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Determination of Vertical Axis Wind Turbines Optimal Configuration through CFD Simulations

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Abstract. Using vertical axis wind turbines at buildings seems favorable due to the fact that they do not suffer from frequent wind direction changes, have a design simply integrate with building architecture and they have better response in turbulence wind flow which is common in urban areas. This paper presents a computational and experimental study into the aerodynamics and performance of small scale Darrieus-type straight-bladed vertical axis wind turbines and describes the effect of some design parameters including number of blades, airfoil type and turbine solidity on the performance of them. K-ε turbulence model is chosen to perform the transient simulations and multiple reference frame(MRF) model capability of a computational fluid dynamics (CFD) solver is used to express the dimensionless form of power output of the wind turbine as a function of the wind freestream velocity and the rotor's rotational speed.The results show that the optimized turbine experienced maximum power coefficient of 0.36 and 0.32 in tip speed ratio of 3.5 for CFD simulations and wind tunnel test respectively.

Keywords: Wind Energy, Vertical Axis Wind Turbine, Computational Fluid Dynamics, Power Coefficient.

1. Introduction

The Darrieus turbine is the most common VAWT invented in 1931 [1], which looks like a giant egg whisk. In the 80s, several wind farms with commercial Darrieus turbines were operated in California [2]; the biggest turbine that was built had a rated power of 4 MW [3]. However, the Darrieus turbine suffered from structural problems and a poor energy market. As a consequent most turbines were dismantled and the research effort was closed [3-5]. The original Darrieus patent also included a turbine with straight blades. Peter Musgrove et al further investigated this concept in the 70s and 80s [3,6]. Subsequently several other researchers developed the straight-bladed Darrieus turbine, also called H-Darrieus. Some of the most notable researches about H-Darrieus concept were conducted at the USA Department of Energy Sandia National Laboratories [7–10] and in the UK by Reading University, and Sir Robert McAlpine and Sons Ltd (through their subsidy VAWT Ltd). They erected several prototypes including a 500 kW version at Carmarthen Bay [11].

Considerable improvements in the understanding of VAWT can be achieved through the use of CFD and experimental measurements. This paper aims at studying the effect of changing the design parameters such as, number of blades, airfoil type and turbine solidity on the performance of the H-Darrieus vertical axis wind turbine with fixed pitch angle through CFD simulations and wind tunnel tests.

2. Overall Design

H-Darrieus, as shown in Fig. 1, also called giromill and cyclo-turbine, have been manufactured in recent years with different specifications. There are some parameters which affect the performance of these turbines.

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Some of the most significant variables are Turbine solidity, Number of blades, Airfoil selection, Blade pitch angle and Turbine aspect ratio (H/D).

This paper concentrates on determination of importance of these factors specifically first three ones to find the best configuration of H-Darrieus turbines. This process completed by using computational fluid dynamics (CFD) method and a CFD solver at the first step and then results validation through wind tunnel tests.

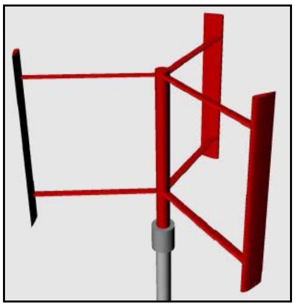


Fig. 1. CAD model of a 3-bladed H-Darrieus turbine

To compare different configurations, power output has been chosen as the design criteria. Generally, power output of wind turbines is defined by the term power coefficient (Cp) as written in equation 1.

$$C_p = \frac{P_m}{\frac{1}{2}\rho A V^3} \quad (1)$$

Where P_m is the mechanical power extracted, ρ is the air density, A is the turbine swept area and V is wind freestream velocity. Power Coefficient is not constant, varying widely across with wind speed due to aerodynamic complexities of blade designs.

