IN-VENTO 2026
International Conference of the Italian Association for Wind Engineering
Bari, September 13th – 16th, 2026

BARI

Performance Comparison of RANS Models for Full-Scale 3D Vertical-Axis Wind Turbines

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SUMMARY
Computational Fluid Dynamics (CFD) is expected to significantly contribute to the development of vertical-axis wind turbines. Reynolds-Averaged Navier-Stokes (RANS) CFD simulations are used to predict the performance of a 17 m vertical-axis wind turbine tested by Sandia National Laboratories. Two turbulence models were evaluated and compared: the standard *k-ε* and *k-ω* SST model. The simulations were carried out using the pimpleDyMFoam solver, embedded in the OpenFOAM C++ libraries. This solver is designed to handle incompressible, turbulent flows on moving meshes through the Arbitrary Mesh Interface (AMI) method, which enables the modeling of rotational mesh motion. Full-scale, three-dimensional results were compared with experimental field data in terms of power coefficients and instantaneous torque. Both turbulence models showed good agreement with the experimental results. Overall, the *k-ω* SST model provided more accurate predictions for both power coefficient and instantaneous torque.

Keywords: Computational Fluid Dynamics, RANS, Wind Turbine

1. INTRODUCTION

Vertical-axis wind turbines (VAWTs) are gaining increasing attention due to their suitability for non-conventional installation sites, as they exhibit limited power coefficient variations under turbulent and non-uniform flow conditions (Balduzzi et al., 2012). Moreover, this technology is being explored for large-scale floating offshore applications. As highlighted by several authors (Raciti et al., 2011), accurate modeling of these systems can no longer neglect recent advances in CFD simulations, which can significantly support rotor design improvements required to advance the technology toward mature industrial production. In recent years, CFD simulations have been extensively employed to assess the performance of VAWTs, including approaches such as two-dimensional RANS simulations, three-dimensional RANS simulations, and Large-Eddy Simulations (LES). These CFD methods have demonstrated strong capability in predicting turbine performance, instantaneous load characteristics, and the surrounding flow field (Paillard et al., 2015, Delafin et al., 2015). The studies mentioned above primarily investigate small-scale wind turbines (except in Delafin et al., 2015). The aim of the present work is to evaluate results obtained from two different RANS models against available field data for a full-scale three-dimensional VAWT.

2. METHODOLOGY

The wind turbine used in this study is the second version of the 17 m-diameter (D) VAWT tested by Sandia National Laboratories in the 1980's (Figure 1). The turbine consists of the rotating components (shaft and blades) held by bearing in the upper collar and in the lower support structure. The rotor is two-bladed with NACA0015 airfoil profile. The rotor has a diameter D of 17 meter and the height of 25 meter.

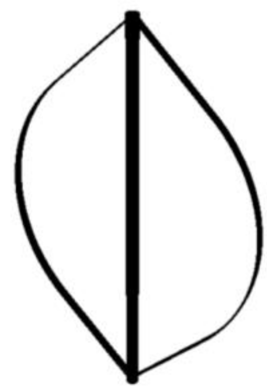

Figure 1. 3D view of the analyzed vertical wind turbine

The main features of the analyzed wind turbine are summarized in Table 1 shown below.

Table 1. Main features of the analyzed rotor

Blades number (N)	Blades Airfoil	Radius (R) [m]	Height [m]
2	NACA0015	8.50	25

The numerical simulations have been executed by solving the Reynolds-Averaged Navier-Stokes equations (RANS) in three dimensions in their formulation for incompressible fluids. Two different models were tested and compared: Standard k-ε and k-ω SST. The RANS governing equations were discretized by means of the FVM. The chosen computational domain, shown in Figure 2, containing all the fluid flow features, was 15D long and 10D wide and 4D high (D is the diameter of the turbine).
As boundary conditions, at the inflow section, located at 5D from the rotor barycenter, the velocity was set to the values corresponding to the field data, whereas the flow velocity gradient was set to zero and a fixed value for the pressure term was imposed at the outflow. To handle the mesh movements (50.6 rpm), the Arbitrary Mesh Interface (AMI) method (Farrell and Maddison, 2011) was adopted. The air flow (with wind speeds between 5.0 *m/s* and 16.0 *m/s*) enters the computational domain through the inlet section. As concerns the grid resolution, various tests were performed before reaching the final configuration of the grid, employing an increasing number of cells in all directions. The final configurations of the grid contain around 3 million cells.

