A MODIFIED SAVONIUS TURBINE WITH MOVEABLE BLADES FOR HIGHER EFFICIENCY

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To my kind parents for their priceless support and motivation and to my devoted wife and my lovely kids, for their sincere help and accompany during my studies.

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ABSTRACT

Previous research works have proposed Savonius vertical axis marine current turbine as appropriate for low current velocity applications such as in the Malaysian sea. The numerous benefits of Savonius turbine such as its simple structure, self-start ability, relatively low operating velocity, independence from flow direction and low environmental impact have generated interests among researchers. Despite these advantages, it suffers from low efficiency. Savonius turbine is composed of multiple physical parts; in which in this study, certain important parameters including blades, end plate, aspect ratio and overlap ratio had been investigated. This thesis proposes a newly modified Savonius turbine, designated ReT (Reza Turbine), for low speed marine currents to enhance the efficiency. The ReT consists of two blades, each blade divided into two parts which are joined by hinge. This makes ReT considerable as a turbine with movable blades. The blades, being movable, necessitates a specific design of endplates to ensure the blades to function properly. This research explored the nonlinear two-dimensional flow numerically over the novel type rotor. Simulations were conducted using Computational Fluid Dynamics (CFD) software, by applying the SIMPLE (Semi-Implicit Method for Pressure Linked Equations) algorithm. The unsteady Reynolds Averaged Navier-Stokes (RANS) equations were solved for velocity and pressure coupling with a code, based on the programming Language C through the User Defined Functions (UDF) at variation of marine current velocities. Dynamic Mesh Method (DMM) was used for solving the movement of the blades and adjusting the mesh according to the position of the blades on the surface. The numerical simulation using turbulence model Shear Stress Transport (SST k-ω) produced satisfactory results when compared with experimental results of the modified turbine and classical Savonius turbine. For validation purpose, the modified model was tested in Universiti Teknologi Malaysia’s low speed wind tunnel at different flow velocities. Important parameters such as torque, power and performance as well as the pressure distribution on the blades surfaces were measured at different angles of attack. Parametric study was conducted in six subsections, in which the modified turbine had been investigated and analysed. The maximum coefficient of power of ReT was found to be 0.34 at tip speed ratio (λ) of 0.9. This is 52% improvement in efficiency (power coefficient) compared to classical Savonius turbine without any extra accessories. The use of ReT will enable power to be extracted more efficiently from low speed marine currents.

ABSTRAK

Kajian-kajian terdahulu telah mencadangkan turbin arus marin paksi tegak Savonius adalah sesuai untuk aplikasi halaju rendah seperti lautan di Malaysia. Beberapa kelebihan turbin Savonius seperti struktur yang ringkas, kebolehan dihidupkan sendiri, halaju operasi yang rendah, bebas daripada arah aliran dan kesan alam sekitar yang rendah telah menarik perhatian para pengkaji. Walaubagaimanapun, turbin ini mempunyai kelemahan dari segi kecekapan. Turbin Savonius terdiri daripada beberapa bahagian fizikal, yang mana dalam kajian ini, beberapa parameter penting termasuklah bilah, plat akhir, nisbah aspek dan nisbah pertindihan, telahpun dikaji. Tesis ini mengusulkan rekabentuk baru konfigurasi turbin Savonius yang diubahsuai (Reza Turbine) untuk halaju arus marin yang rendah untuk meningkatkan keberkesanan yang sedia ada. ReT mempunyai dua bilah; setiap satu terbahagi kepada dua bahagian yang dihubungi oleh engsel. Ini bermakna ReT boleh dikategorikan sebagai turbin dengan bilah yang boleh bergerak. Bilah-bilah ini, disebabkan fungsi gerakan, memerlukan rekabentuk spesifik pada plat akhir untuk memastikan bilah-bilah mampu berfungsi dengan betul. Kajian ini mengkaji arus dua dimensi tidak linear secara numerikal melalui rekabentuk rotor baru. Simulasi telah dijalankan menggunakan aplikasi Dinamik Bendalir Berbantukan Komputer (CFD), dengan pengintegrasian logaritma SIMPLE (Semi-Implicit Method for Pressure Linked Equations). Persamaan Navier-Stokes berasaskan purata Reynolds telah diselesaikan untuk halaju dan tekanan bersama dengan kod komputer, berdasarkan program Bahasa C melalui User Defined Functions (UDF) dengan memanipulasikan halaju arus yang berubah- ubah. Kaedah Dynamic Mesh (DDM) telah digunakan untuk menentukan pergerakan bilah dan melaraskan jaringan berdasarkan kedudukan bilah di permukaan air. Simulasi numerikal menggunakan model pergolakan SST k-ω telah menghasilkan keputusan yang memuaskan, berbanding keputusan oleh rekabentuk terkini dan juga model konvensional turbin Savonius. Untuk pengesahan keberkesanan, satu model daripada rekabentuk ReT ini telah diuji di terowong udara berkelajuan rendah Universiti Teknologi Malaysia. Beberapa parameter penting seperti tork, kuasa, prestasi dan edaran tekanan pada permukaan bilah telah diukur pada sudut berlainan. Kajian parametrik telah dilakukan di enam subseksyen, dalam mana turbin yang diubahsuai telah dikaji dan dianalisa. Pekali kuasa ReT didapati pada tahap tertinggi, iaitu 0.34 pada hujung nisbah kelajuan (λ) 0.9. Ini menunjukkan peningkatan keberkesanan pekali kuasa sebanyak 52% berbanding turbin Savonius konvensional tanpa tambahan aksesori. Penggunaan ReT berupaya menambahkan keberkesanan penghasilan tenaga daripada arus marin yang rendah.

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LIST OF ABBREVIATIONS

2D	-	Two dimensional
3D	-	Three dimensional
AF	-	Advancing Fixed
AM	-	Advancing Movable
AR	-	Aspect Ratio
CCW	-	Counter Clockwise
CFD	-	Computational Fluid Dynamic
CPU	-	Central Processing Unit
CW	-	Clockwise
DMM	-	Dynamic Mesh Methods
ETP	-	Energy Technology Perspective
FKPS	-	Flow Kinetics Pressure Scanner
HAMCT	-	Horizontal Axis Marine Current Turbine
IBT	-	Instrument Bus Terminal
IEA	-	International Energy Agency
LSWT	-	Low Speed Wind Turbine
MCT	-	Marine Current Turbine
MDO	-	Multidisciplinary Design Optimization
MGSVA	-	Mariano Global Surface Velocity Analysis
MRE	-	Marine Renewable Energy
Mtoe	-	Million tons of oil equivalent
OECD	-	Organization for Economic Co-operation and Development
OTEC	-	Ocean Thermal Energy Conversion
PISO	-	Pressure-Implicit with Splitting Operations
PIV	-	Particle Image Velocimetry
RANSE	-	Reynolds Averaged Navier-Stokes Equations

