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Numerical Analysis and Optimization of a Winglet for a Small Horizontal Wind Turbine Blade

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Wind energy is one of the main alternative energy sources and is present in various forms, from large offshore wind turbine installations, to small, privately used, small horizontal wind turbines (SHWT). Optimization of the turbine blades, and eventually of their efficiency, is of great importance, especially for SHWT. SHWT are exposed to a turbulent inflow, where 3D flow effects are dominant due to the relatively small length of the wind turbine blades. At the edge of the blade, tip vortices are generated, inducing high drag and significantly reducing the lift and torque generated near the blade tip. In order to convert this energy to useful lift, a winglet can be applied at the tip of the blade by acting in a comparable manner to a blade span increase. In the current paper the effect of five winglet modifications on the overall generated power of a SHWT is presented. More specifically, four distinct winglet cant angles are selected for this optimization procedure. Parameters such as winglet height, sweep of the winglet, toe angle and twist angle are held constant, in order to highlight the effect of the different cant angles. The sole exception is that one of aforementioned designs is further modified with a sweep angle of 20°, in order to assess the possible change in the aerodynamic behavior. The CFD computations for the evaluation of the proposed modifications use a rotating frame, with one of the three blades of the SHWT. The addition of the winglet alters significantly the flow pattern over the wing tip. As a result, the aerodynamic performance and the torque generation are improved from 1.5 % to almost 11 %, underlining the potential of further optimizing blades of SHWT.

1. Introduction

Wind turbines have been established as one of the leading elements in the global struggle against hydrocarbons, holding a third of the renewable energy share (Thé and Yu, 2017). In the search for a greater energy output, manufacturers turned to increasing hub heights and rotor diameters. This in turn, led to the construction of large offshore wind parks, creating 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. This situation gradually created the demand for distributed generation close to the consumers in the form of small wind turbines (SWT). These SWT can also be used to expand the efficiency of existing Diesel Plants in remote areas, by reducing the fuel consumption and minimizing the maintenance costs of the Diesel Plant (Rozali et al., 2015). SWT have a mean radius of 1.5 to 3.5 m and are capable of generating 1 - 10 kW of electricity in the relatively low Reynolds number of 200,000 to 350,000. With a relatively small energy output, SWT could greatly benefit from optimization modifications, such as the winglet.

Winglets are a well-known feature in aerospace applications since the 70-s (Whitcomb, 1976). They started as simple endplates on the edge of the wings, but have evolved significantly in the last decades, providing airplanes

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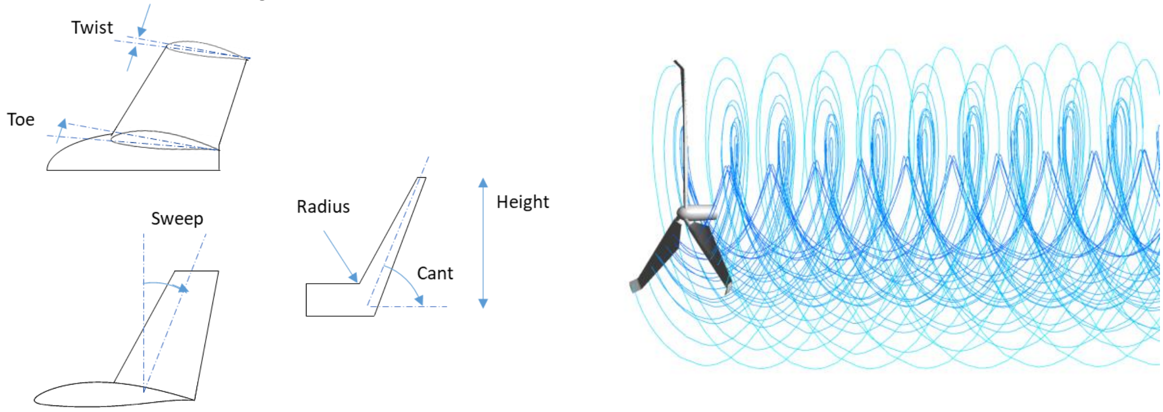
with a greater overall aerodynamic efficiency. Winglets can help reduce the size and the intensity of the tip vortices generated due to the pressure difference between the blade's pressure and suction side. This modification can help reduce the drag, but also possibly increase the lift and torque generated near the blade tip.
While going through the literature, it became evident that the wind turbine industry has experimented only limitedly and empirically with the possible positive effects of winglets until nowadays and regards almost solely large wind turbines. The addition of the centrifugal forces makes the winglet selection different from an airplane winglet. The parameters considered for the design of a winglet in general are its height, sweep angle, cant angle, curvature radius, toe angle and twist angle as shown in Figure 1a and can possibly impact the wake of a SHWT (Figure 1b). Johansen and Sørensen (2006) claim in their report for large wind turbines, that modifying the twist of the winglet tip had at best a 1.5 % improvement. In their study, the winglet had no sweep, while the winglet height is kept constant at 1.5 % of the rotor radius. One of the models had a cant angle of – 90 ° and the other 4 had a cant angle of + 90 °.



