” *Int. J. Integr. Eng.*, vol. 10, no. 1, pp. 92–95, 2018.

[38] Y. El khchine and M. Sriti, “Performance prediction of a horizontal axis wind turbine using BEM and CFD methods,” in *MATEC Web of Conferences 45*, 2016, vol. 45, no. June.

[39] P. Saravanan, K. M. Parammasivam, and S. Selvi Rajan, “Experimental investigation on small horizontal axis wind turbine rotor using winglets,” *J. Appl. Sci. Eng.*, vol. 16, no. 2, pp. 159–164, 2013.

[40] K. Sankaranarayanan, S. Krishnakumar, G. V. PaulRaj, and R. Rahul, “Wind Tunnel Experiment on a Small Horizontal Axis Wind Turbine,” in *Eighth Asia-Pacific Conf. Wind Engineering*, 2013, vol. 6, pp. 978–981.

[41] R. Amano, I. Avdeev, R. Malloy, and M. Z. Shams, “Power, structural and noise performance tests on different wind turbine rotor blade designs,” *Int. J. Sustain. Energy*, vol. 32, no. 2, pp. 78–95, 2013.

[42] M. G. Khalafallah, A. M. Ahmed, and M. K. Emam, “CFD study of some factors affecting performance of HAWT with swept blades,” *Int. J. Sustain. Energy*, vol. 36, no. 5, pp. 489–501, 2017.

[43] M. Ibrahim, A. Alsultan, S. Shen, and R. S. Amano, “Advances in Horizontal Axis Wind Turbine Blade Designs: Introduction of Slots and Tubercle,” *J. Energy Resour. Technol.*, vol. 137, no. 5, 2015.

[44] R. Belamadi, A. Djemili, A. Ilinca, and R. Mdouki, “Aerodynamic performance analysis of slotted airfoils for application to wind turbine blades,” *J. Wind Eng. Ind. Aerodyn.*, vol. 151, pp. 79–99, 2016.

[45] C. J. Bai, W. C. Wang, and P. W. Chen, “The effects of sinusoidal leading edge of turbine blades on the power coefficient of horizontal-axis wind turbine (HAWT),” *Int. J. Green Energy*, vol. 13, no. 12, pp. 1193–1200, 2016.

[46] Y. Kim, A. Al-Abadi, and A. Delgado, “Strategic Blade Shape Optimization for Aerodynamic Performance Improvement of Wind Turbines,” in *Turbomachinery Technical Conference and Exposition GT2016*, 2016, p. V009T46A009.

[47] V. M. Kumar, B. Nageswara Rao, and S. Farooq, “Modeling and analysis of wind turbine blade with advanced materials by simulation,” *Int. J. Appl. Eng. Res.*, vol. 11, no. 6, pp. 4491–4499, 2016.

[48] A. Agha, H. N. Chaudhry, and F. Wang, “Diffuser Augmented Wind Turbine (DAWT) technologies: A review,” *Int. J. Renew. Energy Res.*, vol. 8, no. 3, pp. 1369–1385, 2018.

[49] L. Maia, J. Paulo, J. E. Ribeiro, and L. F. Ribeiro, “Experimental and Numerical study of a Diffuser Augmented Wind Turbine - DAWT,” in *6th International Conference Integrity-Reliability-Failure*, 2018, pp. 1085–1100.

[50] M. Sanuki, “Studies on biplane wind vanes, ventilator tubes. And cup anemometers (I),” *Meteorol. Geophys.*, vol. 1, no. 1, 1950.

[51] M. Sanuki, “Studies on biplane wind vanes, ventilator tubes and cup anemometers (II),” *Meteorol. Res. Inst.*, vol. 1, no. 2, 1950.

[52] M. Iwasaki, “The experimental and theoretical investigations of windmills,” *Reports Res. Inst. Appl. Mech.*, vol. 2, no. 8, pp. 181–228, 1953.

[53] G.M.Lilley and W.J.Rainbird, “A Preliminary report on the design and Performance of Ducted Windmills,” *Rep. 102, Collage Aeronaut. Cranfield,UK.*, 1956.