RES	-	Renewable Energy Source
RES	-	Reynolds Energy Source
RET	-	Renewable Energy Technology
ReT	-	Reza Turbine
RF	-	Returning Fixed
RM	-	Returning Movable
RMN	-	Royal Malaysia Navy
RPM	-	Revolutions per Minute
SIMPLE	-	Semi-Implicit Method for Pressure linked Equations
SST	-	shear stress transport
TSR	-	Tip Speed Ratio
UDF	-	Used Defined Function
UTM-LSWT	-	Low speed wind tunnel of Universiti Teknologi Malaysia
VAMCT	-	Vertical Axis Marine Current Turbine
WEO	-	World Energy Outlook

LIST OF SYMBOLS

A	-	Swept area
a_p & a_{nb}	-	Coefficients associated with ϕ_P and ϕ_{nb} respectively
C_p	-	Power coefficient
C_{pr}	-	Pressure coefficient
C_t	-	Torque coefficient
D	-	Diameter of turbine
D_ω	-	Cross-diffusion term
d	-	Diameter of blade
e	-	Spacing between the blades
F	-	Force
F_n	-	Froude number
H	-	High of rotor
Gk	-	Generation of turbulence kinetic energy due to mean velocity gradients
$G\omega$	-	Generation of ω energy due to mean velocity gradients
I	-	Turbulence intensity
k	-	Turbulence kinetic energy
Kg	-	Kilogram
knot	-	Nautical miles per hour
l	-	Turbulence length scale
Lm	-	Model length
Lp	-	Prototype length
m/s	-	meter per second
N	-	Speed of rotor
N.m	-	Newton meter

P	-	Power
Pa	-	Pascal
$P_{available}$	-	Available power from flow
P_{rotor}	-	Available power by rotor
P_{∞}	-	Atmosphere pressure
R or r	-	Radius of the rotor
R_e	-	Reynolds number
$r_{\perp}$	-	Normal distance between the centre of blade and each point on the blade
T	-	Torque
T_s	-	Static Torque
U	-	Current velocity
u_{avg}	-	Average of free stream velocity
u	-	Rotor tip speed
u_i	-	Velocity components in the directions of xi = (x, y, z)
U_P	-	Velocity near-wall at node P
u^+	-	Speed of flow near the wall
u'	-	Velocity fluctuation in X direction
V_o	-	Flow velocity
W	-	Watt
Y_k	-	Dissipation of k due to turbulence
Y_{ω}	-	Dissipation of ω due to turbulence
y^+	-	Distance from the wall (non-dimensional)
y_P	-	Distance between the point P and the wall
α	-	Angle between the direction of the opening and closing process of the foldable blades parts
α_1	-	Angle between the direction of the flow and deflector for advancing blade
α_2	-	Angle between the direction of the flow and deflector for returning blade
β	-	Overlap ratio
γ	-	Model scale factor

δ	-	Boundary layer thickness
ε	-	Turbulence dissipation rate
θ	-	Rotor angle
λ	-	Tip speed ratio
μ	-	Molecular velocity
μ_t	-	Turbulence viscosity
ρ	-	Density
τ_ω	-	Pressure coefficient
ϕ_P & ϕ_{nb}	-	Properties of known cell and its neighbouring cells
ω	-	Angular velocity

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CHAPTER 1

INTRODUCTION

1.1 Background

Fossil fuel reduction reservoirs, increase of oil price and other petrochemical substances, as well as the irrefutable and inseparable dependence on fossil reserves and resources are obvious in every life. Creation of the environmental pollution is from consumption of fossil fuel that leads to horrible phenomena including greenhouse gas emissions, air pollution, water pollution and the destruction of the ozone layer. These striking threats turn the focus of many governments and societies from conventional energy resources to the pure and renewable energies i.e. wind energy, solar energy, biomass energy, geothermal and ocean energy (Martinot and Sawin, 2009). According to the International Energy Agency (IEA) (Shindell *et al.*, 2012) and World Energy Outlook (WEO) (Alternative policy scenario 2009), by the year 2030, 29% of global required energy and 7% of transport fuel will be provided through renewable energies. Recently, the studies on pure energy has been multiplied and big nations start to take significant advantages of renewable energy (Olivier *et al.*, 2012).

The reports from authorities indicated that nearly 70% of earth surrounded by water. This vast resource can be considered as a giant energy generator. Marine Renewable Energy (MRE) initiatives are being pursued in five fronts; Ocean Thermal, Ocean Tides, Ocean Salinity Gradient, Ocean Current and Ocean Waves (Vega, 1999). Renewable energy development in Malaysia is still in the primary stage, Hashim and Ho (2011) estimated that utilization of 5% of renewable energy for 5 years will save the country RM 5 billion (US$ 1.32 billion). According to Tenth Malaysia plan (2011-

2015) expansion of research on green technology is encouraged towards commercialization through proper mechanism (Chua and Oh, 2010; Ong *et al.*, 2011; Shafie *et al.*, 2011). Recently, three significant moves were introduced by the Malaysian government to encourage Renewable Energy development:

(i) National Renewable Energy Policy and Action Plan (2009)
(ii) Renewable Energy Act 2011
(iii) Sustainable Energy Development Authority Act 2011

To support the national renewable energy policy and action plans, as well as the two new acts, research in renewable energy must be given priority (Ali *et al.*, 2012; Saadatian, 2012; Chong and Lam, 2013). The potential of the ocean as a source of alternative renewable energy is great. To underline this potential, a number of initiatives are being pursued in various parts of the world. A very comprehensive survey of various energy resources, including all forms of ocean energy, is given by World Energy Council (2010). The implementing agreement of the International Energy Agency (IEA) (Shindell *et al.*, 2012) is published in an annual report detailing progress in MRE technology in various countries, IEA. In Figure 1.1 shown the global description of mean daily tidal range, as can be seen the west seas of Malaysia has suitable potential in marine current.

