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Numerical Analysis and Experimental Measurements of a Small Horizontal Wind Turbine Blade Profile for Low Reynolds Numbers

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Wind energy is an important contributor to the generation of electricity amongst the renewable sources, and per long-term political goals it is expected that this contribution will be further increased. For achieving this goal, optimized blades having increased aerodynamic performance must be designed especially for small horizontal wing turbines (SHWT). SHWT are exposed to a highly volatile, low Reynolds number, turbulent flow, where not only boundary layer transition phenomena are significant, but additionally, 3D flow effects are dominant, due to the relatively small length of the wind turbine blades. These blades are usually 1.5 to 3.5 m in diameter and produce 1 - 10 kW of electricity at their optimum design conditions which are closely related to the wind speed. In order to maximize the wind turbine blades efficiency, a thorough analysis of the complex aerodynamic effects that govern the flow has to be performed. In the current paper an assessment of the modelling of a wind turbine blade profile of a SHWT is investigated, with the use of Computational Fluid Dynamic (CFD) and validated with appropriate experiments. More specifically, a characteristic profile of an operating SHWT blade is selected and carefully picked transitional turbulence models are utilized for the CFD computations, for a wide range of angles of attack (AoA). The selected models are the 4-equation SST k-ω turbulence model of Menter et al. (1994) and the turbulence model of Walters and Cokljat (2008) that adopts the laminar kinetic energy concept. Two relatively small Reynolds numbers are chosen for studying the flow, in order to take into account, the transient and complex flow phenomena that are present in real wind turbine operating conditions. For the validation of the computational results, existing literature data (Selig and McGranahan, 2004) are used in combination with the acquired experimental data from the appropriately designed experiments which were performed in the Laboratory of Fluid Dynamics and Turbomachinery (LFMT) facilities. The results show the existing potential of further optimizing the wind turbine blades and as a result enhancing their aerodynamic performance and efficiency.

1. Introduction

Alternative forms of power generation have seen an impressive growth in the last decades. One of the most important contributors to electricity generators, holding a third of the renewable energy share, is the technology of wind harnessing (Thé and Yu, 2017). Only in 2016, wind turbines with the ability to produce more than 54 GW were erected (Pfaffel et al., 2017). The ongoing development, with nearly constantly increasing hub heights and rotor diameters, leads to the exploitation of more and more sites in wind class regions I and II, culminating in off-shore wind parks. This typically goes hand in hand with an imbalance between the regions where electricity is consumed and generated causing heavily increasing investment costs in the electric distribution grid and an increasingly large effort to control the distribution of the wind-generated electricity. Against this background, even for regions connected to the main grid there is a demand for

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distributed generation close to the consumers. Small wind turbines (SWT) can provide such distributed electricity. SHWTs, characterized by a mean radius of 1 to 2 m, and a capability to produce 1 - 10 kW of electricity, operate in the relatively low Reynolds number of 200,000 to 350,000. Compared to Large Wind Turbines (LWTs), current SWT rotors have low tip speed ratios. Although this characteristic decreases the rotor power output by its low(er) rotational speed, it is favorable as less fluctuating rotor torque is induced by the volatile inflow. The SWT blade designs still mainly rely on airfoil shapes originally designed for higher Reynolds numbers. Hence, the characteristics of laminar boundary layers regarding lower frictional losses and higher susceptibility to separations are not considered. This may lead to reported differences between designed and actual SWT power output as much as 10 % (Ren et al., 2018). Either standing alone or being part of a wind farm where the wake of upstream wind turbines affects the efficiency and the operation of downstream wind turbines (Dou et al., 2019), the need of optimization through increased aerodynamic performance becomes more and more clear.

Menegozzo et al. (2018) managed to capture the aerodynamic behaviour of a SHWT under the influence of gusts with the help of unsteady CFD simulations and moving mesh. Fuglsang and Bak (2004) present in their work the development of a typical wind turbine airfoil family for LWT. Douvi et al. (2012) proved that the current turbulence models deviate from experimental values regarding aerodynamic characteristics in high Reynolds numbers. Selig and McGranahan (2004) provide a detailed set of experimental results for low Reynolds wind turbine airfoils. A paper by Timmer and van Rooij (2003) gives an overview of the design and wind tunnel results of wind turbine airfoils for a relatively high Reynolds number. Finally, Singh et al. (2012) present experimental measurements for very low Reynolds numbers aiming to study the startup of a SHWT.