[54] A. Kogan and A. Seginer, “Final report on shroud design,” *Rep. No. 32A, Dep. Aeronaut. Eng. Tech.*, 1963.

[55] R. E. Wilson and L. P.B.S., “Applied Aerodynamics of Wind Power Machines,” *Report. Oregon State Univ.*, 1974.

[56] M. O. L. Hansen, N. N. Sørensen, and R. G. J. Flay, “Effect of Placing a Diffuser around a Wind Turbine,” *Wind Energy*, vol. 3, pp. 207–213, 2000.

[57] O. Igra, “Research and development for shrouded wind turbines,” in *European Wind Energy Conference 22-26 October*, 1984.

[58] M. J. Werle and W. M. Presz, “Ducted Wind/Water Turbines and Propellers Revisited,” *J. Propuls. Power*, vol. 24, no. 5, pp. 1146–1150, 2008.

[59] K. M. Foreman, “Preliminary Design and Economic Investigations of Diffuser Augmented Wind Turbines (DAWT),” *Final Report, Res. Dep. Grumman Aerosp. Corp. Bethpage, New York*, p. 29, 1981.

[60] F. A. Al-Sulaiman and B. S. Yilbas, “Thermoeconomic analysis of shrouded wind turbines,” *Energy Convers. Manag.*, vol. 96, pp. 599–604, 2015.

[61] F. A. Al-Sulaiman, “Exergoeconomic analysis of ejector-augmented shrouded wind turbines,” *Energy*, vol. 128, pp. 264–270, 2017.

[62] A. Kumar and Sachendra, “Development in Augmented Turbine Technology,” *Int. J. Trend Res. Dev.*, vol. 4, no. 1, pp. 2394–9333, 2017.

[63] Y. Ohya, T. Karasudani, A. Sakurai, K. ichi Abe, and M. Inoue, “Development of a shrouded wind turbine with a flanged diffuser,” *J. Wind Eng. Ind. Aerodyn.*, vol. 96, no. 5, pp. 524–539, 2008.

[64] R. A. Kishore, T. Coudron, and S. Priya, “Small-scale wind energy portable turbine (SWEPT),” *J. Wind Eng. Ind. Aerodyn.*, vol. 116, pp. 21–31, 2013.

[65] C. D. Chaudhari, S. A. Waghmare, and A. Kotwal, “Numerical Analysis of Venturi Ducted Horizontal Axis Wind Turbine for Efficient Power Generation,” *Int. J. Mech. Eng. Comput. Appl.*, vol. 1, no. 5, pp. 90–93, 2013.

[66] M. Kardous, R. Chaker, F. Aloui, and S. Ben Nasrallah, “On the dependence of an empty flanged diffuser performance on flange height: Numerical simulations and PIV visualizations,” *Renew. Energy*, vol. 56, pp. 123–128, 2013.

[67] A. Tourlidakis, K. Vafiadis, I. Kalogeropoulos, and V. Andrianopoulos, “Aerodynamic Design and Analysis of A Flanged Diffuser Augmented Wind Turbine,” in *Proceedings of ASME Turbo Expo*, 2013, pp. 1–10.

[68] R. Chaker, M. Kardous, F. Aloui, and S. Ben Nasrallah, “Open angle effects on the aerodynamic performances of a flanged Diffuser Augmented Wind Turbine (DAWT),” *Conférence Int. des Energies Renouvelables*, vol. 2, 2013.

[69] Y. Ohya, “Bluff body flow and vortex - Its application to wind turbines,” *Fluid Dyn. Res.*, vol. 46, no. 6, p. 61423, 2014.

[70] H. M. Elbakry, A. A. A. Attia, O. E. Abdelatif, and M. S. Zahran, “Simulation of Diffuser Augmented Wind Turbine performance,” *2016 World Congr. Sustain. Technol. WCST 2016*, pp. 40–48, 2016.

[71] J. Huang and X. Zhang, “Numerical Study of Air Flow Around Flanged Diffusers Using Actuator-Disk Model,” *ACTS Conf. Island, Korea*, pp. 1–5, 2017.

