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CFD simulations of power coefficients for an innovative Darrieus style vertical axis wind turbine with auxiliary straight blades

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Abstract. The increasing price of fossil derivatives, global warming and energy market instabilities, have led to an increasing interest in renewable energy sources such as wind energy. Amongst the different typologies of wind generators, small scale Vertical Axis Wind Turbines (VAWT) present the greatest potential for off grid power generation at low wind speeds. In the present work, Computational Fluid Dynamic (CFD) simulations were performed in order to investigate the performance of an innovative configuration of straight-blades Darrieus-style vertical axis micro wind turbine, specifically developed for small scale energy conversion at low wind speeds. The micro turbine under investigation is composed of three pairs of airfoils, consisting of a main and auxiliary blades with different chord lengths. The simulations were made using the open source finite volume based CFD toolbox OpenFOAM, considering different turbulence models and adopting a moving mesh approach for the turbine rotor. The simulated data were reported in terms of dimensionless power coefficients for dynamic performance analysis. The results from the simulations were compared to the data obtained from experiments on a scaled model of the same VAWT configuration, conducted in a closed circuit open chamber wind tunnel facility available at the Laboratory of Industrial Measurements (LaMI) of the University of Cassino and Lazio Meridionale (UNICLAM). From the proposed analysis, it was observed that the most suitable model for the simulation of the performances of the micro turbine under investigation is the one-equation Spalart-Allmaras, even if under the conditions analysed in the present work and for TSR values higher than 1.1, some discrepancies between numerical and experimental data can be observed.

1. Introduction

The interest in developing wind energy technology is growing significantly since its potential in power generation is unaffected by political and economic instabilities [1-4]. The increasing prices of fossil derivatives, in fact, is pushing industrialized countries to the diversification of energy sources, also raising awareness to environmental issues related to the exploitation of traditional non-renewable energy reserves. Amongst the different typologies, vertical axis wind turbines (VAWT) are very promising for small scale power generation at low wind speeds, but more attention by scientific community and dedicated industry is needed in order to develop low cost reliable wind energy converters [5, 6]. One of



the aerodynamic issues of the VAWT is its continuously variable angle of attack of the blades with respect to the incoming wind [7] that causes high turbulence on the blades when they pass in the leeward side of the turbine, lowering the overall efficiency. The characterisation of the turbine performances by means of on-field analysis is practically unfeasible because of the high variability of the meteorological conditions and local wind speeds. In this context one of the most powerful tool for the wind turbine characterisation and optimisation is the Computational Fluid Dynamics (CFD) approach. The CFD technique [8-10], anyway, cannot be used without appropriate experimental campaigns aimed to validate the numerical data [11-14]. In order to obtain robust and reliable data from the experiments at constant testing conditions, it is essential the use of a wind tunnel equipment, which allows a velocity uniformity of the flow in correspondence of the measurement section in order to get the more accurate data possible with the corresponding measurement uncertainty [15, 16]. Wind tunnel experiments on Darrieus wind turbine were carried out by Khadir and Mrad [17] and Bianchini, Balduzzi, Rainbird, Peiró, Graham, Ferrara and Ferrari [18] who conducted experiments on different NACA airfoils in order to study the aerodynamic behaviour of the blades, while CFD investigations of static and dynamic performance on a Darrieus type wind turbine in relation to the blade profile, was recently performed by [19, 20]. In the present work, CFD analysis of the performances of an innovative straight-blades Darrieus-style configuration of vertical axis micro wind turbine was performed using the open source CFD toolbox OpenFOAM adopting a moving mesh approach for the turbine rotor. The simulated data were reported in terms of dimensionless power coefficient. The results from the simulations were validated against the data obtained from experiments on scaled models of the same VAWT configuration, conducted in a closed circuit open chamber wind tunnel facility available at the Laboratory of Industrial Measurements (LaMI) of the University of Cassino and Lazio Meridionale (UNICLAM).