a) *b)*

Figure 1: (a) The basic geometric characteristics of a winglet and (b) Streamlines behind one of the proposed winglet designs

Gupta and Amano (2013) proved, using the Spalart-Almaras turbulence model, that a winglet with a cant angle of 45 ° and with a winglet height of 4 % increased the power output by 20 % compared to a straight blade in a wind turbine with a radius of 20 m. Winglets with a cant angle of 90 ° improved only partially the power output. Elfarra et al. (2015) studied the winglet design in a wind turbine with a blade radius of 5 m with the k-e turbulence model. They showcased that winglets that point towards the suction side produce increased power compared to winglets that point to the pressure side. Regarding SHWT, the gap in literature is even greater. Imamura et al. (1998) suggested with the help of the vortex lattice method, that it seems important to have a relatively small curvature radius. Khaled et al. (2019) used an Artificial Neural Network for their winglet optimization study. Their optimized winglet for Small Horizontal Wind Turbine (SHWT) had a cant angle of 48 ° and length 6.3 % of the blade. Concluding, even though there is some literature data about winglets for large wind turbines, there is no clear guidelines for the design of an optimized winglet for a SHWT. In addition, there is no evidence that winglets for SHWT are designed with the same principles as winglets for large wind turbines, given the smaller Reynolds numbers, different rotation speeds and the highly turbulent and volatile air inflow found in SHWT operating environment. Finally, all CFD cases used in the literature had different turbulence models. This paper will try to fill some of this gap by presenting a first step in a more thorough approach.

2. Methodology

In this paper, the CFD modelling and optimization of a wind turbine blade winglet of a Small Horizontal Wind Turbine (SHWT) is presented. More specifically, four winglets (Winglet 1, 2, 3 and 4) were originally designed and a fifth was later added (Winglet 5) as a variation of Winglet 4. Initially, the blade without winglet (baseline) was studied with CFD calculations of a rotating reference frame in average operational conditions. The five designed winglets were tested similarly at the same operating conditions.

2.1 Setting the requirements

The average inflow of air at the area of Hannover, where the SHWT under study has been tested, has been measured to be 10 m/s, leading to an operational Reynolds number region of approximately 200,000 – 450,000.

Another significant aspect in wind turbines operation is the tip speed ratio (Eq(1)). The tip speed ratio is defined as:

$$\lambda=\frac{\omega\cdot R}{U_\infty} \quad (1)$$

where ω is the rotational speed of the blade, R the radius of the blade and U_∞ the wind velocity of the free stream. This variable expresses the ratio between the tangential speed of the tip of the blade and the actual speed of the wind. The design goal was to have a tip speed ratio of 5, as this value offers the greatest increase in the coefficient of power. Coefficient of power is a measure of efficiency, namely the ratio of the extracted power to the total of power of the free stream.

2.2 Winglet geometry

Having the available literature data in mind, five winglet designs are proposed for the investigation. The geometry of each designed winglet is such that it could replace the endcap of the current blade design and provide an easy manufacturing alternative solution. For the same reason, the airfoil used for the winglet was selected to be identical with the most outer blade's airfoil. The most predominant characteristic of a winglet is the cant angle, as it greatly influences the path of the flow. Winglets 1 - 4 have a cant angle of + 90 °, + 45 °, - 45 ° and -90 °, while Winglet 5 has also a cant angle of -90 °. The taper ratio for Winglets 1 - 4 is 1, while Winglet 5 was designed to test the magnitude of the effect of the Leading-Edge sweep angle and has a taper ratio of 0.83 in order to keep the trailing edge constant (Figure 2). The twist and toe angle were 0 for all the designed winglets, as all available literature pointed out that their effect was minimal. The winglet height was constant for all winglet designs and equal to 5 % of the blade radius. As a result, the total spanwise length of each blade differed slightly depending on the cant angle.