[72] R. Chaker, M. Kardous, S. Ben Nasrallah, F. Aloui, and M. Chouchen, “Vortices’ Characteristics to Explain the Flange Height Effects on the Aerodynamic Performances of a Diffuser Augmented Wind Turbine,” *J. Sol. Energy Eng.*, vol. 138, no. 6, p. 061013, 2016.

[73] K. Olasek, M. Karczewski, M. Lipian, P. Wiklak, and K. Józwik, “Wind tunnel experimental investigations of a diffuser augmented wind turbine model,” *Int. J. Numer. Methods Heat Fluid Flow*, vol. 26, no. 7, pp. 2033–2047, 2016.

[74] M. Kardous, R. Chaker, F. Aloui, and I. Abidi, “Locations of vortices and their impacts on the aerodynamic performances of a diffuser and a DAWT,” *2016 3rd Int. Conf. Renew. Energies Dev. Countries, REDEC 2016*, 2016.

[75] A. Nasution and D. W. Purwanto, “Optimized curvature interior profile for Diffuser Augmented Wind Turbine (DAWT) to increase its energy-conversion performance,” *2011 IEEE 1st Conf. Clean Energy Technol. CET 2011*, pp. 315–320, 2011.

[76] A. C. Aranake, V. K. Lakshminarayan, and K. Duraisamy, "Computational analysis of shrouded wind turbine configurations using a 3-dimensional RANS solver," *Renew. Energy*, vol. 75, pp. 818–832, 2015.

[77] S. Hjort and H. Larsen, "A multi-element diffuser augmented wind turbine," *Energies*, vol. 7, no. 5, pp. 3256–3281, 2014.

[78] A. Lotfi and M. Rad, "Drag performance of divergent tubular-truncated cones: A shape optimization study," *Int. J. Environ. Sci. Technol.*, vol. 9, no. 1, pp. 105–112, 2012.

[79] D. P. Georgiou, K. F. Milidonis, and N. G. Theodoropoulos, "A CFD Simulation of a Ducted Wind Turbine With Ejector Assist," in *Proceedings of the ASME 2012 11th Biennial Conference on Engineering Systems Design and Analysis ESDA, July 2-4, 2012, Nantes, France*, 2012.

[80] T. S. Kannan, S. A. Mutasher, and Y. H. K. Lau, "Design and flow velocity simulation of diffuser augmented wind turbine using CFD," *J. Eng. Sci. Technol.*, vol. 8, no. 4, pp. 372–384, 2013.

[81] J. Wang, J. Piechna, and N. Müller, "Computational Fluid Dynamics Investigation of a Novel Multiblade Wind Turbine in a Duct," *J. Sol. Energy Eng.*, vol. 135, no. 1, 2012.

[82] S. Z. Roshan, S. Alimirzazadeh, and M. Rad, "RANS simulations of the stepped duct effect on the performance of ducted wind turbine," *J. Wind Eng. Ind. Aerodyn.*, vol. 145, pp. 270–279, 2015.

[83] S. H. Wang and S. H. Chen, "Blade number effect for a ducted wind turbine," *J. Mech. Sci. Technol.*, vol. 22, no. 10, pp. 1984–1992, 2008.

[84] H. Ahmadi Asl, R. Kamali Monfared, and M. Rad, "Experimental investigation of blade number and design effects for a ducted wind turbine," *Renew. Energy*, vol. 105, pp. 334–343, 2017.

[85] M. Kulak, M. Karczewski, K. Olasek, and K. J????wik, "CFD analysis of Diffuser Augmented Wind Turbine model for wind tunnel investigation," *IECON Proc. (Industrial Electron. Conf.*, pp. 5538–5543, 2016.

[86] H. Jafari, S. Hassanli, and K. C. S. Kwok, "Performance analysis of a small wind turbine mounted inside a tall building," *18th Australas. Wind Eng. Soc. Work. McLaren Val. South Aust.*, no. July, 2016.

[87] B. Ahmed, A. Ahmed, and A. Hussain, "Modelling and Simulation of Diffuser augmented wind turbine," in *4th International Conference on Energy,*

Environment and Sustainable Development (EESD 2016), 2016, no. November.