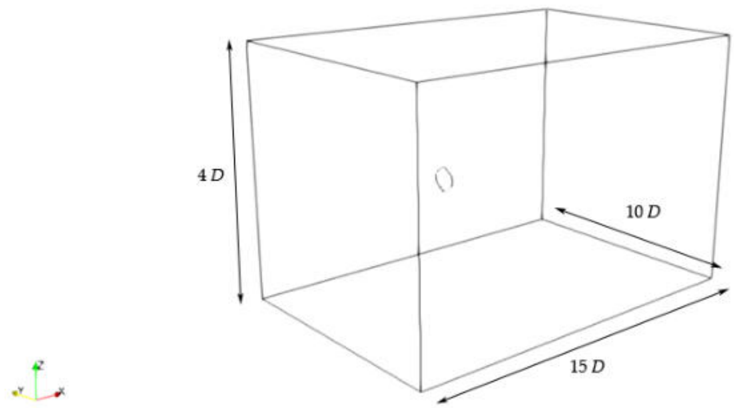

Figure 2. Computing domain

3. RESULTS

Figure 3 presents the average power coefficient predicted by the two numerical models and compares the results with the experimental field data reported by Akins et al., 1987. Overall, good agreement is observed for both models in the Tip Speed Ratio (TSR) ranges of 2.87 - 3.36 and 5.66 - 7.93. Both models tend to overpredict the power coefficient, particularly at a TSR of 4.61. Among the two, the *k-ω* SST model provides more accurate predictions of the power coefficients.

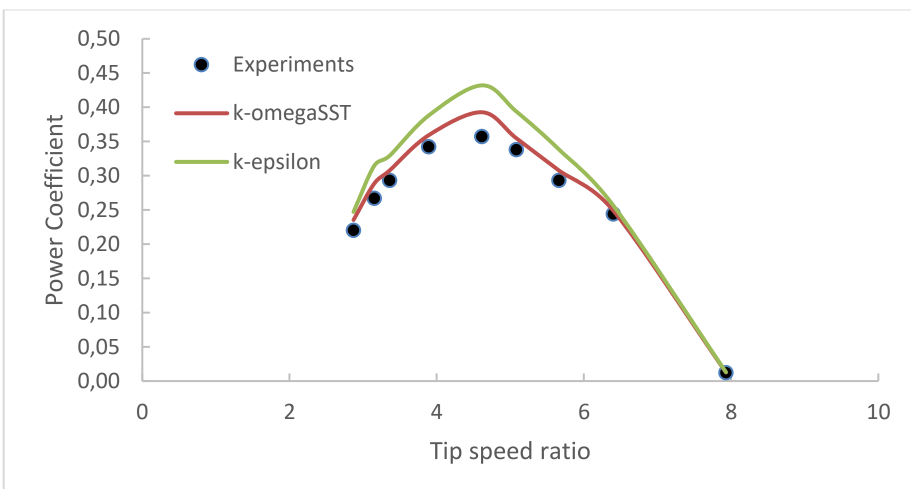

Figure 3. Comparison of power coefficients (50.6 rpm)

Figure 4 illustrates the evolution of turbine torque at different TSR values. Overall, good agreement between numerical and experimental results is observed for both models at TSR of 2.87, 3.89 and 6.40. Also in this case, the numerical results tend to overestimate the torque values. Both models overpredict the power coefficient, particularly at azimuthal positions around 100°. Consistently with the previous analysis, the *k-ω* SST provides the most accurate predictions for the instantaneous torque.

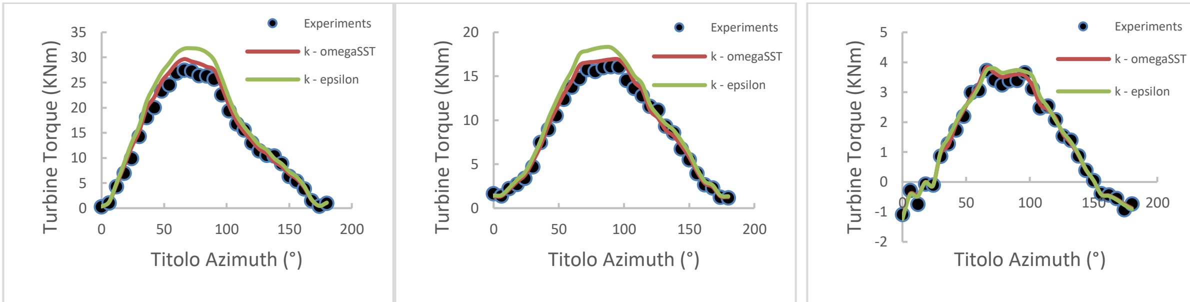

Figure 4. Comparison of turbine torque: (a) TSR=2.87, (b) TSR=3.89, (c) TSR=6.40.

4. CONCLUSIONS

Reynolds-Averaged Navier-Stokes (RANS) CFD simulations were performed to predict the performance of the full-scale Sandia 17 m vertical axis wind turbine using the standard *k-ε* and *k-ω* SST turbulence models. Both models provide satisfactory agreement with experimental field data in terms of power coefficients and instantaneous torque across several TSR ranges. However, a systematic overprediction is observed, particularly at intermediate TSR values and at azimuthal positions around 100°, where complex unsteady aerodynamic effects are likely significant. Overall, the *k-ω* SST model delivers more accurate predictions, making the more suitable turbulence model for this turbine configuration.

ACKNOWLEDGEMENTS

The present research was funded by the European Union – Next Generation EU through the grant of the project PRIN 2022 titled "NonlinEar Phenomena in floaTing offshore wind tUrbiNEs (NEPTUNE)"Project code: 2022W7SKTL.

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