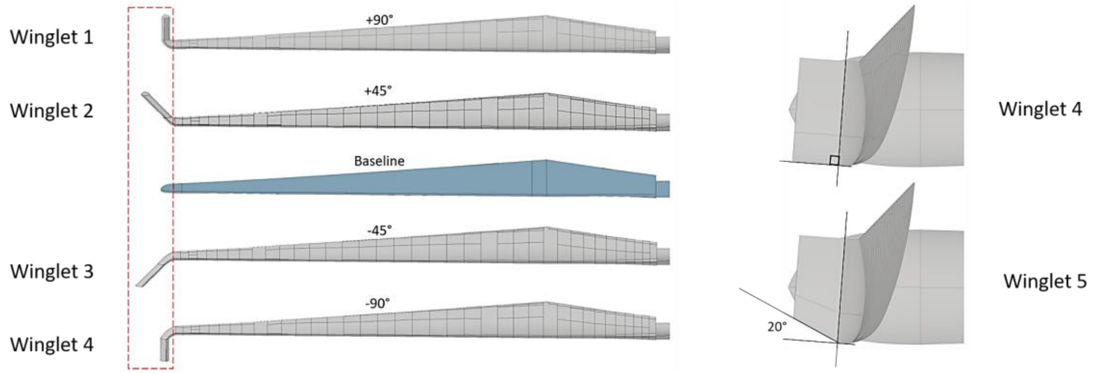


Figure 2: The proposed winglet designs, in comparison with the baseline CAD

2.3 CFD setup and analysis

In order to assess the effects of the winglet and the inboard region, the region close to the wind turbine nacelle, a 3D CFD calculation was initially performed. The boundaries of the computational domain were placed significantly far from the wind turbine blade and are shown in Figure 3a. A rotating reference frame was used, in relation to which the wind turbine blade surface is considered stationary. The computational domain (Figure 3a) had a length of 1.5 diameters of the wind turbine in front of the turbine, 3.5 diameters in the wake of the turbine, and 2.5 diameters in the spanwise direction, to capture sufficiently the wake and ensure a stable numerical convergence, while simultaneously sparing computational power.

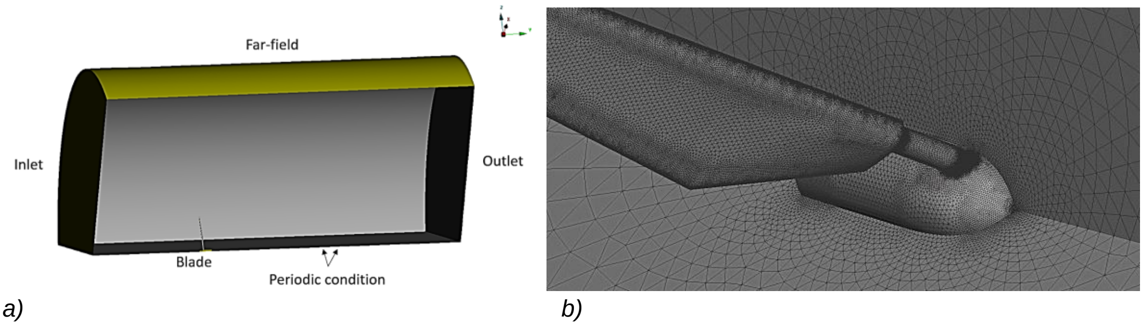


Figure 3: (a) The control volume conditions and (b) The computational mesh of the CFD runs