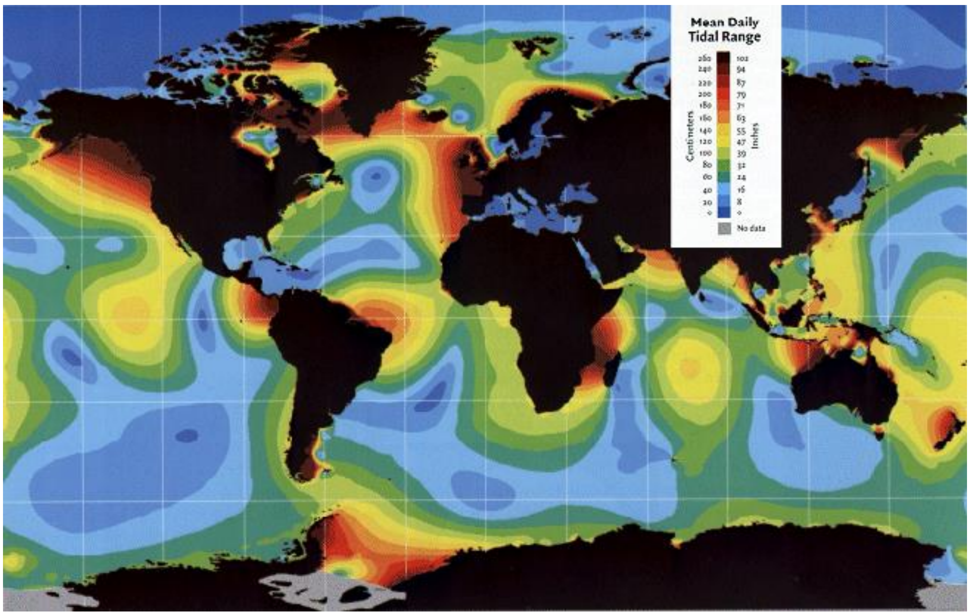

Figure 1.1 Global description of mean daily tidal range (NREL, 2009)

Demand for electricity is growing in Malaysia increasing from 91,539 GWh in the year 2007 to 108,732 GWh in the year 2011 (Chandran *et al.*, 2010). Consequently, it can be predicted that in 2020, the last demand of energy based on an annual increased ratio 8.1% will reach 1,349,080 GWh (116 million tons of oil equivalent (Mtoe)) in Malaysia (Shafie *et al.*, 2011). Therefore, with the rapid growth, it is required that to support the development in the power sector with further resources and to improve the efficiency of capital, labor and other relevant factors (Faez Hassan *et al*., 2012).

According to these references Faez Hassan et al. (2012) and also Hashim and Ho (2011), Malaysia is dependent on fossil fuel for generating electricity because approximately 94.5% of electricity is generated through fossil fuel (i.e. Oil, natural gas, and coal). In the same year, the National Green Technology Policy formulated by Malaysia, cautioned the energy stakeholders to join clean and green group not only to boost the economy but also to find sustainable solutions to migrate to global green movement.

One of the best identified renewable sources is marine current in Malaysia, which is due to the fact that Malaysia is surrounded by water in most areas, yet the marine current is considered to have more advantages to be used in this study compared to other renewable resources.(Yaakob *et al.*, 2006).

In this regards, Yaakob *et al.* (2006) demonstrated that Malaysian coastal environment have shallow water depth and as well as low current velocity. Furthermore, the annual average speed current of 30 meters in deep water of Malaysian coastal environment is estimated to be 0.56 m/s (Yaakob *et al.*, 2008a). Nevertheless, in this condition, operation of low current velocity by turbine design is feasible.

This concept contains Gorlov (helical), Darrieus, Kobold and Davis turbines. These rotary devices are positioned in the ocean and worked with current velocity above 1.1 (m/s) (Yaakob *et al.*, 2008b). Another type the turbine is called Savonius rotor that has been used for wind turbine application.

Nowadays, these turbines are divided into two groups; Horizontal Axis Marine Current Turbine (HAMCT) Jo *et al.* (2012); Bahaj *et al.* (2007); Ben Elghali *et al.* (2007); Myers and Bahaj (2006) and Vertical Axis Marine Current Turbine (VAMCT) Akwa *et al.* (2012a); Yaakob *et al.* (2010); Blackwell *et al.* (1978); Khalid and Shah (2013); Ueno *et al.* (2004).

Different designs of VAMCT have been suggested, among them, several made for marine current turbines, which Savonius turbine is one of the appropriate choice because it can work in low speeds current as well.

At present, due to the different conditions Savonius in water and also whereas, the density of water is about 835 times higher than air; it is expected to produce appropriate power of Savonius turbine.

1.2 Problem Statement

Ocean energy is one of the vastly available renewable energy, that has yet being harvest in big scale around the world. This is mainly due to technical constrain and financially not feasible as compared to other energy sources. In Malaysian coastal environments due to low current velocity and likewise, shallow water the Savonius turbine is convenient perfectly (Yaakob *et al.*, 2006; Yaakob *et al.*, 2008a; Yaakob, 2012; Yaakob *et al.*, 2012).

This study aims to develop a modified vertical axis marine current device using hydro turbine to harvest the current energy from Malaysia's ocean. Many studies have been done previously on ocean energy devices similar existing turbine in UTM, which has the potential in low current velocity (Yaakob *et al.*, 2006; Suprayogi Sunanto, 2008; Yaakob *et al.*, 2008a; Yaakob *et al.*, 2013), nevertheless the efficiency of design is low around 15% needs to be changed to increase the performance in transforming the current energy into harvestable electric energy for direct application in coastal environments and small island communities. However, it suffers from lower efficiency compared to other water turbines. One of the most important parameter that effect on the Savonius turbine efficiency directly is torque. In previous models, negative torque is an important reason of decreasing of turbine performance, which happen at different angles of rotation (Altan and Atılgan, 2008; Kamoji *et al.*, 2009b; Mohamed *et al.*, 2010). On the other hand, for a modified design and achieve a desired result the old method to should be improved. There is a need to develop a Savonius undesirable effect which can reduce the effect of negative torque. In order to reduce the effect of negative torque leading to enhancing the efficiency of the rotor, a modified configuration of Savonius turbine which is called ReT (Reza Turbine) was proposed. This can be suitable for Malaysian ocean conditions too.

1.3 Objectives

The objectives of this research are:

1. To determine effective parameters of the Savonius rotor used for a low current velocity.
2. To develop and redesign a modified vertical axis marine current turbine by employing efficient advanced methods in CFD simulations.
3. To evaluate the performance of the modified hydro turbine using model testing, and to analyze the ReT by a systematic parametric study.

1.4 Scope of Study

The study will look at the new concepts to modify the conventional ones for increasing the efficiency of the turbine. The best items factors of the Savonius rotor are also determined. This research employed an advanced setting oriented Computational Fluid Dynamics (CFD) by using dynamic mesh as a complex method. The lack of facility made the researcher to conduct the CFD simulation as a two-dimensional analysis. A small-scale model was designed, constructed and tested for performance evaluation in Universiti Teknologi Malaysia low speed wind tunnel. Moreover, parametric study was employed to analyse the modified turbine for more investigation at different conditions.

1.5 Significance of the Study

This project starts with reviewing the previous marine current energy devices and tries to introduce a suitable modified turbine for Malaysian seas. The modified rotor called ReT uses movable blades with specific design of end plates. Reducing negative torque and growing positive torque as novel design, the ReT increases the conventional turbine efficiency. Compared to previous models, the novel design has achieved a significantly higher performance. In addition, it provides many coastal areas and islands with electricity, which can be a reasonable activity to reduce environmental pollution in Malaysia. Furthermore, using the ReT can help government to take advantage of ocean energy as a renewable energy more seriously.