[88] L. Michał, K. MacIej, M. Jakub, and J. Krzysztof, "Numerical simulation methodologies for design and development of Diffuser-Augmented Wind Turbines-analysis and comparison," *Open Eng.*, vol. 6, no. 1, pp. 235–240, 2016.

[89] L. Michal, K. Maciej, and J. Krzysztof, "Analysis and comparison of numerical methods for design and development of small Diffuser-Augmented Wind Turbine (DAWT)," *IECON Proc. (Industrial Electron. Conf.*, pp. 5525–5531, 2016.

[90] V. V. Dighe, F. Avallone, J. Tang, and G. van Bussel, "Effects of Gurney Flaps on the Performance of Diffuser Augmented Wind Turbine," *AIAA SciTech Forum 9 - 13 January 2017, Grapevine, Texas 35th Wind Energy Symp.*, no. January, pp. 1–11, 2017.

[91] N. OKA, M. FURUKAWA, K. KAWAMITSU, and K. YAMADA, "Optimum aerodynamic design for wind-lens turbine," *J. Fluid Sci. Technol.*, vol. 11, no. 2, pp. 1–14, 2016.

[92] K. Mansour and P. Meskinkhoda, "Computational analysis of flow fields around flanged diffusers," *J. Wind Eng. Ind. Aerodyn.*, vol. 124, pp. 109–120, 2014.

[93] B. Kosasih and H. Saleh Hudin, "Influence of inflow turbulence intensity on the performance of bare and diffuser-augmented micro wind turbine model," *Renew. Energy*, vol. 87, pp. 154–167, 2016.

[94] S. A. H. Jafari and B. Kosasih, "Flow analysis of shrouded small wind turbine with a simple frustum diffuser with computational fluid dynamics simulations," *J. Wind Eng. Ind. Aerodyn.*, vol. 125, pp. 102–110, 2014.

[95] B. Y. Kosasih and S. A. Jafari, "High-Efficiency Shrouded Micro Wind Turbine for Urban-Built Environment," *Appl. Mech. Mater.*, vol. 493, pp. 294–299, 2014.

[96] M. Lipian, M. Karczewski, and K. Olasek, "Sensitivity study of diffuser angle and brim height parameters for the design of 3 kW Diffuser Augmented Wind Turbine," *Open Eng.*, vol. 5, no. 1, pp. 280–286, 2015.

[97] Y. Ohya, T. Karasudani, T. Nagai, and K. Watanabe, "Wind lens technology and its application to wind and water turbine and beyond," *Renew. Energy Environ. Sustain.*, vol. 2, no. 2, pp. 1–6, 2017.

[98] T. Y. Chen, Y. T. Liao, and C. C. Cheng, "Development of small wind turbines for moving vehicles: Effects of flanged diffusers on rotor performance," *Exp. Therm. Fluid Sci.*, vol. 42, pp. 136–142, 2012.

[99] W. X. Wang *et al.*, "Experimental investigation into the influence of the flanged diffuser on the dynamic behavior of CFRP blade of a shrouded wind turbine," *Renew. Energy*, vol. 78, pp. 386–397, 2015.

[100] J. F. Hu and W. X. Wang, "Upgrading a shrouded wind turbine with a self-adaptive flanged diffuser," *Energies*, vol. 8, no. 6, pp. 5319–5337, 2015.

[101] H. Sun and Y. Kyozuka, "Analysis of performances of a shrouded horizontal axis tidal turbine," in *2012 Oceans - Yeosu, IEEE*, 2012.

[102] R. Gasch and J. Twele, "Scaling wind turbines and rules of similarity," *Wind Power Plants*, vol. 271, pp. 257–271, 2012.

[103] M. H. Giahi and A. Jafarian Dehkordi, "Investigating the influence of dimensional scaling on aerodynamic characteristics of wind turbine using CFD simulation," *Renew. Energy*, vol. 97, pp. 162–168, 2016.

