131. Parametric Study of Three Blade Vertical Axis Micro Hydro Turbines (VAMHT) by changing Blade Characteristics

Intizar Ali[a], Dr. Tanweer Hussain[b,*], Hosh Muhammad[c],Dr. Saad Sami Al Khfaji[d]

[a]*Teaching Assistant Dept.of Mechanical Engineering Mehran UET Jamshoro, Pakistan*
[b]*Associate Professor Dept.of Mechanical Engineering Mehran UET Jamshoro, Pakistan*
[c]*Masters studuent Dept.of Mechanical Engineering Mehran UET Jamshoro, Pakistan*
[d]*HoD of Dept of Foreign Academic Degrees Assessment Ministry of Higher Education and Scientific Research Bhagdad Iraq*
**Email Address: tanweer.hussain@faculty.muet.edu.pk*

Abstract

As the concerns about rising fossil-fuel prices, energy security and climate-change increase, hydrokinetic power plays a vital role in producing local, clean and inexhaustible energy to supply world rising demand for electricity. But in order to obtain optimum power output from hydropower efficiency of system components is highly important. Therefore in this research parametric study of Vertical axis Micro Hydrokinetic Turbine (VAMHT) is carried out in FLUENT to analyze effect of pitch angle and blade profile on turbine performance. Different models were developed in gambit software at pitch angle of 0^o, 5^o and 10^o for two different airfoils of NACA0015 and NACA0020. Simulation is done to solve Reynolds-Averaged Navies-Stokes (RANS) equations through finite volume method on unstructured mesh. Study uses $k-\omega$ SST turbulence model to predict the values of various performance parameters such as torque, lift, drag as well as pressure and velocity contours near turbine blades. Parametric study reveals that maximum torque is obtained at 0 degree pitch angle and increase in pitch angle results decrease in torque produced. Study also found that blade profile NACA0020 have better performance than NACA0015.

Keywords: *Pitch angle; Run-of-the-river (ROR)*

1. Introduction

Rising energy demand increasing global warming and depleting fossil fuels have given great thrust for rapid development of renewable energy extraction. Out of the all renewable energy resources hydroelectric power is one intensive source to extract energy at the large quantity. In addition to that it was investigated that it provides power at very low cost in comparison of other energy resources like nuclear, thermal, wind as well as solar power [1-5]. From last few years most of the developing countries are putting their efforts to enhance hydro power extraction to lessen the threat to carbon emission. Specially for producing electrical energy hydropower is one of the favorable regulatory power sources that is easily control as well as adjust gates of dams. Hydropower regulation performances are comparable with plants burning coal and petroleum products. For the prosperity and development of any country it has become mandatory to produce clean, cost efficient and sufficient power.