1.6 Organization of Thesis

This dissertation is organized by 5 chapters; a brief content of each chapter is explained as follow;

Chapter 1, presents an introduction to the research problem are given such as background, problem statement, objectives of the study, scopes and significant of the study.

Chapter 2, a comprehensive literature review is provided, which includes global energy review, introduction of marine current turbines, explanations of Savonius turbine parameters with its weakness. The research issues are presented with more detailed as well.

Chapter 3 introduced a novel model proposed, the modified configuration of turbine which called ReT is illustrated and shown in this chapter. The computational and experimental methods are explained. The numerical simulation including meshing, turbulence model of flow around the turbine, wall function at near wall and boundary layers, solver, solutions controls and etc. were described. In this section, the turbulence model solves the unsteady Reynolds averaged Navier-Stokes equations with a script, based on the programming Language C through the User Defined Functions (UDF) for various set of marine current velocity coupled with pressure. It employs the Dynamic Mesh Method (DMM) for solving the movements of blades.

In addition, three different experimental works with introduces the low speed wind tunnel of UTM were carried out to evaluate and measure the goal function of the new design. Furthermore, set up of experimental and procedure of tests with several explanation are given. A flow diagram and structure of the research flowchart are given in this chapter. Finally, turbine analysis is usually done through parametric study using CFD simulations.

In chapter 4, the simulation results such pressure contours, velocity vectors, torque and power coefficient were presented and moreover validated with other studies. The results series of experiments of proposed model consist of pressure distribution and measuring of torque and RPM were presented. There are some comparisons between conventional Savonius and the modified model. The advantages of the ReT in low current speeds are described. Many important parameters of the turbine that obtained from tests were presented in this chapter. In the last part of this chapter the design parametric study on the novel turbine is numerically investigated. Items such as various angles of opening blades, force and torque produced by different parts of ReT and different current speed are discovered.

Finally, the major conclusions are given in chapter 5 which including of brief review on the discussion and results of the current study. Additionally, some future are works recommended for further research.

REFERENCES

Abraham, J., Mowry, G., Plourde, B., Sparrow, E. and Minkowycz, W. (2011). Numerical simulation of fluid flow around a vertical-axis turbine. *Journal of Renewable and Sustainable Energy*. 3 (3): 033109.

Afungchui, D., Kamoun, B., Helali, A. and Djemaa, A. B. (2010). The Unsteady Pressure Field And The Aerodynamic Performances Of A Savonius Rotor Based On The Discrete Vortex Method. *Renewable Energy*. 35 (1): 307-313.

Akwa, J. V., Alves da Silva Júnior, G. and Petry, A. P. (2012a). Discussion On The Verification Of The Overlap Ratio Influence On Performance Coefficients Of A Savonius Wind Rotor Using Computational Fluid Dynamics. *Renewable Energy*. 38 (1): 141-149.

Akwa, J. V., Vielmo, H. A. and Petry, A. P. (2012b). A Review On The Performance Of Savonius Wind Turbines. *Renewable and Sustainable Energy Reviews*. 16 (5): 3054-3064.

Alam, M. J. (2009). *Design and development of a marine current energy conversion system using hybrid vertical axis turbine*. Master of science. Memorial University of Newfoundland

Alexander, A. and Holownia, B. (1978). Wind tunnel tests on a Savonius rotor. *Journal of Wind Engineering and Industrial Aerodynamics*. 3 (4): 343-351.

Alfaro, A. J., Gallegos-Muñoz, A. and Manuel, B.-F. J. (2011). Experimental and numerical analysis of vertical axial wind turbine applying the dynamic mesh method. *ASME 5t International Conference on energy sustainability*.

Ali, R., Daut, I. and Taib, S. (2012). A review on existing and future energy sources for electrical power generation in Malaysia. *Renewable and Sustainable Energy Reviews*. 16 (6): 4047-4055.

Altan, B. D. and Atılgan, M. (2008). An experimental and numerical study on the improvement of the performance of Savonius wind rotor. *Energy Conversion and Management*. 49 (12): 3425-3432.

Altan, B. D. and Atılgan, M. (2010). The use of a curtain design to increase the performance level of a Savonius wind rotors. *Renewable Energy*. 35 (4): 821-829.

Bacon, S. (1997). Circulation and fluxes in the North Atlantic between Greenland and Ireland. *Journal of Physical Oceanography*. 27 (7): 1420-1435.

Bahaj, A., Batten, W. and McCann, G. (2007). Experimental verifications of numerical predictions for the hydrodynamic performance of horizontal axis marine current turbines. *Renewable Energy*. 32 (15): 2479-2490.

Ben Elghali, S. E., Balme, R., Le Saux, K., El Hachemi Benbouzid, M., Charpentier, J. F. and Hauville, F. (2007). A Simulation Model for the Evaluation of the Electrical Power Potential Harnessed by a Marine Current Turbine. *Oceanic Engineering, IEEE Journal of*. 32 (4): 786-797.

Birol, F. (2010). *World energy outlook 2010*. France: International Energy Agency.

Bischof, B., Mariano, A. and Ryan, E. (2003). The North Atlantic drift current. Ocean surface currents.

Blackwell, B. F., Sheldahl, R. F. and Feltz, L. V. (1978). Wind tunnel performance data for two-and three-bucket Savonius rotors. *Journal of Energy*. 2 (3).

Blanco Ilzarbe, J. M. and Teixeira, J. A. (2009). Recent Patents on Tidal Power Extraction Devices. *Recent Patents on Engineering*. 3 (3): 178-193.

Box, G. E., Hunter, W. G. and Hunter, J. S. (1988). *Estadística para investigadores: Introducción al diseño de experimentos, análisis de datos y construcción de modelos*. Devore: Reverté.

Camporeale, S., Torresi, M., Pascazio, G. and Fortunato, B. (2003). A 3D unsteady analysis of a Wells turbine in a sea-wave energy conversion device. *ASME Turbo Expo 2003, collocated with the 2003 International Joint Power Generation Conference*, American Society of Mechanical Engineers.

Can, K., Feng, Z. and Xuejun, M. (2010). Comparison study of a vertical-axis spiral rotor and a conventional Savonius rotor. *Power and Energy Engineering Conference (APPEEC), 2010 Asia-Pacific*, IEEE.

Cao, H. (2011). *Aerodynamics Analysis of Small Horizontal Axis Wind Turbine Blades by Using 2D and 3D CFD Modelling*. Doctoral dissertation. University of Central Lancashire, Preston

Chandran, V. G. R., Sharma, S. and Madhavan, K. (2010). Electricity consumption–growth nexus: The case of Malaysia. *Energy Policy*. 38 (1): 606-612.