Based on these findings, an experimental and numerical approach for aerodynamic assessment of a typical wind tunnel blade airfoil regarding low Reynolds numbers was carried out in this paper, to cover the literature gap. The airfoil was initially examined through a 2D experimental analysis and subsequently a set of transitional models were applied through CFD assessment. In the frame of this work, handbooks regarding the well-established Blade Element Method (Hansen, 2015) and the aerodynamics of wind turbines (Burton et al., 2001) were studied.

2. Methodology

In this paper, the CFD modelling of a wind turbine blade profile of a Small Horizontal Wind Turbine (SHWT) is presented and is validated by appropriate wind tunnel experiments. More specifically, a characteristic profile of an operating SHWT blade is selected and different transitional turbulent models are utilized for the turbulence modelling. The selected turbulence models were tested for a wide range of angles of attack (AoA) and for two distinct Reynolds numbers.

2.1 Setting the requirements

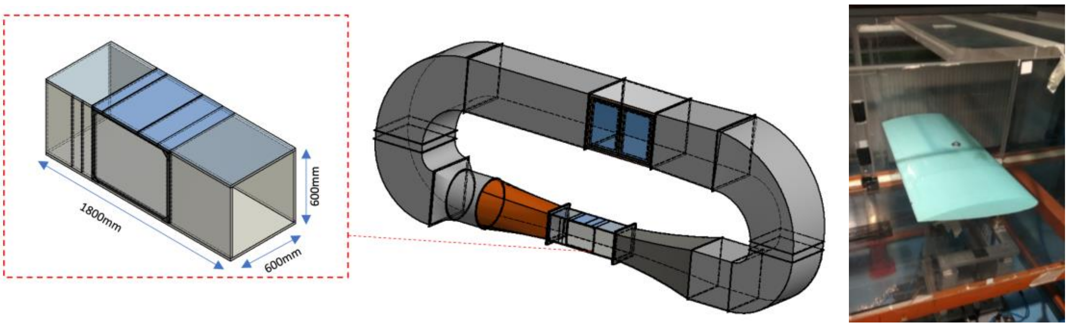
The operational Reynolds number region of a SHWT is approximately 200,000 – 450,000. The two Reynolds numbers of 200,000 and 350,000 were selected, as the lower limit and the mean value respectively. Since these Reynolds numbers are placed well within the transitional regime it was obligatory to perform CFD computations with transitional turbulence models. Additionally, experimental data were needed to calibrate and evaluate the CFD computations. In the current work, measurements only for the 200,000 Reynolds number were performed while experimental data from the literature were used for both Reynolds numbers for comparison. After a detailed literature survey regarding analytical and experimental approaches over a great Reynolds number range, it was decided to focus the investigations on the airfoil NRL S834 (Selig and McGranahan, 2004). This airfoil belongs in a typical wind turbine airfoil family and it was accompanied with Low Reynolds experimental measurements, including experimental setup and conditions.

2.2 Experimental setup

The experiments used in this paper were conducted in a closed-circuit, low-speed wind tunnel facility (Figure 1a) of the Laboratory of Fluid Mechanics and Turbomachinery (LFMT), at the Mechanical Engineering Department of the Aristotle University of Thessaloniki (AUTH). The facility has an 1,810 mm x 600 mm x 600 mm test section and is capable of producing a maximum speed of 18 m/s. The turbulence intensity inside the test section is 0.7 % and the wind tunnel blower speed is controlled by a frequency inverter.

For the lift and drag coefficient measurements, an external force balance is used. Two steel rods are used to support the model and are mounted on an aluminum frame. The measurement of both the drag and lift forces are conducted with four Omega LCEB loadcells.

The tested airfoil was constructed by coated foam (Figure 1b) and had a chord of 300 mm and a span of 590 mm, ensuring a span that covers the test section from one to the other side and thus eliminating 3D aerodynamic flow structures. The angle of attack that was chosen for the experimental assessment of the airfoil NRL S834 varied between 0° and 8°. Further increasing the AoA would lead to inaccurate results due to significant flow blockage and thus, was not investigated. The collection of the experimental data and the corrections of the results (e.g. blockage correction) were both conducted according to the suggestions of Barlow et al. (1999).



a) *b)*

Figure 1: (a) The wind tunnel facility of the AUTH and (b) The constructed NRL S8334 airfoil, mounted inside the windtunnel

2.3 CFD analysis

At the next step a computational mesh was created, as shown in Figure 2, reflecting the experimental setup. Additionally, similar boundary conditions were selected for the computations. For the turbulent kinetic energy and the dissipation of turbulence the boundary conditions are presented in Table 1. The length and height of the 2D computational domain were placed at such distances so that the free stream flow would stay unaffected at all directions, following validated suggestions and conclusions from Dimitriadis (2012).