At the next step a computational mesh was created, as shown in Figure 3b. A fine mesh of about 4.7 million computational nodes was constructed. 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. In the blade critical regions, such as the leading edge, trailing edge, blade tip and the connection of the blade and the nacelle, a finer mesh was applied. In order to capture the boundary layer transition phenomena, 18 inflation layers were used, with a growth rate of 1.2 and a y+ value of less than 1. The selected turbulence model was the 4-equation SST model of Menter et al. (1994), as implemented in Ansys Fluent CFD software (ANSYS® Academic Research Mechanical, Release 18.2), that uses, apart from the transport equations for the turbulent kinetic energy and the specific turbulence dissipation rate, additional transport equations for the Reynolds theta (boundary layer momentum thickness) and the turbulent intermittency factor. This turbulence model was qualified as optimum for this scenario from a previous work of the authors (Papadopoulos et al., 2019). Finally, the turbulence intensity was set to 5 %, a typical value for wind turbine applications.

3. Results and discussion

The baseline model, without a winglet, gives a Cp value of 0.3579 and sets the basis for the optimization study. Table 1 shows the basic geometric characteristics of the designed winglets and the effect they have on the coefficient of power. It becomes evident, that all proposed winglet designs increase the Coefficient of power from 1.4 % up to almost 11 %. The winglets with a cant angle of ± 90° (Winglet 1, 4 and 5) performed with mediocre or no significant efficiency. On the other hand, winglets with a cant angle of ± 45° led to an important increase in the coefficient of power. Regarding the leading edge sweep, the modification did not improve the effectiveness, but on the contrary, had a slight worse performance.

Table 1: The designed winglets and their effectiveness

Winglet design	Cant angle	Height (% of blade radius)	Sweep	Increment	Cp % more than baseline
Winglet 1	+ 90 °	5	0	0.005	1.4
Winglet 2	+ 45 °	5	0	0.042	10.9
Winglet 3	- 45 °	5	0	0.022	6
Winglet 4	- 90 °	5	0	0.013	3.7
Winglet 5	- 90 °	5	20	0.010	3

In order to better understand the effect of the cant angle and leading edge sweep on a wind turbine blade efficiency, streamlines on the tip of the blade were visualized as shown in Figure 4. The baseline model seems to have one uniform, but strongly tangled, wake. Winglet 1 can be observed to have an adverse effect, with recirculation on the trailing edge. Winglet 1 seems to be the only winglet with recirculation, explaining the smallest increment in the coefficient of power. Winglets 4 and 5 seem to have a similar wake, confirming the almost identical aerodynamic effectiveness.

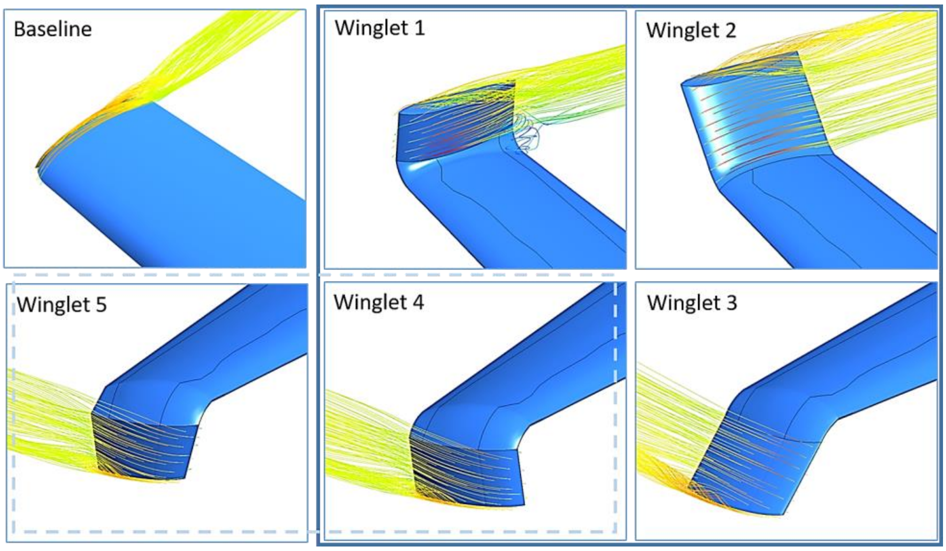


Figure 4: Streamlines on the designed winglets, compared to the baseline blade tip

For having an even better understanding of the winglet effect on the flow development, the vortexes generated by the wing tip were also visualized with the use of the Q-criterion (Figure 5). Q-criterion represents the local balance between shear strain rate and vorticity magnitude, defining vortices as areas where the vorticity magnitude is greater than the magnitude of rate-of-strain (Hunt et al, 1988). The baseline model's blade tip vortex can be observed to be single, but tangled, confirming the previous assumption. Winglet 1 has clearly, the most visible and intense wake. Winglets 4 and 5 appear to have almost identical blade tip wake, consisting from a primary wake at the tip and a secondary wake at the root of the winglet. Winglets 2 and 3 seem to have the best wake behavior.