Chase, N., Rademacher, M., Goodman, E., Averill, R. and Sidhu, R. (2009). A benchmark study of multi-objective optimization methods, Technical Report BMK-3021, Red Cedar Technology.

Chaudhuri, A. H., Gangopadhyay, A. and Bisagni, J. J. (2009). Interannual variability of Gulf Stream warm-core rings in response to the North Atlantic Oscillation. *Continental Shelf Research*. 29 (7): 856-869.

Chong, H.-Y. and Lam, W.-H. (2013). Ocean renewable energy in Malaysia: The potential of the Straits of Malacca. *Renewable and Sustainable Energy Reviews*. 23: 169-178.

Chua, S. C. and Oh, T. H. (2010). Review on Malaysia's national energy developments: Key policies, agencies, programmes and international involvements. *Renewable and Sustainable Energy Reviews*. 14 (9): 2916-2925.

Cochran, B. C., Banks, D. and Taylor, S. J. (2004). A three-tiered approach for designing and evaluating performance characteristics of novel WECS. *American Institute of Aeronautics and Astronautics, Inc. and the American Society of Mechanical Engineers*: 1-11.

Colgan, J. (2009). The international energy agency. *GPPi Policy Paper Series*. 6.

D'Alessandro, V., Montelpare, S., Ricci, R. and Secchiaroli, A. (2010). Unsteady Aerodynamics of a Savonius wind rotor: a new computational approach for the simulation of energy performance. *Energy*. 35 (8): 3349-3363.

Damak, A., Driss, Z. and Abid, M. S. (2013). Experimental investigation of helical Savonius rotor with a twist of 180°. *Renewable Energy*. 52 (0): 136-142.

Danao, L. A., Qin, N. and Howell, R. (2012). A numerical study of blade thickness and camber effects on vertical axis wind turbines. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*: 0957650912454403.

Danmei, H., Jie, T. and Chaohui, D. (2007). PIV experimental study on the wake flow of horizontal-axis wind turbine model. *Acta Energiae Solaris Sinica*. 28 (2): 200.

De Boer, A. M., Gnanadesikan, A., Edwards, N. R. and Watson, A. J. (2010). Meridional density gradients do not control the Atlantic overturning circulation. *Journal of Physical Oceanography*. 40 (2): 368-380.

Dearn, R. A. (2009). *"Causes of tides."* from http://cockpitcards.co.uk/.

Deb, B. and Gupta, R. (2012). Fluid Flow Analysis of Savonius Rotor at Different Rotor Angle Using CFD. *ISESCO, Journal of science and Technology*. 8 (14): 35-42.

Debnath, B. K., Biswas, A. and Gupta, R. (2009). Computational fluid dynamics analysis of a combined three-bucket Savonius and three-bladed Darrieus rotor at various overlap conditions. *Journal of Renewable and Sustainable energy*. 1 (3): 033110.

Dewar, H., Thys, T., Teo, S., Farwell, C., O'Sullivan, J., Tobayama, T., Soichi, M., Nakatsubo, T., Kondo, Y. and Okada, Y. (2010). Satellite tracking the world's largest jelly predator, the ocean sunfish, Mola mola, in the Western Pacific. *Journal of Experimental Marine Biology and Ecology*. 393 (1): 32-42.

Dobrev, I. and Massouh, F. (2011). CFD and PIV investigation of unsteady flow through Savonius wind turbine. *Energy Procedia*. 6 (0): 711-720.

Eriksson, S., Bernhoff, H. and Leijon, M. (2008). Evaluation of different turbine concepts for wind power. *Renewable and Sustainable Energy Reviews*. 12 (5): 1419-1434.

Esfahani, J. and Karbasian, H. (2012). Optimizing the shape of rotor blades for maximum power extraction in marine current turbines. *International Journal of Automotive and Mechanical Engineering (IJAME)*. 6: 722-729.

Faez Hassan, H., El-Shafie, A. and Karim, O. A. (2012). Tidal current turbines glance at the past and look into future prospects in Malaysia. *Renewable and Sustainable Energy Reviews*. 16 (8): 5707-5717.

Fan, R. J., Chaplin, J. and Yang, G. J. (2010). CFD investigation of performance for marine current turbine based on RANS simulations. *Key Engineering Materials*, Trans Tech Publ.

Fernando, M. and Modi, V. (1989). A numerical analysis of the unsteady flow past a Savonius wind turbine. *Journal of Wind Engineering and Industrial Aerodynamics*. 32 (3): 303-327.

Fluent, A. (2009). 12.0 User’s guide. *User Inputs for Porous Media*. 6.

Fujisawa, N. (1992). On the torque mechanism of Savonius rotors. *Journal of Wind Engineering and Industrial Aerodynamics*. 40 (3): 277-292.

Fujisawa, N. (1996). Velocity measurements and numerical calculations of flow fields in and around Savonius rotors. *Journal of Wind Engineering and Industrial Aerodynamics*. 59 (1): 39-50.

Fujisawa, N. and Gotoh, F. (1994). Experimental study on the aerodynamic performance of a Savonius rotor. *Journal of solar energy engineering*. 116 (3): 148-152.

Fujisawa, N., Ishimatsu, K. and Kage, K. (1995). A comparative study of Navier-Stokes calculations and experiments for the Savonius rotor. *Journal of solar energy engineering*. 117 (4): 344-346.

Ghatage, S. V. and Joshi, J. B. (2012). Optimisation of vertical axis wind turbine: CFD simulations and experimental measurements. *The Canadian Journal of Chemical Engineering*. 90 (5): 1186-1201.

Girard, D. (2013). *"Why use current energy."* from http://www. oceanenergycouncil.com.

Golecha, K., Eldho, T. and Prabhu, S. (2011a). Influence of the deflector plate on the performance of modified Savonius water turbine. *Applied Energy*. 88 (9): 3207-3217.

Golecha, K., Eldho, T. and Prabhu, S. (2011b). Investigation on the Performance of a Modified Savonius Water Turbine with Single and Two Deflector Plates. *In The 11th Asian International conference on Fluid Machinery and, The 3rd Fluid power Technology Exhibition*: 21-23.

Guerri, O., Sakout, A. and Bouhadef, K. (2007). Simulations of the fluid flow around a rotating vertical axis wind turbine. *Wind Engineering*. 31 (3): 149-163.

Guide, A. F. U. s. (2009). Version 12. *ANSYS Inc., January*.

Gupta, R., Biswas, A. and Sharma, K. (2008). Comparative study of a three-bucket Savonius rotor with a combined three-bucket Savonius–three-bladed Darrieus rotor. *Renewable Energy*. 33 (9): 1974-1981.