Pakistan is a country having abundant hydropower resources with potential of about 41000 to 45000MW[6]. Whereas Pakistan is producing 6555MW power from hydropower resources which only accounts for 34% of their energy supply. As still there is lot of potential for hydropower which has to be harnessed. In generally there are three hydro-power producing techniques such as Conventional dams, Run-of-the-river (ROR) and Pumped-storage hydroelectricity (PSH). But, all the three hydropower techniques requires high capital cost, complex structure, more negative effects on environment and is highly whether dependent[7-9].Therefore in order to meet rising energy demand, lot of research isgoing on micro-hydro power technologies but still they are at developing stages. Since at present Pakistan is under high energy crises due to various financial and technological issues. Hence this research is conducted to enhance efficiency of well-known Darrieus turbine which is relative simple, requires low maintenance cost, easily manufactured as well as can be installed in existing irrigation channels and canals. This type of power generation system does not require drive system and can be used to produce clean, local electricity for remote areas as well as rural electrification purpose up to few hundred kilowatts[10]. Since other micro hydro power techniques require some catchment for waters storage and to produce water head, if water level changes rate of flow would be affected. For those cases if water level can be estimated then power generation capacity can be estimated [11-13]. But VAMHT power producing characteristics are very different from those turbines which generate power by exploiting potential energy of water. These turbines produce power by utilizing kinetic energy of flowing water without creating any interruption in flow. These turbines don't require so much civil structure and can be easily removed during or for maintenance purpose. Hydrokinetic power is generally believed to be zero-head power but still its share to share to world total energy demand is still very less. Few years ago hydrokinetic power have got importance to harness it. However from literature Vertical axis micro-hydro turbine uses basic structure of wind turbine to extract energy from water. Three straight blade H-Darrieus turbine has got extreme importance in wind power generation. Few years ago in 80s and 90s several turbine models was developed by using double and multiple stream tubes to predict performance of these turbines[14-19]. Sometime later number of wind tunnel experiments was carried out to analyze effect of Tip speed ratio (TSRs) on turbine performance at low wind speed. Their researches enhanced turbine efficiency [20-23]. During 1974 in response to energy crises American government decide to launch research on alternative energy resources including research on wind turbines. At the same time in a group of researchers at Sandia National Laboratory in Albuquerque at New Mexico conducted various experiments on wind tunnel as well as on full models scale. From their models one turbine reaches to 40% efficiency which is very near to horizontal axis wind turbines that is 45% [24].Recently research was conducted on high solidity and low TSR Darrieus turbines through various wind tunnel or water channel experiments but their experiments results showed to have a lower measured efficiency 25 to 30%[22, 23]. From extensive literature review it is concluded that lot of research is being conducted on Darrieus turbine by considering effect of solidity, tip speed ratio and number of blades etc. for considering it as wind turbine. However very less research were conducted on Darrieus turbine for using it as hydro turbines and still there is lot research needs to analyze as well as to optimize turbine performance by using water as working fluid. Therefore this research mainly focuses on parametric study of Darrieus turbine on the bases of hydropower production. This research seeks to explore

- Effect of blade pitch angle on its torque performance
- Blade profile effect on turbine efficiency
- Visualization of Flow behaviour in the vicinity of turbine at various pitch angles.

2. Micro-turbine concept

The turbine exploited in this research basically produce power in same way that of wind turbines. In these types of turbine at the first instant wind energy is converted into mechanical energy through than that energy would be converted into electrical energy though generator. These turbines exploit kinetic energy of moving water rather than potential energy.

Simple construction and installation, which were the perceived benefits of using micro-hydro turbines in this study, allow micro-hydro turbines to be installed in any type of canal or irrigation channel without affecting the water flow. Micro-hydro turbines can exist individually in electrical power supplies. Available water power can be calculated by using an equation.

$$P_w = \frac{1}{2}\rho A U_\infty^3 \tag{1}$$

Where ρ, A and U_∞ represents density of water (Kg/m3), swept area of turbine (m2) and free stream velocity of flowing fluid in (m/s). The equation (2) is used to determine output power at the end of generator after encountering the turbine performance, generator and bearing efficiency.

$$P = K\frac{1}{2}\rho A U_\infty^3 \tag{2}$$

$$K = C_p \eta_b \eta_g \tag{3}$$

C_p = turbine power coefficient

η_b = Bearing efficiency

η_g = Generator Efficiency

Turbine power coefficient is the ratio of generated power to available water power and can be calculated by equation

$$C_p = \frac{T\omega}{\frac{1}{2}\rho A U_\infty^3} \tag{4}$$

As this research uses torque optimization for that torque coefficient corresponding to turbine radius can determined through following formula.

$$C_m = \frac{T}{\frac{1}{2}\rho A U_\infty^2 R} \tag{5}$$

Another important design parameter is the tip speed ratio of turbine that can be calculated if angular

velocity, radius as well as free stream velocity of flowing stream fluid is known