3. Simulation Method

Computational fluid dynamics (CFD) is a useful design tool for wind power analysis. Using CFD simulations, the torque and pressure on the rotor can be predicted. These can then be used to predict the turbine's power coefficient. The simulation was performed in a 2-D space domain since the blade of H-Darrieus is inherently a 2-D device. The procedure contained both static and dynamic simulations. In dynamic simulation Multiple Reference Frame (MRF) model capability of CFD solver was used to express the dimensionless form of torque of the wind turbine as a function of the wind freestream velocity and the rotor's rotational speed. Multiple Reference Frame (MRF) model uses the time averaged information to predict the turbine performance. It analyzes the fluid flow with either a stationary reference frame or rotating reference frame. The model is divided into two sub-domains for the Multiple Reference Frame formulation, one for the rotor and another for the stator (see Fig. 2 for sample mesh discretization). The rotor sub-domain is rotating with consideration to the inertial frame in the model. Continuity of the absolute velocity is enforced at the boundary between the rotor and stator sub-domains to provide appropriate values of velocity for each sub-domain [12,13].

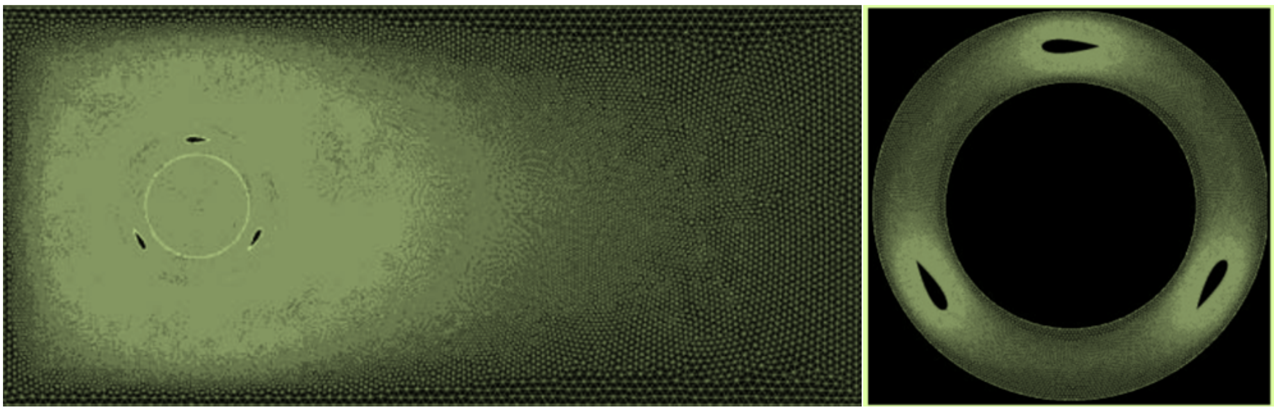


Fig. 2. Sample 2-D mesh discretization of the VAWT

The choice of the turbulence models influences the resultant flow field and the computational resource and time required to achieve solutions. For HAWTs it was found that standard k–ε model gave inaccurate results after flow separation in the previous research done by Wolfe and Ochs [14]. However, the k–ε RNG model is known to predict flow fields involving large flow separations more accurately, so for the present task k–ε RNG turbulence model was used. The renormalisation group (RNG) k-ε model, Eqs. (2) and (3), are coupled to the Navier-Stokes equations through the convection terms.

$$\rho\frac{\partial k}{\partial t}+\rho\overline{u}_j\frac{\partial k}{\partial x_j}=\tau_{ij}\frac{\partial \overline{u}_i}{\partial x_j}-\rho\varepsilon+\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] \quad (2)$$

$$\rho\frac{\partial \varepsilon}{\partial t}+\rho\overline{u}_j\frac{\partial \varepsilon}{\partial x_j}=\left(C_{\varepsilon 1}-C_{1RNG}\right)\frac{\varepsilon}{k}\tau_{ij}\frac{\partial \overline{u}_i}{\partial x_j}-C_{\varepsilon 2}\rho\frac{\varepsilon^2}{k}+\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] \quad (3)$$

4. Experimental setup

Experimental assessments of our numerical calculations were performed in a low speed open circuit wind tunnel, which has a cross section working area of 80□80 cm. Typically for a test run, the wind tunnel speed brought to a steady-state value, nominally 10 m/s, and the turbine with a predetermined load, was allowed to rotate. When steady-state rotation was achieved, a data point was taken. A slight change in the load then caused the turbine to come to a new rotational speed. When the rotational speed was stabilized, another data point was taken. Direct torque measurements were performed with a dynamometer with accuracy ± 0.1 N/cm which was connected to the shaft of the wind turbine, the rotation speed (rpm) was measured using a tachometer with accuracy ± 0.1 Rpm and a data-acquisition card with a computer was used to record the reading of the measured data. The uncertainty of experimental results may be originated from measuring errors of mentioned parameters. Using a method described by Taylor et al. [15] the maximum uncertainties of torque, wind freestream velocity and rotational speed variations are estimated to be ±1.5%, ±3.2% and ±2.7%.