Gupta, R., Das, R., Gautam, R. and Deka, S. S. (2012). CFD analysis of a two bucket Savonius rotor for various overlap conditions. *ISESCO J. Sci. Tech*. 8 (13): 67-74.

Hantoro, R. H., Utama, I. U., Sulisetyono, A. S. and Erwandi, E. (2010). Validation of Lumped Mass Lateral Cantilever Shaft Vibration Simulation on Fixed-Pitch Vertical-Axis Ocean Current Turbine. *IPTEK The Journal for Technology and Science*. 21 (3).

Harrison, M., Batten, W., Myers, L. and Bahaj, A. (2010). Comparison between CFD simulations and experiments for predicting the far wake of horizontal axis tidal turbines. *IET Renewable Power Generation*. 4 (6): 613-627.

Hashim, H. and Ho, W. S. (2011). Renewable energy policies and initiatives for a sustainable energy future in Malaysia. *Renewable and Sustainable Energy Reviews*. 15 (9): 4780-4787.

Hassan, M. (2011). *Twisted Savonius turbine based marine current energy conversion system*. Memorial University of Newfoundland (Canada): ProQuest Dissertations And Theses.

Hayashi, T., Li, Y. and Hara, Y. (2004). Suzuki Proceedings of European Wind Energy Conference and Exhibition. *Wind tunnel test on a three stage out phase Savonius rotor, London, England*.

Hayashi, T., Li, Y. and Hara, Y. (2005). Wind tunnel tests on a different phase three-stage Savonius rotor. *JSME International Journal, Series B*. 48 (1): 9-16.

Holman, J. (2002). *Heat transfer, 9th*. McGraw-Hill.

Howell, R., Qin, N., Edwards, J. and Durrani, N. (2010). Wind tunnel and numerical study of a small vertical axis wind turbine. *Renewable energy*. 35 (2): 412-422.

Huda, M., Selim, M., Islam, A. and Islam, M. (1992). The performance of an S-shaped Savonius rotor with a deflecting plate. *RERIC International Energy Journal*. 14 (1): 25-32.

Irabu, K. and Roy, J. N. (2007). Characteristics of wind power on Savonius rotor using a guide-box tunnel. *Experimental thermal and fluid science*. 32 (2): 580-586.

Islam, M. R., Mekhilef, S. and Saidur, R. (2013). Progress and recent trends of wind energy technology. *Renewable and Sustainable Energy Reviews*. 21 (0): 456-468.

Jamei, S. (2012). *Aerodynamic characteristics of compound wing configuration of wing-in-ground effect vehicle*. Doctor of Philosophy. Universiti Teknologi Malaysia

Jiang, C. and Yan, Q. (2007). Study on the comparison between the horizontal axis and vertical axis wind turbine. *ShangHai Electricity*. 2: 163-165.

Jo, C. h., Yim, J. y., Lee, K. h. and Rho, Y. h. (2012). Performance of horizontal axis tidal current turbine by blade configuration. *Renewable Energy*. 42 (0): 195-206.

Kadam, A. and Patil, S. (2013). A review study on Savonius wind rotors for accessing the power performance. *Journal of Mechanical and Civil Engineering*. 5: 18-24.

Kailash, G., Eldho, T. and Prabhu, S. (2012). Performance study of modified Savonius water turbine with two deflector plates. *International Journal of Rotating Machinery*. 2012.

Kamoji, M., Kedare, S. and Prabhu, S. (2009b). Performance tests on helical Savonius rotors. *Renewable Energy*. 34 (3): 521-529.

Kamoji, M., Kedare, S. B. and Prabhu, S. (2009a). Experimental investigations on single stage modified Savonius rotor. *Applied Energy*. 86 (7): 1064-1073.

Kang, C., Liu, H. and Yang, X. (2014). Review of fluid dynamics aspects of Savonius-rotor-based vertical-axis wind rotors. *Renewable and Sustainable Energy Reviews*. 33: 499-508.

Khalid, S. S. and Shah, Z. L. N. (2013). Harnessing Tidal Energy Using Vertical Axis Tidal Turbine. *Research Journal of Applied Sciences*. 5.

Khan, M. J., Bhuyan, G., Iqbal, M. T. and Quaicoe, J. E. (2009b). Hydrokinetic energy conversion systems and assessment of horizontal and vertical axis turbines for river and tidal applications: A technology status review. *Applied Energy*. 86 (10): 1823-1835.

Khan, N. I., Iqbal, T., Hinchey, M. and Masek, V. (2009c). Performance of savonius rotor as a water current turbine. *The Journal of Ocean technology*. 4 (2): 71-83.

Kolachana, S. (2012). *A Computational Framework For The Design And Analysis Of Savonius Wind Turbine*. Indian Institute of Technology Madras Chennai

Kuhlbrodt, T., Rahmstorf, S., Zickfeld, K., Vikebø, F. B., Sundby, S., Hofmann, M., Link, P. M., Bondeau, A., Cramer, W. and Jaeger, C. (2009). An integrated assessment of changes in the thermohaline circulation. *Climatic Change*. 96 (4): 489-537.

Kumar, A. and Grover, S. (1993). Performance characteristics of a Savonius rotor for wind power generation—a case study, alternate sources of energy. *Proceedings of ninth national convention of mechanical engineers. India: IIT Kanpur*.

Launder, B. E. and Spalding, D. (1974). The numerical computation of turbulent flows. *Computer methods in applied mechanics and engineering*. 3 (2): 269-289.

Leal, C. H. V. (2008). *Optimization of the efficiency of a Savonius wind turbine for urban media using a genetic algorithm*. Master of science. Instituto tecnolgico y de estudios superiores de monterrey

Leon, N., Cueva, J., Villarreal, C., Hutron, S. and Campero, G. (2007). Automatic shape variations for optimization and innovation.*Trends in Computer Aided Innovation* 179-188, Springer.

Leung, D. Y., Deng, Y. and Leung, M. (2011). Parametric study of a fan-bladed micro-wind turbine. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*: 0957650911413974.

Li, Y., Feng, F., Li, S. and Han, Y. (2010). Computer simulation on the performance of a combined-type vertical axis wind turbine. *Computer Design and Applications (ICCDA), 2010 International Conference on*, IEEE.

Manwell, J. F., McGowan, J. G. and Rogers, A. L. (2010). *Wind energy explained: theory, design and application*. John Wiley & Sons.

Martinez, F. (2010). Drag study of the nacelles of a tidal stream device using CFD.

Martinot, E. and Sawin, J. (2009). Renewables global status report: 2009 update. *Paris, France: REN21 Secretariat*.