2. Materials and methods

2.1. Characteristics of the turbine blades

The proposed micro wind turbine configuration is composed of three pairs of airfoils placed at 120° each other. Each pair is composed of two airfoils, whose features are reported in Figure 1. The blades are a modified version of the DU 06-W-200 airfoil [21]. The angle of attach, α is equal to 13° for both the main and auxiliary airfoils; the ratio between main and auxiliary airfoils chord lengths, C_1/C_2 , is equal to 0.57; the distance between the two airfoils, y , is equal to $0.29 \times C_1$ while the longitudinal distance between the airfoils, x , is equal to $0.38 \times C_1$. In order to fit the micro turbine model into the wind tunnel measurement section, it was scaled and printed in PLA (polylactic acid) through a Fused Deposition Modelling (FDM) technique using a 3D printer. Referring to Figure 1, the main dimensions of the proposed rotor are the following: main and auxiliary airfoil chord lengths, C_1 and C_2 , equal to 47.2 mm and 27 mm, respectively; distance between the two airfoils, y , equal to 13.8 mm; longitudinal distance between the airfoils, x , equal to 18.2 mm; angle of attach, α , equal to 13° for both the main and auxiliary airfoils. The height and diameter of the micro turbine model are equal to 150 mm and 200 mm, respectively.

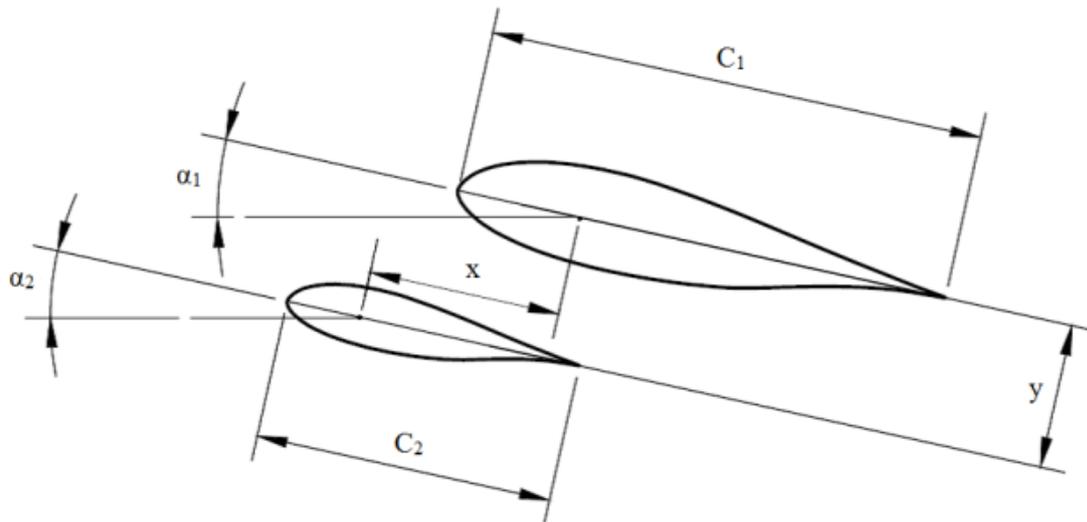


Figure 1. Scheme of the two-bladed design of the micro wind turbine under investigation.

2.2. CFD modelling setup

The numerical CFD software used for the simulation of the wind turbine performance is the open source OpenFOAM toolbox. In our simulations the default linear interpolation scheme has been adopted while as a linear solver the GAMG - Geometric agglomerated algebraic multigrid solver) with a tolerance value equal to 10^{-6} . A moving mesh technique was adopted for the reproduction of the fluid-airfoil interaction in correspondence of the turbine rotor. The simulations were conducted in a bi-dimensional domain configuration using a time step value necessary to obtain a rotation of the moving mesh of 1° ; as observed during the simulations, two full rotations (720°) are necessary, in order to reach a stable periodic state. A detail of the mesh adopted is reported in Figure 2. A fully unstructured grid also in non-rotating region has been used in order to obtain acceptable values of the skewness factor and aspect ratio. In particular, the grid is composed of about 88000 triangular elements. The maximum and minimum grid dimensions were set to 10^{-2} and 10^{-4} , respectively. The grid was refined in correspondence of the airfoil surfaces using a refinement factor of 1.1. At the rotating domain interface, the static and the rotating grids present the same dimension of elements. With these characteristics of the grid, the y^+ value was maintained under about 5 and then no wall functions were adopted. Different turbulence models were evaluated for the numerical simulations, and after a preliminary analysis of the performances of each one, the two-equations SST $k-\omega$ and the one-equation Spalart-Allmaras models were chosen for the complete simulations since they showed the best overall capability of reproducing the experimental measurements. As boundary condition at the inlet section for the turbulence model a value equal to 1% of the turbulence intensity has been imposed. This value was measured in our laboratories by a PIV system.