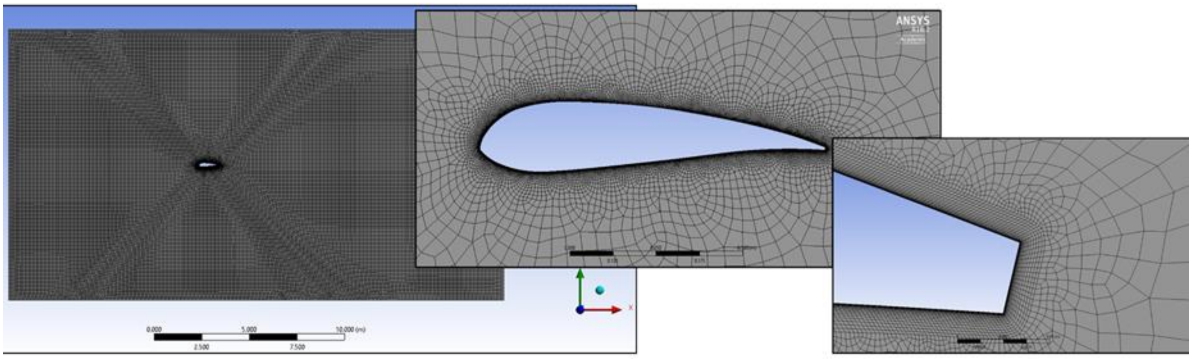


Figure 2: The computational mesh regarding the CFD calculations

Table 1: Turbulence boundary conditions for the test cases

Turbulent Intensity (%)	1
Turbulent Length Scale (m)	0.13

The mesh was unstructured, except for a restricted region around the airfoil surface, where the mesh was structured-like, to better capture the boundary layer development and its transitional characteristics. In the airfoil critical regions, such as the leading edge and the trailing edge, a finer mesh was applied while the inflation layer was constructed with more than 20 layers and a growth rate of 1.2. For the turbulence modelling and since the boundary layer is expected to have transitional characteristics, two transitional turbulence models were selected, the k-kl-ω turbulence model of Walters and Cokljat (2008) which is a model that adopts the laminar kinetic energy concept and the 4-equation SST model of Menter et al. (1994) that uses additional transport equations for the Reynolds theta (boundary layer momentum thickness) and the intermittency factor. The distance of the first layer from the walls was placed accordingly, in order to achieve y+ values less than 1 for the entire airfoil, ensuring accurate computations for the selected transitional turbulence models.

A series of computational test runs (Figure 3) were carried out in order to achieve a grid-independent solution for the 200,000 Reynolds number. It was concluded that a computation mesh of 114,000 computational nodes was sufficient, enabling a time efficient and effective investigation of the airfoil aerodynamic behaviour. The angle of attack for the grid-independency study was chosen to be the 10°, ensuring that the grid will be able to capture the developed flow phenomena for the most demanding case, away from the linear aerodynamic region of the airfoil. The selected transitional model for the grid-independency study was the 4-equation SST, as implemented in Ansys Fluent CFD software (ANSYS® Academic Research Mechanical, Release 18.2).

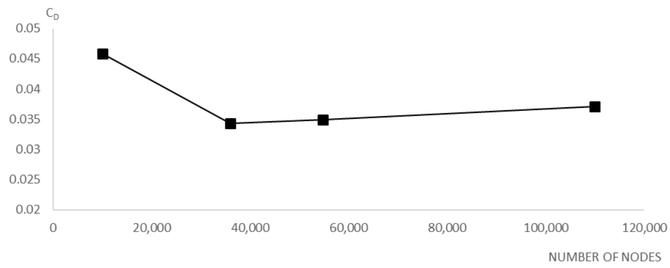


Figure 3: Grid dependency study (Coefficient of Drag)

3. Results and discussion

As seen in both Figures 4 and 5, the experiments performed at the wind tunnel of the LFMT have a close agreement with the literature experimental data (Selig and McGranahan, 2004). CFD results for Reynolds number of 200,000 depicted in Figure 4, and especially the k-kl-ω turbulence model, have a good agreement with both the experimental measurements and literature findings between angles -6° and 8° regarding the lift coefficient. This region is characterized by linear behaviour and lack of major flow detachments. Generally, the literature results seem to be contained between the two transitional models. As the angle of attack (AoA) increases, the simulation deviates from the experimental data. Regarding the drag coefficient, as presented in Figure 5, a significant difference between the computations and the experimental measurements can be observed. Even though the trend from the simulations appears to have a similarity with the literature findings, CFD overestimates the coefficient of drag between 3° and 10°.