The torque and rotation speed were measured at free stream mean velocity of 10 m/s which correspond to Reynolds number based on blade length of 0.35×10^5. The finished assembly of the model turbine is pictured in Fig. 3.

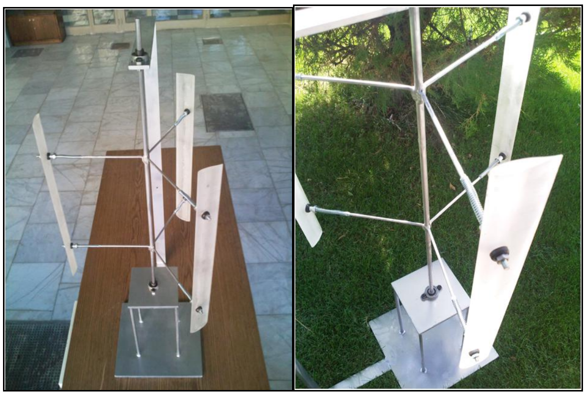


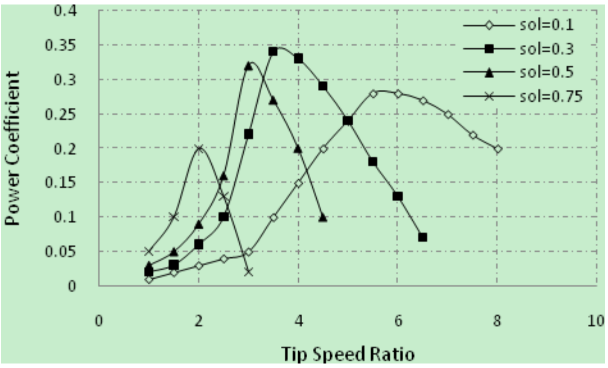
Fig. 3. Finished assembly of the model turbine

5. Results

In this section, results from the numerical and experimental studies will be presented.

The experiment and simulations conducted in 10 m/s wind velocity and dynamic torque of turbine, with NACA0018 and DUW200 airfoils, found in different tip speed ratios. Then they have been compared through figures.

Fig. 4 and 5 present the effect of different solidities and number of blades on the performance of H-Darrieus VAWTs with NACA0018 airfoil, respectively, determined through CFD simulations.



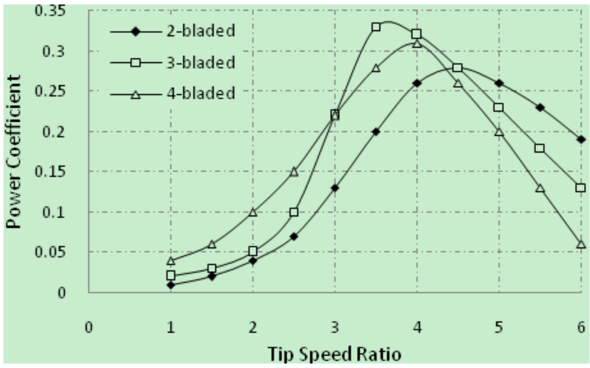
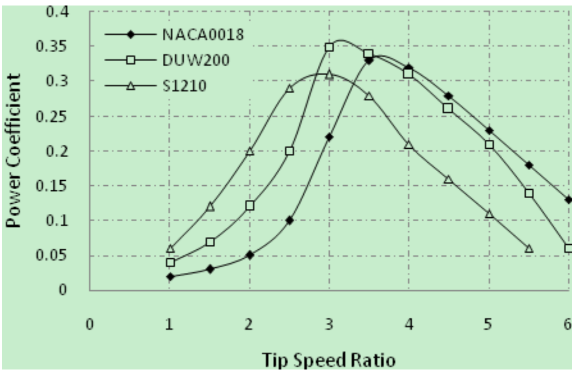


Fig. 4. Effect of solidity on power coefficient of H-Darrieus Turbine

Fig. 5. Power coefficient variations of H- Darrieus wind turbines based onnumber of blades

Fig. 4 discloses that increasing solidity to range 0.3 to 0.5 improves turbine performance, however above this range power coefficient decreases significantly and the curve gets more peaky. From Fig. 5 it can be found that 3-bladed H-Darrieus perform more efficient than 2 and 4 bladed turbines.