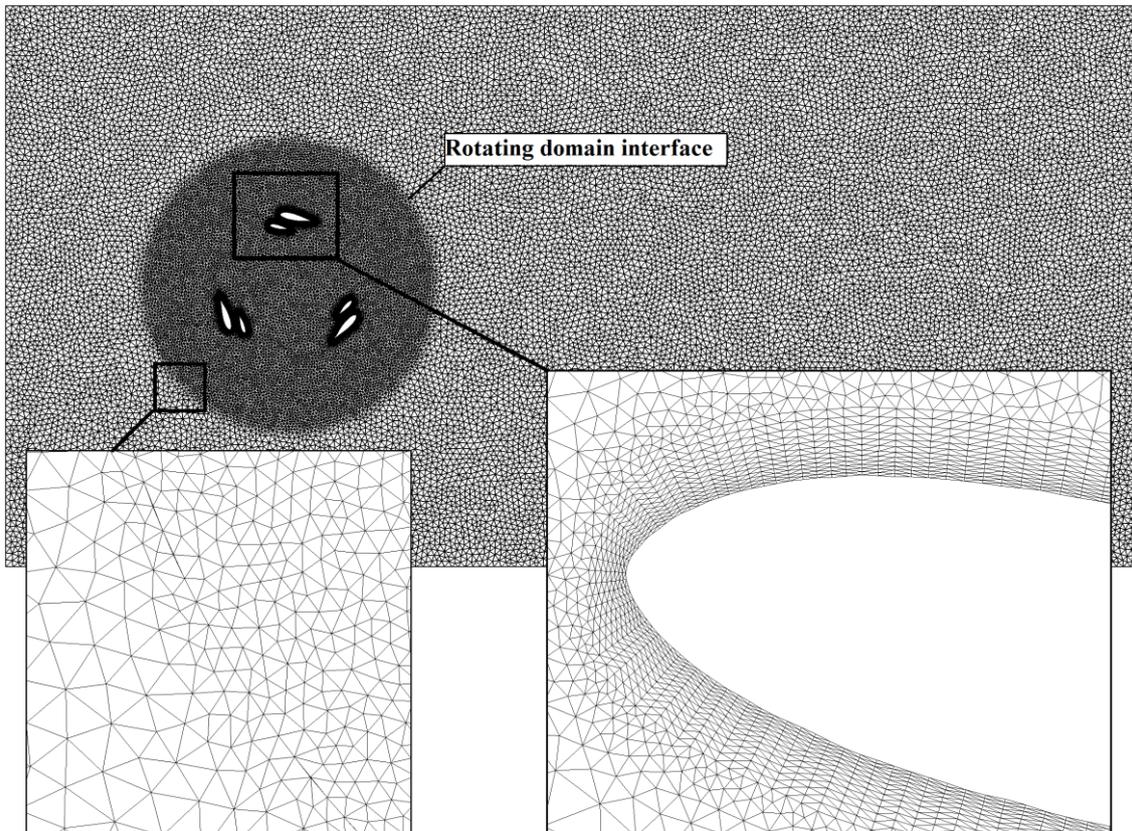


Figure 2. Computational domain adopted for the numerical simulations and detail of the grid in correspondence of the blade surfaces and at the rotating domain interface.

2.3. Wind tunnel testing setup

The experimental investigations were carried out in the wind tunnel of the Laboratory of Industrial Measurements (LaMI) of the Department of Civil and Mechanical Engineering (DICeM) at the University of Cassino and Lazio Meridionale. In Figure 2 a scheme of the wind tunnel (on the left) and the 3D printed model of the turbine (on the right) are reported.