McCombes, T. (2006). *Performance evaluation of oscillating hydrofoils when used to extract energy from tidal currents*. Master of science. Delft University of Technology

McNaughton, J. (2013). *Turbulence modelling in the near-field of an axial flow tidal turbine in Code Saturne*. doctoral dissertation. University of Manchester

Menet, J.-L. (2007). Aerodynamic behaviour of a new type of slow-running VAWT.*Wind Energy* 235-240, Springer.

Menet, J.-L. and Bourabaa, N. (2004). Increase in the Savonius rotors efficiency via a parametric investigation. *Europen Wind Energy Conference and Exhibition*. E. n. s. d. i. e. i. a. m. e. e. d. v. (ensiame). Universite de Valenciennes - Le Mont Houy, London, U.K.

Menet, J. L. (2004). A double-step Savonius rotor for local production of electricity: a design study. *Renewable energy*. 29 (11): 1843-1862.

Menter, F., Kuntz, M. and Langtry, R. (2003). Ten years of industrial experience with the SST turbulence model. *Turbulence, heat and mass transfer*. 4 (1).

Mittal, N. (2001). Investigation of Performance Characteristics of a Novel VAWT. *Department of Mechanical Engineering, University of Strathclyde, Glasgow*: 45-70.

Mohamed, M. H., Janiga, G., Pap, E. and Thévenin, D. (2010). Optimization of Savonius turbines using an obstacle shielding the returning blade. *Renewable Energy*. 35 (11): 2618-2626.

Mohamed, M. H. A. (2011). *Design optimization of savonius and wells turbines*. Ph.D. Ottovon-Guericke University Magdeburg

Mojola, O. (1985). On the aerodynamic design of the Savonius windmill rotor. *Journal of wind engineering and industrial aerodynamics*. 21 (2): 223-231.

Myers, L. and Bahaj, A. S. (2006). Power output performance characteristics of a horizontal axis marine current turbine. *Renewable Energy*. 31 (2): 197-208.

Nakajima, M., Iio, S. and Ikeda, T. (2008). Performance of Savonius rotor for environmentally friendly hydraulic turbine. *Journal of Fluid Science and Technology*. 3 (3): 420-429.

Nasef, M., El-Askary, W., AbdEL-Hamid, A. and Gad, H. (2013). Evaluation of Savonius rotor performance: static and dynamic studies. *Journal of Wind Engineering and Industrial Aerodynamics*. 123: 1-11.

Navy, R. M. (2005). Tide Tables Malaysia 2005. *The Hydrographic Department*. Kuala Lumpur, Royal Malaysia Navy.

Ng, K.-W., Lam, W.-H. and Ng, K.-C. (2013). 2002–2012: 10 years of research progress in horizontal-axis marine current turbines. *Energies*. 6 (3): 1497-1526.

Nicholson, K. M. (2010). *Numerical investigation of the aerodynamic performance of a double-stage savonius rotor with twisted blades*. Master of science. University of Louisville

Nobile, R., Vahdati, M., Barlow, J. and Mewburn-Crook, A. (2013). Unsteady flow simulation of a vertical axis wind turbine: a two-dimensional study. *EngD Conference, 2nd July*.

Noor, A. and Mansor, S. (2013). Measuring Aerodynamic Characteristics Using High Performance Low Speed Wind Tunnel at Universiti Teknologi Malaysia. *J Appl Mech Eng*. 3 (132): 2.

NREL, N. R. E. L. (2009). Ocean energy technology overview. *EnergyEfficiency and Renewable Energy*: 32.

Ogawa, T., Yoshida, H. and Yokota, Y. (1989). Development of rotational speed control systems for a Savonius-type wind turbine. *Journal of fluids engineering*. 111 (1): 53-58.

Olivier, J. G., Janssens-Maenhout, G. and Peters, J. A. (2012). *Trends in global CO2 emissions: 2012 Report*. PBL Netherlands Environmental Assessment Agency The Hague, The Netherlands.

Ong, H., Mahlia, T. and Masjuki, H. (2011). A review on energy scenario and sustainable energy in Malaysia. *Renewable and Sustainable Energy Reviews*. 15 (1): 639-647.

Pritchard, R. W. F. A. T. M. P. J. (2003). *Introduction of Fluid Mechanics*.

Rahai, H. and Hefazi, H. (2005). Development of optimum design configuration and performance for vertical axis wind turbine. *Feasibility Analysis and Final EISG Report*. California Energy Commission.

Rogers, S. E., Kwak, D. and Chang, J. L. (1989). Numerical Solution Of Navier-Stokes Equations. NASA Ames Research Center; Moffett Field, United States, NASA Tech Briefs.

Ross, I., Altman, A., Bowman, D., Mooney, T. and Bogart, D. (2010). Aerodynamics of vertical-axis wind turbines: Assessment of accepted wind tunnel blockage practice. *Proc. of the 48th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, Paper AIAA*.

Rourke, F. O., Boyle, F. and Reynolds, A. (2010). Tidal energy update 2009. *Applied Energy*. 87 (2): 398-409.

Roy, S. and Saha, U. K. (2013). Review of experimental investigations into the design, performance and optimization of the Savonius rotor. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*. 227 (4): 528-542.

Saadatian, O. (2012). Review Of Current National Energy Policies In Malaysia. *3rd International Conference On Business And Economic*

Research (3rd Icber 2012) Proceeding Golden flower hotel, bandung, indonesia.

Sabaeifard, P., Razzaghi, H. and Forouzandeh, A. (2012). Determination of vertical axis wind turbines optimal configuration through CFD simulations. *2012 International Conference on Future Environment and Energy IPCBEE*.

Saha, U. and Rajkumar, M. J. (2006). On the performance analysis of Savonius rotor with twisted blades. *Renewable Energy*. 31 (11): 1776-1788.

Saha, U., Thotla, S. and Maity, D. (2008). Optimum design configuration of Savonius rotor through wind tunnel experiments. *Journal of Wind Engineering and Industrial Aerodynamics*. 96 (8): 1359-1375.

Scheurich, F., Fletcher, T. M. and Brown, R. E. (2011). Effect of blade geometry on the aerodynamic loads produced by vertical-axis wind turbines. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*. 225 (3): 327-341.

Setoguchi, T., Kinoue, Y., Kim, T., Kaneko, K. and Inoue, M. (2003). Hysteretic characteristics of Wells turbine for wave power conversion. *Renewable Energy*. 28 (13): 2113-2127.

Setoguchi, T., Santhakumar, S., Takao, M., Kim, T. and Kaneko, K. (2001). Effect of guide vane shape on the performance of a Wells turbine. *Renewable energy*. 23 (1): 1-15.

Setoguchi, T., Takao, M., Kaneko, K. and Inoue, M. (1998). Effect of guide vanes on the performance of a Wells turbine for wave energy conversion. *International Journal of Offshore and Polar Engineering*. 8 (2): 155-159.