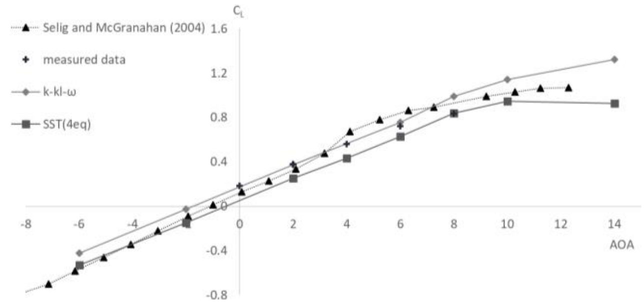


Figure 4: Lift coefficient versus angle of attack for Re number of 200,000 for the NRL S834 airfoil

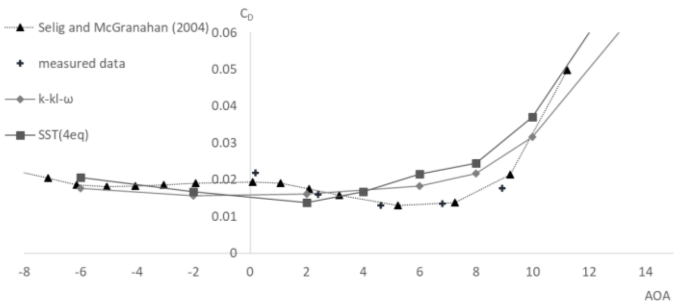


Figure 5: Drag coefficient versus angle of attack for Reynolds numbers 200,000 for the NRL S834 airfoil

Figures 6 and 7 refer to a Reynolds number equal to 350,000. The CFD results are in closer agreement in this Reynolds number region and almost identical to the literature experimental data (Selig and McGranahan, 2004). This effect can be attributed to the more turbulent behavior of the flow which is better captured by the applied CFD models. Again, a drag overestimation between angles 3° and 10° can be observed. Finally, the k-kl-ω turbulence model seems to have a greater accuracy.

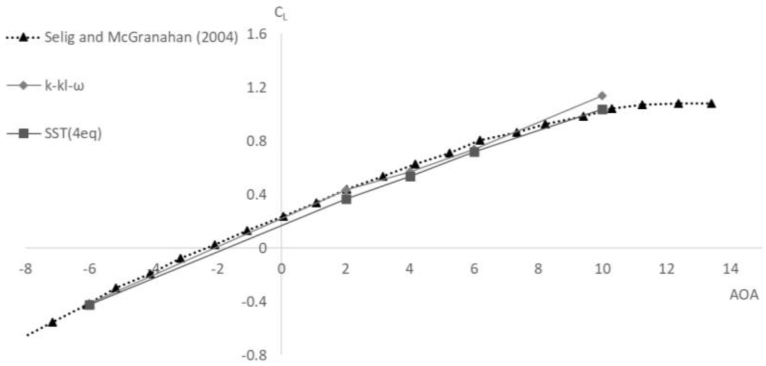


Figure 6: Lift coefficient versus angle of attack for Reynolds numbers 350,000 for the NRL S834 airfoil

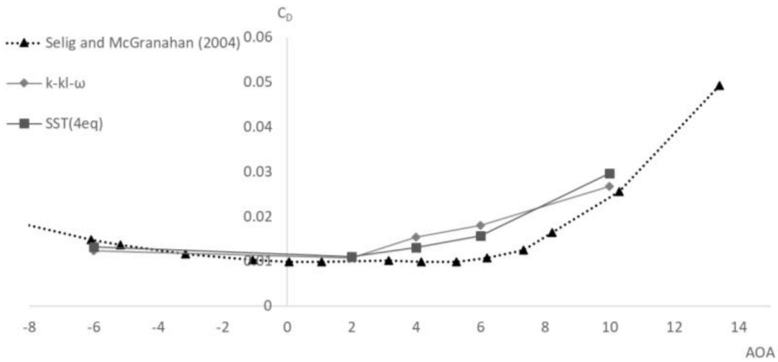


Figure 7: Drag coefficient versus angle of attack for Reynolds numbers 350,000 for the NRL S834 airfoil