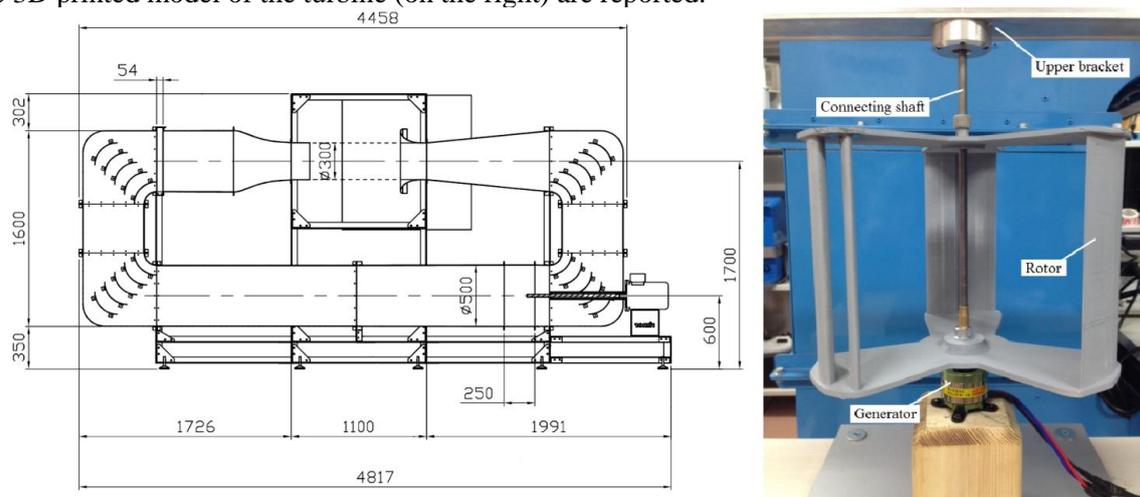


Figure 3. Scheme and main dimension of the closed circuit-open chamber wind tunnel (left panel) and 3D printed model of the turbine under investigation (right panel).

The wind tunnel works in the range 0.2 – 30 m/s at a maximum temperature of 80°C, providing good characteristics of response time, repeatability and flow uniformity. The performance analysis of the

micro turbines was made by using a brushless electric motor, acting as generator, directly connected to the rotor axis, while the variable load was simulated by means of electric resistors connected on the three phases of the brushless motor. The wind turbine characteristic curve was obtained point by point varying, for a fixed wind speed value imposed in the wind tunnel, the resistance on each phase, and measuring the electric power and the rotational speed, once stable operating conditions were achieved for each point. Additional details about the wind tunnel characteristics, the instrumentation used for electric power measurements, and the testing procedure can be found in Scungio, Arpino, Focanti, Profili and Rotondi [22].

2.4. Dimensionless performance parameters

For the performance evaluation of the VAWTs under investigation, the following non dimensional parameters were used. Tip Speed Ratio (TSR), defined as the ratio between the tip speed of the blade and the wind speed:

$$TSR = \frac{\omega \cdot R}{V} \quad (1)$$

where ω is the rotational speed in (rad/s), R is the radius of the rotor in (m) and V is the wind speed in (m/s).

Power Coefficient:

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

where P is the power in (W), ρ is the air density in (kg/m^3), and A is the swept area in (m^2).

2.5 Measurements uncertainty analysis

Uncertainty affecting measurements has been estimated taking into account type A and type B contributions and applying the well-known uncertainty propagation law. In particular, type A uncertainty has been evaluated *a posteriori*, through the statistical analysis of data obtained by repeated measurements, while type B is evaluated *a priori*, by applying the uncertainty propagation law to equations (1) – (4). The calculation of the combined uncertainty, u , has been made on the two extreme points and on the middle point of the measured power-rpm curve, taking as a final value the average of the three evaluated. The expanded uncertainty, U , was obtained multiplying the combined uncertainty by the coverage factor, k [15, 23] as follows:

$$U_y = k \cdot u_y \quad (3)$$

By fixing a value for the coverage factor equal to 2, i.e. fixing a probability of 95% that the measured value falls within the defined range, and normalizing the extended uncertainty to the corresponding measured quantities, the relative expanded uncertainty values reported in Table 1 were obtained:

Table 1. - Relative expanded uncertainty values for TSR and CP evaluated for three wind speeds as an average on three points for each power-rpm curve.

	$U_{r,TSR}$	$U_{r,CP}$
$U_r(\%)$	2.01	11.29

A detailed discussion about the equations used for the estimation of the above mentioned propagation law of the uncertainty can be found in Scungio, Arpino, Focanti, Profili and Rotondi [22].