Shafie, S. M., Mahlia, T. M. I., Masjuki, H. H. and Andriyana, A. (2011). Current energy usage and sustainable energy in Malaysia: A review. *Renewable and Sustainable Energy Reviews*. 15 (9): 4370-4377.

Shindell, D., Kuylenstierna, J. C., Vignati, E., van Dingenen, R., Amann, M., Klimont, Z., Anenberg, S. C., Muller, N., Janssens-Maenhout, G. and Raes, F. (2012). Simultaneously mitigating near-term climate change and improving human health and food security. *Science*. 335 (6065): 183-189.

Sivasegaram, S. (1979). Concentration augmentation of power in a Savonius-type wind rotor. *Wind Engineering*. 3: 52-61.

Sivasegaram, S. and Sivapalan, S. (1983). Augmentation of power in slow-running vertical-axis wind rotors using multiple vanes. *Wind Engineering*. 7: 12-19.

Soerensen, H. C. and Weinstein, A. (2008). Ocean energy: position paper for IPCC. *Key Note Paper for the IPCC Scoping Conference on Renewable Energy, Lübeck, Germany, January*.

Statistics, I. (2011). *"International Energy Agency."* from http://www.iea.org/statistics/.

Stokes, G. G. (1851). *On the effect of the internal friction of fluids on the motion of pendulums*. Pitt Press.

Suprayogi Sunanto, D. T. (2008). *Savonius rotor vertical axis marine current turbine for renewable energy application*. M.sc. University Technologi Malaysia

Świrydczuk, J., Doerffer, P. and Szymaniak, M. (2011). Unsteady Flow through the Gap of Savonius Turbine Rotor. *TASK Quarterly: scientific bulletin of Academic Computer Centre in Gdansk*. 15: 59-70.

Tang, Z. P., Yao, Y. X., Zhou, L. and Yu, B. W. (2013). A review on the new structure of savonius wind turbines. *Advanced Materials Research*. 608: 467-478.

Tansley, C. E. and Marshall, D. P. (2001). Flow past a cylinder on a β plane, with application to Gulf Stream separation and the Antarctic Circumpolar Current. *Journal of physical oceanography*. 31 (11): 3274-3283.

Thakker, A., Frawley, P. and Bajeet, E. S. (2001). Numerical analysis of Wells turbine performance using a 3D Navier-Stokes explicit solver. *Proceedings of the lllh ISOPE, Stavanger, Norway, June*: 17-22.

Ueno, H., Mino, M. and Takada, N. (2004). Savonius type wind turbine (The influence of wind concentrator). *Journal of Japan Solar Energy Society*. 30 (5): 35-40.

Ushiyama, I., Mino, M. and Nagai, H. (1982). The optimum design configurations of Savonius wind turbines. *Proc., Intersoc. Energy Convers. Eng. Conf.;(United States)*, Dept. of Mechanical Engineering, Ashikaga Institute of Technolog, 268 Omae-cho, Ashikaga-city, Tochigi-pref.

Ushiyama, I. and Nagai, H. (1988). Optimum design configurations and performance of Savonius rotors. *Wind Engineering*. 12 (1): 59-75.

Vaishnav, E. (2010). *An investigation on the aerodynamic performance of a vertical axis wind turbine*. Master of science. Oklahoma State University

Vega, L. (1999). Ocean thermal energy conversion (OTEC). *OTEC News-Clean Energy, Water and Food*.

Vermaak, H. J., Kusakana, K. and Koko, S. P. (2014). Status of micro-hydrokinetic river technology in rural applications: A review of literature. *Renewable and Sustainable Energy Reviews*. 29: 625-633.

Versteeg, H. K. and Malalasekera, W. (2007). *An introduction to computational fluid dynamics: the finite volume method*. New York: Pearson Education.

Vishwakarma, R. (1999). Savonius rotor wind turbine for water pumping—an alternate energy source for rural sites. *Journal of Institution of Engineers (India)*. 79: 32-34.

WEO, I. (2012). World Energy Outlook 2012. *International Energy Agency. Paris*.

Whalley, J., Johnson, M. and MacMillin, B. (2009). Effect of turbulence on savonius rotor efficiency. *Fluids Laboratory*.

Woodward, R. (2009). Organisation for Economic Co-operation and Development (OECD). held in paris, Routledge.

Yaakob, O. (2012). Marine renewable energy initiatives in Malaysia and South East Asia. *13th meeting of the United Nations Open-ended Informal Consultative Process on Oceans and the Law of the Sea* New York.

Yaakob, O., Ab Rashid, T. T. and Mukti, M. A. A. (2006). Prospects for ocean energy in Malaysia. *International Conference on Energy and Environmental (ICEE)* Kuala Lumpur.

Yaakob, O., Abdul Ghani, M., Tawi, K. B., Suprayogi, D. T., Aziz, A. and Bin Jaafar, K. E. (2008a). Development of ocean wave and current energy device. *Proceedings Seventh UMT International Symposium on Sustainability Science and Management (UMTAS).*

Yaakob, O., Ismail, M. A. and Yasser, M. A. (2013). Parametric Study for Savonius Vertical Axis Marine Current Turbine using CFD Simulation.

Yaakob, O., Tawi, K. and Suprayogi, D. (2008b). Development of vertical axis marine current turbine rotor. *International Conference Marine Renewable Energy* RINA, London, UK.

Yaakob, O., Yasser, M. A. and Ismail, M. A. (2012). Validation study for savonius vertical axis marine current turbine using CFD simulation. *6th Asia-Pacific workshop on marine hydrodynamics-APHydro2012*.

Yaakob, O. B., Tawi, K. and Sunanto, D. S. (2010). Computer simulation studies on the effect overlap ratio for savonius type vertical axis marine current turbine. *Int. J. Eng. Trans. A Basics*. 23: 79-88.

Yonghai, H. and Zhengming, T. (2009). The Influence of Windshield on Aerodynamic Performance of VAWT. *Energy and Environment Technology, 2009. ICEET'09. International Conference on*, IEEE.

Yu, H. (2009). *Numerical investigation of a rotating system using OpenFOAM*. Master of science. University of Magdeburg

Zhao, Z., Zheng, Y., Xu, X., Liu, W. and Hu, G. (2009). Research on the improvement of the performance of savonius rotor based on numerical study. *Sustainable Power Generation and Supply, 2009. SUPERGEN'09. International Conference on*, IEEE.

Zhu, Y.-h. and Liu, Z.-z. (2008). Structure and performance analysis for hybrid vertical axis wind turbines with lift and resistance leaves [J]. *East China Electric Power*. 7: 030.

Zullah, M. A., Prasad, D., Ahmed, M. R. and Lee, Y.-H. (2010). Performance analysis of a wave energy converter using numerical simulation technique. *Science in China Series E: Technological Sciences*. 53 (1): 13-18.