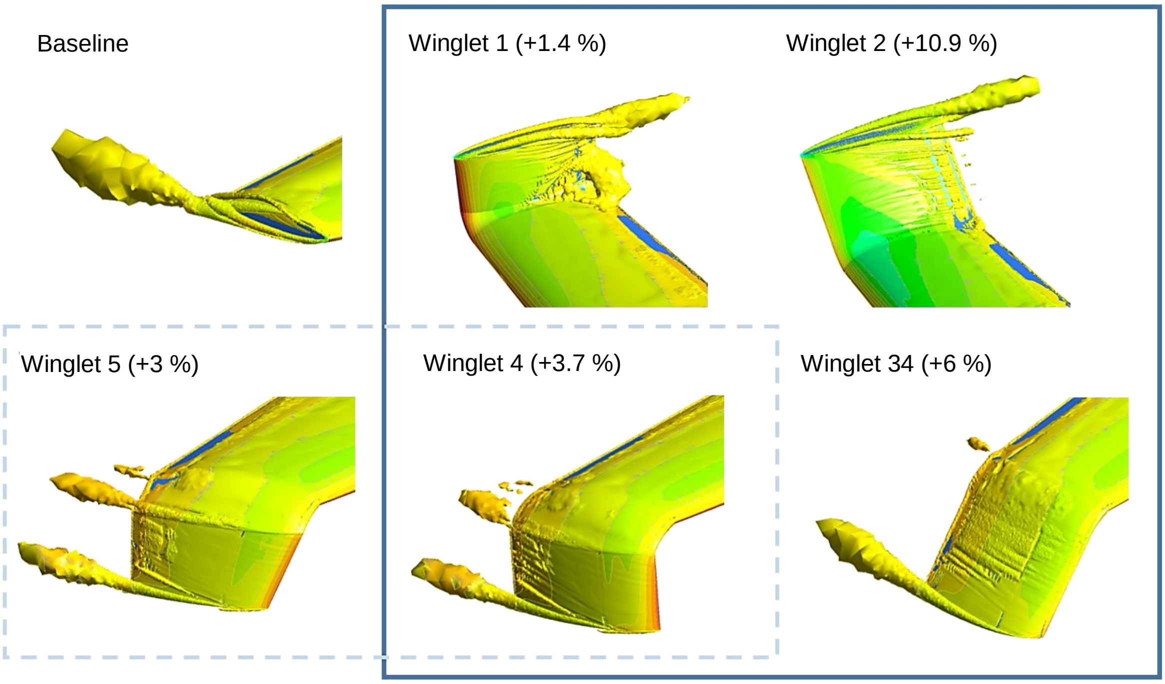


Figure 5: Pressure distribution, with a Q-criterion value of 26,490 s^{-2}, on the designed winglets, compared to the baseline blade tip

Regarding the pressure distribution, all winglets together with the baseline model, can be observed to have similar distribution. Exception is Winglet 2 with what seems to be a favorable pressure distribution.