3. Results and discussion

In this section the results in terms of the dimensionless performance parameters presented in the previous sections are reported. In Figure 4a the power coefficient, C_p , obtained from the numerical simulations and from the experimental measurements in the wind tunnel is showed as a function of the tip speed ratio (TSR), while in Figure 4b the torque on the turbine shaft as a function of the rotational angle is reported for the two turbulence models considered. The power coefficient – TSR curves were measured/calculated for a wind speed equal to 12 m/s. For the numerical simulations, the SST $k-\omega$ and the Spalart-Allmaras turbulence models were considered, as stated previously, while the experimental curves have been constructed point by point, and each point was obtained as average value of a sufficiently large number of acquisitions in the wind tunnel. Looking at Figure 4a it can be seen that both the turbulence models considered tend to overestimate the power coefficient for the higher TSR values (i.e. for the lowest loads applied to the turbine generator in the wind tunnel measurements), while for higher loads (i.e. lower TSR), the experimental data are well reproduced from both the turbulence models. As a general remark, anyway, the Spalart-Allmaras model tends to match the experiments better than the SST $k-\omega$. The discrepancy between the experimental and numerical results for $TSR > 1$ could be attributed to two different reasons. The first regards 3D effects not considered in the present numerical simulation and the second one could be due to the characteristic of the brushless electric motor which present a strong efficiency reduction in correspondence of $TSR > 1$ ($RPM > 1000$) as showed in Figure 4 (c).

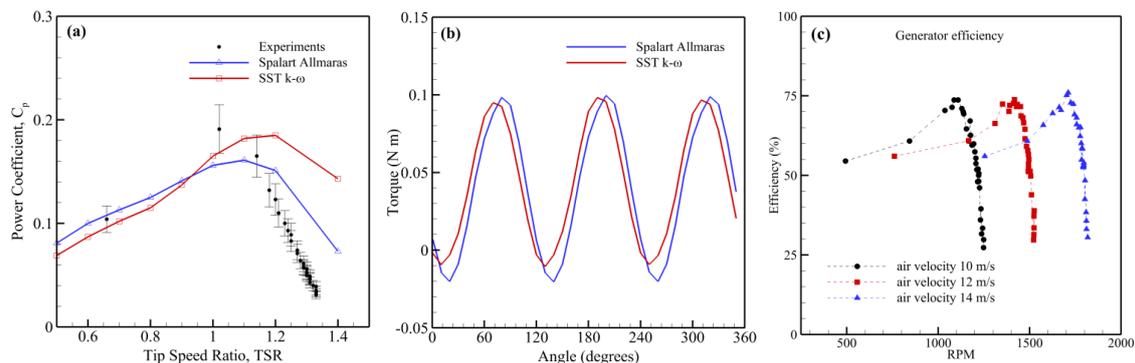


Figure 4. Power coefficient as a function of the Tip Speed Ratio (a) torque value as a function of the rotational angle of the turbine rotor with respect to the incoming wind flow (b), and generator efficiency as a function of RPM (c). Wind speed of 12 m/s.

In Figure 4b, the torque as a function of the rotational angle of the turbine with respect to the incoming wind flow is reported for both the turbulence models under examination. As can be seen, the results from the two models are almost overlapped, with only a slightly higher amplitude of the torque values for the Spalart-Allmaras model with respect to the SST $k-\omega$. In Figure 5 the x-velocity and pressure fields are showed for the same rotational angle of the turbine rotor, for a fixed TSR value of 1, for the Spalart-Allmaras model (a), (b) and for the SST $k-\omega$ model (c), (d). As can be seen, the fields result very similar close to the blade surfaces, while in the wake flow the Spalart-Allmaras model tends to reproduce zones with lower and higher velocity values with respect to the SST $k-\omega$ model.