[104] M. J. Fowler and A. J. Goupee, "Wind/wave basin verification of a performance-matched scale- Model wind turbine on a floating offshore wind turbine platform," in *Proceedings of the ASME , International Conference on Ocean, Offshore and Arctic Engineering OMAE2014 San Francisco, California, USA*, 2014, pp. 1–10.

[105] D. T. Griffith and T. D. Ashwill, "The Sandia 100-meter All-glass Baseline Wind Turbine Blade," *Tech. report, Sandia Natl. Lab. California, United States*, 2011.

[106] K. W. Van Treuren and T. A. Burdett, *Experimental Testing of Wind Turbines Using Wind Tunnels With an Emphasis on Small-Scale Wind Turbines Under Low Reynolds Numbers: Chapter 4*, vol. 81. Department of Mechanical Engineering, Baylor University, Waco, TX, USA., 2014.

[107] D. A. Tavares Dias Do Rio Vaz, A. L. Amarante Mesquita, J. R. Pinheiro Vaz, C. J. Cavalcante Blanco, and J. T. Pinho, "An extension of the Blade Element Momentum method applied to Diffuser Augmented Wind Turbines," *Energy Convers. Manag.*, vol. 87, pp. 1116–1123, 2014.

[108] M. Ozen, "Mesh Metric Spectrum Quality," *Ozen Engineering, California*. Available:https://www.ozeninc.com/wpcontent/uploads/2014/11/MESHING_WORKSHOP_2014.pdf.

[109] R. Acharya, “Investigation of Differences in Ansys Solvers CFX and Fluent,” 2016.

[110] F. R. Menter, “Two-equation eddy-viscosity turbulence models for engineering applications,” *AIAA J.*, vol. 32, no. 8, pp. 1598–1605, 2008.

[111] ANSYS Inc., “ANSYS CFX-Solver Theory Guide,” vol. 15317, no. January, pp. 1–336, 2015.

[112] H. R. Martin, R. W. Kimball, A. M. Viselli, and A. J. Goupee, “Methodology for Wind/Wave Basin Testing of Floating Offshore Wind Turbines,” *J. Offshore Mech. Arct. Eng.*, vol. 136, no. 2, p. 020905, 2014.

[113] Fluke Corporation, “Fluke 922 Airflow Meter,” *User Manual*, 2007. Available: https://dam-assets.fluke.com/s3fs-public/922 umeng0100.pdf.

[114] RS. PRO, “Laser, Photo Tachometer,” *RS 445-9557, datasheet*. Available: https://docs-emea.rs-online.com/webdocs/1583/0900766b81583e4b.pdf.

[115] UCTRONICS, “16- Channel Relay Module Board,” *datasheet*.Available: https://www.uctronics.com/download/Amazon/U604302_print.pdf.

[116] ANEGN, “AN8002 AC/DC Digital Multi-meters” datasheet.”. Available: http://eletricall.com/wp-content/uploads/2017/11/Manual-do-Aneng-8002.pdf.

[117] M. Torresi, N. Postiglione, P. F. Filianoti, B. Fortunato, and S. M. Camporeale, “Design of a ducted wind turbine for offshore floating platforms,” *Wind Eng.*, vol. 40, no. 5, pp. 468–474, 2016.

[118] John R. Taylor, *An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements*, 2d Edition. University Science Books, 1997.

[119] “Accuracy and precision,” *Laboratory Experiments, Los Angeles Harbor College,LAHC.*.Available:https://effectiveness.lahc.edu/academic_affairs/sfcs/chemistry/Shared Documents/Chem101Arias/Exp 1 - AccPreF11.pdf.

[120] A. Alaimo, A. Esposito, A. Messineo, C. Orlando, and D. Tumino, “3D CFD analysis of a vertical axis wind turbine,” *Energies*, vol. 8, no. 4, pp. 3013–3033, 2015.

[121] S. M. AR, H. B. S. B, M. N. Nemah, B. A. Al-Quraishi, and N. Z. B. Asmuin, “Performance evaluation of savonius wind Turbine based on a new design of blade shape,” vol. 10, no. 01, pp. 837–846, 2019.