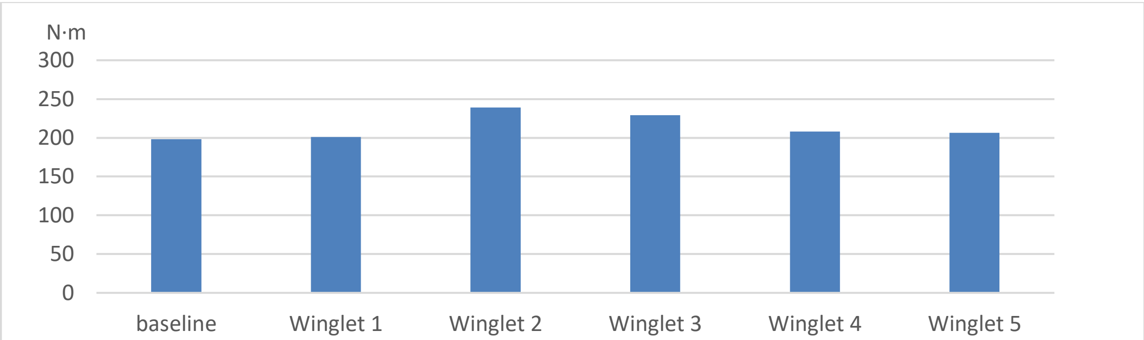


Figure 6: Torque per blade, as calculated in the 3D CFD comparing the baseline model with the proposed designed winglets

Finally, in Figure 6, the torque per blade is presented. Larger torque leads to greater coefficient of power, proving once more the superiority of winglets with a cant angle of 45 °. Specifically, Winglet 2 produced the greatest torque, with almost 41 N·m more than the baseline model.

4. Conclusions

In the current paper, 5 different winglet geometry designs were numerically investigated for their effect on the overall performance of a small horizontal wind turbine. The performed computations proved, that the addition of a winglet significantly improves the performance of a small wind turbine blade. The cant angle of + 45 ° had the most positive effect on the generated power. On the other hand, the Winglet 1, with a cant angle of + 90 °, had the least positive effect. It can be concluded, that winglets with a cant angle of 45 °, either in the positive or negative direction, were more effective than winglets with a cant angle of 90 °. These results confirm that a cant angle of 45 ° seems to be the most beneficial for both SHWT and large wind turbines. Regarding the leading edge sweep, it seems to have only a slight positive effect on the efficiency of the winglet. A more meticulous study is planned to be performed in the future, where the variation of additional geometric characteristics will be considered. In overall, the optimized winglet had an almost 11 % increase in the efficiency of a wind turbine blade, enabling the possible reduction of the total amount of hydrocarbon emissions. Future work based on this outcome should address the other crucial winglet variables, such as winglet height and sweep, in order to conclude about the possible similarity between SHWT and large wind turbines winglet design. Finally, variables such as toe angle and twist have almost nonexistent literature data and should also be addressed, for both cases.

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References

Elfarra M.A., Sezer Uzol N., Akmandor İ.S., 2015, Investigations on blade tip tilting for HAWT rotor blades using CFD, International Journal of Green Energy, 1, 12(2), 125-138.

Gupta A., Amano R.S., CFD analysis of wind turbine blade with winglets, 2012, ASME 2012 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, August 12-15, 2012, Chicago, IL, USA, American Society of Mechanical Engineers Digital Collection, 843-849.

Hunt J.C., Wray A.A., Moin P., 1988, Eddies, streams, and convergence zones in turbulent flows, Center for Turbulence Research Report, CTR-S88, 193-208.

Imamura H, Hasegawa Y, Kikuyama K., 1998, Numerical analysis of the horizontal axis wind turbine with winglets, JSME International Journal Series B Fluids and Thermal Engineering, 15, 41(1), 170-176.

Johansen J., Sørensen N.N., 2006, Aerodynamic investigation of Winglets on Wind Turbine Blades using CFD, Risø-R-1543(EN), Risø National Laboratory, Roskilde Denmark, No 1543.

Khaled M., Ibrahim M.M., Hamed H.E.A., AbdelGwad A.F., 2019, Investigation of a small Horizontal–Axis wind turbine performance with and without winglet, Energy, 187, 115921.

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.

Papadopoulos C., Kaparos P., Vlahostergios Z., Misirlis D., 2019, Numerical Analysis and Experimental Measurements of a Small Horizontal Wind Turbine Blade Profile for Low Reynolds Numbers, Chemical Engineering Transactions, 76, 187-192.

Rozali N.M., Alwi S.W., Ho W.S., Manan Z.A., Klemeš J.J., 2015, Expansion of a diesel plant into a hybrid power system using power pinch analysis, Chemical Engineering Transactions, 45, 343-348.

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.

Whitcomb R.T., 1976, A design approach and selected wind tunnel results at high subsonic speeds for wing-tip mounted winglets, NASA Langley Research Center, NASA TN D-8260.