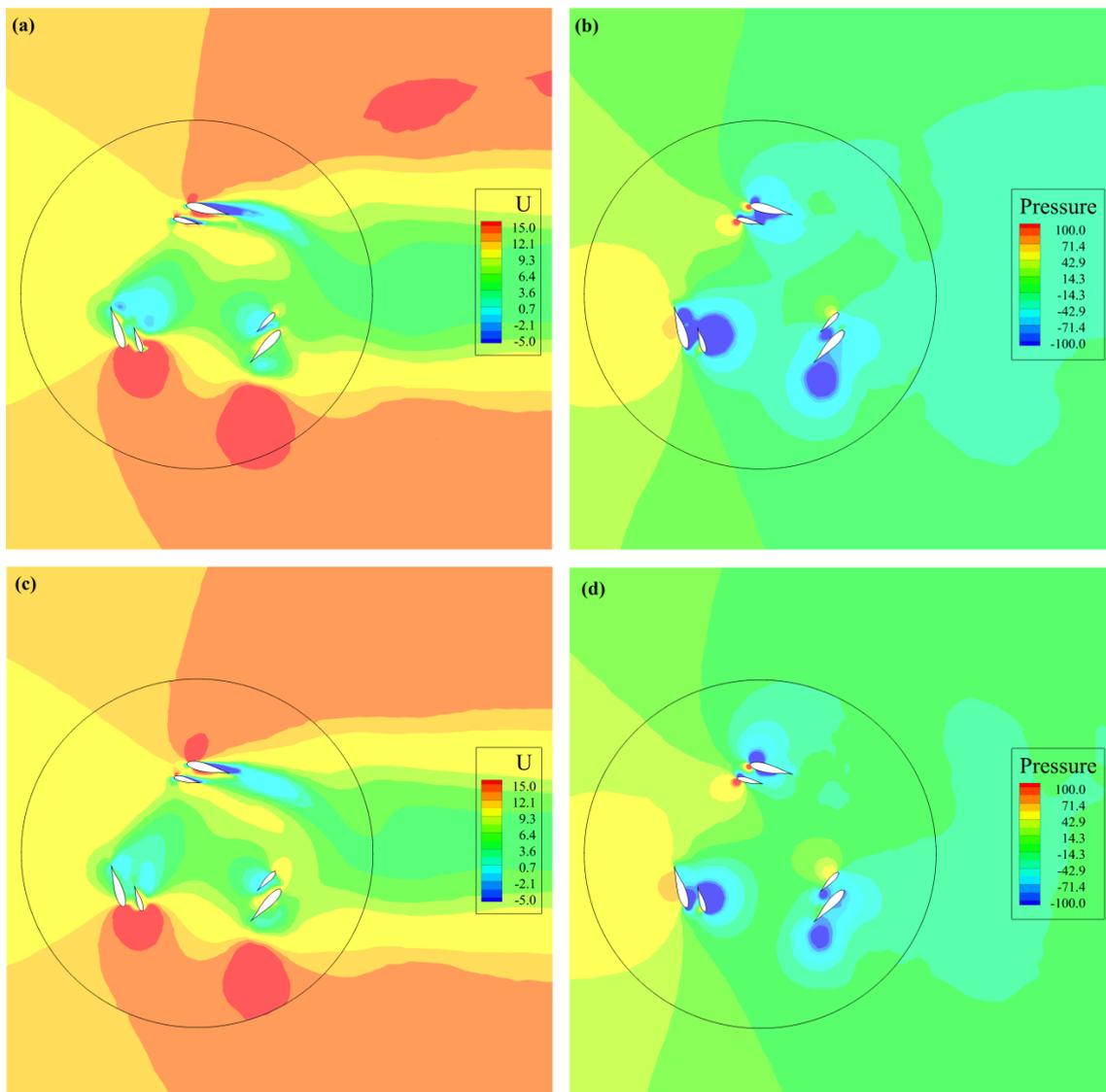


Figure 5. x-velocity and pressure fields for a fixed value of TSR (1.0) in the same rotor angle for both the turbulence models analysed at wind speed of 12 m/s: SST $k - \omega$ (a), (b); Spalart-Allmaras (c), (d).