$$\lambda = \frac{\omega R}{U_\infty} = \frac{C_p}{C_m} \tag{6}$$

3. Numerical Simulation

3.1. Turbine Modelling and Gird generation

In this research Darrieus turbine is selected because it is simple, easy to manufacture and requires less maintenance. The turbine size is kept in such a way that it can be installed in existing canals as well as in irrigation channels. Three bladed vertical axis turbines are designed with two different airfoils and at three different pitch angles. All the three blades are connected with central axis through arms in the turbines. Fig. 1 shows the turbine designed at 0^o pitch angle and its specification is given in table#1.Three dimensional model of turbine is imported and fluid domain of appropriate size is generated in order to predict realist behaviour of flow around turbine as well as get accurate turbine performance. The gird generation is next most important step in Computational Fluid Dynamics (CFD) analysis of turbine. For that solid turbine model is subtracted from flow domain and processed for mesh generation. Mesh is generated in ANSYS ICEM where fine size tetrahedral mesh elements are used to generate large number of control volumes. Unstructured mesh is generated through patch conforming algorithm to get finer mesh in areas of interest.

Table 1. Geometric details of micro Hydrokinetic turbine

Geometry of turbine	Dimensions
Blade pitch angles	O
Blade length	1.5m
Turbine diameter	1.5m
Number of blades	3
Blade chord length	0.15m

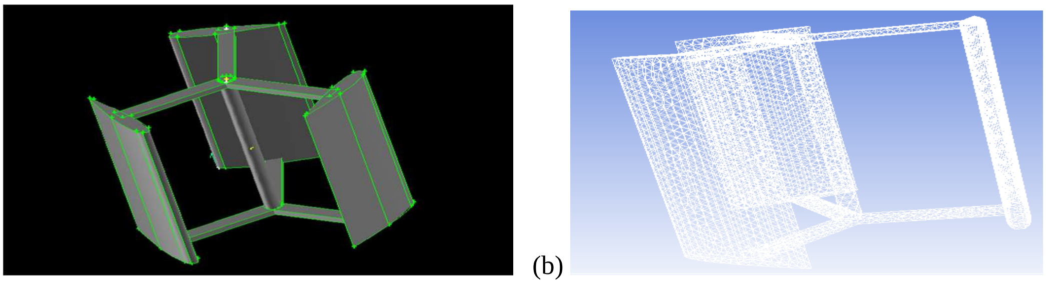
(a)  (b)

Fig. 1. (a) Three dimensional geometry of turbine (b) Meshing of turbine

3.2. Governing Equation & Turbulence Modeling

The fluid flow governing equations includes the conservation of mass, momentum as well as energy. Equations derived by using these principles are generally complex Partial Differential equations (PDE) which encounters small-scale fluctuation occurs in flow which make them even more difficult to solve analytically. In order to simplify those equations Reynolds averaging technique is applied. Here Reynolds average Navier-Stokes (RANS) equations along with turbulence models are numerically solved by using FLUENT. According to Reynolds averaging rule the solution variables in exact Navier-Stokes (NS) equations are decomposed in time averaged and fluctuating parts. By using averaging velocity of fluid in X-direction is

$$u_i = \bar{u}_i + u_i'$$

Where $\bar{u}_i$ and u_i' are average and fluctuating parts of velocity respectively. Following equations are obtaining by substituting all the flow variables by time averaged components in exact continuity and momentum equations results following equations.

$$\frac{\partial}{\partial x_i}(u_i) = 0 \tag{7}$$

$$\frac{\partial}{\partial x_j}(\rho u_i u_j) = \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho \overline{u_i' u_j'}\right) \tag{8}$$

The equations 1 and two are known as Reynolds average Navier-Stokes equations. Additional terms in above equation are encountering the effect of turbulences. The last term $\left(-\rho \overline{u_i' u_j'}\right)$ in equation 2 is called Reynolds stresses. Reynolds stress $\left(-\rho \overline{u_i' u_j'}\right)$ terms should be modelled by selecting appropriate turbulence model to get accurate results [25]. To select best turbulence model various researches are conducted which come know that $k-\omega$ model provides good results then $k-\varepsilon$ model for near wall problems [26-28]. Though $k-\omega$ model is better but its great sensitivity for the ω values near ir-rotational boundaries creates problem in case of shear flows. But this problem was solved by Menter's $k-\omega$ SST model which combines merits of $k-\omega$ and $k-\varepsilon$ model for near the wall and away from wall flows[29, 30]. The Shear Stress Transport (SST) model proved to be very helpful for encountering the effects in boundary layer and flow separation regions and also number of researches proved that $k-\omega$ SST turbulence model highly suitable for vertical axis turbine simulation[31-35], transport equations of $k-\omega$ SST model are[36].