The performance prediction achieved from CFD simulations curves for a straight-bladed VAWT with the DU 06-W-200 airfoil and S1210 airfoils in comparison with NACA0018 airfoil at wind velocity V=10 m/s($\mathrm{Re} = 0.35 \times 10^5$) is shown in Fig. 6. Fig. 7 also shows that experiments results conducted for two turbines with NACA and DUW type airfoils on the same conditions as CFD simulations maintain the same trend as the numerical studies have. To increase test results accuracy, data recordings for each turbine repeated 3 times and indicated in diagram via error bars.



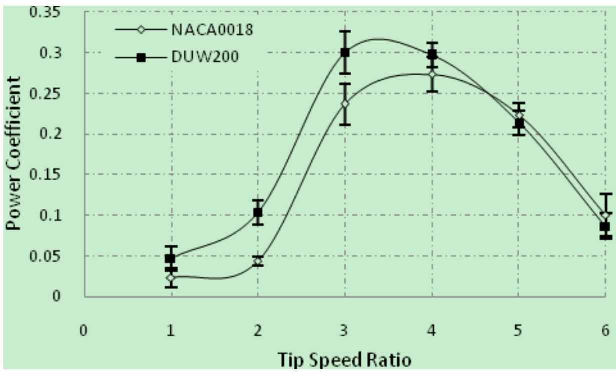


Fig. 6. Performance curve of H-Darrieus turbine with different airfoils

Fig. 7. Variations of power coefficient with rotational velocity in wind tunnel test at V=10m/s

The performance curve discloses that choosing DUW airfoil increases turbines self-starting ability and maximum efficiency comparing symmetric NACA0018 airfoil and S1210. Although S1210 airfoil can improve turbines performance in lower tip speed ratios, its peak point and rotational velocity is significantly below two other types and cannot be selected as a proper choice for this case. Pressure distribution and velocity pathlines around turbine and its blade is shown in Fig.8.

6. Conclusion

In this study geometrical parameters and airfoil type effects on H-Darrieus wind turbine efficiency studied numerically by CFD method. As a result, it has been found that a 3-bladed turbine with 35% solidity has the best self-starting ability and efficiency among all geometries. Therefore, the turbine modeled with mentioned geometry and equipped with DUW airfoil simulated and showed 9% increase in efficiency reaching 36% in contrast with NACA0018 common airfoil. Finally two experiments conducted for the same condition manufactured models with both airfoils to validate achieved results. While there was about 10% error in 2-D CFD results comparingexperiment data, accurate prediction of performance trend on different rotational velocities and higher power coefficient of DUW200 turbine than NACA0018, confirmed simulation method and process with proper accuracy.

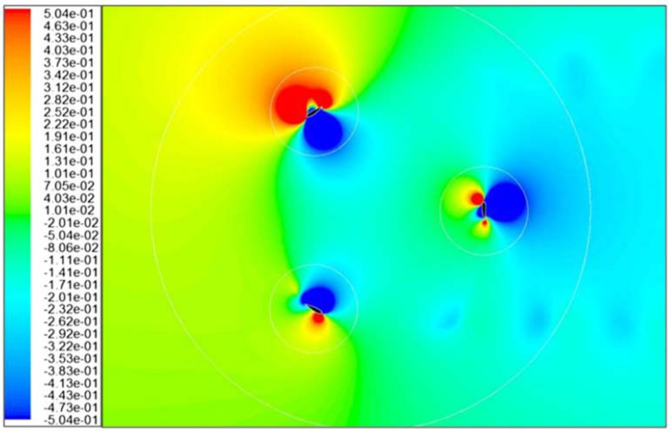


Fig. 8. Pressure distribution contour and pressure coefficient calculated around turbine at λ=3

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