4. Conclusions

In the present paper, an experimental campaign was carried out at the Laboratory of Industrial Measurements (LaMI) of the Department of Civil and Mechanical Engineering at the University of Cassino and Lazio Meridionale, in order to analyse the performance of an innovative micro Vertical Axis Wind Turbine (VAWT). The performance analysis was conducted by means of a numerical CFD approach using the open source OpenFOAM toolbox by using different turbulence models and adopting a moving mesh approach. The results from the numerical CFD toolbox were compared to experimental data measured in a wind tunnel, reproducing a scaled model of the micro turbine through a Fused Deposition Modelling (FDM) 3D printer. The dynamic performance of the micro turbine was analysed in terms of power coefficient, CP evaluated as a function of the tip speed ratio, TSR. From the measured and numerical data, it was found that the most suitable models for the simulation of the performances of the micro turbine under investigation are the one-equation Spalart-Allmaras and the two-equations SST $k - \omega$. In particular, between these two models the Spalart-Allmaras resulted able to better reproduce the experimental data, even if for the highest TSR values both the turbulence models tend to overestimate the measured power coefficients. Looking at the torque values as function of the rotational

angle of the turbine, instead, the two models reproduce almost the same results. In conclusion, from the presented experimental campaign, it was found that for the simulation of the power coefficient-TSR curves of a vertical axis micro wind turbine, the moving mesh simulation approach with the Spalart-Allmaras turbulence model is able to give satisfactory results, even if some discrepancies between numerical and experimental data can be found for TSR values higher than 1.1, under the conditions analysed in the present work.

References

- [1] Tjiu W, Marnoto T, Mat S, Ruslan M H and Sopian K 2015 *Renew. Energ.* **75** 50-67
- [2] Akwa J V, Vielmo H A and Petry A P 2012 *Renew. Sust. Energ. Rev.* **16** 3054-64
- [3] Monteiro J P, Silvestre M R, Piggott H and André J C 2013 *J. Wind Eng. Ind. Aerod.* **123** 99-106
- [4] Bottasso C L, Campagnolo F and Petrović V 2014 *J. Wind Eng. Ind. Aerod.* **127** 11-28
- [5] Balduzzi F, Bianchini A, Carnevale E A, Ferrari L and Magnani S 2012 *Appl. Energ.* **97** 921-9
- [6] Bianchini A, Ferrara G and Ferrari L 2015 *Energ. Convers. Manage.* **89** 690-707
- [7] Bazilevs Y, Korobenko A, Deng X, Yan J, Kinzel M and Dabiri J O 2014 *J. Appl. Mech-T Asme, Trans. ASME* **81** (8) 081006
- [8] Arpino F, Cortellessa G, Dell'Isola M, Massarotti N and Mauro A 2014 *Numer. Heat Tr. A-Appl.* **66** 839-62
- [9] Arpino F, Cortellessa G and Mauro A 2015 *Numer. Heat Tr. A-Appl.* **67** 605-31
- [10] Arpino F, Carotenuto A, Ciccolella M, Cortellessa G, Massarotti N and Mauro A 2016 *Int. J. Heat Tech.* **34** S512-S8
- [11] Arpino F, Cortellessa G and Frattolillo A 2015 *Sol. Energy* **118** 7-19
- [12] Massarotti N, Ciccolella M, Cortellessa G and Mauro A 2016 *Int. J. Numer. Method. H.* **26** 1187-225
- [13] Scungio M, Arpino F, Cortellessa G and Buonanno G 2015 *Atmos. Pollut. Res.* **6** 351-64
- [14] Neft I, Scungio M, Culver N and Singh S 2016 *Aerosol Sci. Tech.* **50** 937-46
- [15] Natrella M G 1966 *Experimental statistics* (New York: Wiley-Interscience)
- [16] Sparrow E M 1976 *Measurements in Heat Transfer* Washington: E.R.G. Eckert and R.J. Goldstein
- [17] Khadir L and Mrad H 2015 *Int. J. Multiphys.* **9** 383-96
- [18] Bianchini A, Balduzzi F, Rainbird J M, Peiró J, Graham J M R, Ferrara G and Ferrari L 2015 *Energ. Convers. Manage.* **106** 373-84
- [19] Zamani M, Maghrebi M J and Varedi S R 2016 *Renew. Energ.* **95** 109-26
- [20] Bedon G, De Betta S and Benini E 2016 *Renew. Energ.* **94** 328-40
- [21] Claessens M C 2009 *The Design and Testing of Airfoils for Application in Small Vertical Axis Wind turbines* Delft University
- [22] Scungio M, Arpino F, Focanti V, Profili M and Rotondi M 2016 *Energ. Convers. Manage.* **130** 60-70
- [23] Baker R C 2000 *Flow Measurement Handbook - Industrial designs, operating principles, performance and applications* New York: Cambridge University Press