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}(\Gamma k\frac{\partial k}{\partial x_j})+\tilde{G}_k-Y_k+S_k \quad (9)$$

$$\frac{\partial(\rho\omega)}{\partial t}+\frac{\partial(\rho\omega u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}(\Gamma\omega\frac{\partial\omega}{\partial x_j})+\tilde{G}_\omega-Y_\omega+D_\omega+S_\omega \quad (10)$$

4. Computational Method/methodology

This study presents a novel numerical method of predicting turbine performance for unknown tip speed ratio. From the literature it was found that numbers of simulations are performed by assuming tip speed ratio. In this research numerical simulation of H- Darrieus hydrokinetic turbine is carried out in which turbine is assumed to stationary and torque due to force of flowing fluid is determined and optimized for three different pitch angle and different airfoils. CFD analysis is performed on FLUENT to solve Reynolds average Navier-Stokes (RANS) with turbulence models on unstructured mesh. This study solves partial differential equations governing fluid flow are generally linearized through implicit scheme because it converges more quickly than explicit scheme solver [37]. SIMPLE pressure-velocity coupling solution method is used to compute flow properties. Steady state simulation is performed by using pressure-based solver because flowing fluid is liquid water which incompressible.

5. Results and discussion

In this research CFD analysis of micro hydro turbine is carried out study effects of various deign parameters on turbine performance. For that purpose several turbine models are simulated at three different pitch angles as well as at two different air foils. Results are presented as follow.

5.1. Effect of pitch angle for air foil NACA0015

In order to determine effect of pitch on turbine performance the airfoil NACA0015 is tested for three different pitch angles such as 0^o , 5^o and 10^o .Static pressure and velocity distributions on near the blades are shown in Fig 2, and 5 at different pitch angles. From pressure contour it is observed that pressure increase in front of blade whereas decreases on backside of turbine blade. This causes wake on the backside of turbine.

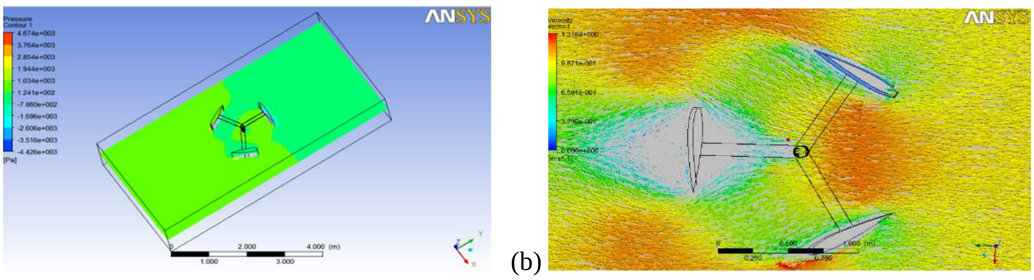
(a)  (b)

Fig. 2. (a) Pressure variations near Turbine the blades at pitch angle 0 degree (b) Velocity Vector near Turbine blades at pitch angle 0 degree.

5.2. Effect of pitch angle for air foil NACA0020

In this case air foil NACA0020 is selected to analyse effect of pitch angle for that purpose CFD simulation of three different pitch angle turbine model is conducted. Pitch angle of 0^o, 5^o and 10o are selected to analyse their effect. Static pressure and velocity distributions on near the blades are shown in Fig 2, and 5 at different pitch angles. From Fig. 6 it is observed that velocity of flowing water decreases when it comes closer to turbine because its pressure rises near the turbine blade. This decrease in velocity remains till to the point where fluid regain its kinetic energy.