4. Conclusions

The experiments conducted at the present paper in the wind tunnel of LFMT of AUTH were validated with the use of experimental data available from the literature. Regarding the lift coefficients, the applied transitional models provide results of reasonable accuracy, especially for the linear region in relation to the angle of attack. Furthermore, the achieved accuracy is significantly improved as the Reynolds number is increased. Both transitional models (k-kl-ω and the 4 equation SST) can be used for applications regarding SHWT aerodynamic analysis regarding the transitional flow regime. The CFD results for the drag coefficient show that there is a good agreement of the computations in comparison to the experimental data for both turbulence models and Reynolds numbers below 3º AOA. On the other hand, between the region of 3º to 10º AOA, it is observed that both turbulence models overestimate the effect of drag for the two selected Reynolds numbers. The results prove that the current turbulence models cannot completely capture the aerodynamic phenomena that appear in this Reynolds number vicinity since some deviation occur mainly in the region between 3° to 10° degrees regarding mainly the drag coefficient. Therefore, it is suggested, that experimental approaches are still necessary for the aerodynamic exploration of Low Reynolds SHWT blade characteristics when high accuracy is targeted. Additionally, it is suggested that more advanced turbulence models that are able to capture the Reynolds stress anisotropy should be also considered. Such models are the Reynolds stress model (RSM) of Craft (1998) and the non-linear eddy-viscosity transitional model of Vlahostergios et al. (2009).

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References

Barlow J.B., Rae W.H. Jr, Pope A., 1999, Low speed wind tunnel testing, Wiley-Interscience, New York, United States of America.

Burton T., Sharpe D., Jenkins N., Bossanyi E., 2001, Wind Energy Handbook (Vol. 39), Wiley-Interscience, New York, United States of America.

Craft T.J., 1998, Developments in a low-Reynolds-number second-moment closure and its application to separating and reattaching flows, International Journal of Heat and Fluid Flow, 19, 541–548.

Dimitriadis E., 2012, Flow Field Investigation of a Horizontal Axis Wind Turbine, MSc Dissertation, International Hellenic University, Thessaloniki, Greece.

Dou B., Guala M., Lei L., Zeng P., 2019, Experimental investigation of the performance and wake effect of a small-scale wind turbine in a wind tunnel, Energy, 166, 819–833.

Douvi C.E., Tsavalos I.A., Margaris P.D., 2012, Evaluation of the turbulence models for the simulation of the flow over a National Advisory Committee for Aeronautics (NACA) 0012 airfoil, Journal of Mechanical Engineering Research, 4(3), 100–111.

Fuglsang P., Bak C., 2004, Development of the Risø wind turbine airfoils, Wind Energy, 7(2), 145–162.

Hansen M.O., 2015, Aerodynamics of wind turbines: Second edition, Earthscan, London, UK.

Menegozzo L., Dal Monte A., Benini E., Benato A., 2018, Small wind turbines: A numerical study for aerodynamic performance assessment under gust conditions, Renewable Energy, 121, 123–132.

Menter F.R, Langtry R. B., Likki S. R., Suzen Y. B., Huang P. G., Volker S., 2004, A Correlation Based Transition Model Using Local Variables Part 1 - Model Formulation, ASME, Turbo Expo: Power for Land, Sea, and Air, 4, 57–67.

Pfaffel S., Faulstich S., Rohrig K., 2017, Performance and reliability of wind turbines: A review, Energies, 10, DOI: 10.3390/en10111904.

Ren G., Liu J, Wan J., Li F., Guo Y., Yu D., 2018, The analysis of turbulence intensity based on wind speed data in onshore wind farms, Renewable Energy, 123, 756–766.

Selig M.S., McGranahan B.D., 2004, Wind Tunnel Aerodynamic Tests of Six Airfoils for Use on Small Wind Turbines, Journal of Solar Energy Engineering, 126, 986–1001.

Singh R.K., Ahmed M.R., Zullah M.A., Lee Y.H., 2012, Design of a low Reynolds number airfoil for small horizontal axis wind turbines, Renewable Energy, 42, 66–76.

Thé J., Yu H., 2017, A critical review on the simulations of wind turbine aerodynamics focusing on hybrid RANS-LES methods, Energy, 138, 257–289.

Timmer W.A., van Rooij R.P., 2003, Summary of the Delft University Wind Turbine Dedicated Airfoils, Journal of Solar Energy Engineering, 125, 488–496.

Vlahostergios Z., Yakinthos K., Goulas A., 2009, Separation-induced boundary layer transition: Modelling with a non-linear eddy-viscosity model coupled with the laminar kinetic energy equation, International Journal of Heat and Fluid Flow, 30, 617–636.

Walters D., Cokljat D., 2008, A Three-Equation Eddy-Viscosity Model for Reynolds-Averaged Navier–Stokes Simulations of Transitional Flow, ASME Journal of Fluids Engineering, 130, 121401–121401–14.