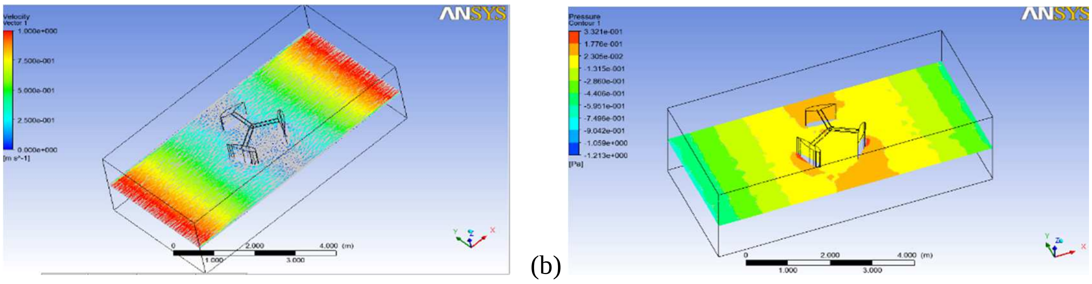

(a) (b)

Fig. 3. Illustration of (a) Pressure variations near Turbine the Pressure variations near Turbine the and (b) Pressure variations near Turbine the at pitch angle 5 degree.

CFD simulation of three blades micro- hydrokinetic turbine also predicted numerical values of different turbine performance parameters such as torque, lift and drag coefficient. But out of them this research is more interested in analysing the effect of air foil thickness as well as pitch angle on torque production. Numerical simulation results reveals that increasing pitch angle from 0 to 10° results decrease in torque production for both of the airfoils. CFD simulation also reveals that blade profile NACA0020 have better performance than NACA0015. The comparison of variation in torque produce for two different airfoils at three different pitch angles given in table 3 and Figure 8.

Table 2. Showing comparative analysis of torque by changing blade pitch angle

Turbine blade pitch angles	Torque generated on NACA 0015	Torque generated on NACA 0020
0 degree	220.1 Nm	265.12 Nm
5 degree	212.23 Nm	256.64 Nm
10 degree	190.3 Nm	235.57 Nm

5.3. Comparative Analysis of Torque with Varying Blade Angle

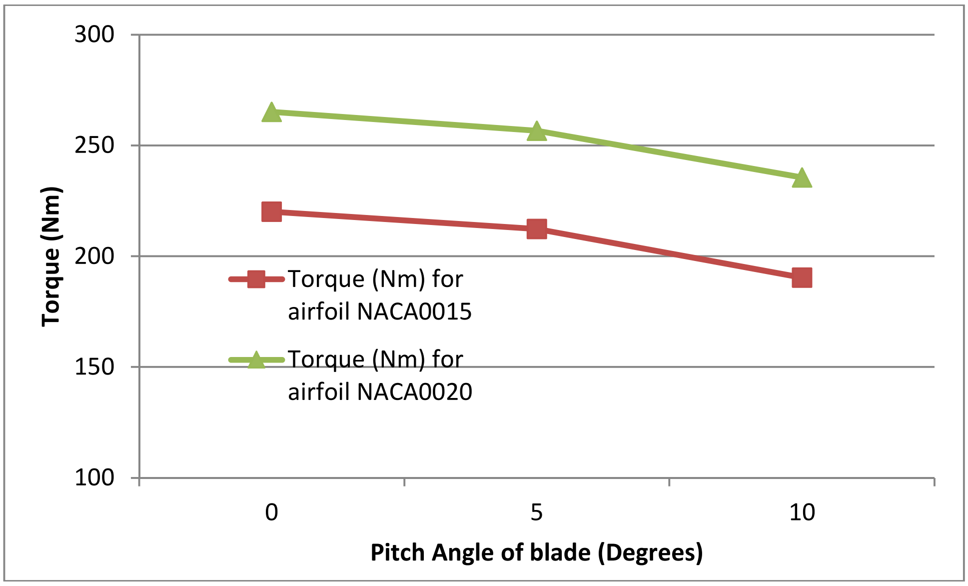


Fig. 3. Illustration of Comparative Analysis of Torque with Varying Blade Angle and airfoil

6. Conclusion

CFD simulation of Three bladed Vertical Axis Micro hydro Turbine (VAMHT) is carried out in order to find the analyse the effect of pitch angle and airfoil on torque production. In this study six different turbine models was developed in gambit and simulated in FLUENT 14.5. Numerical simulation of three bladed vertical axis micro hydrokinetic turbine simulation results reveals that increasing pitch angle from 0 to 10° results decrease in torque production for both of the airfoils. CFD simulation also reveals that blade profile NACA0020 have better performance than NACA0015. Through CFD simulation it was concluded that 0° pitch angle is capable of providing best results and airfoil NACA0020 has better performance, therefore study suggest that turbine should be designed by keeping 0° pitch angle.

References

[1] Chacra, F.A., et al., *Impact of energy storage costs on economical performance in a distribution substation.* IEEE Transactions on Power Systems, 2005. **20**(2): p. 684-691.

[2] Pérez-Díaz, J.I., J.R. Wilhelmi, and L.A. Arévalo, *Optimal short-term operation schedule of a hydropower plant in a competitive electricity market.* Energy Conversion and Management, 2010. **51**(12): p. 2955-2966.

[3] Santolin, A., et al., *Techno-economical method for the capacity sizing of a small hydropower plant.* Energy Conversion and Management, 2011. **52**(7): p. 2533-2541.

[4] Shafie-Khah, M., M.P. Moghaddam, and M. Sheikh-El-Eslami, *Price forecasting of day-ahead electricity markets using a hybrid forecast method.* Energy Conversion and Management, 2011. **52**(5): p. 2165-2169.

[5] Yuan, X., et al., *Optimal self-scheduling of hydro producer in the electricity market.* Energy Conversion and Management, 2010. **51**(12): p. 2523-2530.

[6] resources, M.o.P.a.N., *Pakistan Energy year book*, H.d.i.o. Pakistan., Editor. 2010.

[7] Deane, J.P., B.Ó. Gallachóir, and E. McKeogh, *Techno-economic review of existing and new pumped hydro energy storage plant.* Renewable and Sustainable Energy Reviews, 2010. **14**(4): p. 1293-1302.

[8] Hammons, T.J., P. Naidoo, and L. Musaba, *Run of river bulk hydroelectric generation from the Congo river without a conventional Dam.* Natural Resources, 2011. **2**(01): p. 18.

[9] Margeta, J. and Z. Glasnovic, *Role of water-energy storage in PV-PSH power plant development.* Journal of Energy Engineering, 2011. **137**(4): p. 187-197.

[10] Sun, Y. and Q. Gao, *The design and operation of 700MW class Totally Air-Cooled Hydroelectric generators*, in *IEEE EUROCON 2009*. 2009.

[11] Cheng, C., et al., *Short-Term Hydroscheduling with Discrepant Objectives Using Multi-Step Progressive Optimality Algorithm1.* JAWRA Journal of the American Water Resources Association, 2012. **48**(3): p. 464-479.

[12] Taormina, R., K.-W. Chau, and R. Sethi, *Artificial neural network simulation of hourly groundwater levels in a coastal aquifer system of the Venice lagoon.* Engineering Applications of Artificial Intelligence, 2012. **25**(8): p. 1670-1676.

[13] Wu, C., K. Chau, and Y. Li, *Predicting monthly streamflow using data-driven models coupled with data-preprocessing techniques.* Water Resources Research, 2009. **45**(8).

[14] Beans, E.W., *Approximate aerodynamic analysis for multi-blade darrieus wind turbines.* Journal of Wind Engineering and Industrial Aerodynamics, 1987. **25**(2): p. 131-150.

[15] Grylls, W., B. Dale, and P. Sarre. *A theoretical and experimental investigation into the variable pitch vertical axis wind turbine*. in *Proceedings of 2nd International Symposium on Wind Energy Systems, Amsterdam, The Netherlands*. 1978.

[16] Mays, I. and B. Holmes, *Commercial development of the variable geometry vertical axis windmill.* International Power Generation, Surrey, UK, 1979.

[17] Paraschivoiu, I., *Wind turbine design: with emphasis on Darrieus concept*. 2002: Presses inter Polytechnique.

[18] Strickland, J.H., *Darrieus turbine: a performance prediction model using multiple streamtubes*. 1975, Sandia Labs., Albuquerque, N. Mex.(USA).

[19] Templin, R., *Aerodynamic performance theory for the NRC vertical-axis wind turbine*. 1974, National Aeronautical Establishment, Ottawa, Ontario (Canada).

[20] Armstrong, S., A. Fiedler, and S. Tullis, *Flow separation on a high Reynolds number, high solidity vertical axis wind turbine with straight and canted blades and canted blades with fences.* Renewable Energy, 2012. **41**: p. 13-22.

[21] Gosselin., R., *Control of flow separation on vertical axis wind turbine blades*, in *Departement of Mechanical Engineering*. 2008, University of Sheffield.

[22] Li, Y. and S.M. Calisal, *Three-dimensional effects and arm effects on modeling a vertical axis tidal current turbine.* Renewable energy, 2010. **35**(10): p. 2325-2334.

[23] Howell, R., et al., *Wind tunnel and numerical study of a small vertical axis wind turbine.* Renewable energy, 2010. **35**(2): p. 412-422.

[24] Pope, K., I. Dincer, and G. Naterer, *Energy and exergy efficiency comparison of horizontal and vertical axis wind turbines.* Renewable Energy, 2010. **35**(9): p. 2102-2113.

[25] Wilcox, D., *and 1998, Turbulence Modeling for CFD, DCW Industries.* Inc. La Canada, California, 1993.

[26] Ferreira, C.S., et al. *Simulating dynamic stall in a 2D VAWT: modeling strategy, verification and validation with particle image velocimetry data*. in *Journal of physics: conference series*. 2007. IOP Publishing.

[27] Wang, S., et al., *Numerical investigations on dynamic stall of low Reynolds number flow around oscillating airfoils.* Computers & Fluids, 2010. **39**(9): p. 1529-1541.

[28] Castelli, M.R., A. Englaro, and E. Benini, *The Darrieus wind turbine: Proposal for a new performance prediction model based on CFD.* Energy, 2011. **36**(8): p. 4919-4934.

[29] Dai, Y.M., N. Gardiner, and W.-H. Lam. *CFD modelling strategy of a straight-bladed vertical axis marine current turbine*. in *The Twentieth International Offshore and Polar Engineering Conference*. 2010. International Society of Offshore and Polar Engineers.

[30] Menter, F.R., *Two-equation eddy-viscosity turbulence models for engineering applications.* AIAA journal, 1994. **32**(8): p. 1598-1605.

[31] Chong, W., et al., *The design, simulation and testing of an urban vertical axis wind turbine with the omni-direction-guide-vane.* Applied Energy, 2013. **112**: p. 601-609.

[32] Lim, Y., W. Chong, and F. Hsiao, *Performance investigation and optimization of a vertical axis wind turbine with the Omni-direction-guide-vane.* Procedia Engineering, 2013. **67**: p. 59-69.

[33] Nobile, R., et al., *Unsteady flow simulation of a vertical axis augmented wind turbine: A two-dimensional study.* Journal of Wind Engineering and Industrial Aerodynamics, 2014. **125**: p. 168-179.

[34] Almohammadi, K., et al., *Computational fluid dynamics (CFD) mesh independency techniques for a straight blade vertical axis wind turbine.* Energy, 2013. **58**: p. 483-493.

[35] Mohamed, M., A. Ali, and A. Hafiz, *CFD analysis for H-rotor Darrieus turbine as a low speed wind energy converter.* Engineering Science and Technology, an International Journal, 2015. **18**(1): p. 1-13.

[36] Kumar, T.M.P. and D. Chatterjee, *Numerical study of turbulent flow over an S-shaped hydrofoil.* Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 2008. **222**(9): p. 1717-1734.

[37] Guide, F.I.U. *FLUENT 6.3.2, User Guide*. 2006.